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# Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities

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July 2003

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## 1.0 Introduction

The exploration of the Moon first undertaken in 1950s and culminating with Apollo between 1969-1972 contributed immensely to our understanding of the Moon, its early history, its relationship to the Earth and its place in our solar system (c.f. Taylor, 1982). It also formed the basis for many new questions about the Moon as a planet and provided stimulating conceptualization of a future role of the Moon in the human exploration of space and the potential commercial development of space. Immediately following the Apollo program's termination, the next phase of lunar exploration was perceived to be a Lunar Polar Orbiter, an orbiting remote sensing program, to understand the chemistry and mineralogy of the Moon on a global basis (JPL, 1977). Over twenty years later, the Department of Defense's Clementine mission and NASA's Lunar Prospector mission began to address these global mapping issues. They will be further addressed with the European Space Agency's SMART-1 mission (Foing et al., 2002) and Japan's Lunar-A and SELENE missions (Mizutani et al. 2002; Sasaki et al. 2002), which should be carried out by 2005-2006.

Scientifically, the new data from Clementine and Lunar Prospector have shown that the Moon is more complex than was appreciated following the Apollo missions (Haskin et al. 2000). It is now clear that important geochemical provinces exist (Figure 1-1) that must be related to the early history of the Moon and that can provide important information on the evolution of rocky planets like the Earth. Following the SMART-1 and SELENE missions, the next steps in lunar exploration will once more require surface missions, both robotic and human, to continue the detailed study of important planetary problems such as the nature of initial planetary melting and segregation into core, mantle and crust and the early bombardment history of the Moon (and Earth). Many other scientific objectives can be uniquely or most effectively accomplished on the surface of the Moon.

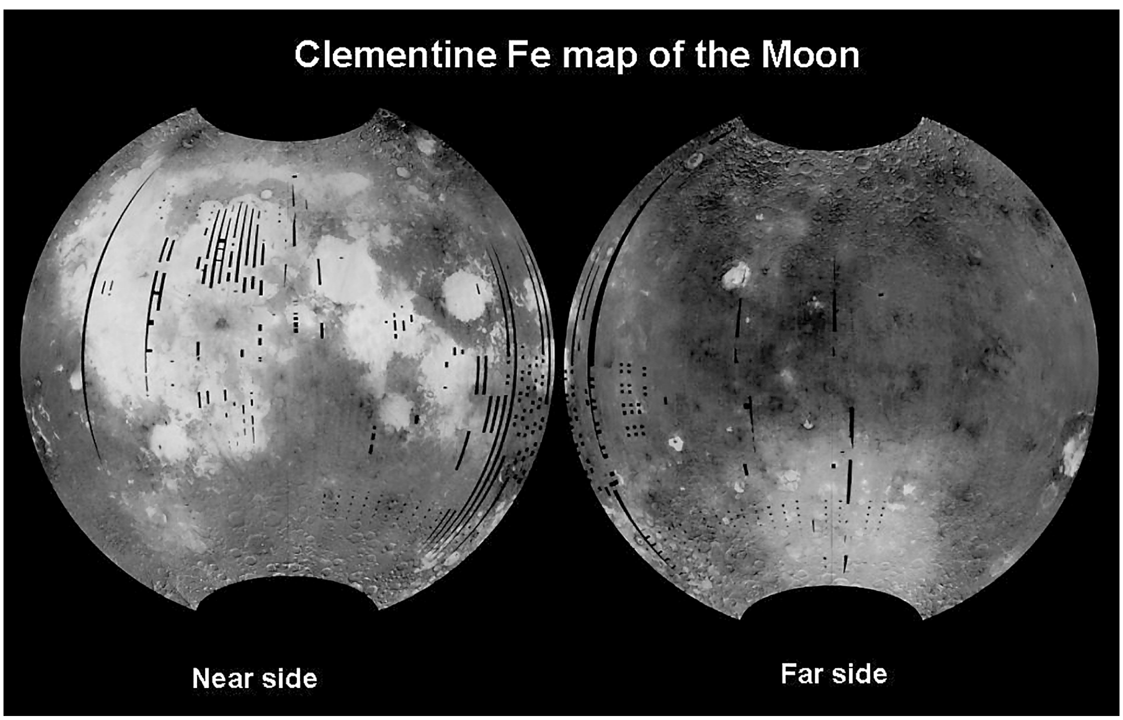


Figure 1-1. Iron map of the Moon. Based on interpretation of spectroscopic data obtained by the Clementine mission. The bright areas on the near side are the mare regions, dominated by basaltic lava flows. The dark areas represent the highlands, composed of calcium-aluminum-silicon-rich anorthositic rocks. The light area in the southern hemisphere of the far side is the South Pole – Aitken Basin.

Likewise, the exploration of other bodies in the solar system, most notably Mars, must proceed to the surface, eventually leading to human exploration. The Moon is viewed in this light as a place, close to the Earth, where the design of human missions to Mars can be perfected in an appropriate environment, but one that is only a few days away from Earth. The establishment of test beds for technology and operations can yield information and provide confidence in our abilities to explore Mars that will be essential when humans are sent there.

Our current understanding of meteorite impact as a planetary phenomenon was an important contribution of the Apollo program, leading to the discovery that asteroid impacts have been devastating to life in the past on Earth and could be to civilization in the future (c.f. Morrison, 2002). One product of these discoveries has been the reawakening of thoughts of the migration of humans into space on a permanent basis. The colonization of, and even the human engineering of, the Martian environment (terraforming) have become popular discussion topics. The Moon may also be a place where humans decide to establish permanent outposts or settlements. This will require that the capabilities of humans on the surface of the Moon be determined and that useful activities be identified. Some of these may include economic activities that can be best implemented on the Moon or with the use of the natural resources of the Moon.

All of these themes contribute to the need for new exploration of the Moon's surface with robots and humans. This document is a start toward defining the types of activities that should be undertaken by the next wave of surface investigations of the Moon. It is patterned after the Mars Surface Reference Mission (Hoffman, 2001), which was developed to allow a better understanding of the requirements for human exploration of Mars. Discussions of many of the topics covered in Hoffman (2001) have been used extensively here, because they are equally applicable to the Moon as to Mars. In other sections, we have developed new descriptions and approaches, based on discussions in the literature that has been developing since the mid 1980's (e.g. Mendell, 1985) regarding the future human exploration and development of the Moon.

The organization of this document begins with a description of several major objectives of renewed exploration of the Moon: (1) Scientific exploration; (2) Determining the suitability of the Moon as the basis for astronomical and other observations; (3) Developing technology and conducting tests relevant to long-term human stays on the Moon; (4) Developing technology and conducting tests of technical and human systems relevant to the human exploration of Mars and beyond; (5) Testing technologies and conducting investigations that can lead to economically beneficial activities on the moon; and (6) Understanding the conditions under which crew health, safety and performance and effective facility operations can be extended for long-duration missions. For each of these areas, the rationale for the activities, their scope and scale, how they might be accomplished, and the functions required to conduct them, are provided.

Many of the capabilities required to carry out the objectives are common between objectives, so they are presented and discussed in a section that describes major functional requirements, such as field investigations, mobility, sample analysis, teleoperations, and various crew functions. These are the functions that must be carried out on the lunar surface. Missions will be designed to allow some or all of these functions to be conducted to achieve specific mission objectives, which may differ from mission to mission.

Finally, scenarios are provided for two classes of missions: (1) a short-stay time mission, similar to Apollo, in which 4 astronauts spend four days on the lunar surface; and (2) a longer stay time mission, with the capability to support 4 people for 30 days on the Moon. In the long stay time missions, it is possible to add infrastructure incrementally that builds toward even longer stay times for crews on subsequent visits. To provide a true test bed for human exploration of Mars, infrastructure suitable for stays of up to 18 months with crews of 6 or more people on the lunar surface could be required. Construction of these scenarios allows a visualization of potential missions. The scenarios also allow the discussion of operational issues and strategies to allow the optimal use of the resources available, particularly crew time.

The choice of locales for lunar exploration will be a complex process, depending on the emphasis placed on a number of considerations, including political commitment and international cooperation. For that reason, some candidate sites are discussed as examples, but should not be considered definitive. Three candidate sites for short-duration missions and two candidate sites for long-term missions are discussed.

Planetary protection issues for the Moon were resolved by the Apollo explorations. In general, it is not necessary to take extra precautions with crewmembers or for samples returned to Earth for planetary protection purposes. The preservation of samples free from human contamination will be an issue for some samples. The collection of samples for return to Earth from polar ice deposits raises significant sample containment issues and potentially could be considered an issue for planetary protection, as they may contain evidence for prebiotic compounds derived from meteorites and comets.  Technologies and techniques for planetary protection in future exploration of Mars and beyond might be tested first on the Moon.

It should be noted that the Lunar Surface Reference Mission is a tool, not a prescription for a program. The selection of tasks to be accomplished will vary according to the emphases placed on the major themes of lunar exploration and development and the capabilities of specific missions. The technology for accomplishing the tasks will change with time, offering opportunities to improve the concepts presented here or replace them with other tasks. The Lunar Surface Reference Mission is intended as a tool for mission planners, to determine the general level of transportation and surface infrastructure support that must be provided. It can also be used by scientists and engineers who have ideas about what should be, or may be, accomplished on the lunar surface, to examine their ideas in the context of the resources expected to be available.

## 2.0 Objectives of Lunar Missions

The principal goals of lunar missions will be scientific, including lunar science as well as other science that can be done on or from the Moon; preparation for subsequent human exploration of Mars and/or long-duration human activities on the Moon, and understanding the potential economic implications of lunar development. The particular emphasis remains to be determined and is subject to a set of essentially political considerations, such as what the scope of international participation will be, whether the human exploration of Mars is viewed as a nearer- or farther-term prospect, and what seem to be the most compelling of the rationales at the time the program is undertaken. For purposes of organization, the goals selected here include: (1) Scientific exploration; (2) Determining the suitability of the Moon as the basis for astronomical and other observations; (3) Developing technology and conducting tests relevant to long-term human stays on the Moon; (4) Developing technology and conducting tests of technical and human systems relevant to the human exploration of Mars and beyond; (5) Testing technologies and conducting investigations that can lead to economically beneficial activities on the moon; and (6) Understanding the conditions under which crew health, safety and performance and effective facility operations can be extended for long-duration missions. There is considerable overlap between the technology goals. An attempt has been made to describe the goals under each of these objectives in a way that is specific for that goal.

### 2.1 Scientific Exploration of the Moon

The exploration of the Moon has principally been carried out in the Apollo Program the Russian Luna Program and, more recently, by the Clementine and Lunar Prospector missions. In the late 1980s, the Lunar Exploration Science Working Group (LExSWG) examined the scientific strategy for lunar exploration, focusing principally on the need for additional orbital data (LExSWG, 1995). Much of the strategy proposed by the LExSWG has either been accomplished by Clementine and Lunar Prospector, or will be accomplished by the SMART-1, SELENE and Lunar A missions. Recently, a project, New Views of the Moon, has been undertaken by the lunar science community to consider the implications of merging the diverse data sets obtained from lunar samples and the orbital data that has recently been collected (Lunar and Planetary Institute, 1998). This will lead to the publication of a compendium targeted for 2003. Taylor and Spudis (1990) documented questions of lunar origin and history that could be addressed through a lunar base program.

Recently, the National Research Council has concluded a study for NASA (NRC, 2002) that has provided priorities for scientific exploration of the solar system through the next decade (2003-2013). Their proposed strategy includes a South Pole – Aitken Basin sample return mission to the lunar far side, which could address a number of scientific issues and is to a place where human missions are not likely for considerable time in the future. The scientific community is also interested in the possibility of conducting polar exploration to understand the nature of volatile concentrations that appear to exist at the lunar poles, based on Lunar Prospector data (Feldman et al., 2001).

The lunar science problems that have the most interest for the scientific community are those for which what is learned on the Moon can be applied to understanding the origin and history of the solar system and the evolution of planets in a general sense. Several sub-goals within lunar science are described below, which can be understood both as lunar science problems, but also as broader planetary science problems.

#### 2.1.1 Origin of Earth-Moon System

Classical explanations of the origin of the Moon fit into three general categories: separate accretion, capture, and tidal spinoff of material from the Earth. In the mid 1980s a new hypothesis, the giant impact hypothesis (Figure 2-1), suggested that the Moon was formed in a collision of a large object with the early

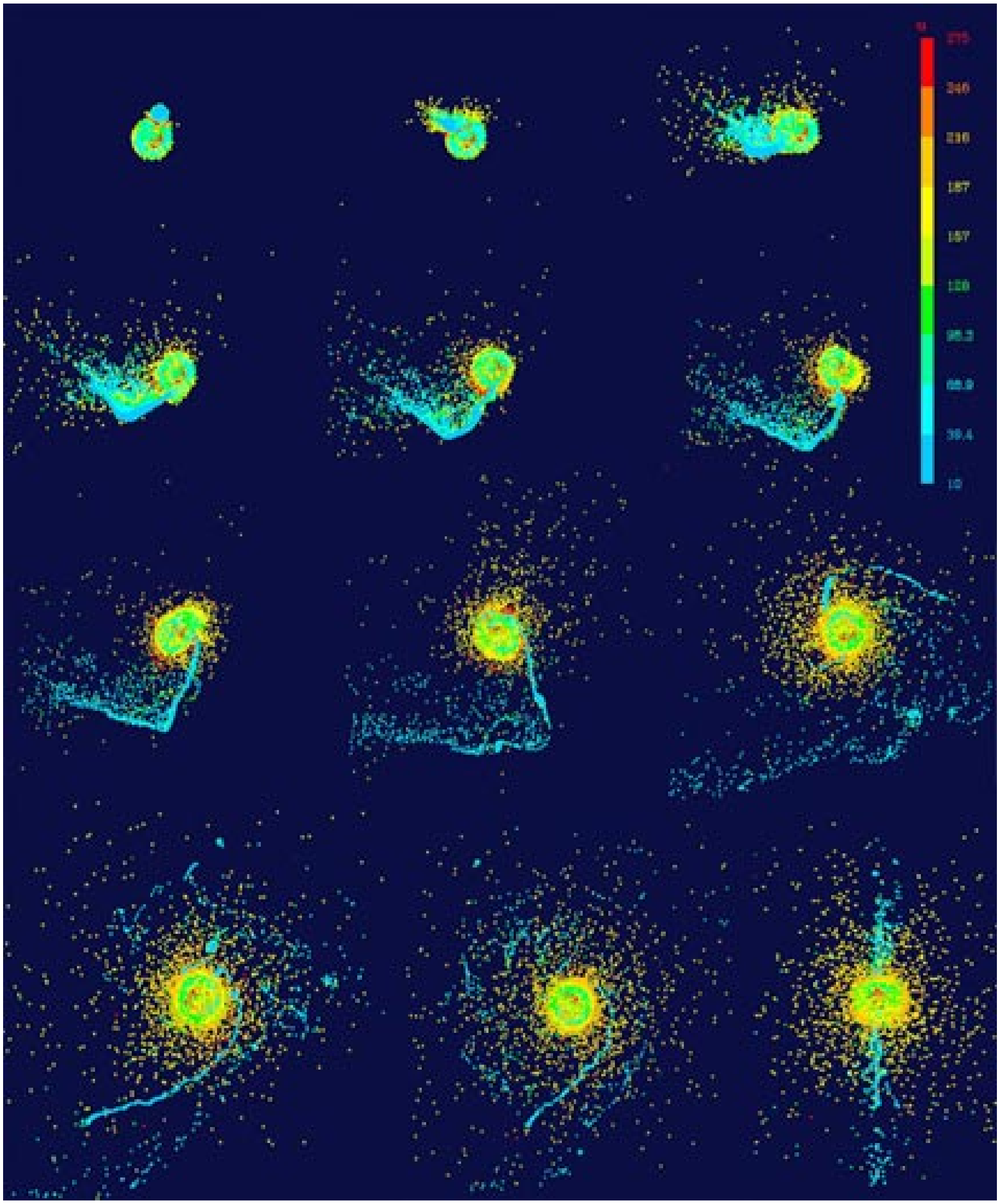



Figure 2-1 A giant impact with Earth may have formed the Moon – Figure shows results of a lunar-forming impact simulation from Canup and Asphaug (2001). The smaller, impacting object is Mars-sized and impacts the Earth obliquely in a counter-clockwise sense. Most of the impacting object eventually ends up on the Earth, but some fraction of it remains dispersed in a cloud of debris orbiting the planet. Color in the simulation is representative of the degree to which the planetary rock has been heated by the impact. The entire impact sequence covers about 24 hours of simulated time. At the end of the impact, the central Earth has a rotational day of only about 5 hours). Individual time frames are shown looking down onto the plane of the impact; the last frame is the final system viewed on edge, with a cooler (blues/greens) disk of material orbiting in the Earth's equatorial plane surrounded by a hot cloud of material (oranges/red).

Earth, which spun off material from the Earth and the impactor to form the Moon (Hartmann and Davis, 1975). This hypothesis is consistent with existing chemical and isotopic information from the Moon and Earth and with current understanding of the dynamics of the early solar system (Canup and Asphaug, 2001). Nevertheless, it remains untested by new lunar data obtained with an eye to serious examination of the hypothesis. The issue is significant for the Earth, as such a formative event could have played a role in early terrestrial evolution. It would also speak to the early impact history of the inner solar system. Finally, a giant impact and the accumulation of its debris would have provided the starting point for subsequent lunar evolution. It is important to understand whether the early history of the Earth and Moon were dominated by such an event, or whether less chaotic processes contributed to the composition and structure of both planets.

This problem can be addressed with additional studies of the Moon aimed at understanding the bulk composition of the Moon. This can be accomplished by thoroughly understanding lunar interior structure, based on geophysical techniques and through detailed understanding of the chemical and isotopic composition of the rocks of the surface that represent specific phases of lunar history. These data provide insight into the earliest compositional features of the Moon, including whether it was initially compositionally homogeneous. The earliest history of the Moon can also be studied by finding rocks that represent the oldest geological processes on the Moon. Some very old rocks (4.5 billion years) were recovered by Apollo astronauts, which indicate that materials from the first 50 million to 100 million years of solar system history can be recovered on the Moon.

The studies that would be undertaken are principally:

- Geophysical networks to probe the deep interior, using instruments at the surface
    - Seismic network. A series of 8 seismometers, distributed around the Moon and operating for at least 10 years. This network will record seismic wave information from moonquakes and meteoroid impacts, from which internal structure, including density, can be determined. These data, in conjunction with compositional information from surface materials, can be used to infer internal composition as well as structure.
    - Heat flow sensors. The heat now coming out of the Moon represents residual energy from the formation of the Moon as well as the release of heat from radioactive decay within the Moon. It can provide information on the current and past thermal state of the Moon.
    - Other geophysical sensors. A variety of other geophysical techniques, such as electrical conductivity and magnetic field observations, may contribute.
- Analysis of samples of the earliest Moon, principally in laboratories on Earth
    - Chemical composition. The chemical composition of the earliest lunar rocks that can be recognized can relate them to their predecessor materials. Many trace elements can be used as tracers for the processes that derived these rocks from the predecessor materials.
    - Isotopic composition. Variations in isotopic composition of many elements have been shown to be sensitive tracers of early processes. It may be possible to more precisely date the time of formation of the Moon.
    - Petrology. The mineral components of rocks and their textural relationships provide information on the processes that were active to form the earliest lunar rocks.

### 2.1.2 History of the Moon as a Planetary Body

Whatever the origin of the materials that produced the Moon, it is evident from lunar sample data that an anorthositic crust had formed at about 4.4 billion years ago. Some rocks in the Apollo lunar sample collection were crystallized at that time, which means that a great deal of thermal processing of the Moon, including wholesale melting of the interior, occurred very quickly after the Moon was formed (Lunar magma ocean hypothesis). It seems likely that this process of crust formation occurred on the other terrestrial planets (Mars, Venus, Mercury and the

Earth). However, on those other planets, that portion of planetary history has been lost to later geological processing. On the Moon, the evidence from that period is still preserved in the crust and mantle as well as in the impact breccias that constitute the lunar "megaregolith," a layer of fragmental debris approximately 2 km in thickness that is constituted of the ejecta from the large craters that were formed in the first several hundred million years of solar system history.

Lunar Prospector and Clementine have demonstrated definitively that, perhaps associated with the formation of the lunar crust, significant movements of material occurred in the lunar interior, resulting in global heterogeneities. In the region of Mare Procellarum, in the northern hemisphere of the near side, impact processes have excavated iron-rich and thorium-rich deposits that have been termed the Procellarum KREEP Terrain (Haskin et al. 2000) (KREEP stands for rock compositions rich in potassium (K), rare earth elements and phosphorus). Rocks of this composition appear to be missing in the South Pole – Aitken Basin of the southern far side of the Moon (e.g. Figure 1-1), though the South Pole – Aitken Basin appears to represent the oldest, deepest impact basin on the Moon. Also, the far side highland crust appears to be thicker than that on the near side and most of the Moon's mare basalts occur on the near side. Thus, the major early internal movements of material may well be related to the subsequent volcanic activity. Such movements are likely to have occurred on other "one-plate" planets, such as Mercury and Mars, which, unlike the Earth, have not undergone continuous renewal of the surface through plate tectonics. The distribution of mare basalt deposits, concentrated on the lunar near side, has become known as the "global dichotomy." Mars similarly has a global dichotomy, with ancient crust being preserved over much of the planet and volcanism concentrated in another portion. Further definition of the characteristics of these major lunar features clearly has consequences for planetary evolution in general.

Volcanic processes apparently dominated the history of the Moon from about 4 billion years to about 2.5 billion years ago. Following solidification of the crust, the interior was still hot and was being heated by decay of radioactive elements. At depth, material was partially melted and the molten magma was able to make its way to the surface where basaltic lava flows filled the deeper impact basins to form the maria. Basaltic rocks also emerged locally in other areas of the Moon, including the South Pole – Aitken Basin, but not in sufficient quantity to form continuous maria. Each of the basalt flows contains information on the composition of the rocks of the deep interior from which they were obtained, the temperature of melting, and the time at which the melts were formed. Therefore, they provide indirect probes of the nature of the lunar mantle and the thermal history of the Moon.

In order to understand these problems of lunar evolution and history, additional investigations are required, including:

- Global structure. In particular, a network of seismic stations operated over a long period of time can use natural moonquakes and meteorite impacts to determine the properties of the lunar crust, mantle and core. These investigations can provide information on major boundaries where composition changes, such as between the core and mantle, the presence of fluid elements of the core, and physical properties of the solid materials (from the velocity of seismic waves). The thickness and composition of the crust can be inferred.
- Tectonics. The upper regions of the Moon have also responded to thermal changes through structural transformations known as tectonics. Among these are features that show evidence for periods of expansion or contraction (grabens and faults) as well as more local features such as displacements associated with mare lava flows (wrinkle ridges). Local geophysical traverses across these structures can provide information on the means by which they were formed.
- Chemical composition of crustal units. Clementine and lunar prospector data have begun to show that there are more rock types in the lunar highlands than have previously been identified in the Apollo or Luna sample collection or among the few lunar meteorites that have been discovered on Earth. This

sampling will require careful fieldwork in which a picture of the lunar crust can be built up by unraveling the sequence of major impact events that have redistributed material on the lunar surface.

- Reading the history of the crust. Upper sections of the original lunar crust were fragmented and mixed to form the lunar megaregolith. The predominant rock type is breccia, which consists of broken up rock fragments. It may be possible to reconstruct crustal history by careful studies of fragments within breccias from many areas of the Moon.
- Volcanic rock studies. Studies of the composition and age of a variety of basaltic rocks from maria and highlands can further elucidate the interior composition and thermal history of the Moon and regional differences to help understand the initial differentiation and the causes of major heterogeneities. A wide sampling of basaltic rocks of different composition and age is required. Some volcanic rocks may contain a history of the Moon's magnetic field. In the presence of a magnetic field, iron-bearing minerals in volcanic rocks can retain a magnetization due to the Moon's field, as the rocks cool through the Curie point of the minerals. Presumptive evidence of this effect was found in some rocks collected by Apollo, in a narrow time range. Additional tests in well-chosen field areas, utilizing remnant magnetization sensing techniques on oriented rock samples (from outcrops or drilled samples) can elucidate this possibility.

### 2.1.3 Early Impact Processes in the Solar System

Very large impact basins that appear to have formed in a short interval of time, around 3.9-4.0 billion years ago, dominate the lunar near side. This is a time after most of the initial material from which the solar system formed should have been swept up into planets. This "terminal cataclysm (Tera et al., 1974)," if it can be verified, would have also affected the early history of the Earth, perhaps being involved in a fundamental way in the early evolution of life on Earth. The ejecta and melted rocks formed in these major early events carry information about the times of impact as well as the composition of the impactors. It is thought that, by studying samples of ejecta from the major near side impact basins, it can be determined whether a single class of impactors or several different impactors were involved. Although the characterization of impactor types has been attempted with samples from the Apollo collection (Norman and Bennett, 2002), there is still controversy over whether the breccias studied can be related to the events that formed them (Korotev et al., 2002).

The South Pole – Aitken Basin is the largest, oldest and deepest impact basin on the Moon. Studies of the ejecta outside of the basin, melt rocks from within, and the subsequent history of the basin can provide evidence on the nature of the impact event, including such questions as the age of the basin, the composition of the impactor, and whether the impact was high angle (greater than $45^o$ from the surface) or grazing (low impact angle), which should have had major consequences for the ejected material and the amount of melt formed.

Studies required principally involve fieldwork to characterize ejecta deposits and impact melts from early basins. This will involve iterative field sampling and analysis of a large number of fragments.

### 2.1.4 Recent Impact Flux

Just as it may be possible to identify the timing and nature of impacts in the ancient lunar record, the more recent lunar record is also of great interest. Following the initial period in which the lunar crust formed and became highly cratered, the impact flux has diminished with time to a low level. Furthermore, the Moon has experienced little internal activity for the past 2.5 billion years. Craters formed on the Moon are well preserved and it is possible to find impact glasses made in the cratering process within the crater. Horz (1985) suggested a statistical sampling of craters 5 km or larger could be used to establish the time variation of the impact flux. Impact glasses can be analyzed to determine their age and perhaps the composition of the impactor. The study of a large number of impact craters in this size range would establish the timing of lunar and Earth impact events over the past few hundred million or a billion years. Even small craters will preserve glass, so the areal extent of craters to be explored may not be great. These data are relevant to issues of the constancy or periodicity of the impact flux. For example, it has been speculated that major impact events on Earth, such as that which caused the extinction of the dinosaurs, are periodic, determined by long-term galactic processes (e.g. Schwartz and James, 1984). A statistical sampling on the Moon could establish whether any periodicity exists. The question of the proportion of asteroids to comets hitting the Moon could also be addressed. Comets are currently believed to be a major source of volatile elements for the Earth. If the relative proportions of asteroid and comet impacts can be determined, it may be possible to extrapolate backward through time to determine the flux of volatiles to the Earth in the ancient past.

Studies required include:

- Sampling of a large number of small craters in an accessible area on a lunar mare, perhaps 10 km square. Collecting samples of glass formed in impact to determine age. Samples of glass formed in impacts that penetrate the regolith will be more likely to yield information on the composition of the impactor. Investigation of regolith nearby craters to identify ejecta layers may also yield information on (fragments of) the impactors. With time, the exploration could be extended to much larger areas and larger craters, which could represent collisions from a different component of the impact flux.
- Analysis of age of impact glass; cosmic ray exposure ages.
- Determining chemical composition of glass and meteoroid fragments

Collection and documentation of samples must be done on the Moon. Most of the analyses required are so difficult that it is likely that they must be done in laboratories on Earth.

#### 2.1.5 The Lunar Atmosphere and Volatile Movements on the Lunar Surface and Their Significance

The Moon's surface is a near-perfect vacuum; however, atoms of volatile elements do exist above the surface, moved by temperature, micrometeoroid bombardment, or by energetic radiation. These atoms and ions are termed the "lunar atmosphere." Volatiles, including water, have been added to the lunar surface by the solar wind, micrometeoroids (comet dust?), meteoroids and comets (Arnold, 1979). Water molecules, once released on the Moon's surface, are lost from the Moon, imbedded in the surfaces of lunar regolith grains, or move by ballistic hops until they are frozen out within cold traps in permanently shadowed craters near the lunar poles. There, they may be lost by various means (including meteoroid impact) or covered by dust, in which case, at the very low temperatures, they may have been preserved for billions of years. Thus, the volatile content of the regolith in these cold traps may provide information on the mechanisms of volatile transport on the Moon, the history of addition of volatiles by comets, and the loss mechanisms. Recently, the Lunar Prospector mission has shown that there are concentrations of hydrogen, partly associated with shadowed craters that may represent water ice deposits (Feldman et al., 2001). In addition to the scientific interest, significant deposits of water may constitute a resource for human support and propellant production.

The Moon's atmosphere normally consists of species that are derived from the interior and surface of the Moon, for example, argon that has been released by the radioactive decay of potassium in the lunar interior, but is too heavy to have been lost from the surface. The phenomena associated with volatiles on the Moon are typical for other airless bodies, such as Mercury. The study of the dynamics of these atmospheric species began in the Apollo program, but was hampered by the contamination introduced by the spacecraft, particularly from propellants. New investigations will require instruments that are installed at locations where human contamination is minimal or where long-lived sensors can function well after humans have left the area. These instruments can also document the extent of atmospheric contamination due to human activities.

The exploration of permanently-shadowed craters will require surface investigations, including surface geophysical investigations to determine the horizontal and vertical distribution of hydrogen or ice, determinations of the volatile or ice concentration as a function of depth, chemical analyses to determine the composition of the volatiles, isotopic analyses to determine the origin of the volatiles, and analyses to determine the physical properties (strength, cohesion, etc.) of the deposits.

#### 2.1.6 History of the Sun

The lunar surface, because the Moon's atmosphere is so slight and the Moon has no internal magnetic field, is impacted directly by the relatively low energy radiation coming from the sun as well as by high-energy cosmic radiation (Silberberg et al. 1985). Determination of the products from radiation, which can include spallation of elements to produce new isotope ratios as well as physical evidence such as radiation damage and charged particle tracks, can indicate the amount of time that surface regolith particles have been exposed to space and the nature of the impacting radiation. For example, there appears to have been a systematic change in the isotopic composition of nitrogen in the lunar regolith over time (Kerridge**,** 1979), which may be associated with changes in solar activity. It may be possible, by careful fieldwork, to identify regolith units that were exposed to space for relatively short periods of time in the distant past. The time at which the regolith was exposed could be determined from the age of underlying and overlying units (e.g. basalt flows). Thus, it may be possible to track changes in the radiation flux through time, at least for the past 3.9 billion years in which basalt flows have been a significant process on the lunar surface.

Investigations might include:

- Geological investigation of craters that penetrate mare basalt flows into pre-existing regolith to determine locations of ancient regolith
- Deep drilling to penetrate basalt flows to sample ancient regolith in place
- Analysis of regolith materials for evidence of ancient solar wind and solar particle events

#### 2.1.7 Functions Required:

The principal functions of the astronauts on the lunar surface are to conduct field investigations, describe geological relationships, collect samples, conduct preliminary analyses of some of these samples and prepare others for return to Earth, emplace geophysical instruments, monitor and calibrate instruments as needed, and report their observations and discoveries to Earth. In order to carry out these activities, they must be able to: (1) have sufficient mobility on the lunar surface to enable a good selection of terrains and materials for emplacement of instruments and collection of samples; (2) carry out EVAs away from the specific landing zone; (3) have accurate navigational capabilities (such as the GPS system on Earth) for correlation of location to images and surface features, and for tracking and traverse planning; (4) teleoperate mobile robotic exploration and sampling systems, (5) utilize special purpose tools for sample collection, including core tubes and drills; (6) conduct analyses in a field laboratory; (7) store and archive samples; and (8) communicate their findings to Earth. They must be sustained on the lunar surface by various types of systems, participate in the planning of day-to-day activities, and communicate regularly with Mission Control and scientists on Earth.

### 2.2 Establish the Suitability of the Moon for Astronomical Observations and Other Studies

Within the next decade, the Webb Space Telescope (WST) is expected to replace the Hubble Space Telescope as the workhorse of space astronomy. The WST, which will be significantly larger and more powerful than HST, will be launched to the Sun-Earth L2 Libration point. History of the HST suggests that it will be desirable to be able to service such telescopes, but servicing missions would require astronauts to take trips of several weeks duration beyond the radiation shielding provided by the Van Allen belts, thus exposing them to significant radiation risk as well as other risks of space flight. Thus, the WST will not be designed for servicing. Even larger telescopes are planned with time, including telescopes capable of detecting and characterizing planets around nearby stars. These, too, might be placed in the L2 point; but are likely to require human attention for construction as well as servicing of the telescopes.

The Moon has been advocated as a base for astronomy that could be competitive with placement of telescopes in the L2 point (Mumma and Smith, 1990). The Moon's surface provides a very stable base for large telescopes or interferometers, with no atmosphere and only occasional meteoroid impacts or very small moonquakes to jiggle its surface. A telescope emplaced on the Moon should be more easily pointed and should have less time lost to movement-induced vibrations than one in free space, due to the ability to transfer energy to the surface. The shadowed craters near the lunar poles may provide a low temperature environment that may be suitable for very low temperature infrared telescopes (van Susante, 2002). And the lunar far side is available for radioastronomy with no chance of interference from artificial radio waves from Earth. Telescopes generally will be operated from Earth without on-site attention. However, the most important characteristics of a lunar telescope facility may be the relative ease of maintenance and evolution of the facility by astronauts. Astronauts could work from a facility that could be shielded against both solar particle events and cosmic rays using lunar regolith as the shielding material. A single set of facilities can be provided that would allow astronauts to perform routine maintenance and upgrading of the observatory in occasional visits, including adding telescopes or upgrading instruments. The same facilities can be used to support other lunar exploration objectives. Design of the telescope, infrastructure and operations can mitigate threats from lunar and meteoritic dust.

The principal scientific arguments against such a facility involve residual concerns about the suitability of the lunar environment, including ways of working in the lunar environment to avoid contamination of the telescope. The relevant investigations to be undertaken in an early lunar exploration program to validate the use of the Moon as a base for very large telescopes include:

### 2.2.1 Environmental Considerations for Large Telescopes and Interferometers

These investigations would include high sensitivity seismometers to monitor lunar surface motions caused by moonquakes, meteoroid and micrometeoroid impacts, and human-induced disturbances. The frequency of natural lunar dust originating from meteoroid impact elsewhere on the Moon should be determined, using meteoroid detection technology that can determine the flux, size, mass and direction of particles impinging on the detector. The thermal environment of deeply shadowed areas near the lunar poles should be studied, as well as experiments to determine the thermal shielding techniques needed to design very low temperature telescopes for the lunar surface. Experiments are also needed to demonstrate the operation of mechanical systems within the shadowed, very cold areas. The presence and behavior of volatiles that could affect telescope construction and operation should be monitored.

Sets of instruments that characterize the environment have application to the problems of telescopes, but also to the science of the lunar environment:

- Particle detector, to determine the abundance of micrometeoroids and secondary ejecta particles
- Seismometer, to determine the vibration regime from meteoroids and moonquakes
- Atmospheric detector, to determine the abundance and composition of volatiles that could contaminate telescope surfaces, using active sources to trace behavior of man-made gases.
- The Apollo 17 equipment left on the surface of the Moon was well-documented and remains a resource for future investigations of the long-term effects of the lunar environment on materials.

### 2.2.2 Operational Demonstrations of Lunar Observatories

The Apollo 16 mission demonstrated the operation of a small ultraviolet telescope on the lunar surface. Additional demonstrations are required of larger telescopes, particularly on missions that can access permanently shadowed areas. For equatorial locations, it may be possible to design an instrument that can be housed within a thermal enclosure during the lunar day and opened at night when temperatures are low. An optical interferometer consisting of two small instruments separated by 100 meters could provide a demonstration of interferometry as well as determine the effects of natural vibrations on a working interferometer. Typical installations could include the following (see Budden (1990) for more complete descriptions of experiments):

- Lunar ultraviolet telescope (LUTE). This is one of a number of telescopes that were studied in the 1980s. It would build upon the Apollo Lunar Ultraviolet Telescope carried by the Apollo 16 mission.
- Far side sub-mm array. The far side of the Moon is shielded from noise that emanates from the Earth's ionosphere. Substantial reduction in noise can be obtained on anti-Earth facing mountainsides or crater rims near the lunar poles.
- Interferometer demonstration. A three instrument demonstration package was defined that would be useful in demonstrating the utility of a lunar interferometer.

#### 2.2.3 Large Telescope Technology Demonstration

Several aspects of the installation of a large telescope in a permanently shadowed crater near the South Pole of the Moon have been suggested (Van Susante, 2002), which would require new technology. Telescope designs were suggested in which high temperature superconducting magnet bearings replace conventional bearing surfaces, providing better control and less concern about dust. Surface transportation systems that minimize dust generation, such as cable systems, may be important. And energy transmission systems, either by cable or beamed power systems, which can transport energy from areas that are sunlit to facilities in the permanent shadow, will be required.

Experiments that may be conducted include:

- High temperature superconductor bearing tests
- Cable system construction demonstrations
- Beamed power demonstrations, to transmit energy from sunlit area into permanent shadow

#### 2.2.4 Assess Other Opportunities for Science on or from the Moon

The Moon is not normally considered to be a venue for astrobiological investigations, as it is carbon-poor and water-poor. However, the very absence of these substances on the Moon may provide some opportunities for astrobiology. Of particular interest is the organic content of any volatile deposits near the lunar poles, as is the long-term flux of comets to the Moon as discussed in section 2.1. The development of techniques and technologies for astrobiological investigations on the moon could be relevant to future studies of life on other planetary surfaces.

Closed ecological life support system studies will also be undertaken to resolve remaining issues with respect to the long-term viability of such systems. Initially, these tests will have to be designed so that results can be obtained in short crew stays; as the level of occupancy of the lunar facility grows, long-term experiments relevant to long-term habitability on the Moon and to similar systems on Mars will be undertaken (see 3.2 below).

It is possible to synoptically view the Earth and its surroundings from the Moon. For typical high-resolution remote sensing studies, the Moon is generally too far away to compete with observations from low Earth orbit. However, there may be some global measurements that benefit from the Moon's perspective. The use of a lunar platform to monitor the Earth's ionosphere has been discussed (Freeman, 1990).

The Apollo missions established an array of laser ranging retroreflectors. These have been used to very accurately measure the distance of the Moon from the Earth and the rotation of the Earth. Upgraded systems established on the Moon could significantly improve the utility of these data (Bender et al., 1990).

When firm plans have been developed for a lunar facility, the opening of opportunities for scientists to propose new types of uses of the Moon could prove to be very productive.

#### 2.2.5 Functions Required

The functions that must be performed by astronauts on the lunar surface consist principally of installing observational systems on the lunar surface, adjusting and calibrating them, and insuring that their power and communications links are operating properly. They may monitor the installed system from their habitat during the "commissioning" phase, in which multiple visits to the site of the installation may be required. In order to carry out these activities, they must be able to: (1) Access stowed equipment and remove it from the lunar lander(s); (2) transport the equipment to sites, in some cases many kilometers from the landing zone; and (3) and maintain 2-way communication with Earth during these procedures. For most astronomical instruments, once installed, human activity in their vicinity is to be avoided, to minimize the possibility for contamination of the optics.

### 2.3 Conduct Tests of Technologies and Operations Leading Toward Long-Term Human Stays on the Moon

Although near-term human exploration and development missions to the Moon are expected to be relatively brief in duration, perhaps with a total of 30 days of surface activity, they will lay the basis for longer periods of activity leading to long-term and possibly permanent human activities. Some of the capability important for future missions will be contained in the design of the elements installed to support the lunar outpost (e.g. life support systems), while experiments may be required to understand the feasibility of a future objective (e.g. pilot studies of resource extraction). The characteristics of the technology and operations demonstrations that would be beneficial can only be suggested here. The specific experiments to be conducted should be designed to demonstrate current capabilities and suggest directions for subsequent development. All proposed demonstrations should be peer reviewed for technical content and programmatically reviewed for relevance. Where it is possible, several capabilities might be demonstrated with a single experiment. Each experiment can be designed to provide benefits to the current mission as well as feed-forward to future capabilities. Because of the demands of EVA, experiments should be designed for deployment by astronauts with operation from control rooms on the Moon or on Earth.

Initial long-duration stays on the Moon for periods of about 30 days may mimic the surface stay time for early Mars missions, in which astronauts might spend 30 days on Mars, living out of their lander. The entire range of operational procedures (logistics, maintenance, consumables management, etc.) that must be carried out in the Mars surface missions could be practiced on the Moon. A good understanding of these operations and the design of technical support for the crew could have a major impact on the amount of useful time spent by astronauts doing scientific work in short-duration stays on Mars.

#### 2.3.1 Habitat Design and Development

Lunar habitat design will need to meet a number of new requirements not familiar to designers of habitats in space. The designs for long-term occupancy should emphasize modularity for growth, resiliency, and safety. They should be amenable to "hardening" utilizing natural materials for radiation and micrometeoroid shielding. Airlock design should address issues of loss of atmosphere, as the components of air are mostly deficient on the Moon and makeup losses must be transported from Earth. They should be designed to provide adequate volume for crew activities in a reduced gravity field. New concepts should be tested that offer the possibility of providing additional space with minimal transport from Earth, utilizing the natural environment and resources of the Moon (e.g. use of lava tubes, construction of artificial cavities lined with impermeable membranes transported from Earth, construction with lunar materials) (Cohen, 2002).

Experiments can be performed at the system or subsystem level. For example, a new inflatable habitat design can be demonstrated at the system level, or techniques for inflating and rigidizing inflatable habitats could be demonstrated. The first connection of two habitat elements brought from Earth will be a signal event in the evolution toward long-term habitation.

Habitability support features of the habitat will be evaluated in the partial-g environment of the lunar surface. Potential targets of evaluation are architectural layout and arrangement of the interior spaces of the living and working quarters with specific focus on the manner in which the partial-g environment either enhances or complicates daily work-related and self-sustaining chores. Particular attention will be paid to the interface of the crew with the living features of the habitat, and the manner in which the g-field influences mobility, accessibility, food preparation and consumption, hygiene activities, and any other aspects of interface with the overall interior environment of the surface habitat and vehicles. All aspects of habitability are subject to review and evaluation during the surface stay, but particular emphasis is on those that are specifically associated with the partial-g environment.

### 2.3.2 Closed Life Support Systems

Long-term habitation of the Moon or of any other place outside of Earth will require a highly closed life support system, capable of operating without significant transportation of materials from Earth to replace materials lost from the system or to unrecoverable waste. Air and water must be recycled; for complete closure, food must be grown and utilized (e.g. Schwartzkopf). This latter technology, food growth and recycle of solid waste, may not be reasonable, or even possible, for 30-day missions separated by months of vacant periods, but trials of the technology for permanent habitation can be begun. Experiments should be undertaken from the earliest stages to demonstrate systems, subsystems and components capable of supporting complete closure of the life support system. Examples include small greenhouse facilities capable of growing multiple generations of plants such as wheat and the capabilities to harvest biomass grown at the station and process it into useful food. Efficient lighting and thermal management systems must be demonstrated for energy efficiency. Nutritional studies on foodstuffs produced in reduced gravity must be assessed.

Experiments to be carried on early human missions include: (1) an experimental greenhouse, sufficient to provide food for a crew of four and perhaps capable of long-term operation without humans on site; (2) Water recycling systems, capable of operating for extended periods in 1/6 g; and tolerant of long periods of dormancy (3) $CO_2$ recovery and carbon recycling technologies; and many others.

### 2.3.3 Medical Sciences (Adaptation) Research

The ability of humans to exist in reduced gravity for long periods of time needs to be demonstrated before long-term occupation of a lunar outpost is undertaken. It is known that 0-g produces systematic effects on humans that reduce their capabilities on return to Earth, but readaptation occurs within weeks to months of exposure (Nicogossian et al., 1994). It is not known whether 1/6 g induces similar adaptation problems. Although some tests on animals can be conducted in centrifuges in the International Space Station, tests on more animals for longer periods of time are likely to be more effective in a lunar facility. Astronaut health and performance will be monitored closely for operational reasons and the data obtained can also contribute to an understanding of the long-term effects of reduced gravity. Studies of long-term radiation effects on humans and animals in facilities of different natural radiation backgrounds are needed to reduce risks to humans in missions to Mars and beyond.

Activities to be conducted in support of this objective include: (1) monitoring health and performance of crew; (2) monitoring of the health of animals grown through full life cycles in 1/6 gravity; and (3) conducting longitudinal experiments in techniques of mitigating negative effects of space adaptation. Applications of modern biological techniques, such as gene therapy and molecular biology in a constant 1/6-g environment may provide significant new approaches to understanding and dealing with the long-term effects of the space environment on humans.

Placing humans on the Moon for an extended period will allow the acquisition of data on human (and possibly other biological species') physiological adaptations to reduced gravity. The effects observed on lunar crews are expected to be more severe than those that would be associated with astronauts on the surface of Mars, therefore, successful long-duration stays of people on the Moon can be used to demonstrate the feasibility of maintaining people through long-duration stays on Mars, and determining the levels of countermeasures that must be provided to crews. In addition, the influence of other environmental parameters on human physiology will be investigated, such as the means of adaptation to the lunar day/night cycle or to very long nighttimes or near permanent daylight near the lunar poles. Environmental contaminants, such as surface and airborne dust and soil, will be assessed for their toxicological potential, including possible pulmonary effects. Solar proton and galactic cosmic radiation exposure will be monitored in order to maintain crews within allowable radiation exposure levels. It is assumed that acceptable levels of radiation exposure will have been determined through tests on Earth.

The lunar facility will allow the effects of isolation and separation from home, family, and friends on human behavioral and psychological health to be studied in a setting of unprecedented remoteness using modern techniques. This will be important in planning and properly supporting the crew in its enforced isolation and prolonged interaction among a small number of individuals and will be critical to planning for Mars missions. Most biomedical research with crewmembers will be in support of, if not driven by, the medical monitoring required to ensure their health and fitness to continue their mission as planned. Thus, any studies conducted will have both scientific and operational value. In addition, biomedical studies will be scheduled so they do not interfere with the high-priority surface exploration tasks.

The following discussion assumes that crewmembers will be on the Moon for long periods of time, perhaps 90 days and more as experience with the outpost grows. For early missions, in which crewmembers are away from Earth for a few days, up to a month, some of the information and tests described below may be done only before departure and on return to Earth. The validity of the lunar experience for Mars missions depends on extending surface stays on the Moon to periods of at least several months, so that information can be compared to data obtained in the International Space Station Program and will be considered adequate for decision making with regard to Mars missions.

- The physiological assessment of primary interest will probably be that of bone integrity, such as the measurement of bone density. Use of a noninvasive, non-ionizing technique, probably based on ultrasound, will permit frequent repetitions of bone density measurements at a variety of sites within the body. This will document the effect of 1/6 g on retention of bone density. Information on the benefits (if any) of 1/6 g (relative to 0-g) will permit/facilitate modifications of crew exercise and other countermeasures and may influence the design of future spacecraft that provide “artificial” gravity.

- Other organ systems will be assessed for their responses to the 1/6 g environment and to the high physical workload expected to result from frequent, vigorous surface exploration tasks. Periodic assessments of cardiovascular and cardiopulmonary function may use such standardized techniques as electrocardiography, ultrasound cardiography, noninvasive blood volume measurement, measurement of vasoactive circulating factors (including norepinephrine and epinephrine), and perhaps the introduction of cardio- and vasoactive pharmacological agents. Testing may require measurements at rest, during exercise (perhaps on a cycle ergometer), and during orthostatic stress (perhaps using lower body decompression to simulate loads greater than experienced in 1/6 g). Similarly, ultrasound or other minimally invasive techniques may be used to assess skeletal muscle status. Muscle strength and endurance and aerobic fitness will be measured regularly, using aerobic and resistive exercise devices that will also be used for routine conditioning and recreation.

- Neurological function, including control of locomotion, postural stability, hand-eye coordination, fine motor control, eye movement control, etc., will be regularly assessed at rest and during appropriate stimulation, to document the effect of prolonged exposure reduced gravity on the gravity-sensing elements of the neurosensory system. Comparisons will be made to baseline measurements of cardiovascular, neurological, and musculoskeletal status that were made before departing from Earth.

- The pharmacodynamics and pharmacokinetics of drug therapy in the lunar gravity environment will be assessed for comparison to the 1-g and 0-g databases and to adjust medical therapeutics as required. Crewmember immune status will be tracked, to develop real-time health strategies and for future mission health planning.

- Sleep cycles will be investigated to determine optimal adjustments that allow maximum crew effectiveness.

- Crew nutritional status will be regularly monitored, to ensure adequate intake to support the surface activities, and to provide a background for interpretation of other observed physiological changes.

- The surface environment will be monitored for radiation levels and characteristics as well as for surface soil and dust with possible toxicological effects. Radiation levels and their effects on cells can be monitored at the surface, within the habitat, and under various depths of regolith cover, in order to assess appropriate methods of shielding.

- Operationally, a great deal of real time and occasional monitoring of astronaut vital signs, metabolism, and physical status will be taken to ensure that the astronauts remain fit and healthy in order to maintain high levels of performance. These data will also be archived for evaluation of trends and interpretations of data in terms of medical status and adaptation to the lunar environment.

In addition to human-based research, animal studies may be undertaken in the lunar gravity environment, when ethical animal care issues have been resolved. Of particular interest is the long-term survival of simple and complex organisms from Earth in reduced gravity. Fundamental information can be obtained through a set of simple cross-species survival, adaptation and change experiments, including with archaea, bacteria and simple eukaryotes (such as nematodes), each in an array of sample containers with necessary nutritional elements for their survival. At regular intervals, testing samples of each organism using DNA chips will quantify adaptation changes. If appropriately designed, these containers could be left on the Moon for future missions to examine, even years later. A longitudinal ecosystem study can also be conducted, with an analytical approach similar to that described above.

In addition, animal and plant-based research will reveal if the organism structure and function on the Moon are the same as those observed after equivalent periods of 1/6 g on an ISS centrifuge. This will validate the use of in-flight centrifugation as a simulator of the biological aspects of planetary surface gravitational environments.

### 2.3.4 EVA Test Bed

EVA during the Apollo program was very successful, but also very tiring for Apollo astronauts. The effort involved in conducting EVAs with heavy, inflexible suits and particularly gloves, would detract significantly from the long-term performance of crewmembers on the lunar surface. The ability to reuse space suits many times is central to long-term lunar surface activities, as is the ability to clean suits. The certification of suits for reuse must be addressed. A variety of tools and capabilities that can improve EVA performance must be demonstrated, including advanced information systems allowing easy communications between the crewmember on EVA, the crew inside a habitat, and Earth. Combinations of EVA with mobile transportation systems should be demonstrated. The ergonomics of EVA should be evaluated in sufficiently controlled and numerous experiments to be statistically significant. The problem of requiring pre-breathing of oxygen prior to EVA either has to be addressed through habitat design or through a new generation of high pressure suits. For later missions and for Mars missions, more than one EVA team may be in the field at the same time. Operational and safety procedures for this event must be developed.

Some initial activities that might be performed in early lunar missions include: (1) demonstration and tests of new classes of space suits; (2) demonstration of new approaches (tools) to add flexibility of mechanical operations by suited astronauts, including human-robotic interaction; (3) demonstration of EVA suits and supporting systems that provide for longer EVAs, such as a pressurized vehicle that supports EVAs and recharge of EMUs; (4) demonstration of simultaneous operation of 2 EVA teams and rescue operations.

### 2.3.5 Navigational Systems

One of the most difficult challenges of planetary exploration historically has been locating equipment and personnel with respect to maps or georeferenced coordinate systems on orbital, aerial, and ground imagery. Consequently, in past missions and mission simulations, both human and robotic, have required too much time for basic navigation or traverse commands (NASA, 2003). Early deployments of experimental systems for local precise navigation, such as distributed beacons or other types of triangulation equipment, or a network of global positioning satellites, similar to Earth's Global Positioning System will be required for any short or long-duration scientific exploration missions on the Earth or Mars. If only local navigational systems are available, there must be a way to correlate local coordinates with global geo-referenced coordinate systems, and all humans and automated systems such as rovers, steering devices, cameras, scientific instruments, etc. must be able to:

- Point to a specified heading
- Determine location to within a meter in coordinates that are meaningful to all teams on the Moon and on Earth
- Correlate location and heading with exact synchronized time stamp

### 2.3.6 Electrical System Development and Test

Charge differences exist between lunar surfaces in sunlight and in shadow, which may build to detrimental levels (Criswell, 1972). The grounding capabilities of the lunar surface are nil. Experiments should be conducted that demonstrate the degree to which charging issues are important for human operations outside of controlled environments. The charging of dust at the terminator (day-night boundary) leads to a process of dust levitation that can lead to motion of dust (pick up and deposition) with detrimental effects on the operation of equipment. This effect should be better quantified. Methods of discharging static electricity should be investigated.

### 2.3.7 Radiation Shielding Using Natural Materials

The lunar surface receives solar radiation, in the form of low energy solar wind, high-energy radiation from solar particle events (solar flares), and from very energetic cosmic rays (Figure 2-2). Solar wind radiation can be shielded against easily. Complete protection against solar flare particles can be provided by a modest thickness of water or solid materials. However, the thickness of shielding required is too great to be carried on the surface by astronauts on EVA, which means that crewmembers on extended EVA must be provided with an emergency shelter for solar flares or supported by a highly effective prediction system.

It is very difficult to protect people from cosmic rays on the lunar surface, in part because of the secondary particles, including neutrons, which are generated when cosmic rays interact with surface materials (Figure 2-2). Approximately two meters of lunar regolith are sufficient to reduce the radiation dose from cosmic rays to the level accepted for workers in the radiation industry on Earth. Greater thickness is required to reduce the radiation level to that acceptable for general the general population. The natural radiation level of some lunar materials is quite low, so it is possible to reduce the ionizing radiation levels to very low levels with adequate cover and appropriate selection of materials. Radiation shields constructed from natural materials will also provide thermal and meteoroid protection.

The generalities of the last paragraph need to be tested and confirmed by experiment on the lunar surface. An experiment such as MARIE, which was initially proposed for the Mars 2001 surface lander (not implemented) to measure the effective dose of radiation to humans, and which was conducted in Martian orbit on the Mars Odyssey mission, could be emplaced under shielding materials of different thickness to determine the levels of radiation and the effectiveness of different shielding materials.

Natural material shields could be readily constructed using precast forms (such as bricks), by filling prefabricated volumes, or by layering regolith over a structure. Tests are needed to determine the most effective means of fabricating such shields. For equatorial locations, the provision of a natural radiation shield will modify the thermal behavior of a system, so that tradeoffs exist between the requirements for thermal management and those for radiation shielding.

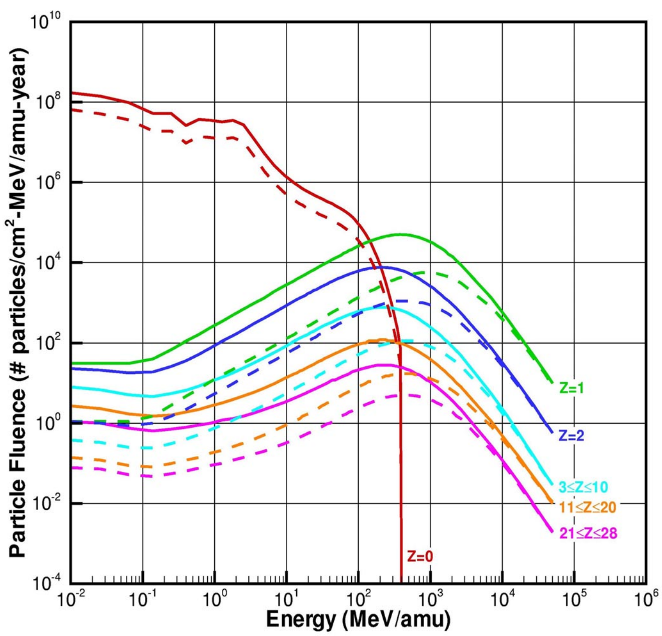


Fig. 2-2. Lunar surface GCR spectra at the 1977 Solar Minimum (full lines) and Solar Maximum (dashed lines). Atomic number Z identifies the charges of the ions. Neutrons (z=0) are generated by the interaction of cosmic rays and the lunar surface, and contribute significantly to the radiation environment that can affect humans. (From Tripathi et al., 2002).

### 2.3.8 Regolith Excavation and Movement Technology

Lunar regolith excavation will be required for many purposes in a long-duration lunar facility. These purposes could include surface grading for dust control, excavation of regolith for use as shielding or for emplacement of subsurface systems, and excavation for the purpose of extracting useful resources from the regolith. A variety of machines and approaches have been suggested for regolith excavation and movement, from front-end loaders to bucket wheel excavators and from trucks to conveyor belts. A wide range of experimental verifications of fundamental principles of excavation and transportation could be performed in conjunction with developing the practical applications of the technology. Protection against dust is a significant issue for mechanical systems and experiments to demonstrate dust-resistant designs should be undertaken. Regolith excavation and movement may require special approaches if they are to be carried out during the lunar night or in permanently shadowed areas near the lunar poles.

In order to properly design regolith excavation and materials transportation systems, additional information on the physical properties of the surface regolith are needed, obtained with in-situ instrumentation that can measure compressive and tensile strength, compaction, density and other geotechnical parameters. Simple demonstrations of excavators using a variety of approaches should be conducted, to develop and validate excavation machine design. Tests of movement of regolith with a variety of mechanisms should be performed.

#### 2.3.9 Surface Mobility Systems (Robotic and Piloted)

Apollo astronauts were well served by the Lunar Rover, which attained speeds of up to 5 km/hr and allowed the crews to explore to a range of several kilometers from their lunar lander. The area available for exploration increases as the square of the distance from a central facility, so surface mobility is a good way to increase the productivity of exploration missions. Because the energy required for systems that move on the surface is low, compared to rocket devices for point-to-point or hovering trajectories, extending exploration range with surface vehicles is effective, though more time is required as surface speeds are likely to remain low, in the absence of prepared roadways. For early lunar exploration, a variety of surface mobility systems is likely – robotic systems with teleoperation capability from Earth or a lunar operations center; piloted rovers for short duration – relatively short distance traverses, and pressurized vehicles for long distance traverses that may extend over several Earth days and hundreds of kilometers.

The issues for long-duration lunar missions or permanent facilities include the robustness of vehicles and space suits that have to operate in the lunar environment for extended periods of time (the Apollo Lunar Rovers had mechanical problems and would not have survived much more use), designs that are amenable to maintenance and repair, multipurpose systems with replaceable tools that can be used in teleoperated or piloted mode, long-lived bearings, dust protection, pressurized systems, light weight airlock designs, and support systems for astronauts on EVA. Power systems for mobility systems need to be developed. As surface exploration strategy depends on the reliability of surface transportation (Apollo astronauts were limited in range to the distance that they could walk back to their lander), many issues must be faced with respect to crew safety, ranging from reliability of systems to strategies using multiple surface vehicles.

Examples of technology and operations demonstrations that could be conducted on early missions include: (1) Regenerable fuel cell demonstration, in which reagents are replenished from a central supply; (2) Wheel maintenance and repair demonstration; (3) Pressurized vehicle capable of sorties out to 10s of kilometers from a surface outpost; (4) demonstration of rescue of a stranded crew.

#### 2.3.10 Dust Mitigation Techniques

Lunar dust was a significant issue during Apollo. Dust that adhered to astronaut space suits could never be completely removed. It is not believed that the dust represented a health risk to astronauts, but accumulation of dust within a lunar habitat could represent a problem in time. The lunar regolith contains considerable material less than 10 microns (1/100 of a millimeter) in size, which is very hard and irregular in shape, that represents a hazard to any surface that must be sealed, such as those on space suits, hatches, airlocks, or systems with rotating bearings. The problem of dust mitigation must be addressed at many levels. In heavy use areas, dust may be controlled in part by removal from the surface; technologies for keeping rotating parts sealed from dust must be improved; cleaning and maintenance techniques must be demonstrated, and techniques for repair or replacement of dust-damaged devices should be investigated.

Early lunar missions could demonstrate (1) techniques for removing dust from high traffic areas; (2) techniques for inspecting seal surfaces for the presence of dust or damage from dust; and (3) new classes of materials that are resistant to accumulation of dust.

### 2.3.11 Parts Fabrication Demonstration Facility

For long-term highly self-reliant operations on the Moon, it is anticipated that a capability to repair equipment may require the ability to manufacture replacement parts. A machine shop could be equipped with the tools needed for parts fabrication, utilizing modern rapid prototyping approaches to provide flexibility for producing the variety of parts that might be required. This capability must be supported by a logistics system in which some amount of required materials can be made available. In advanced facilities, some of the materials used might be derived from local resources. An early version of the parts fabrication system could evolve into a production facility that could make new utilitarian items for the lunar facility. In addition to parts manufacturing capabilities, repair facilities for electronic systems will also be required. An experiment that could be performed on an early mission could involve producing a variety of sample containers from stock materials. This could have the function of saving volume required for transporting empty containers to the Moon.

### 2.3.12 Ergonomics Research

For long-term activities on the Moon, a better understanding of the energy and strength required by astronauts should be obtained. The adaptation of humans to 1/6 g is a medical issue; the most effective use of humans and their capabilities within the lunar environment is an engineering issue. Both must be considered in designing long-term approaches. The needs and capabilities of astronauts working within a lunar facility must be considered in all areas of design and a good data base will be needed to guide studies, particularly those associated with expansion of facilities on the Moon. Experiments conducted by early lunar explorers should be designed to provide information to the developers of subsequent facilities.

### 2.3.13 Resource Utilization Studies

The use of lunar resources is based in the premise that energy (either solar or nuclear), in association with processes that require relatively small amounts of machinery, can be used to extract useful products from local materials. Long-term occupancy on the Moon will benefit from and perhaps be impossible to support without the use of local resources. The largest early use of lunar resources could be the production of propellant for rocket transportation from the surface, as in-situ production of propellant can significantly reduce the amount of mass that must be taken to Earth orbit to support a round trip to the Moon. The highest performance chemical propellant combination is hydrogen and oxygen, of which oxygen is ubiquitous on the Moon and hydrogen may be found in the regolith or in polar water ice. When lunar propellant production is integrated with an L1 propellant depot, the amount of propellant required from Earth to conduct a lunar mission such as Apollo would be reduced by about 3/4.

Other uses for lunar resources will be found. For example, regenerable fuel cells, which react hydrogen and oxygen to produce water, releasing energy, could be charged using solar energy during the day and operated at night. Because the long lunar night requires rather large amounts of reagent hydrogen and oxygen, provision of some of this from local resources could significantly reduce the need for imported reagents. Relatively small amounts of water and oxygen (compared to use as propellants) could be utilized to create consumable reservoirs that would increase the robustness of a human facility. At advanced states of resource development, metals and non-metals could be produced. This includes the possibility that materials for production of solar photovoltaic cells could be derived almost entirely from lunar materials, providing a means of expanding a lunar power system using local materials. Metals such as iron and aluminum, glass of various compositions, and ceramics may also find use in construction, repair and expansion of lunar facilities. Propellant, in particular, may become commercially viable for support of space transportation in the Earth's vicinity and for support of Mars human exploration missions carried out from the L1 Gateway.

Apparent concentrations of hydrogen near the lunar poles suggest that water ice is mixed into the regolith, although other explanations have been advanced for the form of the hydrogen. The hydrogen content in permanently shadowed craters appears to be more than 10 times higher than the hydrogen content of typical regolith. Thus, these areas may be sources of water for rocket propellant production as well as life support. However, these deposits are currently known in only a general manner. The form of hydrogen needs to be confirmed, along with its lateral and vertical distribution, and its concentration. The search for extractable deposits with defined reserves capable of supporting lunar operations for several years is a basic requirement for early utilization of the resource. Such exploration could be conducted with robotic systems in conjunction with studies of the scientific issues associated with lunar polar volatiles. Technology must also be developed and tested for extracting the resource from its challenging environment (surface temperatures less than 80 K).

A wide variety of resource extraction systems have been proposed, many of them aimed at the extraction of oxygen from lunar materials. Hydrogen reduction of iron-bearing materials (ilmenite, pyroclastic glass), carbon reduction of silicates, and electrolysis of melts are the leading candidates; however, complete processes applicable to the lunar surface have not been designed. For most of these, exploration is not a significant issue, as the proposed techniques can be conducted on bulk regolith materials. Some specialized extraction processes may involve beneficiation (concentration and separation of one of the minerals in a rock or regolith) by physical or chemical means.

Exploration of the hydrogen concentrations near the lunar poles is the highest priority early objective leading to a resource utilization theme. This could be done robotically or with early human missions. Small pilot plants capable of producing oxygen from ilmenite or pyroclastic deposits, metals such as iron and aluminum, and silicon could be demonstrated as stepping-stones to production facilities to support self-sufficient or expanding human activities on the Moon. Pilot unit scales can be quite small (10s of kilograms) but still capable of producing significant amounts of material if allowed to operate for long periods of time.

#### 2.3.14 Lunar Art and Literature

If long-term lunar activities are conducted, the needs of humans must be addressed. Many of these are in the realm of medical issues (including psychological issues); however, a long-duration crew should also have the capability of expressing themselves in art, music and literature, photography, music or other creative activities. With growing lunar capability, the range of experience and expression may also grow. The time available for observation as well as introspection may grow as well. Thus, studies should be carried out that would begin to establish the basis for such intellectual activities. These should include studies aimed at direct utilization of local materials in artistic expression. Experiments with crews isolated in terrestrial analog environments have shown that outlets for artistic expression have a significant impact on the overall well being of the crews (Snook and Burbank, 2003). Creative endeavors provide opportunities for bonding between crewmembers and in some cases have been shown to reduce tension among the crew. It has also been observed that such activities can be undertaken collaboratively between crewmembers and other participants on Earth, decreasing the sense of isolation in the crew and providing more avenues for interaction between the public and the planetary explorers.

#### 2.3.15 Construction Technologies Demonstrations

Construction utilizing local materials will have many ramifications for long-term human activities at a central facility. Many types of materials have been suggested in the literature, including sintered regolith (Allen et al. 1994), cast basalt (Jakes, 2000) and special materials produced by reacting previously separated components of the regolith (Duke, 2000), fiberglass, and metals (iron, aluminum) (Criswell, 1978). Techniques for foundation construction, subsurface excavation, and other means of constructing substantial facilities, including pressurized structures, have been described (e.g. Nowak et al., 1992).

For components transported from Earth, techniques are needed for offloading equipment from landers, transporting them to the construction site, and mating them to previously installed components. Dust control technologies will be essential for surfaces that must be mated. Sealing technologies, such as welding, need to be developed to create vacuum-sealed connections on the Moon.

Experiments such as the following could be included: (1) formation and mechanical testing of bricks made of sintered regolith; (2) demonstrations of regolith melting at a scale consistent with materials production (may be integrated with resource utilization experiments); (3) construction of radiation-shielded, unpressurized structures using beams and plates; (4) construction and test of assembled vacuum tight apparatus. These experiments should either produce useful products or be directly associated with the future production of needed products.

#### 2.3.16 Environmental Degradation Abatement Tests

When humans begin to operate on the Moon, certain aspects of the lunar environment may begin to degrade. In particular, expulsion of reaction products from propulsion systems or pressurized surface systems may introduce local and extended atmospheric and surface contaminants. In cases where excavation activities or others that disturb the lunar regolith are undertaken, release of loosely bound trapped gas, such as argon or helium, may also occur. Although volatile species will be lost over time, condensation can occur in shadowed areas or at night, so that the time constant for the disappearance may be extended as species first condense in shadows, then are mobilized at their next illumination. Measurements made at the Apollo landing sites indicated that water was present in the lunar atmosphere with a decay time of several months (Johnson et al., 1972).

Experiments that actively release gases from a point source and detect them at a distant source should be devised. These experiments should cover the range of gaseous species that may be released by human activities. The fate of these released gases should be followed for enough time that their behavior can be modeled as a function of time and surface temperature history.

#### 2.3.17 Regolith Chemical Properties Studies

The lunar regolith has been formed under extreme conditions of high vacuum and low water content. This has led to the formation of activated surfaces on mineral and glass fragments in the regolith. The solubility of regolith was studied in samples from the Apollo missions (Keller and Huang, 1971). More extensive studies of the release of chemicals and volatile species in the lunar regolith in the presence of liquid water and water vapor should be undertaken, with applications for resource extraction and agricultural use of lunar regolith materials (Ming and Henninger, 1989).

Experiments will include sampling and analysis of volatiles and other important species. This may include setting up analytical equipment outside the habitat and delivering samples to it. Subsurface properties may be addressed with instrumented drills. Ming (1989) discussed the production of synthetic soil from lunar regolith materials, which could provide substrates for plant growth in lunar enclosures. Experiments of this sort can be carried out first on Earth, and then demonstrated at suitable scales using natural materials on the Moon.

#### 2.3.18 Launch and Landing Facilities

In places where more than one landing and ascent occur to support a long-term presence of humans, it may be prudent and effective to create permanent launch and landing facilities. Such systems would facilitate safe and routine landing and take off, as well as provide logistics services such as off-loading the payload from a robotic lander or refueling of a reusable ascent vehicle. Particulates driven from the surface by launch and landing of rockets may prove to be a hazard to other operations, but may be mitigated by preparing the surface to reduce the amount of loose dust. This preparation could range between removing the surface dust from a prepared area to thermal, mechanical or chemical treatment of the surface to stabilize it.

Early experiments could consist of: (1) measurement of the amounts of loose regolith that can be removed by a means such as blowing or surface scraping; (2) surface fueling of ascent vehicle; and (3) demonstrating the removal of heavy loads from a lander utilizing a fixed or mobile crane system.

Technology for communications is relatively well understood. From the near side of the Moon, direct communications with Earth are possible. For polar sites (within about 5 degrees of the poles the Earth is not always in view) and for the far side, communications relay systems are needed. For sites near the poles, it may be possible to install point to point beamed or fiber optic systems to a near side location where direct communication is possible (e.g. Sharpe and Schrunk, 2002). For far side communications, a satellite system will have to be utilized. A halo orbit around the L-2 point can be used, which can view the lunar surface and Earth simultaneously.

#### 2.3.19 Maintenance, Repair and Operations

As is being demonstrated by the International Space Station, maintenance and operations of facility systems and experiments can become a major consumer of astronaut time and effort, and could be hampered by designs that are not conducive to easy maintenance or by logistics systems that fail to provide needed spare parts or materials when they are required. Standard approaches to this problem have utilized design principles (maximize commonality of replacement items), spare part inventories, and training. For long-duration missions, many innovative techniques will be required in each area - systems will be designed for both maintenance and upgrading, production of spare parts on-site may become desirable, and distance and just-in-time learning will be emphasized. This area is one where a great deal of technology development work will be needed.

#### 2.3.20 Functions

To carry out these investigations, the astronauts will be required to deploy experiment packages on the surface, collect samples (including subsurface samples), provide sample materials to certain experiments, conduct analytical investigations (including mobile field geophysics), document their observations, and monitor the results of their experiments. The will need surface mobility, navigational capabilities, and EVA, various sampling tools, appropriate field analytical capability, and communications systems that allow them to monitor experiments and discuss findings with Mission Control and the scientific community on Earth. They may also be called upon to maintain or repair electronic equipment, computer networks, and deployed equipment.

### 2.4 Conduct Tests of Technologies and Operations That May Be Used in the Exploration of Mars and Beyond

The technologies that are useful in the exploration of Mars are very similar to those needed for long-term operations on the Moon, because many have envisioned initial Mars surface missions that spend 500 days on the surface (NASA, 1997; Zubrin and Wagner, 1997). Thirty-sixty day surface missions to Mars are possible (though it takes more propulsive energy to get there and back than it requires for longer surface stay missions). Therefore surface activities on a 30 day lunar mission are directly relevant to short stay time Mars missions, while it will require a buildup of infrastructure on the Moon to extend stay times to 500 days. However, building these capabilities for the Moon will provide important steps toward achieving them on Mars. Therefore, some of the “experiments” done for Mars missions will consist of deployment of infrastructure for the lunar mission and monitoring its performance. The addition of infrastructure and experiments at a lunar facility to prepare for Martian exploration could appear to be a costly burden to a lunar program. It will only be done if both Martian and lunar exploration are viewed as part of a larger effort for the improvement of human exploration capability in the solar system.

### 2.4.1 Power System Development

Solar energy is readily available on the Moon, but is reduced by a factor of two at the distance of Mars from the Sun, and further reduced at the surface by atmospheric effects. Furthermore, the orbit of Mars about the Sun and the tilt of its axis produce seasonal effects that would require elements of significant size to provide baseload power for a Martian facility. Although solar systems are feasible in some Martian applications, nuclear systems can provide more reliable power and can do so anywhere on the planet. Development of a 100 kW nuclear reactor system (SP-100 was undertaken in the 1980's and 1990's, but never completed. Other concepts for nuclear systems have been advanced (e.g. Houts, 1996). Currently NASA emphasis in nuclear power is on high power nuclear reactor design for nuclear thermal propulsion, as well as more efficient dynamic isotope power systems (radioisotope thermal generators) of about 100 W capability for planetary exploration. Recently, renewed interest in nuclear power systems has become evident in NASA. While not absolutely required for the Moon, power supplies of this magnitude would have very effective performance for lunar activities, including the capability y of powering a fully closed life support system with food production, or extracting water from ice at the lunar poles. The demonstration of a nuclear power system at a lunar station can provide operational experience and enough confidence in such systems that they can be chosen for human Mars missions. Additionally, astronauts could demonstrate operations to clean and maintain small solar power systems, such as testing dust removal and replacement of solar array elements.

A nuclear power supply could be delivered to the Moon on a separate robotic mission and deployed robotically. The crew could be required to connect the power plant to their habitat’s power distribution system when they arrived. These steps might also be carried out robotically.

### 2.4.2 Closed Life Support Systems

It has been stated above that fully closed life support systems are important for extended stays of people on the Moon. There are three potentially significant differences between a plant growth facility on the Moon and Mars. The Moon’s gravity field is about half that of Mars, which will provide a more extreme growth environment than Mars. The presence of some Martian atmosphere may make the production of atmosphere for greenhouses easier than on the Moon and may make a Martian greenhouse somewhat more forgiving of losses of atmosphere than on the Moon. Finally, solar energy is less concentrated on Mars. The surface radiation environment, particularly the galactic cosmic ray flux, is about the same. Because of the Martian atmosphere, people have envisioned greenhouses on Mars with direct illumination of growing plants; however, it is not clear that such facilities are practical. One possible conclusion is that greenhouses on the Moon and Mars will be identical, powered by a nuclear reactor rather than solar energy, and will be highly contained such as to minimize leakage of atmospheric gases. If that is the case, demonstrations of closed life support systems on the Moon are directly relevant to similar facilities on Mars.

### 2.4.3 Surface Mobility Systems

Rovers have been utilized on the Moon and Mars. On the Moon, the Russians teleoperated Luna rovers in the 1960s and Apollo astronauts utilized their Lunar Rover quite successfully. Capability for Mars missions has been limited to rather small rovers, such as the Sojourner Rover on the Mars Pathfinder mission, though somewhat more capable rovers are being constructed for the Mars Exploration Rover missions and later missions. Teleoperation is a key difference in the lunar case, where light travel times are short. Light travel times for Mars are much longer, but teleoperated rovers for Mars could be operated if people were in the vicinity (on the surface or in orbit). Piloted surface mobility systems for Mars could be quite similar to those designed for the Moon, with the exception that the Mars systems will require higher power due to the greater gravity field. Many places on Mars are rockier and more treacherous than the typical lunar surface, so that Mars rovers might have to be somewhat larger than lunar rovers to achieve the same surface speed. In any case, design and operation of both teleoperated and piloted rovers should have significant commonality between human missions to the Moon and Mars.

Providing safe havens for astronauts during extended rover sorties on the Moon and Mars is a serious concern. In the Mars Surface Reference Mission (Hoffman, 2001), the concept of a “Field Camp,” a location where a portable shelter could be set up, was discussed. Pressurized rovers can function as a field camp, if two are available. Leaving a pressurized rover at a distant location from the prime habitat can serve as a safe haven as well as a means of rescue. Alternatively, two pressurized rovers can carry out traverses in tandem. Under the currently expected operations rules, such operations would require that a pressurized rover be drivable by a single astronaut.

#### 2.4.4 Extravehicular Activity

The basic requirements for EVA systems for the Moon and Mars are similar. The very low atmospheric pressure of the Martian surface is not a significant benefit for space suit operation; however, the generally lower temperatures on Mars’ surface may provide benefits for thermal radiator design. The gravitational acceleration on Mars is about twice that of the Moon, so either more intensive weight reduction will be needed or concepts pursued in which resources are provided by a mobile system. It may well be that EVA systems on Mars will be dissimilar to those used on the Moon, although accepting the potential commonality of Mars and Moon suits could lead to acceptable suits for Mars that would be very good for use on the Moon.

#### 2.4.5 Logistics, Maintenance and Repair

As is the case for the Moon, long-duration visits to Mars will require support that can be provided by on-site maintenance and repair facilities. These facilities are likely to be quite similar to those of the fabrication and repair shop described above for the Moon.  For long-duration missions, maintaining the spare parts system and keeping track of on-board consumables will be a significant effort.  These systems should be very similar between Moon and Mars and can be developed as part of a lunar program.

#### 2.4.6 Dust Mitigation Techniques

The problem of dust on Mars will be similar to that encountered on the moon, but the nature of the dust could be different enough that more complex or enhanced mitigation techniques could be necessary.  For example, dust is always present in the atmosphere of Mars, and not just when disturbed from the surface, creating a potentially more difficult problem for surface systems on Mars.  Further research to the nature of the dust on Mars as compared to the Moon will enable better and more relevant mitigation techniques to be developed and tested on the Moon. Another potential issue introduced in the Mars dust is the possibility of contamination and planetary protection, both forward and backward.  While planetary protection has been shown to be a relatively minor problem on the Moon, the conditions on Mars are different, so dust exposure and transport will require higher levels of caution.

#### 2.4.7 ISRU Technologies

Some technologies for utilization of Martian resources may not be similar to those developed for the Moon. On Mars, carbon and oxygen can be extracted from the atmosphere and, with a relatively small mass of hydrogen (from Earth or from Martian water), can be converted to propellant and fuel cell reagents. Techniques for extracting water from icy regolith on Mars and in the lunar polar regions may have some similarities. Techniques for extracting metals and non-metals may have similarities, although little relevant data on Martian minerals currently exist on which to base Mars metallic resource extraction systems. Mars may eventually be shown to have concentrations of ore minerals similar to those on Earth, due to the action of hydrous fluids around volcanic deposits (hydrothermal deposits); however, early Martian missions will not have any dependency on such deposits. Therefore, demonstration of specific processes for resource extraction on the Moon may not be directly applicable on Mars.

However, at the subsystem and component levels, there may be more similarities. Many processes for propellant production will require water electrolysis, propellants will have to be liquefied, high temperature furnaces will be required for extraction of metals, and chemical processes for concentrating particular substances may well be similar. In addition, proving the basic principles of in-situ resource utilization on the Moon will take a large step toward adopting a similar strategy for Martian exploration.

#### 2.4.8 Radiation Shielding

The radiation environment on Mars is similar to that of the Moon. The interaction of galactic cosmic rays in the atmosphere may produce a higher surface neutron radiation dose on Mars than that on the Moon, while the atmosphere will provide minimal protection from solar particle events and cosmic rays. Thus, radiation shielding similar to that used on the Moon will be required and the evidence gathered from experiments conducted on the Moon will be directly relevant. As more is learned about the chemical and mineralogical composition of Mars' surface materials, it will be possible to design more specific experiments to be carried out on the Moon. Although the radiation environment of the lunar or Martian surface is damaging to humans, many of the effects require long times to accumulate, suggesting that long-duration experiments using biological materials on the Moon and different amounts of radiation shielding will be useful.

#### 2.4.9 Adaptation to Reduced Gravity

The Martian gravity environment is less extreme than that of the Moon. Experiments carried out on the Moon should allow the Martian surface adaptation effects to be modeled with better fidelity that would be possible with only 1-g and 0-g data. In addition, the establishment of a long-duration facility on the Moon could allow larger test populations to be studied at 1/6-g than could be studied using experimental centrifuges in 0-6.  The creation of animal test facilities at a lunar outpost could rapidly advance understanding of the effects of 1/6 g on living systems.

#### 2.4.10 Spacecraft Launch and Landing Operations

Crews arriving at Mars may be in a state of reduced functionality, due to the rigors of 0-g flight over a period of months.  Architectures for long stays on the surface generally require transfer of the crew from their lander to a permanent habitat.  These operations can be developed, simulated and tested on the Moon.  The utility of landing aids and the preparation of landing sites ahead of the crew can be evaluated.  Crews can practice landing and transfer procedures in a realistic environment.

#### 2.4.11 Operational Strategies

New modes of scientific exploration operations will need to be developed to account for increased autonomy of crew, and to take advantage of real-time analysis capabilities on Earth.  New operations paradigms in the areas of communications, frequency and nature of interactions between ground and crew, command and control, traverse planning, scientific analysis and reporting, task management, and crew scheduling will be necessary for future Mars missions.

##### 2.4.11.1 IVA and Surface Systems Operations

Day to day operations and functioning of systems within the habitat and other structures, such as those described in Section 3, will require more advanced planning and autonomy by the crew for simulated or actual Mars missions. Menu planning, task scheduling, status logging, and other activities will be planned in longer cycles, on the order of weeks, and then managed by the crew rather than by mission support.  This will impact the time available to the crew for productive scientific work, and operations planning for onboard science experiments or equipment will have to take this into consideration.

#### 2.4.11.2 EVA Science and Exploration Operations

The Apollo EVAs and most EVA activity done to date has been heavily scripted and planned in detail prior to the EVA. As mission duration increases, and as the EVAs take on more of a quality of exploration, crews will expect more autonomy and freedom in designing and executing EVA traverses, particularly the scientific EVAs. In preparation for long-term Mars exploration, lunar crews should experiment with modes of traverse planning and interaction with scientists and engineers on Earth to determine the most productive and effective balance of crew autonomy and execution of requests or commands from the Earth.

#### 2.4.11.3 Science Backroom Activities and Communications

Scientists on Earth will be continually faced with the challenge of performing geology, biology, or physics experiments on systems without being physically present to observe them first hand. The problem of situational awareness and efficient correlation of data with maps, pictures, or even sounds will be the main concern of those scientists participating in mission remotely from ground. Simulations both on Earth and on the Moon can go a long way towards developing communications protocols, practicing interactions with significant light-time delays, and finding efficient ways of reporting information to and from the crews to maximize scientific productivity of the missions.

#### 2.4.11.4 Maintenance Operations

The activities required here are similar to those discussed in 2.3.20.

### 2.4.12 Functions Required

Functions required are quite similar to those required for 2.3.20, but may be more complex. They also involve various forms of utilization of IVA capabilities to monitor and control experiments and to carry out innovative research on human systems and human-machine interactions. Functions driven by new modes of scientific exploration and surface activities of long-term Mars missions will include (1) capabilities for high-bandwidth reliable communication and data transfer between crews on extended EVA and those at the base, (2) IVA capabilities for detailed traverse planning and autonomous exploration planning by crew, (3) automated communication of crew activities to mission control and scientists on Earth, (4) capabilities for sub-meter accuracy in navigation for locating rovers, equipment, surface features, and areas of scientific interest, and for effective communication and repeatability of scientific findings and discoveries.

## 2.5 Test Technologies and Conduct Investigations That Can Lead to Commercial Activities on the Moon

The Moon is near enough to Earth that its resources could be commercially developed for activities in space and potentially on Earth. Because of the high cost of transportation, it is unlikely that any lunar resources will be directly returned to Earth. The exception is $^3He$, which is scarce on the Earth but might be harvested on the Moon, and for which the anticipated price that might be paid by a nuclear fusion reactor operator would be in the range of $2 million/gram. It has been proposed also that lunar materials could be utilized in the construction of large space structures such as solar power satellites, reducing the cost of these systems, which would beam clean energy to the Earth from space. A similar concept, the Lunar Power System (Criswell and Waldron, 1991) suggests that energy could be beamed from the Moon to Earth from systems constructed primarily from lunar materials at significantly lower cost than energy from solar power satellites. Other material resources will find customers only in space and therefore are dependent on the initiation of the activities that would utilize them. The only economic activity that might have a use for lunar resources is propellant, which is required by satellites being transported from the Earth to orbits beyond low Earth orbit. If propellant can be provided at low cost to users in Low Earth orbit, a profitable business enterprise might emerge (Duke et al., 2002a). Lunar propellants could be useful in Mars exploration. Providing propellant to government programs is not likely to be a commercial undertaking, due to its limited scope, but a government program could provide much of the technology development needed for a commercial program. The early lunar exploration program can improve the probability that economic uses of lunar resources can appear at a later time. Some types of investigations that are relevant are listed below. They all may be useful in part for other applications, but are listed together here because of their potential economic significance.

### 2.5.1 Explore for Ore Deposits

The Moon's geological history is quite different from the Earth. In particular the absence of water has probably limited the range of concentration mechanisms associated with ore deposits on Earth. Whereas some types of metallic ore deposits may exist, their need and use are far in the future, so exploration for them at this stage is not high in priority.

The hydrogen enrichments detected by the Lunar Prospector near the lunar poles are a peculiar type of ore deposit in the context of the Moon. Sufficiently high concentrations of hydrogen or water could enable their commercial extraction (Duke et al., 2002a). Thus, surface exploration that could locate concentrations of hydrogen or water (>2% water may be a target) could enable commercial activity. Such exploration may be partly possible from lunar orbit, but probably requires ground exploration, including geophysical sounding and sampling for hydrogen or ice content.

### 2.5.2 Conduct Research on Metals Extraction

A variety of techniques have been explored for the production of oxygen from lunar materials (Taylor and Carrier, 1992). When oxygen is produced, typically a metallic phase appears (e.g. when $FeTiO_3$ is reduced by hydrogen, metallic iron is produced). Therefore, many of the techniques that have been suggested for oxygen extraction can be used as well for metals extraction. In addition, specialized techniques that would not be applied to the extraction of oxygen, an inexpensive product, may be of interest for the extraction of high purity silicon, a more valuable product, for use in fabrication of semiconductors or photovoltaic cells. The principal oxygen-metal production processes that bear investigation at a prototype level include hydrogen reduction, carbothermal reduction, silicate electrolysis and fused salt electrolysis. The presence of water near the lunar poles could enable other types of processes as well. A principal requirement is that consumables should be recycled with low requirements for replacement with new materials from Earth.

### 2.5.3 Demonstrate In-Situ Solar Cell Production

If silicon can be extracted in high purity from lunar materials, the production of photovoltaic devices made nearly entirely from lunar materials may become possible. This has the potential of gaining great leverage in the development of power systems on the Moon, because relatively small amounts of material are required to produce large quantities of energy. Criswell and others (e.g. Ignatiev et al., 1998) have proposed that silicon photovoltaic devices be emplaced directly onto the lunar surface using vacuum deposition techniques. If this can be accomplished, rapid expansion of a lunar power system could be envisioned, displacing the need to carry large masses of power systems to the Moon and greatly reducing the cost of energy on the Moon. Creation of the capability to produce power on the Moon from lunar resources has commercial implications, as power is a major expense for many other activities, such as resource processing.

Relatively simple experiments, having masses of a few kilograms, can be devised to demonstrate the key steps in lunar solar cell production. It also would be possible to test complete systems of the type proposed by Ignatiev et al as part of the initial phase of establishing a permanent outpost.

#### 2.5.4 Demonstrate Mining Technologies

In order to extract useful products from lunar surface materials, mining systems will be required. As most of the early products will be extracted from bulk regolith materials, the mining equipment needed is essentially excavation and hauling equipment as was discussed previously. Efforts are needed to demonstrate the proper scale of mining and hauling equipment. On Earth, such systems become more efficient (amount of material mined per mass of mining equipment) as their size increases. Efforts are required to create and demonstrate effective excavation and materials handling technologies that have acceptable mass/product and are robust, either very durable or repairable. Low operating cost is a major consideration in a system that is intended to be commercially viable.

#### 2.5.5 Demonstrate Spacecraft Fueling

If water or hydrogen is present near the poles, liquid hydrogen and oxygen can be produced. Oxygen can also be produced by the techniques described above. In order to enable the use of these cryogenic propellants it is necessary to develop delivery systems that allow the propellant to be transferred to spacecraft. High purity of the cryogens is a major consideration, as is reduction of losses from the system. Systems would be required to transport propellants from where they are produced to the spacecraft. Early lunar spacecraft may require propellant loads of several metric tons. Learning to handle these masses of cryogens on the lunar surface is critical to commercial activities requiring the delivery of propellants to customers off of the Moon.

Current studies sponsored by DARPA are examining the possibilities for refueling spacecraft automatically in Earth orbit (http://www.darpa.gov/tto/programs/astro.html). These experiments can provide a basis from which experiments can be designed for the lunar surface.

#### 2.5.6 Fabricate Replacement Parts

For small production quantities it may be appropriate to build unitary systems that are allowed to produce until they fail. However, for commercial applications that require the lowest cost, at some scale that remains to be determined, humans on site who can repair and replace failed parts will become cost-effective. Because of the number of activities and types of parts that may fail is large and the probability of failure will be designed to be small, the provision of spare parts for every possible failure may be infeasible. At that point, fabrication of replacement parts can become cost effective, with respect to the cost of transportation from Earth, and may be able to provide replacement parts much more quickly than transporting them from Earth.

#### 2.5.7 First Lunar Commercial Broadcasts

Broadcasting from the Moon could be an early commercial utilization of the Moon that provides benefits to Earth. Audio or video signals beamed from the Moon by a lunar reporter or part time by crewmembers at a lunar outpost could provide a unique perspective to people on Earth (the Earth would always be in view from an outpost on the near side).

#### 2.5.8 Demonstrate Power Transmission and Storage on the Moon

Energy generated on the Moon from solar or nuclear sources must be transported to its place of use. In the case of nuclear sources, reactors will have to be located at a distance from human activity. Solar sources may be local, except that in polar regions where activities in permanently shadowed areas are contemplated, energy will have to be transported into the permanent shadow. It may be effective to export energy from the Moon to space, for example in the concept of the Lunar Power System, beaming energy to Earth, or to space where beamed energy may provide an alternative means of powering low-thrust propulsion vehicles in near-Earth space. In order to take advantage of these long-term and potentially commercial activities, experiments must be carried out to demonstrate useable energy storage and transmission systems. Experiments that could be carried out on early missions include: (1) demonstration of power beaming from point to point on the surface, possibly from a fixed point to a rover in a shadowed crater; (2) Demonstration of power beaming from the Moon to space or to Earth, to demonstrate the physical feasibility and understand the potential interferences to beam transmission; (3) Demonstrations of regenerable fuel cell operations on the Moon.

#### 2.5.9 Extraction, Purification, Liquefaction, Storage and Delivery of Water, Oxygen, Hydrogen

A number of key technical steps must be undertaken if commercial use is to be made of lunar propellants. These technologies are well understood for applications on Earth, but engineering development and demonstration in the lunar environment will be needed to ensure that: (1) Efficient technologies are applicable in the 1/6 g environment; (2) thermal integration requirements for a production system are fully understood; (3) storage system operation, including thermal control systems, are feasible; and (4) demonstrate transfer of water and cryogenic propellants with minimal loss.

#### 2.5.10 Functions Required

The functions required for this activity are similar to those discussed in 2.3.20, but may be more complex.

### 2.6 Maintain Crew Health, Safety and Performance and Effective Facility Operations

The workload associated with conducting the investigations that will be required for scientifically and technically rewarding missions will be heavy on the crew, so the facilities that support them must be effectively designed and operated. The results from lunar missions, particularly those that grow in duration to a scale that is relevant for Mars exploration, will provide a strong database from which the Mars missions can be planned. Each step in the process must be thoroughly understood. The Moon is important in this regard, because many of the functions that are required for Mars missions can be studied in relatively similar environments and in a location that is not several months in travel time and as much as 40 minutes in communications time away. Having a facility close to the Earth promises a better opportunity to demonstrate the performance of the equipment and the human systems on more than just a single crew that might go to Mars. Over time, many versions of surface system hardware and many people could participate in the lunar missions.

A requirement for the Moon to be a faithful analog to Mars missions can have significant implications for the lunar outpost. The principal implication is the design lifetime of the facility. If it is expected that crews will eventually spend up to 18 months on the Moon to mimic a Mars surface mission, the capability to support such a use or be expanded to support such a use must be built in from the beginning, even though the initial lunar missions may be much shorter in duration

In some ways, everything that the crew does on the surface of the Moon will be an experiment, from which we will learn better how to survive for long periods of time on the Moon and on Mars. This will place a burden on the crew that must be accommodated in timelines and work assignments, so that they can have the time to record their experiences, making comments and observations on the success or difficulty met in using equipment or procedures.

Approaches to radiation protection can be developed and tested on the Moon. These include experiments on provision of radiation shielding, design and use of "storm shelters" and detection of solar particle events on the Moon and in space.

### 2.6.1 Functions Required

Among the functions that are relevant to this area are the "living and working" functions, such as health maintenance, exercise, and health monitoring; personal hygiene and care, food preparation and consumption, waste management, entertainment and free-time activities, communications with Earth (both personal and technical), general housekeeping and training. Current experiments in orbit and in terrestrial analogue environments are addressing open questions in these areas (Snook and Morphew, 2003).

## 3.0 Functional Descriptions

The following functional descriptions are provided for those activities that will dominate the astronaut's time while on the surface, with information on the types of activities needed, the facilities required to carry them out, and the operations philosophy. From these functions, giving consideration to the mission's objectives and the technology available, estimates can be made for the amount of time and effort required by crews on the lunar surface. Recognizing that the Apollo program demonstrated fairly thoroughly the capabilities of astronauts on the lunar surface for short missions and identified significant areas for technology improvements (e. g. space suit glove dexterity), this section is prepared primarily from the point of view of long-duration lunar missions. Further, although initial lunar visits may be limited to 30-45 days, the flavor of these descriptions is written from the perspective of somewhat longer crew stay times. Facilities, once installed on the Moon, can be designed to be permanent and reusable, if appropriate attention is paid to their maintenance and modularity, so the buildup of infrastructure is a reasonable strategy and eventually quite long-duration missions could be undertaken, including stays equivalent in duration to human flights to Mars. Many of the descriptions of this section were first prepared for the Mars Surface Reference Mission (Hoffman, 2001). In that regard, accomplishment of many of these functions in a lunar mission would directly support their definition for Mars missions.

### 3.1 Work Activities

#### 3.1.1 Field Investigations

Field geology on the Moon is unlike field geology many places on Earth, in that the Moon is nearly everywhere covered by regolith, fragmental material produced by impact processes. The amount of regolith is a function of the age of the surface and the amount of impact "gardening" that has been experienced. Few real outcrops can be sampled directly. Therefore, a variety of sampling strategies will need to be utilized: (1) Impact craters as sampling tools. Impact craters excavate material to a variety of depths. The rims of impact craters tend to consist of material that has been lifted from close to the original surface and overturned as it is deposited. In a general sense, the deeper the material was originally, the more likely it is that it will be found farther from the crater. Therefore, sampling patterns for craters involve "radial" traverses, so that ejected materials farther from the crater rim can be correlated with rock units deeper in the surface. Within larger craters, material that consists of melted rock as well as fragmental rock (breccia) form relatively fluid (and therefore finally relatively flat) deposits. Such deposits can also be investigated for their content of preexisting rocks. (2) In some places, such as the rims of sinuous rilles, bedrock may be sampled because the regolith is kept thin because it is collapsing into the depression. These places are relatively common, but they only provide samples of the very surficial rock units; (3) In many places, the regolith is so thick and so old that the only effective way to sample the rocks below the regolith is to obtain rock fragments from the regolith and conduct statistical studies to determine which are the local rocks and which represent impact debris from distant events. It may be possible in some areas, but is considered difficult, to make accurate determinations based on inspection of larger rocks. In the larger sized samples collected by Apollo, there are many more regolith breccias (impact welded rocks) than are found in the finer portions, indicating that the examination of large numbers of surface rocks greater than a few centimeters will not be very efficient; (4) drilling on the Moon could be very useful, but is likely also to be difficult, due to the vacuum conditions and absence of drilling fluids. In many places, drill holes of a few tens of meters to hundreds of meters could be very useful; (5) In some places, particularly in areas of recent pyroclastic deposits, trenching may be useful. Extensive studies of Apollo core tube samples showed a few places where stratigraphic information could be obtained in that way, but most of the cores were quite uniform to the naked eye. Special sampling tools, including hand held sensors, will likely be needed. Local geophysical studies may aid in decision making about where to sample.

#### 3.1.1.1 Field Campaign Strategies and Approaches

Although the list of these field exploration activities will undoubtedly grow as specific objectives are chosen and the means to accomplish them are defined, two examples serve to illustrate the range of these activities: field geology and/or mapping and intensive fieldwork at a specific site. The following paragraphs describe some of the key characteristics of each of these activities.

The activities of a field geologist on the surface of the Moon will differ greatly from EVA activities of the Space Shuttle and International Space Station (ISS) eras. These differences will impact both the design and use of EVA systems for surface activities. Some of these activities and the impacts that will result include the following (Eppler, 1997):

> "Geologic fieldwork involves collecting data about the spatial distribution of rock units and structures in order to develop an understanding of the geologic history and distribution of rock units in a particular region."
>
> "It is an oft-stated but correct maxim that the best field mappers are the ones who have seen the most rocks. Geologic fieldwork on the planets, if it is to be worth the significant cost needed to get the geologists there, will require both EVA suits that will allow EVA crew to walk comfortably for hours at a time, and rovers that will allow the crew to see as much terrain as possible."
>
> "One distinction that needs to be emphasized is the difference between field mapping and pure sampling. A popular misconception is that geologists conduct fieldwork purely for the purposes of sampling rock units. Sampling *is* an important part of field mapping, but sampling in the absence of the spatial information that field mapping provides leads to, at best, a limited understanding of the geology of a particular area. Having said that, the nature of the rock exposure in a given area can limit the amount of field mapping that can be done, and *can* drive fieldwork efforts to conducting a sampling program that, with some ingenuity, can provide the basics for understanding the broad geologic context of a particular locality."

With this background, a typical field exploration campaign will begin with one or more questions regarding the geology in a particular region and the identification of specific surface features, based on maps and orbital photos, that offer the potential for answering these questions. Traverses are planned to visit these sites, typically grouping these sites together (into multiple traverses if necessary) to meet the limitation of the equipment or environment (e.g., EVA suit duration limits, rover unrefueled range, crew constraints, local sunset, etc.). Depending on the anticipated difficulty of the planned traverse, the crew may choose to send a teleoperated robot to scout the route, sending back imagery or other data for the crew to consider. The EVA crew walks, or rides if rovers are planned for the traverse, toward the first of these planned sites using visible landmarks and cues available through the surface navigation system. The crew stops at this site to make observations, record data (e.g., verbal notes to be transcribed later, imagery, sensor readings from those instruments brought on the traverse, etc.), and gather samples as appropriate. If a return visit to this site is deemed necessary to gather additional data or samples, then the position can be marked with a small flag or other visible marker or as a "way point" for future use within the navigation system used for surface traverses. The crew then proceeds to the next site in the plan until all sites have been visited or until they are required to return to the outpost. At any point in the traverse it may be desirable to stop at unplanned locations due to interesting features that may not have been recognized as such during planning. Real-time voice and data, along with some amount of video, are sent back to the outpost to those crewmembers monitoring the progress of the traverse. On returning to the outpost, the EVA crew will ensure that all curation procedures are carried out and that information gathered in the field is transcribed, downloaded to Earth or stored in the outpost data system. (Sample curation and sample analysis are described in later sections). IVA time needs to be allocated for the EVA crew to review and digest the results from their EVA and to prepare for their next EVA.

The ability to return to a site following an initial visit, after performing analysis in the outpost laboratory, is a key attribute of long-duration lunar missions. The mission planning must provide the flexibility of time and resources to allow this possibility. EVA and IVA are interactive, therefore, and the time provided for those activities must likewise be balanced. Analog mission simulations have demonstrated that at least 1-2 hours of pre-EVA traverse planning and 2-3 hours of IVA post analysis per 4-hour scientific traverse are required for adequate scientific return (Snook and Morphew, 2003, NASA 2003a).

Intensive fieldwork at a single site may include several activities associated with science and exploration payloads as described in Section 2 of this report. In some cases, this will simply involve off-loading equipment from a rover and installing it in the field. In other cases, however, continuing intensive work may be needed. For example, drilling operations may require considerable time. This was the case during Apollo, where more time was needed than had been anticipated to retrieve the 3 m drill samples (Figure 3-1). Some of the problems can be addressed in system design for the next generation lunar drill; yet, deeper drill samples and multiple drill sites will likely be desired in some areas and could require considerable time.

Consider the use of a 10-meter drill to characterize ice in permanently shadowed craters. A traverse will be carried out to examine candidate sites for the drill, with the acceptable sites being placed in a priority order. Drill equipment will be moved to the first site, most likely on a trailer pulled by either the unpressurized or robotic rovers, and set up for operations. The setup process will likely be automated, but with the potential for crew intervention. Drilling operations are also likely to be automated but under close supervision. (At present, drilling is still something of an art, requiring an understanding of both the nature of the material being drilled through (or at least a best guess of the nature of that material)and of the equipment being used. While drilling is a candidate for a high level of automation, it is likely that human supervision for purposes of "fine-tuning" the operations and intervening to stop drilling will remain a hallmark of this activity). Down hole data may be recorded during the drilling process, which may require stopping from time to time to take measurements and record data. Core samples will be retrieved by the crew and packaged in a customized curation process defined for these special samples.

After concluding drilling at a particular site, the drill equipment will be disassembled and moved to the next site, where this procedure will be repeated. Because of the nature of the drilling process, there is a high probability that the above-surface equipment will fail or the below-surface equipment will break or seize. Crew intervention is highly likely in either event. In the first case, the crew must decide if the failure can be fixed in the field or if the equipment must be returned to the outpost for repair. Either option will involve some amount of equipment disassembly. If the subsurface equipment fails, the crew must decide how much of this equipment can be recovered or retrieved with the tools it has available and whether it is worth the effort and resources to make this retrieval. Due to cargo mass constraints, the drill will not have an unlimited supply of drill bits, auger bits, or drill stem. This makes it worthwhile to expend some effort to retrieve as much of the salvageable subsurface equipment as possible and attempt a repair, the alternative being to halt drilling operations until adequate replacements arrive, probably with the cargo flights supporting the next crew. The two key characteristics that should be noted here are that drilling activities, and by inference other intensive fieldwork, will involve repeated trips to a single location (or the use of a remote field camp; see Section 2.5) and an extensive interaction with tools and equipment at these sites. The interaction of sample analysis and drilling is also important. If the characteristics of the regolith that are correlated with ice concentration can be determined during the drilling campaign, it may be more effectively carried out. For example, if it is found that ice does not extend below 5 m depth in a particular area, twice as many holes, each half as deep, might be studied.

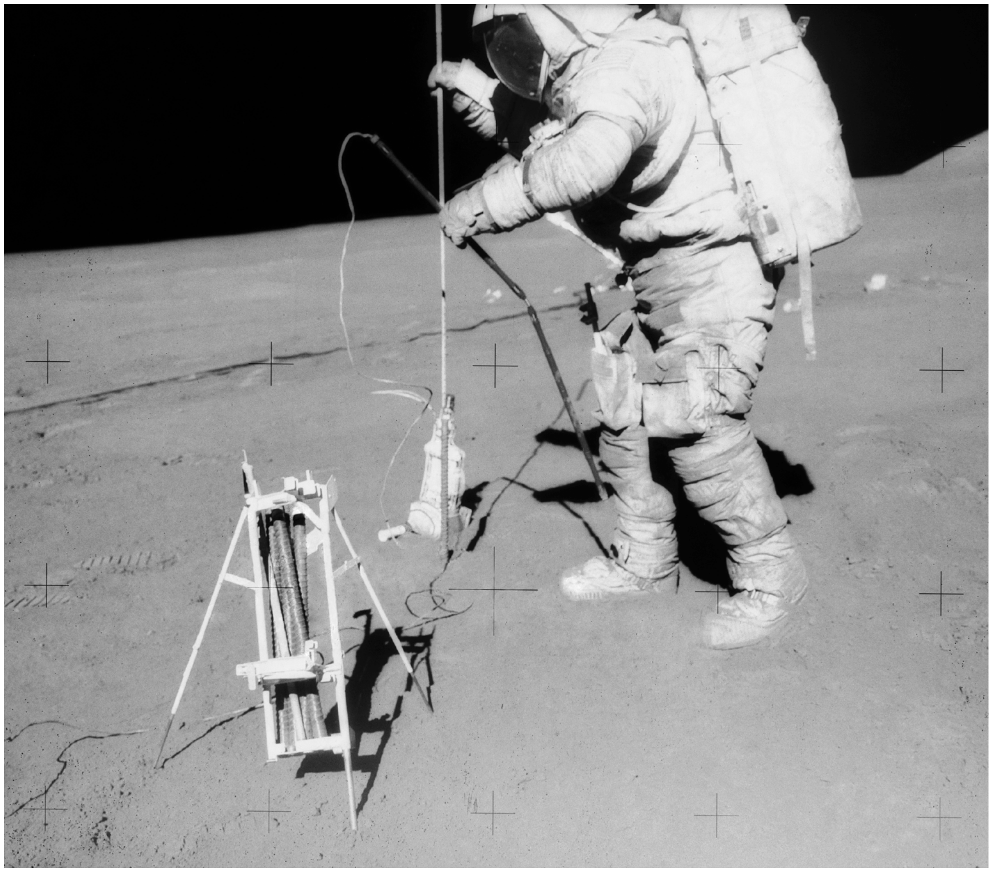

Figure 3.1 Astronaut Dave Scott threading a drill stem onto the drill motor before obtaining a core sample on the Apollo 15 mission. (AS15-92-12407)

#### 3.1.1.2 Navigational Requirements

Efficiency, automation, and scientific return of EVAs is greatly enhanced by the deployment and use of one or more navigation systems that allow determination of location any time to within 1 meter and heading to within one degree (NASA 2003a). The type of navigational system used could be a satellite-based triangulation method such as GPS on earth, or dynamic three-dimensional modeling correlated with high-resolution orbital or landing site imagery. The ability to accurately correlate position with time (to within 1 meter and 1 second) is a recommended minimum requirement, with increased accuracy possibly required by some scientific instruments or imaging systems (NASA 2003a).

#### 3.1.1.3 Extravehicular Activity

EVA is the sine-qua-non of lunar missions. Every effort has to be taken to make EVA routine, safe and effective. This will dictate requirements on suit design, maintenance and operation. Operation of EVA suits in the Apollo missions was highly successful (Figure 3-2), though fatiguing to astronauts and not acceptable for long-duration missions. Both new technology and new operational strategies can improve on the Apollo capability.

As a practical matter, the examples described above, and other EVA tasks that are identified as the surface mission matures, will be translated into more specific design assumptions and operational guidelines. These will in turn lead to specific requirements and flight rules.

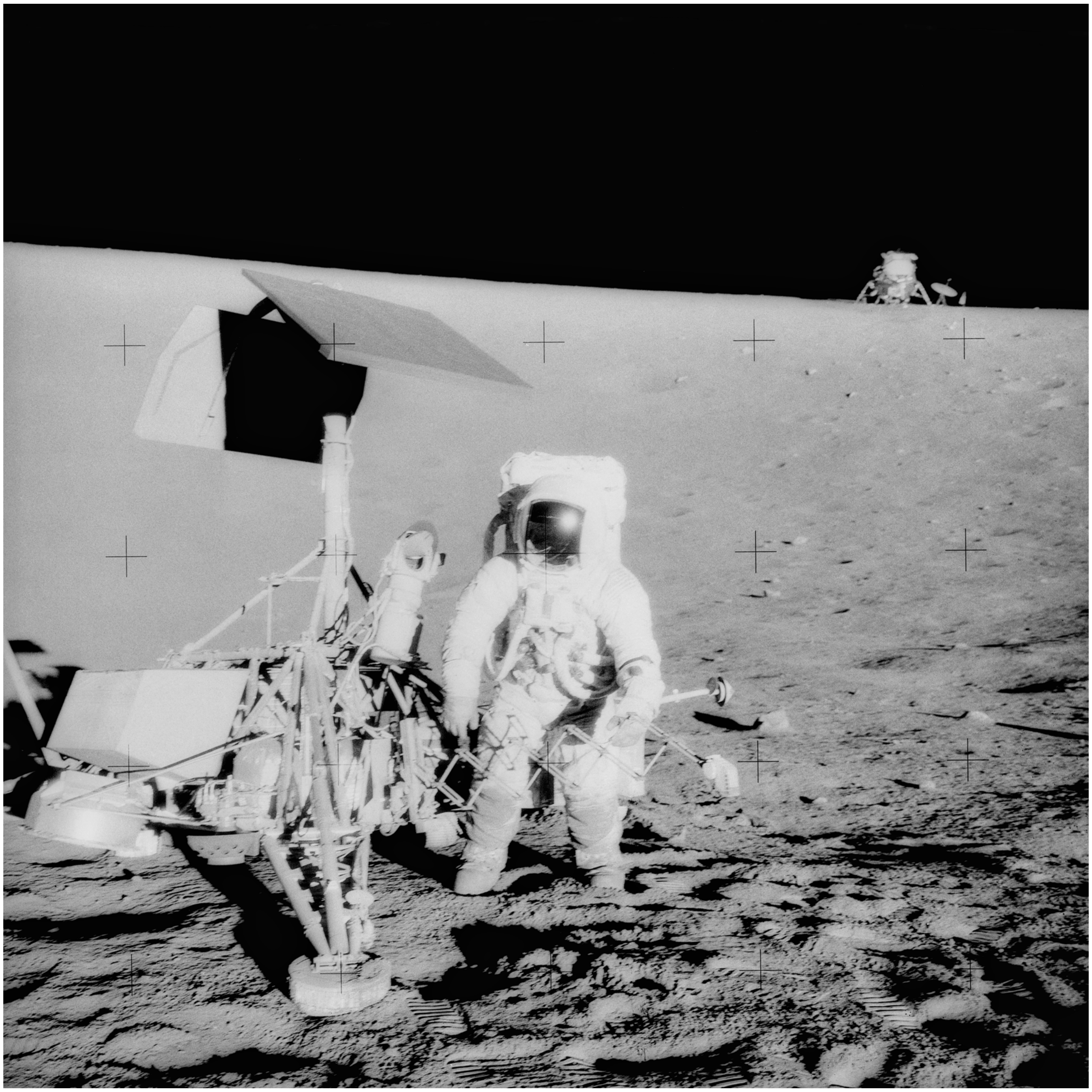

Figure 3-2. Astronaut A. Bean and two U. S. Spacecraft on the surface of the Moon (Apollo 12 and Surveyor III). This photograph shows how close astronaut P. Conrad landed the LM to its target point (AS-12-48-7135)

3.1.1.3.1 Requirements for EVA Systems

A wide range of activities will be carried out on EVA. The most important operational characteristics of the EVA systems are:

- "Ability for suited crewmembers to observe the environment around them. First and foremost, geologic fieldwork is an exercise in seeing rocks and structures. The accommodations that allow observation must allow as wide a field of view as possible. Further, the visibility provided must be as free of optical distortion [as possible] and preferably without degradation of color vision. In particular, seeing colors allows discrimination between otherwise similar rock units (Eppler, 1997)".

- "EVA suits and other exploration accommodations must allow as much mobility as possible, both in terms of suit mobility and the ability to see as much countryside as possible. …. Where suit mobility is difficult or disallowed by the mechanics of inflated suits (e.g., bending and squatting down), an easily used suite of tools should compensate for the lack of mobility, so rock samples and dropped tools can be picked up with as little effort as possible (Eppler, 1997)." It is also important that the suits be designed with respect to any specific equipment with which they must interact. On Apollo 15-17, the suits were designed to permit bending at the waist so that the astronauts could sit on the lunar rover.
- Tools and equipment must be maintainable in the field and the EVA suit/tool interface must accommodate the environmental conditions under which this maintenance will take place. The level of maintenance that must be accomplished in the field versus maintenance at the outpost has yet to be determined. However guidelines on maintenance activities are discussed in a later section of this document.
- Communication between the EVA team in the field and the outpost, as well as navigational aid for the EVA team while in the field, must be available for all field activities envisioned for the surface crew.

###### 3.1.1.3.2 Proposed Assumptions for EVA and EVA Suits

The following list indicates some of the assumptions being proposed for EVA activities:

- The buddy system of at least paired EVA crewmembers (larger groups meet this minimum requirement) will always be used.
- Standard EVA protocols such as gloved hand access, no sharp edges, touch temperatures within supported limits, and simplified tool interfaces must be applied to every element expected to be handled or encountered by suited crews.
- A safe haven must be readily available at all ranges beyond walkback distance. (See NASA, 1998b, for additional discussion of safe haven requirements.)
- Seasonal effects, such as number of daylight hours and possibly radiation events, will be taken into account during planning, timing, and support of EVAs. In addition, for polar traverses, more complex planning involving thermal loads and the limits they place on EVAs will be required.
- Planned EVA contingency support will account for sickness, injury, and potential incapacitation of an EVA crewmember in addition to suit and equipment problems.
- Earth-based personnel will provide the primary link to astronauts on the surface (however, alternate scenarios for operations and communications modes might be investigated for long-term Mars missions). The crew within the habitat will monitor EVA operations of the other crew, in part to provide them support, in part to gain information useful in subsequent EVAs. Both locations require real-time voice, video, and data between the EVA crew, the habitat, and Earth. Loss of these links may, depending on distance, terminate the current EVA.
- Nominally, only one pair/group of crew will be allowed outside the habitat or a pressurized rover at a time. It may be possible to have two groups outside in extreme cases, but only for local maintenance/support or one pair rescuing the other. For short-duration missions, the lander may not be equipped with an airlock. In that case, the entire crew will effectively be outside when the cabin is depressurized.
- EVA during nighttime will be trained for and possible, but not nominally planned, and will be constrained to a local area (i.e., in the vicinity of the habitat or a pressurized rover). EVA during periods where Earthshine is sufficient for EVA visibility will be studied as a special case.
- The EVA suits will have minimal prebreathe and require minimal turnaround maintenance between uses.
- EVA suits will be easy to maintain and will be suitable for (TBD) numbers of EVAs before they are discarded or returned to Earth for maintenance.
- EVA suits will be designed with astronaut comfort and performance in mind, particularly addressing the issues involved with extending the duration of EVAs. Extension of EVA duration from 6 to 9 hours can offer much more than 50% increase to the crewmember's effectiveness, if fatigue can be reduced.

### 3.1.1.3.3 EVA Duration

The duration of an EVA is determined principally by the ability of the system to support normal functioning of the crewmember and by the stamina of the crewmember. There is an operational overhead that is associated with donning/doffing the EVA equipment, pre-breathing (if needed) and airlock operations. The longer the period of an EVA, the more efficient it might be with respect to the overhead activities; however, crewmember fatigue will provide a limitation on total duration. Typically an 8-hour crew workday can produce a 6.5-hour EVA capability. Extending the workday by 25% could increase the EVA time by 30%. Suit design and procedures should have the goal of supporting the most effective EVA periods.

### 3.1.1.3.4 EVA Frequency

The frequency of EVAs is likely to be equally limited by the suits themselves (maintenance, cleaning) and the schedule constraints imposed by scientific EVA planning and analysis. Daily scientific EVAs, although proposed in Section 4 (Tables 4-4 through 4-7), might be too ambitious due to underestimation of time required for pre- and post- EVA preparation, analysis, documentation, and reporting. Depending on the degree of real-time analysis expected during the mission, and depending on the dependence of later EVAs upon results of earlier exploration, fewer EVAs combined with more analysis and communications time could result in increased scientific productivity overall. Timelines should be carefully planned, taking into consideration results from analog and precursor science-driven exploration missions and simulations.

### 3.1.1.4 Surface Mobility

Surface transportation for EVA crews is a requirement that greatly improves the efficiency with which crews can explore the surface. It is anticipated that a suited astronaut will not be allowed to venture farther from the outpost than he/she is able to walk back in a reasonable period of time (≤ 6 hr, a typical EVA duration). If an astronaut is on foot, and the maximum speed is 1 km/hr, an astronaut would never venture beyond 3 km from the outpost (3 hours out, 3 hours back). If supported by an unpressurized vehicle, the walkback distance would be of the order of 6 km. With a pressurized vehicle or another strategy to provide consumables to a surface explorer, the area of exploration would increase markedly. To a first approximation, the number of useful scientific observations and samples will increase with the accessible area, or the square of the walkback distance, so a 6 km range could provide four times the science of a 3 km range, and probably much more. Safety considerations for landing may drive landing site selection to a location that is free of terrain features that have the dual distinction of being both “landing hazards” and “interesting geological sites,” further reducing the interesting terrain that can be investigated if astronauts are on foot. As the time spent at a given landing site increases, the opportunity to investigate features that are different from those already studied decreases, so the need for mobility increases. Also, as distance of a particularly interesting site from the landing site or outpost grows, the amount of time available to investigate it diminishes. The break point between where an unpressurized rover and a pressurized mobile facility (much more expensive and harder to support) is dictated requires more study. Also, additional strategies, such as the provision of temporary shelters, pressurized field camps (Hoffman, 2001), or multiple rovers require more study.

### 3.1.1.4.1 Near-Base Mobility

In near-base locations, unpressurized rovers will augment travel by foot. Astronauts in the pressurized base facility will prepare for EVA within the habitat and use the rover just as did the Apollo astronauts. The capabilities and interfaces of the unpressurized rover will be intimately tied to those of the EVA suit and it can be viewed as an extension of the EVA suit. From this perspective, heavier or bulky systems that would otherwise be an integral part of the suit can be removed and placed on the rover, or the functionality of certain systems can be split between the suit and the rover. Some capabilities of navigation, long-range communication, tools, and experiment packages can be integrated with or carried by the rover. Portions of various life support system consumables (e.g., power, breathing gases, thermal control, etc.) can be located on both the rover and within the EVA suit. This division or reallocation of EVA support functionality may restrict the maximum duration in the EVA suit to something less than that has been previously demonstrated. During Apollo EVA activities using the lunar rover vehicle (LRV), the crew spent approximately 20 percent of the total EVA time on the LRV moving from site to site. Thus, a rover can carry at least that part of the consumable load. Providing multiple sources of consumables and support systems in the field also enhances crew safety by providing contingency options should EVA suit systems degrade or fail.

EVAs will be conducted by a minimum of two people. This provides for a buddy system while on EVA, and for missions where larger crews are landed, leaves additional people in the surface habitat if contingency operations are needed. If an unpressurized rover is used, the EVA team will be constrained to operate within rescue range of the outpost. Rescue means either the team has sufficient time to walk back to the outpost if the rover fails, or there is sufficient time for a rescue team from the outpost to reach them. Taking multiple rovers into the field allows the EVA team to expand its range of operation because these vehicles are now mutually supporting and thus able to handle a wider range of contingency situations, such as one rover providing power or lighting for repairs to the other rover, rescuing riders of an immobilized vehicle, or helping to extract a stuck rover.

This description suggests two additional characteristics for unpressurized rovers: (1) These rovers must be reliable but also easily repairable in the field (or at least have the capability to be partially disassembled in the field so the failed component can be returned to the outpost for repair); (2) The rover must be sized so it could carry the crew of a disabled rover if its cargo were off-loaded.

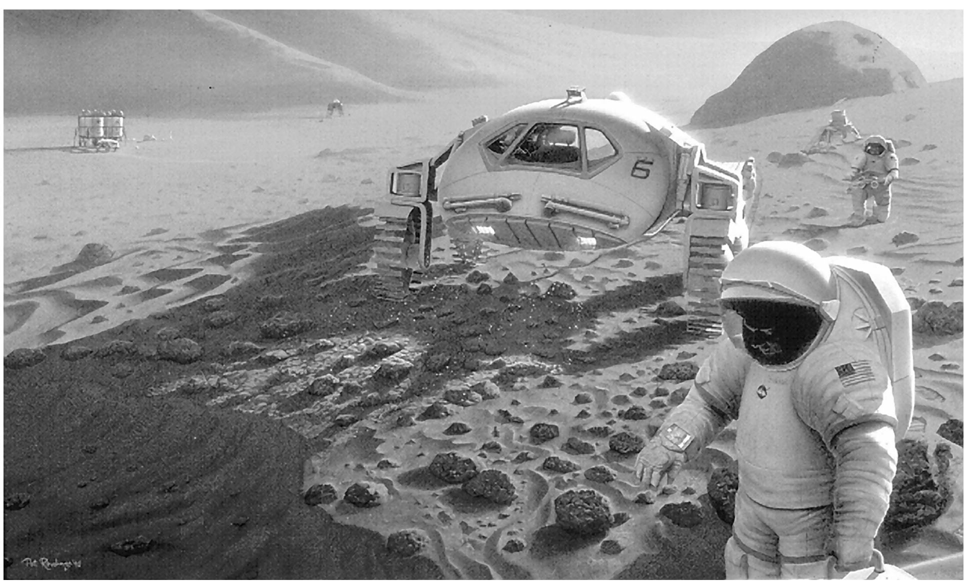

Figure 3-3. EVA crewmembers begin to explore the region in the immediate vicinity of the landing site.

Pressurized rovers, such as the one illustrated here, will be used for a variety of tasks both close to and distant from the pressurized habitat. These rovers will allow the crew to conduct EVAs, as required, in the vicinity of the rover

#### 3.1.1.4.2 Long-Distance Mobility

Pressurized rovers would extend the crew’s EVA range, in terms of both distance and duration. While exact distances and durations will be dependent on the specific site chosen, in initial lunar missions, extending the range to

50 km from the outpost would potentially increase the scientific return of the mission, in terms of making additional terrain accessible. Adding a pressurized rover will also be substantially less expensive than an additional full-scale mission to a nearby location. For lunar missions, the pressurized rover must be capable of performing many of the same functions as at the outpost, but at a reduced scale. Thus a crew using a pressurized rover can be expected to be capable of commanding and controlling teleoperated rovers, equipment, or instruments, conducting EVA activities (comparable to those discussed earlier) within the vicinity of the rover, and otherwise being supported for the duration of the excursion.

If only a single pressurized rover is available, operations will be constrained in a manner similar to that imposed on multiple unpressurized rovers: the pressurized rover must remain within range of the unpressurized rovers to allow for rescue should the pressurized rover become immobilized or disabled. While this circumstance does not allow for the rover to be deployed at great radial distances from the outpost, it does offer some interesting uses that can be equally productive. In one example, the pressurized rover can be used as a temporary base camp at a location where intensive fieldwork will be carried out for an extended period of time (e.g., a drill site) but still within unpressurized rover “commuting” distance of the outpost. Crews can be exchanged and consumables can be resupplied for as long as the fieldwork continues at that site. In a second example, the pressurized rover can be used to “circumnavigate” the outpost site at a distance defined by the range of the unpressurized rover rescue constraint. This will allow a traverse of potentially hundreds of kilometers to be conducted, visiting a significant number of sites along the way, for extended periods of time. As with the fixed site scenario, crews and supplies can be delivered periodically to the pressurized rover.

If a second pressurized rover is delivered, the radial distance away from the outpost can be significantly expanded. These distances will preclude resupply and thus the maximum range will be limited by the consumables brought along with the pressurized rovers. One pressurized rover could be used by an exploration crew of two to journey to a site of particular interest, say 50 km from the outpost (see section 4 for site descriptions and an understanding of the potential of such range). At a surface traverse speed of 5 km per hour, it would require at least one full day to reach the site, probably more as interesting sites might be visited along the way. Assuming that the exploration of the site requires two days, and an alternative route of return is taken, such a traverse may last 6 days.

For sampling during the traverse to the site, a teleoperated rover carried on the pressurized rover could be utilized, with samples being stored outboard on the pressurized rover, or perhaps transferred to its interior if immediate study was required. The pressurized rover, however, would have limited sample analysis capability.

The second pressurized rover could remain at the outpost habitat, in case of a failure of the first pressurized rover. As discussed for the unpressurized rovers, dual pressurized rover operations allow for mutual support in the field. It also implies that limited maintenance and repair in the field should be possible, with the contingency capability for a single pressurized rover to bring the entire deployed crew should one of the pressurized rovers be disabled beyond the crew’s capability to repair it in the field.

Whether a pressurized rover should include an airlock remains to be determined. If an airlock is provided, loss of consumables can be minimized and an isobaric chamber capability becomes available. If an airlock is not provided, either the entire crew will participate in each EVA or the rover must be repressurized, which requires additional consumable storage. A docking mechanism might also be provided, allowing transfer of astronauts between rover and habitat; however, this would add complexity.

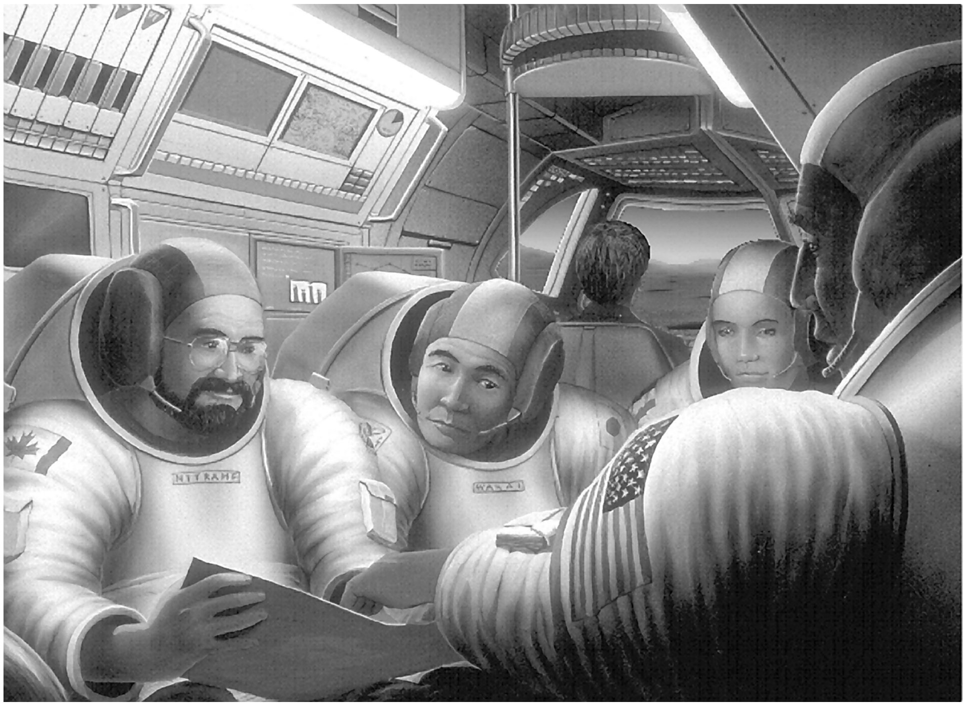

Figure 3-4. Interior view of a pressurized rover as the crew prepares for an EVA at a site located at a significant distance from the pressurized habitat.

3.1.1.4.3 Robotic Mobility Applications

Several applications of robotic mobility systems are implied by the scientific objectives and tradeoffs concerning the cost of hardware vs. the effective utilization of crew time on the surface, perhaps the most valuable commodity on human missions. In general, the robotic mobility systems envisioned here are similar to the Mars Exploration Rover (MER) capabilities, i.e., rovers that have a mass of approximately 150 kg and carry a variety of sample collection tools and a limited range of sensors or analytical instruments, mostly imagers. Field chemical analysis is not of high priority if the samples are to be brought back to a laboratory at the outpost habitat or to Earth, particularly if the opportunity exists to revisit interesting sites.

Under teleoperation, a MER-class rover could have a useful range of several kilometers per day. These rovers could be teleoperated from Earth, so that samples could be collected while astronauts were involved with other activities and the astronauts could inspect and select samples as part of their EVA or IVA activities. For example, if astronauts are operating from a pressurized rover, the teleoperated rover could be operated from Earth while the astronauts are asleep and samples could be secured before the next day’s work begins. These teleoperated systems could also be deployed to locations distant from the surface habitat outpost, bringing samples back to the outpost. If they are robust, traverse distances of several hundred kilometers under supervision from Earth might be carried out during a 30-day human mission. Finally, the teleoperated systems could be deployed in advance of sending humans on short stay missions, to scout out a site, gather samples from well beyond the range accessible to astronauts, and bring them to the outpost or landing site. The impact of increased time delay for Mars missions could be evaluated by developing quantitative metrics for how such robots, teleoperated from Earth, increase overall efficiency and scientific return.

### 3.1.2. Sample Collection

Collecting samples that address major problems in lunar and planetary science and investigate resource potential of the Moon will be a major activity for early lunar investigations. As stated above, one important aspect of having people on the Moon is to allow the results of early investigations to influence later studies. This may occur because analyses show that other materials that should be sampled are likely to exist in an area, or sample studies indicate that more intensive study of a feature is likely to provide answers to new problems identified through the initial sample studies.

The Moon is an interesting place to sample, because one has to look back through the history of the surface to identify materials that can be correlated to “bedrock.” The ubiquitous presence of the lunar regolith both covers the underlying materials and to some extent confuses them through mixing. In any given regolith sample, one finds evidence of local rocks, rocks thrown in by distant impacts, volcanic materials that may have been ejected by local or distant volcanoes, and glasses, agglutinated regolith, and compacted regolith (regolith breccias) that represent the action of impacts on the lunar regolith. The regolith is layered, with each spot on the Moon consisting of a complex series of layers that represents the removal of material by craters followed by the filling in of material from other craters.

Three forms of sampling were employed in the Apollo missions: (1) collection of rock fragments found distributed on the surface. In many cases, these could not be correlated with local materials, while, in others, it was clear that the rock fragments represented local material. For example, boulder tracks descending slopes showed that rocks collected down slope came originally from higher up on the side of mountains. Astronauts did not sample actual bedrock, though bedrock in mare sites is located within a few meters of the surface. Thus, all rock fragments collected by Apollo could be termed regolith samples; (2) Samples of regolith, the fine grained materials that cover most of the lunar surface. These samples, when returned to Earth, were typically sorted by sieving to extract the particles in the 1-10 mm size range. These particles, commonly crystalline basalt, breccia or other lunar rock types, were used to construct the geological history of the site and surrounding areas. The Apollo experience showed that similar sample size classification on the Moon would be an effective strategy to optimize the scientific return on the regolith samples collected. Similarly, a rake was utilized on the later Apollo missions to retain fragments larger than 1 cm in diameter. These fragments proved to be very valuable when returned to Earth; (3) various subsurface samples were collected, typically utilizing drive tubes (aluminum tubes pushed or pounded into the lunar surface) or drill cores, which were taken to a maximum depth of 3 m.; (4) an attempt was made to collect a variety of other samples, including samples intentionally collected to be free of contamination from spacecraft propellant or outgassing of space suits and samples that were collected in specific environments (e. g. under a rock).

At any given site, the mixing of the lunar regolith by eons of meteorite impact has yielded a material that is a mixture primarily of local materials with some fraction of material from distant impacts. At the Apollo 12 site, a common type of glass with ropy form was identified as ejecta from the crater Copernicus. Fragments of highlands material were found in mare samples, even though the closest outcrop of highland material was hundreds of kilometers distant. On the other hand, rocks in the regolith around recent craters of significant size were found to be largely from local sources. These types of observations will dictate sampling strategies for subsequent lunar exploration missions.

#### 3.1.2.1 Sampling Strategies

There is a high priority on sampling bedrock. In a few places, particularly in the mare, where topography has prevented a thick layer of regolith from forming, outcrops of bedrock may exist. Otherwise, to sample bedrock will require drilling. On mare surfaces, where regolith layers are a few to perhaps 10 meters in thickness (the older the surface, the greater the regolith thickness), a 10 – 25 meter drilling capability will be very useful. On highlands surfaces, which are older, the thickness of the regolith can be hundreds to thousands of meters thick. As the materials of the highlands have been thoroughly stirred by relatively large impact craters, there does not seem to be a particular advantage to deep drilling. However, in the mare, where the rocks are relatively young and were presumably deposited by a series of lava flows, drilling to depths of a few kilometers will be fruitful. Sampling the bottom of the earliest mare flow (the one at the bottom of the volcanic pile) will allow the time of initiation of filling of the mare to be determined, along with the times and compositions of the overlying, more recent flow units.

Sampling rock in place is required to address the problem of the ancient lunar magnetic field. If oriented rock specimens can be obtained from bedrock, and the rocks were formed in a period during which the Moon had an internally generated magnetic field, magnetic studies of the samples can be used to determine the strength and orientation of the lunar magnetic field. The presence of an early magnetic field, associated with fluid motions in a lunar core, is among the most intriguing studies that could be undertaken with carefully collected bedrock samples.

The procedure identified above of concentrating rock fragments collected in regolith samples is an important sampling technique. This can be combined with geologic studies of the distribution of features on the lunar surface to recognize local rocks as well as distant ones. A simple sorting device has been defined in an earlier section. This could allow the collection and return of more useful sample materials than would be provided by bringing back either large samples of unsorted regolith or large rock fragments.

#### 3.1.2.2 Tools

The tool kit prepared for Apollo worked satisfactorily and a similar one will be utilized in future lunar exploration. This tool kit included a scoop, tongs, the rake, core tubes and drive tubes, as well as a gnomon, a tool used in documenting samples collected on the surface. The gnomon provided a demonstration of local vertical and carried also a color calibration strip that could be used in determining the true color of rocks on the surface. In addition, the crew had sample bags and sample boxes. Initially, it was thought that all samples should be returned in the lunar vacuum. However, many of the vacuum containers prepared for that reason failed and it proved to be too difficult to handle such samples back on Earth, where high vacuum systems were clumsy and risked contamination to the samples. Careful bagging of samples, particularly fines, in special sample collection bags, was used successfully to help in preserving the materials free from contamination and also to keep their collection histories straight. Allton (1989) has prepared a catalog of lunar surface tools.

#### 3.1.2.3 Field Documentation

Field documentation of samples is essential to obtaining the most scientific information possible. The documentation begins before the sample is collected, with explorers recording the location of the sample and any special characteristics of the setting in which it is found. Photo documentation of the sample on the surface, as was done in Apollo, provides information that will later allow samples to be recognized and their original orientation recovered. The person collecting the sample will describe the sample and note particular features that may make it important. A sample number should be assigned, which can be done by the use of special sample collection containers (bags were used in the Apollo missions). If samples are too big to place into bags, it will be important to note where the sample is stored until it can be delivered to the outpost for further work. Documentation of regolith samples is similar, with location and a description of the sampling procedure to be provided. Documentation of core tubes and other special samples is handled in a similar manner, with care taken to maintain the relative position of samples. Hand-held data and automated data communications systems may be useful for recording these data while in the field.

#### 3.1.2.4 Curation

The capability for conducting EVAs and collecting samples on the Moon will be unprecedented when long surface stay missions are undertaken. Samples will be collected by the crew and may also be collected by teleoperated rovers. Because samples are collected sequentially, it may not be apparent when a sample is collected that it should be returned to Earth. In many cases it will be easier to collect a sample that is too large to return to Earth. In both of these cases, collected samples may be left on the Moon. Methods of handling and curation of these samples is critical to ensure that any specimens chosen for shipment to Earth are minimally contaminated and that the effort of collecting and documenting the samples that are left on the Moon is not wasted.

Sample curation includes documentation, sample tracking, sample splitting, preliminary examination, contamination control, and storage. Treiman (1993) described a curation approach for samples collected at a lunar outpost.

Sample curation begins with the field documentation described above and with sample collection. Knowing that all samples may not be returned to Earth, it would be prudent in the sample collection process to collect two or more representative sub samples, one of which can be studied in the habitat or packaged for return to Earth. In this way, at least one minimally contaminated sample will be archived from every collection site. "Minimally contaminated" refers to samples only exposed to contamination derived from sample collection and storage. Some contamination is inevitable for samples removed from their natural position, from outgassing of an astronaut's space suit, a robotic rover vehicle, or EVA tools and containers. This level of contamination is unavoidable, as it was during the Apollo program, but experience with lunar samples suggests it will not impede or prevent detailed analyses on Earth (Treiman, 1993). After splitting, the sub samples will be "bagged and labeled." The bags used to hold the samples should prevent cross contamination between samples, and will most likely be similar to those used on the Moon during the Apollo program (Allton, 1989). However, the choice of materials needs further study because Teflon, like that of the Apollo bags, abrades and rips easily and can lose much of its strength from long exposure to solar radiation (Treiman, 1993). The small sample bags will then be loaded into a larger storage bag or container, which can be carried on the astronauts' space suits, mounted on their roving vehicle, or mounted on a robotic rover.

When an EVA or robotic rover traverse is completed, the collected samples will be delivered to two separate storage areas. Minimally contaminated samples will be stored in a clean area that is distant from the outpost to avoid contamination from gases emitted from the habitat, local surface activity around the outpost, and exhaust gases resulting from spacecraft launches and landings. This can be a storage area for samples that are to remain on the Moon and sub samples that are being aggregated for return to Earth. The distance between this remote storage area and the outpost may be on the order of one to a few kilometers. Better understanding of the location of this storage area can be developed by environmental monitoring experiments described in 3.1.4.1.4. A second storage area will be located at the outpost, where sub samples can be easily retrieved for preliminary examination in the habitat's laboratories (see Section 3.1.3). These samples will experience varying degrees of contamination during examinations and tests. Samples, once studied, may be selected for transportation to Earth or left on the surface.

The storage areas can range from simply organizing the collected samples in a grid on the surface (i.e., a "rock garden") to housing the samples in a container, structure, or building. Leaving samples on the lunar surface would not lead to serious contamination in the clean storage area and natural effects should be much smaller than those already experienced by samples derived from the lunar regolith. A "storage shed" concept was considered optimal (Taylor and Spudis, 1988), and might be easily constructed from natural materials as the capability of the outpost and the number of samples increases. The facility does not have to be sealed and need only provide mechanisms to reduce the addition of dust and protect the samples from micrometeoroid impacts. Shelves allowing ready access by astronauts with markings or bins to facilitate keeping track of samples are desirable. An electronic means of keeping track of samples in storage and as they may be removed from time to time for additional sub sampling are required.

It is anticipated that many core samples would be returned to Earth in their initial form, without being removed for study on the Moon. In the special case of deep drill samples, much more material may be collected than is reasonable to return to Earth. Special sampling tools or techniques may be needed. Recent studies of deep drilling techniques under study for the exploration of Mars suggest that the drilling mechanism can be kept relatively short, with sections being brought to the surface from time to time. The sections can be inspected and sub sampled, although this is likely to require a great deal of time. Alternatively, as sections are retrieved to the surface, the ends can be sampled for study or return to Earth, while the individual sections can be retained in the clean curatorial area for additional study if that is warranted.

Keeping volatile-rich samples in their pristine state also will present significant challenges. Samples such as ice-bearing regolith retrieved from permanently shadowed areas will require storage at liquid nitrogen temperatures (or in an ever-shaded area). The study of these samples is likely best done in-situ.

### 3.1.3 Sample Analysis

Lunar missions are relatively short in duration, with a limited number of opportunities to conduct multiple EVAs to a single site during a mission. Most sample analysis will be done on Earth after return of samples. Nevertheless, there are some observations that could be useful if made on the Moon. These include analyses that can best be made in-situ, where returning the samples to Earth could contaminate or degrade the samples unacceptably. Examples of these studies are studies of surface properties of regolith mineral grains and outgassing of volatiles from subsurface samples in polar regions. The distinction between in-situ sample analysis, using a sensor inserted into the regolith, and more traditional sample analysis, where a sample is taken and delivered to an instrument, is blurred. Typically, samples that could be contaminated by returning them to Earth would be best done as close to in-situ as possible. This type of sample analysis requires both the development of the rationale and approach to the problem as well as the design of specialized sample analysis tools.

Sample analysis on the Moon can be useful in the confirmation of a surprising new discovery. Consider the case of the Apollo 17 orange soil. If the materials could have been subjected to microscopic analysis on site and the relationship between orange and black soils confirmed quickly (and if Apollo 17 crew had had additional time for exploration) a more deliberate sampling of the feature might have been undertaken (Figure 3-5).

The facilities required for analysis of samples within the habitat should be relatively simple, as samples selected for analysis on the Moon could be discarded after they have been studied (additional pieces of the same samples are available for return to Earth). A binocular microscope and sample preparation tools (chisel, mortar and pestle, etc.) can be the most important tools. For longer duration missions, it may be possible to cut and polish thin sections, which, used with a petrographic microscope, provide a very powerful, quick and routine sample analysis tool. For most lunar samples examined inside the habitat, protection of samples from the habitat environment is not required. A glove box facility, using ambient air, would provide the capability for dust control on samples brought into the habitat (Figure 3-6).

Sample analysis on site also can be useful in studies of rock fragments separated from the regolith. Rake samples obtained by Apollo astronauts and separated fragments in the 1-10 mm size range showed a wide variety of rock fragments. Some experiments that could be undertaken in new lunar missions would benefit from collecting fragments from large quantities of regolith, but this could lead to the collection of far too much material to return to Earth. In particular, regolith breccia samples in many cases are considered less important than samples of crystalline materials. Techniques of screening samples microscopically, by their physical properties, or chemically could be developed, which could classify and select among rock fragments for return to Earth. These techniques would operate outside the habitat and would be highly automated. The astronauts would deliver the bulk sample to the device, the samples would be classified automatically or under control from Earth, and the selected fragments packaged for return either automatically or by the crew. Residual samples could be packaged for retention on the Moon. Suggested areas of investigation for these techniques include microscopic examination, X-ray fluorescence, which can be done rapidly for distinguishing elements, and perhaps magnetic or electrostatic separation. These types of characterization may also be applicable to resource beneficiation.

Figure 3-5. Apollo 17 site where orange soil was sampled by Astronaut Harrison Schmitt.

In the case of lunar resource investigations, it may be desirable to analyze samples on site to determine the nature of materials being fed to experimental systems, so that the performance of the system on the Moon can be determined while the experiment is in process. Because the most highly variable species are volatiles, mass spectrometric capabilities may be utilized.

The study of samples from permanently shadowed areas will be a particularly interesting and challenging undertaken. Currently, it has been shown that hydrogen enrichments are associated with the polar regions, perhaps highly correlated with shadowed craters (Feldman, et al., 2001); however, the form of the hydrogen has not been verified. If the hydrogen is present because it has been brought to the Moon by comets, other compounds, such as hydrocarbons, may be present. Determining the three dimensional distribution of volatile materials would be a major objective. This might be done using an instrumented coring device, but it might also be done using trenches and selecting samples for analysis by mass spectrometry or other techniques.

As mission duration becomes longer and the capability for sample collection at greater distance from the outpost is developed, selection of rock samples for study on the Moon may be undertaken to provide feedback for subsequent investigations or to select samples for return to Earth. If rock samples are to be studied in this manner, more sophisticated sample preparation and analysis capability may be desired. This could include capability to prepare polished thin sections and utilize a petrographic microscope or scanning electron microscope for sample characterization. As such investigations would best be carried out within the habitat, procedures for obtaining and documenting sub-samples outside the habitat would need to be developed.

The effective use of astronaut time is an important consideration. In short stays, astronauts' time will be best utilized by maximizing the number of observations made and samples collected. Automated means of selecting among samples to bring the best samples back to Earth has a high priority. The sampling techniques to be used in special cases like the polar permanent shadow need to be developed. As stay time and exploration capability grows, the need for in-situ sample analysis will also grow. A suggested set of capabilities that should be investigated includes:

- Rapid screening techniques, perhaps using X-ray fluorescence, to select among samples for return to Earth
- Sample collection, documentation and analysis techniques for subsurface samples in permanently shadowed craters
- Development of compact, but effective, tools for thin section preparation, microscopic analysis and possibly scanning electron microscopy.

Additional studies to determine the appropriate amount of time that should be spent by crewmembers in analyzing samples on the surface should be conducted.

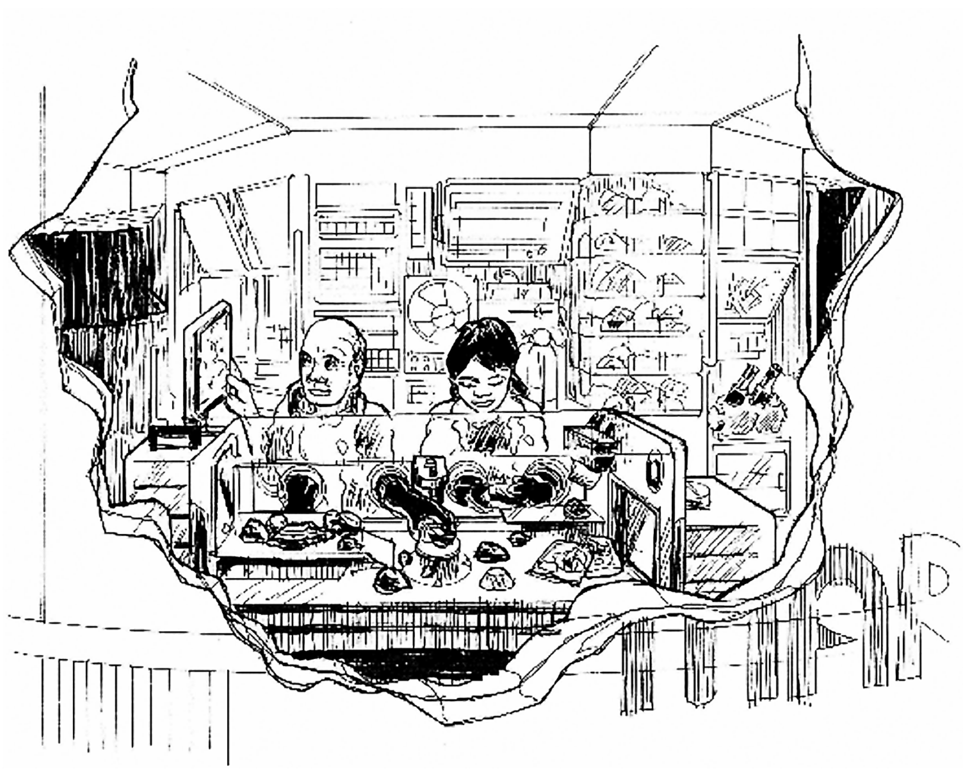

Figure 3-6. Crewmembers examine a number of collected surface samples inside a glove box facility.

### 3.1.4 Deployment of Experiments on the Surface

The Apollo Program successfully deployed the Apollo Lunar Surface Experiment Package (ALSEP) at each landing site (e.g., NASA, 1972). The components of the ALSEP evolved with time. On Apollo 11, astronauts deployed a passive seismometer, a laser ranging retroreflector, and a solar wind collection foil, which was subsequently retrieved for return to Earth. By the end of the Apollo missions, a wide range of experiments had been deployed, including magnetometers, a UV telescope, a lunar atmosphere detector, the lunar ejecta and meteorite detector, a heat flow experiment, neutron experiment, and a surface gravimeter. A complete listing of the Apollo lunar experiments and operations involved in deploying them can be found in Sullivan (1994). The ALSEPs were equipped with radioisotope thermal generators (RTGs) that provided power for several years and by the time of the last Apollo mission, an effective seismic network had been deployed, which operated until all but two seismometers were operating and power levels were diminishing in 1976. A new generation of experiments would build on the experience of the Apollo instruments, some of which did not work effectively. In addition, experiments will be defined to address other long-term objectives of a lunar exploration program, leading to the possibility of long-duration stays on the Moon and applications to Mars exploration.

Some aspects of the design of experiments could be improved over Apollo and better tools might be provided to astronauts to aid in their emplacement. For example, seismometers benefit from tight coupling to the surface and must be leveled. There were operational difficulties on Apollo missions that could be eliminated with new instrument designs. RTGs have been difficult to use on NASA missions in the recent past, due to their expense, availability of radioisotope sources, and environmental concerns on Earth. A new generation of RTGs has been designed that may reduce some of the previous difficulties and should be in a position to support a new lunar ALSEP program.

#### 3.1.4.1 Surface-Deployed Science Instruments and Experiments

##### 3.1.4.1.1 Geoscience

A revised ALSEP should deploy, at a minimum, a seismometer, heat flow probe, and a laser retroflector at every site at which astronauts land on the Moon (retroreflector only on Earth-facing sites). Special experiments, such as the neutron experiment carried by Apollo 17, might be deployed in selected locations and at deeper depths than attained by the Apollo experiment. A lunar atmosphere experiment (neutral and ionized species mass spectrometers) and lunar ejecta and meteorite experiment should be re-examined, as these experiments did not work as was intended. In the case of the lunar atmosphere detector, contamination from the lander/ascent vehicle overwhelmed the natural atmospheric species for a long time. In the case of particulates, it was found that levitated dust dominated the events recorded by the instrument. Different designs might overcome these problems. The detector could be raised on a mast to avoid near-surface dust, could have directional sensitivity to exclude or identify dust events from specific directions, or could have energy discrimination to identify low velocity and high velocity events. The ALSEP should be deployed at a distance of up to 10 km from any place of long-term human activity.

Budden (1990) has cataloged the characteristics of possible science experiments that could be deployed at a lunar outpost. Instruments should be selected on the basis of an analysis of the pressing science problems at the time of the mission as well as the technical readiness of the instrument technology. A fundamental instrument technology program within a lunar exploration program could improve its scientific return by insuring that the most effective instruments are available when the system is prepared to carry them to the Moon.

The introduction of deep drilling to the stable of exploration techniques carries with it the concept of down-hole sensors. In terrestrial drilling operations for oil, sensors typically are mounted in the drilling apparatus that can determine temperature, porosity, hydrogen (water or oil) content, and other variables. On the Moon, down hole sensors will be useful where they can make measurements on samples whose properties might change if they were drawn out of the drill hole, as could be the case for water ice contained in the pores of regolith in polar craters. Also, down hole sensors can give information to the drill as to the difficulty of the units that they are penetrating.

#### 3.1.4.1.2 Telescope and Array Deployment

There are a variety of potential experiments that could be deployed to demonstrate the utility of the Moon for supporting very large telescopes. These would generally be deployed in particular locations, such as in a permanently shadowed area near a lunar polar outpost, or behind a mountainside where shielding from Earth ionospheric noise can be obtained. Telescopes must be firmly mounted to the regolith, or may require minor construction to install. An interferometer test apparatus or small-scale interferometer will require careful alignment and calibration, using laser techniques. Association with a seismometer and dust detector can provide the necessary environmental information. Once installed, the facility should be far enough from human activity that dust and vibrations from that activity are avoided.

Long wavelength detectors require the deployment of antennas, which could be emplaced by robotic or human means. For detector arrays of limited scale, human deployment may be utilized, with transportation provided by an unpressurized rover to carry instruments and traverse the appropriate distances. Some of these instruments could be emplaced at significant distance from an outpost, for example a radio telescope that might be deployed on the lunar far side, reached from a polar or equatorial limb outpost. This would require the use of a pressurized rover as well as local mobility system.

#### 3.1.4.1.3 Space Physics

Space Physics experiments may consist of particle and field detectors or sensors to study radiation from the Earth's magnetosphere stimulated by interaction with the solar wind. These experiments would require deployment and orientation, possibly with minimal site preparation (smoothing and leveling). At a more mature lunar outpost, advanced detectors such as cosmic ray and neutrino detectors, which might require the utilization of local materials for shielding and energy moderation, may be installed.

#### 3.1.4.1.4 Environmental Sensors

The Moon is still imperfectly understood for long-term occupancy. Although geologically, the Moon has been quite stable for a long time, there are some characteristics of the environment that should be routinely monitored. These include:

- Radiation, particularly solar particle events. These are harmful (potentially deadly) to unprotected crewmembers. The Moon is close enough to Earth that sensors anywhere in the Earth-Moon system will be useful (Earth orbit, lunar orbit, or lunar surface) although sensors at the surface will allow the measurement of induced radiation caused by interaction with the regolith. This backscatter component is mainly caused by galactic cosmic rays, which are fairly constant over the short term (but vary over the solar cycle) and contributes to the total dose experienced by the crew. SPEs must be linked with a radiation warning system that can communicate with astronauts when they are outside their habitat. It is assumed that habitats or portions thereof will be adequately shielded against solar particle events.
- Dust. Dust is known to move on the lunar surface due to electrostatic effects. Some dust is distributed by micrometeorite impacts, though the instantaneous flux is very small. Particle sensors that can distinguish between low and high velocity particle impacts will be useful.
- Volatiles. The release of volatiles from human activities is potentially harmful to the lunar environment. Sensors should be installed in the vicinity of human habitation that can assess any environmental degradation due to human activity.

#### 3.1.4.2 Deployed Technology Demonstrations

This area has not been addressed thoroughly in the past, as the technology demonstration aspects of a lunar program have not been given priority as program goals. The Apollo program focused on scientific experiments, but future lunar programs should have broader, longer-term goals. Some examples of possible deployed technology experiments are suggested here, but more detailed work is required to define specific experiments for deployment on the lunar surface. For demonstration of nearly all listed technologies, reliable and accurate means of navigating and locating equipment and personnel will be required (see Section 2.3.5). Recommendations for long-term technology demonstrations required for human exploration of Mars are outlined in Goal IV of the report by the Mars Exploration Payload Assessment Group (MEPAG) (Greeley, 2001).

##### 3.1.4.2.1 Power – Beaming

Power beaming experiments on the surface should be straightforward and power beaming may be used operationally in special circumstances for the transmission of energy, for example from a central nuclear power station to a distributed experiment location. Power beaming has also been proposed as a way to provide energy to a rover exploring within a permanently shadowed area (Henley, 2002) (Figure 3-7). The proposals for beaming energy from the lunar surface to Earth (Criswell and Waldron, 1990) could be demonstrated by the emplacement of several transmitters in the form of a pattern that could be detected on Earth to insure that the fundamental physics of microwave transmission from the Moon to the Earth has been demonstrated. It is noted that microwaves have already been transmitted from the Moon to the Earth any time an Earth-based radar is used to image the Moon. This would require deployment of transmitters and their power supply and communications systems. Deployment of several transmitters could be required at distances of 10 km or more from one another.

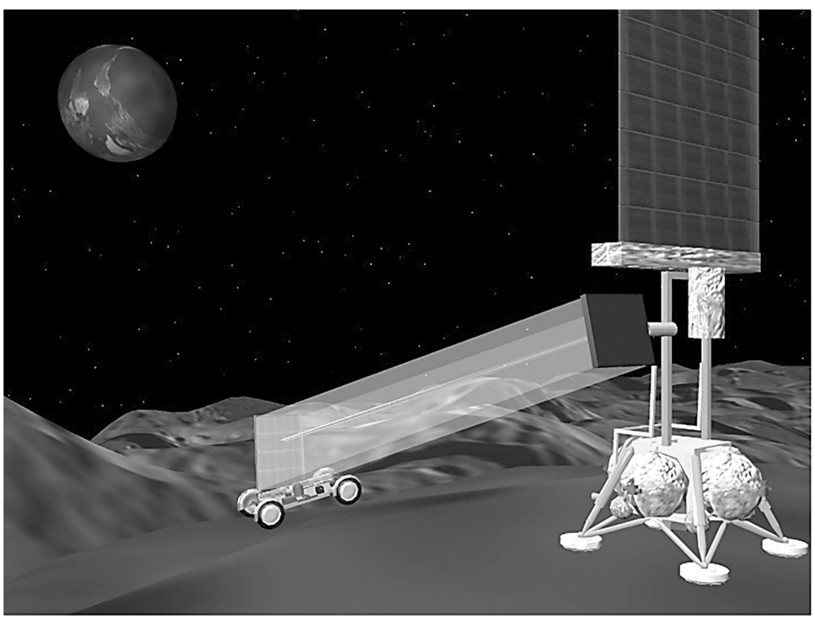

Figure 3-7. Artist’s conception of power being beamed to a rover operating in a permanently dark location near the lunar poles (Courtesy of Henley, et al 2002).

#### 3.1.4.2.2 Thermal Control System Demonstrations

Thermal control hardware for operating on the Moon may be demonstrated entirely by assessing the operation of engineering systems designed for supporting an outpost. Special problems, associated with applications in polar regions (illumination changes as the Moon rotates) as well as equatorial areas (too hot during midday) are the principal phenomena that must be addressed. If new technology is developed and remains to be tested during a period in which only short-duration missions to the Moon are being undertaken, it may be desirable to design standalone experiments that would demonstrate that technology in a relevant environment.

#### 3.1.4.2.3 ISRU Demonstrations

Most of the techniques that have been proposed for extraction of oxygen, hydrogen, water, metals, etc. require either high temperature operations (e.g. reduction, electrolysis) or chemical separations. It will be important during early lunar missions to design experiments that can demonstrate principles and practices for resource utilization that can operate within the lunar environment. These can be standalone experiment packages that can be deployed by astronauts on the lunar surface. The nature of many resource-related experiments is that they will require lunar regolith as the test materials to be processed by the system. In some cases, physical separation (beneficiation) will be required, for which techniques must be developed and tested. These separation techniques might be integrated with the resource experiments or be studied separately. They also, presumably will require feeding with regolith by the astronauts. Finally, there are potential experiments to be performed, such as the production of bricks utilizing local regolith materials, which also may be deployed on the surface with the crews adding regolith to the machine. Thus, these experiments will need to be located nearby the habitat or lander and be accessible to loading with material by the crew.

#### 3.1.4.2.4 Surface Excavation Demonstration

Excavation of the lunar regolith eventually will be required for several purposes: excavation of trenches for scientific studies, excavation of materials as part of construction of large structures, roads or other infrastructure needs, or excavation of materials for resource extraction systems. The development of efficient excavation systems will require both an understanding of the physical properties of the lunar regolith and approaches that maximize excavation efficiency. These will ultimately require demonstration and test in the lunar environment. For example, a bucket wheel excavator may be an effective excavation tool (Muff et al., 2002) if the forces required to excavate are less than the traction forces that must be developed by the excavator. These can be demonstrated using scaled-down versions of operational equipment, deployed on the lunar surface and operated from Earth or from the habitat.

#### 3.1.4.2.5 Construction Demonstrations

Construction, including construction utilizing lunar materials will be undertaken in support of long-term lunar operations on the Moon. These may range from simple construction processes, such as grading roadbeds, as suggested above, to building foundations for massive structures, such as the foundations of a large telescope facility, to erecting buildings on the lunar surface. Here again the problem is one of tailoring techniques to the particular physical properties of the lunar regolith and the lunar environment, and will benefit from in-situ experiments. Such experiments could include: (1) construction and testing of various ways of building piers firmly coupled to the regolith and testing these for properties such as seismic coupling, compaction and settlement; (2) building small test structures that might have a practical application, as well. For example, a radiation-shielded structure might be demonstrated by the erection of a support system made of aluminum struts, which support a roof made of lunar regolith blocks, on top of which lunar regolith is piled to provide an unpressurized canopy. Erection of such a canopy might provide significant radiation protection for structures resting on the lunar surface.

The deployment of these experiments is likely to require direct and complex human involvement, at least by teleoperating robotic vehicles under direct supervision of an astronaut. They might involve making a series of holes with a mechanical auger, placing foundation supports into the holes, and back filling with regolith to create a stable unit, then attaching structural pieces to the foundation by bolting or otherwise fastening pieces. When constructed, sensors might be attached to the structure to measure its properties.

###### 3.1.4.2.6 Radiation Shielding Demonstration

The amount of shielding provided by regolith can be determined directly, by emplacing experimental detectors at various depths in the regolith or by building up layers of regolith over a detector. The neutron probe deployed by the Apollo 17 mission was inserted into a hole that had been drilled into the surface. A somewhat larger instrument, like MARIE, might have to be emplaced by excavating a hole or a trench into which it could be inserted. The instrument might be powered and possibly cooled by leads emplaced to a surface station. This would require a complex interaction between the crewmember and the instrument, which might be repeated from time to time when enough information had been gathered at a given depth of regolith cover.

###### 3.1.4.2.7 Solar Cell Production Demonstration

Ignatiev et al (1998) proposed a system for depositing solar cells directly on the lunar surface. They proposed a robotic system, but the presence of a human crew might allow simpler demonstrations of the technology needed to perform vacuum evaporation of solar cell materials on the lunar surface. The experiment might consist of a deployable vacuum evaporator, which could be moved over some distance across the lunar regolith, depositing one of the layers required for a solar cell. Then, the material required for the next vacuum deposited layer could be introduced into the evaporator unit and the next layer applied. The principal astronaut interaction would be in providing the unit with material; however, inspection of the installed system and testing its operation could be readily done by a human crewmember operating on EVA.

###### 3.1.4.2.8 Spacecraft Refueling Demonstration

A reusable lunar transportation depending on liquid oxygen produced on the Moon or on liquid hydrogen and liquid oxygen, would require refueling capability on the surface, eventually a service provided by a lunar launch pad. On-site humans could do experimental verification of hardware. Their activities might include handling small dewars of liquid oxygen or hydrogen, moving the dewars to the receiving system, connecting leads, and operating the system to deliver propellants to the spacecraft or its surrogate. Early experience with this type of experiment could lay the way for the development of robotic systems to provide the refueling capability at a mature outpost.

###### 3.1.4.2.9 Ice Recovery, Propellant Production, Liquefaction, Storage

The full process of providing cryogenic propellants from lunar resources includes the recovery, liquefaction and storage of these products. If the propellants were derived from lunar ice, both liquid hydrogen and liquid oxygen would be produced. Establishment of a scaled-down version of such a facility could be deployed as a test on early missions. The source of hydrogen and oxygen could be from supplies brought from Earth, if production has not been started from lunar sources.

##### 3.1.4.3 Mobile Science Instruments

Mobile science instruments are typically used where some important property of the surface or subsurface varies on a local scale. This might be the case where a particular resource was being investigated using drilling or subsurface sounding. Or, it might be a traverse that is meant to determine the local extent of a regolith deposit by determination of its depth or other properties. A geophysical traverse across a rille, to determine its structural properties or the presence of lava tubes is another example.

Various geophysical tools are typically carried on mobile rovers. These include magnetometers, gravimeters, and ground penetrating radar. Rovers can deploy seismic instruments and provide a source of energy for active geophysics experiments. Any scientific data acquired by mobile instruments will need to be accurately correlated with the exact time and spatial location at which they were acquired.

#### 3.1.5 Teleoperation of Exploration and Demonstration Experiments

Robotic exploration vehicles teleoperated by crewmembers in the field or from the habitat, or by controllers on Earth, will be utilized as independent exploration vehicles, traveling to areas that are inaccessible to astronauts due to distance or terrain concerns, making observations and collecting samples for return to the base or as direct assistants to crews, carrying supplies, storing samples, or participating in sample documentation. Crew time will be the most valuable resource on the Moon; so robotic field assistants should have many applications. Control of robots will be placed where crew time and attention and robot capabilities can be optimized. This will depend on the level of technological capability available at the time. A field assistant could be teleoperated directly by an astronaut conducting exploration tasks where the robot response time must be very short and it can be controlled with simple and quickly given commands. If a rapid response is not crucial (a few seconds or more), astronauts in the habitat might operate the rovers following instructions provided by the field crew. Where robots are not involved in the same activity as astronauts, teleoperation may be carried out from Earth and robots can be autonomous for the most part, requiring teleoperation control only for specific tasks. It is probable that response times for teleoperation from Earth will be similar to those for teleoperation from the Moon, so teleoperation from Earth will be favored due to the value of astronaut time on the Moon.

Some uses of mobile robots include:

- Reconnaissance in advance of an EVA traverse. As is now routinely done in underwater work, remotely operated vehicles (ROVs), typically teleoperated from the surface, are used to examine work sites or other targets at close range in advance of a human diver (Anon., 1998). Information gathered in this way allows the work crews to visually identify the target or inspect the work site to help decide what it is they are looking at, what problems need to be fixed, what tools may be needed, and perhaps most importantly, whether this is a place a human diver needs to go or if the task can be accomplished by other means. Robotic vehicles can be utilized in similar manner for reconnaissance of sites that may be visited by astronauts on EVA. These vehicles could inspect terrain, determine its trafficability, and collect samples. They may be used to decide whether astronauts should, indeed, visit particular locations, or whether special tools are required (e.g. a core drill). In this way, EVAs can more effectively use astronaut time.

- EVA assistance.
    - If a site has not been previously visited by either a robot or the crew, these teleoperated rovers can be used as defined in the previous paragraph.
    - Experience from underwater work with divers indicates that ROVs are useful as platforms to which functionality previously carried by the diver can be off-loaded (Anon., 1998). ROVs are now routinely used to carry tools, lights, cameras, and even hot water for the divers. Most divers are now accompanied by an ROV which, at a minimum, provides lights for the diver and camera views for support personnel on the surface, — providing a “God’s eye view” of the activity from which surface personnel can give the diver directions and suggest actions to take. Divers consider the ROV a significant safety-enhancing capability and would always use them if they were available (Anon., 1998). This also has implications for support of EVA personnel in the field. While at a site, a mobile

robot can function as a camera platform for the crewmembers remaining in the habitat that are monitoring the progress of the EVA and providing support as required. This rover can also carry tools, equipment, EVA life support consumables, and any collected samples. Sensors not carried by the EVA crew, particularly those requiring long integration times, can be positioned by the robots at crew-designated targets to gather data while the crew moves on to other features of interest.

  - Follow-up investigation or data gathering. If additional data or samples are required from a site already visited, teleoperated or supervised robots offer an option for accomplishing this task. Site positions will be marked in the navigation system and a viable route will be known. A rover used for this type of task can be supervised during its traverse to and from the site and can be teleoperated while at the site to gather the desired data or samples.

- Independent science and exploration traverse. Even when the surface crew has multiple pressurized rovers available for extended traverses, there will likely be sites beyond the maximum range of these vehicles that will be of interest to the crew or its Earth-based colleagues, perhaps several hundred kilometers away from the outpost. Teleoperated rovers provide a means for reaching these distant sites to gather data or samples for return to the outpost. A rover sent on such an excursion would likely require several days or weeks to complete the round trip. Several factors will contribute to the overall duration of such a traverse - the difficulty of the terrain, the limitations of teleoperating the rover (if this is the mode used for the traverse), and the number of stops along the way. Because this vehicle would be traveling beyond the range that the crew can safely reach should the rover become disabled or stuck, those planning the route of travel and controlling the motion of the rover should exercise caution. This capability also provides an opportunity for Earth-based operators to explore various sites when no crew is present on the surface (i.e., before the first crew arrives or while crews are being rotated).

Operations of these systems may be controlled from various places and with various degrees of autonomy. The location and degree of autonomy are dependent on the task assigned to the rover and the level of interaction required with the crewmember controlling the rover. The immediacy required for response to an operational command and the complexity of issuing the command would dictate the style of autonomy.

While supporting EVA crewmembers in the field, the mobile robots can be controlled by the EVA crew, by those stationed in the habitat, or from Earth. The robot will be under active control (teleoperation) or supervision, with built-in autonomous safeguards while in the vicinity of the EVA crew to avoid unintentional collisions. In a "supervised" operation, the operator issues a general or high-level command and the robot is allowed to determine the best set of steps necessary to respond to that command. If the robot is unable to complete the command or reaches a condition that exceeds certain preset constraints, it stops, informs the operator, and waits for additional input from the operator. Control of the mobile robot during EVAs will likely be accomplished through a combination of voice commands and workstation inputs from the crew, the habitat or from Earth. The EVA crew may accomplish workstation control through wrist- or suit-mounted systems or through computing capability built into the crew-transport rovers. Control from the habitat or Earth would be using standard computational hardware at the level of technology that then exists.

Long-range robotic traverses are likely to be accomplished using a combination of teleoperation and supervision. As an example, the rover may be commanded to return to a previously explored site with the intent of using this location as the starting point for a more extensive traverse. The rover will be under supervision as it returns to the previously explored site, with the rover using local navigation aids and its own onboard sensors to retrace a path previously used. Once at the site to be studied, the operators will take a more active role in guiding the rover and directing the onboard sensors at interesting features. Occasionally the operator may stop the rover to spend additional time examining an interesting feature or to gather samples for later analysis at the outpost. For the Moon, these operations will be conducted from Earth. The supervised mode for Mars robotic rovers may be directed by astronauts on Mars, suggesting that experimental studies should be carried out on the Moon to test the effectiveness of crew telerobotic operations.

Research is underway at NASA Johnson Space Center on the development of robotic assistants for the International Space Station program (http://vesuvius.jsc.nasa.gov/er_er/html/robonaut/robonaut.html). This research is aimed at producing humanoid-type robots that have better dexterity than space-suited humans (Figure 3-8). Research such as this is leading in the direction of capable field robotic assistants on the Moon.

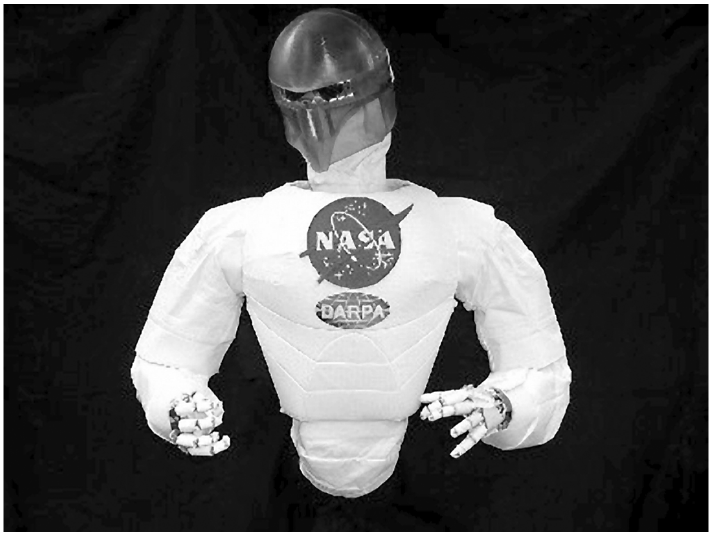


Figure 3.8. Robonaut.

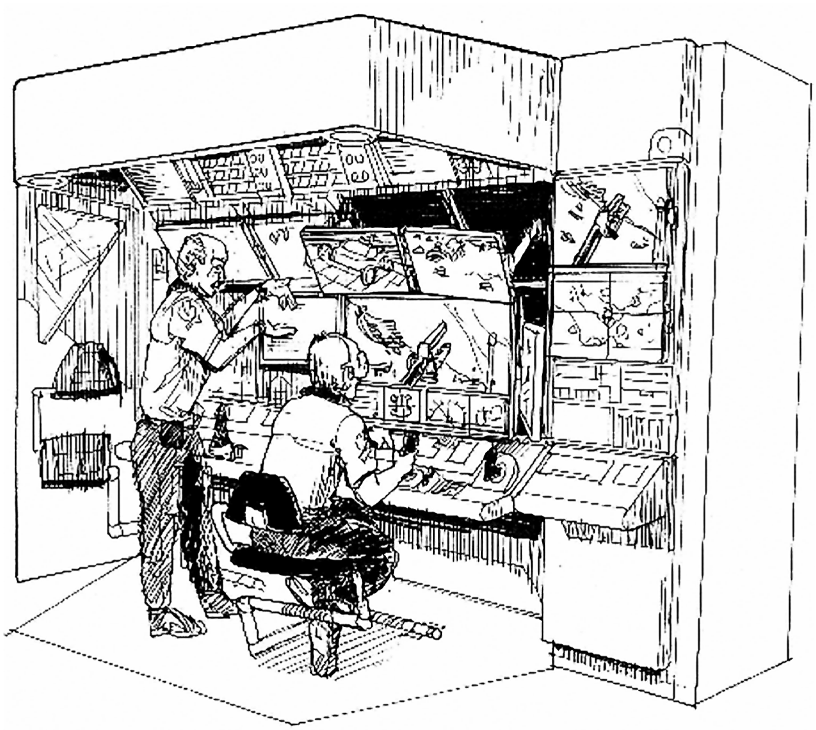

Figure 3-9. Artist's concept of a crew operating a rover via a teleoperations workstation inside their habitat. More than one workstation will probably be available to allow multiple rover operations to be carried out simultaneously.


Figure 3-10. An EVA crewmember peers at his own image as transmitted by a teleoperated rover in a wrist-mounted display and control system. The crew will be able to use control systems similar to this as a means of operating robots that accompany the crew into the field. © SAIC

### 3.1.6 IVA Experiments

Considerable crew time may be available for the conduct of experiments within the habitat, particularly during lunar nighttime periods. With the off-loading of most teleoperation of external systems to controllers on Earth, IVA work time (as distinguished from housekeeping and other personal and group activities) will be divided between monitoring EVA activities, principally for educational purposes, analyzing data from previous EVAs, planning for subsequent EVAs and conducting and monitoring IVA experiments. IVA experiments may be complex, similar to experiments now being conducted on the International Space Station, and may be ongoing, long-term experiments aimed at understanding requirements for long-duration missions on the Moon or Mars. The nature of these experiments is not well known at this time, and their definition should be undertaken in consultation with the science/technical community within the context of mission constraints. Among these constraints, the mass and volume of equipment for these experiments will be most critical, as landing them on the surface and containing them on or within the spacecraft has significant implications. Given that reality, equipment that needs to be there anyway can perhaps be put to a ‘dual use’ in a manner that can support research goals. Additionally, their power requirements will need to fit within the available resources, especially for lunar nighttime operation. Some of the types of experiments that could be undertaken include:

#### 3.1.6.1 Life Science Experiments

The development of closed biological life support systems has high priority for long-duration stays on the Moon or missions to Mars. The study of these systems principally will be done using species of plants, including those that provide edible foodstuffs for the crew. The issues that must be resolved particularly concern the selection of plants and their ability to grow well in 1/6-gravity, as well as the stability of a closed system over long periods of time. For an intended long-duration facility on the Moon, a set of greenhouses could be established within the habitat. If permanent occupancy is not intended, automated systems capable of operation between crew visits may be desirable. This dormant period, where the life support system doesn’t have any human life to support, is a difficult period to cover for living systems, and it may be that additional mass (i.e. $CO_2$) may be required to maintain plants while humans are not present.

#### 3.1.6.2 Physical Science Experiments

As an example, combustion science is currently being studied in the International Space Station, to provide practical information on dealing with combustion as a hazard, as well as learning to use combustion processes in space for production of new materials. Experiments on self propagating high temperature synthesis might be carried out at the lunar facility, using lunar derived materials, to study the possibility of producing structural elements from natural materials (Duke, 2000).

#### 3.1.6.3 Educational Experiments

A lunar outpost could become a venue for attractive educational experiments. Support could be provided to allow students on Earth to design and conduct experiments on the Moon that take advantage of the lunar gravity environment and perhaps high vacuum.

#### 3.1.6.4 Remote Collaboration

Remote collaboration in both scientific and creative ventures would provide new ways for people on earth to participate in the lunar missions. Experiments have shown that such collaboration can increase feelings of connectedness and reduce some of the negative effects of long-term isolated confinement (Snook and Burbank, 2003). Scientific collaboration will be essential, and creative or artistic collaboration will be highly desirable for any long-term exploration missions.

#### 3.1.6.5 Psychology and Human Factors Experiments

While the spaceflight environment is characterized by temperature extremes, microgravity, solar and galactic cosmic radiation, lack of atmospheric pressure, and high-speed micrometeorites, it is also characterized by an additional group of stressors that impact crew performance, well-being, and health.

Experience on long-duration space missions has revealed that it is often the human element pertaining to poor human-technology interface design, team and interpersonal dynamics, spacecraft internal environmental conditions (habitability), and psychological factors that limit successful performance in spaceflight, rather than the purely technological factors of the environment. Russian experience in long-duration spaceflight has revealed that among the most critical problems facing humans in long-duration spaceflight, after the biomedical, are the psychological and psychosocial (Herring, 1997; Jdanov [personal communication, August 1996] Manzey & Lorenz, 1997; Manzey, Schiewe, & Fassbender, 1995; Morphew, MacLaren, Herring, Azar, & Thagard, 1997; O. Atkov [personal communication, August 1996]).

Among the most critical of stressors of long-duration space missions are isolation and confinement, which pose a very real challenge to the performance of crews living and working in environments including spaceflight and polar stations (Palinkas, 1998; Morphew, MacLaren, Herring, Azar, & Thagard, 1997). A variety of psychological and physical effects have been noted from both operational and simulated isolated and confined environments. Examples include motivational decline, fatigue, somatic complaints, (e.g., insomnia, headaches, digestive problems), and social tensions (Connors, 1985; Ikegawa, Kimura, Makita, & Itokawa, 1998; Palinkas, Johnson, Boster, Houseal, 1998; Christensen & Talbot, 1986; Kanas, 1990). Strained crew relations, heightened friction, and social conflict are expected correlates of isolation and confinement, as is found in long-duration spaceflight (Kanas, 1990; Nicholas, 1987).

Human missions to both the Moon and Mars will serve as an opportunity to conduct research aimed at understanding and supporting the human condition in long-term spaceflight. Experiments shall be designed for lunar missions that will assist in the identification of major issues to be addressed in future Mars Missions.

3.1.7 System Maintenance and Repair

The capability to perform inspections, maintenance, and repair on all systems will be required during all phases of the surface mission in order to assure that the crews will meet their mission objectives. This section will discuss the philosophy that underlies the approach proposed for accomplishing these tasks on the surface and will present some specific examples to illustrate the approach in practice. Large amounts of hardware from many systems will be exposed to the lunar environment—surface dust, wide-ranging temperature extremes, and high vacuum—all life-span-shortening, problem-enhancing factors for hardware. In addition, operations in 1/6 g may produce unexpected failure modes.

Some equipment and facilities may be emplaced prior to the arrival of humans. This could include the habitat, propellant production systems, and life support systems as well as power and thermal control systems. A failure in any of these systems that is not repairable threatens the surface exploration activities of the human crews. Until the facility is permanently inhabited, some systems will have to operate in the absence of on-site humans. Inspection, maintenance, and repair of these systems may be carried out by robotic systems. Other systems will require robotic maintenance even when the crew is present.

Figure 3-11. An EVA crewmember changes a faulty line replaceable unit on one element of the surface infrastructure. EVA-accessible enclosures and compatible disconnects will be necessary to allow for effective use of crew time during maintenance and repair activities. © Lockheed Martin

The crew, while much more capable of detailed maintenance than robotic systems, will still be constrained by bulky, dexterity-reducing EVA suits when doing exterior work (Figure 3-11). Mass and volume restrictions will limit the types and amounts of maintenance equipment and spare parts the crew has available. The time devoted to maintenance will be borrowed from other activities that the crew (and others) may want to perform and use skills in which the crew must be trained instead of deeper training in other skills. Distance from the Earth (and potential sources of information about problems and repairs) will hamper maintenance efforts. All of these factors must be taken into account early in the equipment design phase to ensure that the best use is made of the crew and equipment on the surface. Time spent performing routine maintenance cannot dominate the crew's schedule. Russian repairs and upgrades of *Mir* required approximately 50% of the crew workday (Thomas, personal communication) in later stages of the program. For the International Space Station, designed originally for 6 people, between 2 and 3 crewmembers must spend full time on maintenance and operations tasks. Better data on mean time between failures and the time required for maintenance and repair on the ISS will help refine these numbers and provide a better basis of estimating in the future.

#### 3.1.7.1 Inspection, Maintenance and Repair Philosophy

Systems and equipment will be designed such that inspection and maintenance actions can be easily performed by humans and, where necessary or applicable, by robots. Specifying a concept for inspection and maintenance for those items requiring these actions will be part of the design criteria established for these systems. This will be particularly important for those systems that must be serviced robotically. Experience with underwater systems shows that the system and the robotic device that will perform necessary maintenance and repairs should be designed concurrently (Anon., 1998). Externally accessed equipment should be minimized for those habitat systems that will be maintained exclusively by humans—as much system hardware and equipment as possible should be accessible by interior activity. Anything that can reduce the amount of EVA maintenance work is desirable (by either bringing it inside a pressurized structure for work, or by making external systems accessible or primarily located internally), since this will reduce the complexity, duration, and manual effort involved in maintenance.

For those actions that do require external maintenance, making the maintenance actions easy begins with the architecture used to package elements and subsystems of those items as well as the interface the human or robot uses for the servicing. At present, the preferred architecture for these systems is one consisting of line replaceable units (LRUs), which themselves contain shop replaceable units (SRUs). As necessary, external LRUs will be grouped into assemblies of field replaceable units (FRUs). FRUs will easily be removed and replaced by an EVA-suited crew person or, in some instances, by a robot. The characteristics of an FRU will be:

- The FRU is sealed from the lunar environment, protecting more sensitive LRUs inside it.
- The FRU has mechanical, electrical, fluid, and pneumatic connections that are easily broken, sealed, opened, and connected by humans in EVA suits or, where appropriate, by robots.
- Surrounding items and support connections (like power, cooling, and instrumentation lines) connected to the FRU can also be opened or sealed in the lunar environment when the FRU is being removed and installed.
- The FRU fits into the outpost habitat through any openings from the airlock all the way to the maintenance area.
- If the FRU contains hazardous commodities or items, it can be safed or purged externally in an uncomplicated but verifiable manner, so that the crew and its habitat are not threatened.
- Once in the work area of the habitat, the FRU can be easily broken down into its component LRUs.
- The FRU can be tested as a unit after the required maintenance but before being taken back outside, simplifying post-reinstallation checkout.

Of course, some LRU components may be too large to be in an enclosure of some sort or it may be more appropriate to remove and replace only one LRU at a time. These LRUs will have to be designed to meet FRU standards. In extreme cases, LRUs may not be able to fit into the habitat. Large items may have to undergo some sort of time- and condition-sensitive disassembly to gain access to specific parts, then temporary reassembly (for protection from the environment, perhaps covering exposed sensitive openings and equipment) until the part is ready for reinstallation. One of the most important tools the crew will have is an integrated health status information system that allows the monitoring of all the critical functions and systems (and many of the less critical but still important ones). It will include the transportation vehicles' active systems (i.e., the ascent vehicle), surface power system, any previous mission's hardware, propellant manufacturing and storage systems, etc. It will include both an active monitoring capability, plus some level of expert system that can evaluate long- and short-term hardware performance and alert the crew to developing problems or requirements. This system will be able to notify the crew of upcoming scheduled maintenance actions and provide the crew with the capability to forecast potential problems and schedule repairs based on the rate of loss of system function and the condition of redundant hardware. The maintenance history and historical data produced by this system will be transmitted to Earth where assistance in maintenance planning can be provided. This monitoring ability represents a considerable time- and labor-saving measure, allowing maintenance time to be reduced, but retaining a level of information that can be extremely useful for any maintenance effort.

Reducing the amount of time and labor the crew must spend on maintenance is a desirable goal. Achieving that goal may be difficult without adding significant amounts of mass, power usage, and complexity to an already complex, constrained mission. At the system and subsystem level, using built-in test equipment (BITE) will allow for reduced maintenance time and efforts. This capability will be key for mission-critical maintenance actions that will be assigned to robots when the crew is not present. However, usage of BITE will add complexity and mass to those systems, and must be balanced with the actual need. In flight-critical and crew-support-critical systems, the need for continuing use or critical period usage will make BITE worthwhile. In ground and science/ exploration systems, BITE may not be as cost-effective as a good testing facility for hardware. Also, equipment too large to be taken into a protected environment may need some level of BITE to help locate the discrepant hardware. That specific piece of hardware can then be detached and taken inside for repair. Thus as a general guideline, BITE should be included on all electronic, electrical, and electromechanical hardware, where clear benefit can be demonstrated, to allow failure isolation to the lowest, or next-to-lowest, repairable level. Those items that are to be repaired only by the crew may require BITE at the next-to-lowest level because the crew will have test equipment that can isolate the failure at the lowest level.

The crew should have ready access to maintenance documentation—specifications, drawings, procedures, failure causes, and other information—for all the hardware on the mission. This information could be stored in electronic format, then accessed through a set of standard interfaces. This would include a normal computer interface, but could also utilize some sort of EVA/IVA usable interface, such as an eyepiece or a small flat-screen display, which would have pertinent maintenance data loaded on it before a maintenance action. The main information database can be updated periodically from Earth as the hardware matures and a maintenance database (kept on Earth to minimize data storage requirements, since the data would not be of immediate use to the crew) is built up. On Earth, a significant capability for sustaining engineering and failure analysis will be maintained to test and evaluate hardware on Earth just like the lunar hardware. This will provide a follow-on capability to support testing by the crew on the Moon, but will minimize the requirement for detailed failure testing equipment (and the inherent mass and volume requirements associated with it). This will also aid the crew in the search for repair parts from previous missions' hardware with part history and design information. However, as the lunar infrastructure grows, some method of determining how to utilize possibly different generations of hardware and piece-parts will have to be developed. The alternative to this is to freeze the design of hardware at the first mission, guaranteeing commonality, but forcing the program to use old-generation hardware. This is a problem the Shuttle program faces now, causing increases in manufacturing, maintenance, training, and support equipment costs due to required usage of less-than-current technology items, primarily because the various manufacturers have left the older technology behind, and more must be paid to sustain it.

#### 3.1.7.2 Spares Philosophy

Accessibility to spare parts is a large part of maintenance. Current missions include spares to cover most if not all anticipated repairs. If a facility on the Moon is built for a long period of use, the likelihood that any given system will fail sometime during the use of the facility will be significant and successful use of the facility may depend on rapid replacement. Thus, a comprehensive store of spare parts will be needed, with the number of spares available at any time determined by the likelihood of that part's failure and the frequency of missions that could bring replacement parts. Most parts should be built with long life expectancies, because any transportation of replacement parts will be expensive.

This suggests that a different approach should be used for the long-duration surface facility on the Moon. A limited set of repair parts will come from three areas:

- Dedicated spare parts brought in the cargo vehicle or crew habitat. These items will be stored for use when needed, but due to the mission-imposed mass and volume restrictions, they will be limited in nature. In general, systems will be designed for commonality among their piece-parts to the greatest extent possible, allowing for fewer types of spares, but greater numbers of those fewer types. Also, parts to be stored will be at the lowest hardware level—electrical components, fasteners, seals, tubing, etc. This will make repair efforts somewhat more complicated, but also more flexible. Spares will be stocked "deeper" for critical systems, allowing for fast repair turnaround times.
- Use of the same item out of a different unused system (or a less-critical system). Part of the maintenance data with the crew will be a listing of where the same item can be found in every other system, including suggestions for which specific one to pull for repair use first. Thus the crew will immediately know where to look for a replacement.
- Use of a specific repair piece-part out of a similar item (or a less-critical system). Again, part of the maintenance data with the crew will be a listing of where the same piece-part item is in other non-critical systems, again with a suggestion for which one to use first. Also, as items fail they will be "harvested" for usable piece-parts, which will be stored until needed with the dedicated spares and marked as "harvested" parts. (The implication is that harvested parts will be available for use but only after the supply of unused spares has been exhausted.) Before a departure in which the station is to be left untended for some time, the crew may disassemble unused external items, perhaps pulling entire FRUs and storing them in a protected environment for the next crew's usage.

Parts storage and logistics may present a problem to the first crew, but as more pressurized infrastructure is added to the outpost, storage issues may be eased.

#### 3.1.7.3 Repair Facilities

The need for spare parts and repair equipment, as well as the untidy nature of some anticipated repairs, justifies the inclusion of a separate area within the habitat devoted to repairs. The nature of the work area and the items used in it can reduce time and labor requirements for maintenance. Located in this area will be maintenance and test equipment, general and specific tools for maintenance, maintenance data access, and standard utilities. Some spare parts and consumable items will also be stored in this location. Other spares will be in storage locations around the site. A workbench is one extremely important item to include in the shop. Crewmembers and mission planners must expect repairs to include disassembly of equipment into their component parts. This activity will take place not only in the shop area but also at the site of failed systems, and thus could potentially occur anywhere within the habitat. Habitat designers should consider including a portable "tool box" of some kind in the habitat, in addition to the room reserved as a shop and the tools it contains, to address this situation.

The fewer specific repair tools for specific pieces of hardware the better, because every specialized tool taken for only one or two uses deletes a place for a more common tool and a logistics system to track it.

EVA tools and their interfaces must be designed for simplicity, with few moving parts (to limit their exposure to the lunar environment). Both of the above concepts also apply to test equipment— the more general the better, and for EVA, the simpler the better. One major problem facing ISS maintenance plan developers is the organization of the tools necessary for internal vehicle repairs. There are currently over 400 tools stored in 20 different storage kits. These kits fit into a larger toolbox weighing 165 kilograms (Van Cise, personal communication). Authors of ISS maintenance procedures and crewmembers find this method of storage cumbersome, as the tool stockpile is not necessarily near the usage points of any certain tool. Requiring that hardware be designed to be maintainable with a standard, more limited, tool kit, was found to be important for ISS. A developer deviating from this requirement is responsible for providing the necessary maintenance tools. While specific tools that deviate from this standard exist, they are not encouraged. The lunar mission will also employ such guidelines for its hardware systems to eliminate as many specialty tools as possible, potentially through the early adoption of one measurement system, along with standard fasteners, components, and materials.

#### 3.1.7.4 EVA Suit Maintenance

EVA suits will be used for a large percentage of the exploration work carried out on the lunar surface. This makes availability of the suits a high-priority item, which in turn places a high priority on reliability and ease of maintenance.

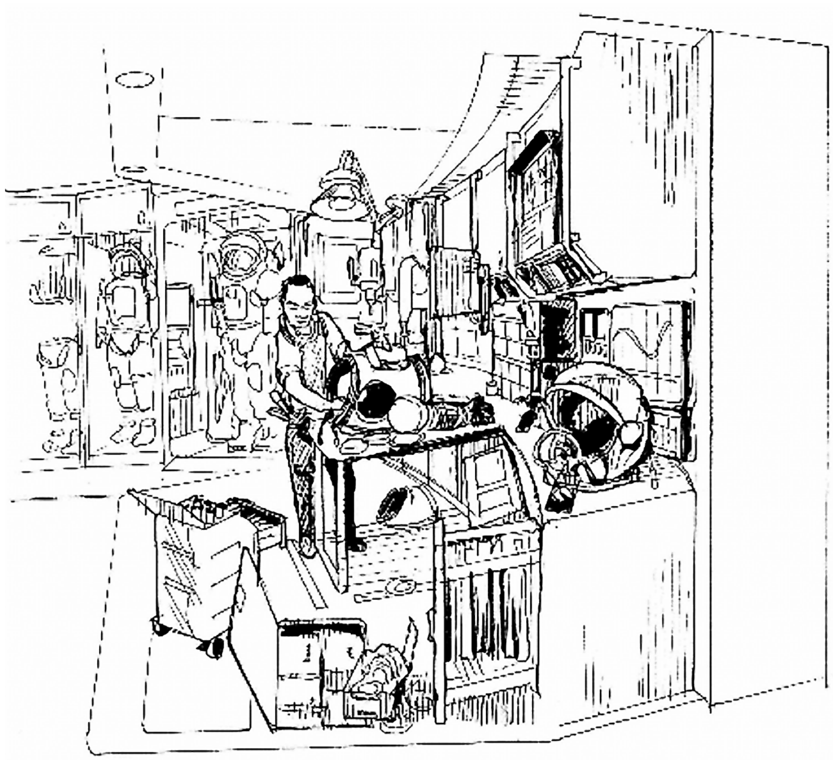

Figure 3-12. Artist's concept for a maintenance and repair facility within the pressurized habitat. This facility will be capable of maintaining the EVA suits that will be a key element in supporting the crew's exploration activities.

Suits[1] are assumed to use the built-in health-monitoring capability and BITE as discussed above. While a suit is in use, the health-monitoring system will be recording performance data that can be downloaded later for use in trend analysis, and will be logging maintenance actions that will be required once the suit is returned to the habitat. When the suit has been cleaned and brought into the habitat, the suit data system will be connected to the integrated health status information system for transfer of the performance data and the maintenance action log. The crew will be able to review the maintenance action log to determine the priority of those actions compared with other maintenance tasks on its schedule. The crew can also access, from the integrated health status information system, the specific maintenance procedures and a list of required repair tools and parts, as well as a list of the location of the required spare parts. The suit should be capable of being disassembled so that all moving parts susceptible to dust intrusion can be cleaned and, if necessary, lubricated. Disassembly using the FRU/LRU concept will allow those parts of the suit requiring maintenance, as noted in the maintenance action log, to be taken out of the suit and moved to the shop area. Component commonality among the suits and among other systems used at the outpost will allow discrepant

[1] "Suit" as used here is assumed to include the garment worn by the crewmember and the PLSS, the portable life support system.

parts to be replaced immediately, restoring the suit's availability and allowing the discrepant part to be repaired (if possible) at a pace that does not impede further EVA activities. BITE will be used to verify that the suit component(s) is functional and that the reassembled suit is ready for use. The suit health-monitoring system is also assumed to be capable of discriminating between maintenance items that can be logged for later action and those that require immediate attention in the field. The health-monitoring system will provide appropriate notification to the crew (the crewmember in the suit as well as the other crewmember(s) participating in the EVA) of the nature of the emergency and advised action(s) to take. Examples of repairs that will require immediate action include a suit puncture resulting in an ongoing loss of pressure or a failure of one of the several systems contained in the PLSS. The EVA crew will have the capability to make temporary repairs (e.g., patch the suit puncture) or to isolate the failed component and switch to another system that provides the same functionality (e.g., tap into another EVA suit power supply or into an EVA consumables supply on board a rover). These emergency actions will be designed such that sufficient time is available for the EVA crew to return to the habitat where permanent repairs can be made.

#### 3.1.7.5 Rover Maintenance and Repair

Mobility for the EVA crew will also be important for accomplishing exploration goals. Maintaining a high level of rover availability will thus be key in sustaining both the number of EVAs anticipated and allowing these EVAs to reach those important sites beyond the safe walking distance of the crew. Maintenance actions for the rovers will be in many ways comparable to that discussed above for the EVA suits— health status monitoring equipment recording performance data and logging maintenance actions, BITE verifying repairs. The FRU/LRU concept as used for the rovers must be EVA-compatible from the outset. These rovers are not likely to be of a size that can be brought into the repair shop without some disassembly outside of the pressurized habitat. If these vehicles are sized to carry a single person under normal operations, the possibility exists for a common chassis and power train to be shared with the teleoperated rovers discussed in previous sections. This gives the crew the option of gradually degrading its capability by cannibalizing parts from selected rovers to keep others in operation rather than simply losing all capability when a certain class of rover runs out of spare parts.

#### 3.1.7.6 Automated and Teleoperated Maintenance of Surface Systems

Investigations carried out for the International Space Station Program have addressed the use of remotely operated imaging systems as well as construction robots. Analysis of the use of these systems for the Moon will be required to demonstrate that they either perform unique activities or reduce the amount of time that crewmembers would otherwise have to spend in conducting tasks. Some types of inspections that might be conducted include:

- Structural inspection of habitats for meteoroid damage
- Inspection of deployed experiments
- Additional information (e.g. images) during assembly of elements on surface
- Images to support astronaut construction/erection activities

These systems will probably be teleoperated from the habitat or from Earth, depending on the amount of time that is needed to perform their operation. Where very rapid response is needed for short-duration activities, teleoperation from the habitat or by the field crew will be the preferred mode.

Certain key elements of the surface infrastructure must be capable of inspection, maintenance, and repair without the presence of the crew. A nuclear power plant and a propellant production plant are two examples. These systems, and in particular the FRU/LRU elements they contain, must be designed from the outset to be maintained by robotic devices. Because of the important role these teleoperated robots play—maintaining certain key surface systems while no crew is present—they must have the capability to maintain each other in the absence of the crew. It is unlikely that these robots will be as capable as humans in making repairs, which may limit them to making and breaking connections and replacing FRUs/LRUs. The dividing line between what maintenance the robots will be capable of doing and what must be left for the human crew to accomplish is currently uncertain and will be an area of significant research and technology development. This further implies that these systems and the robots that will service them should be designed concurrently, and indicates the importance of simplicity and reliability in equipment design to minimize the need for spare parts.

Many aspects of a long-term lunar outpost operation can benefit from teleoperation of a vehicle that can inspect systems and, in principle, make simple repairs, or perform repetitive operations. Many experiments or instruments will be entirely automated, with the potential of receiving commands from Earth or the crews on the Moon to affect their operation, which is closely akin to teleoperation. However, the term teleoperation is usually reserved for direct control of mechanical systems, capable of movement.

#### 3.1.7.7 Internal Configuration Control

Any long-term facility, particularly one that is augmented from time to time with new capabilities and new crews, encounters a configuration control and logistics problem. Tools are utilized and then stowed. Spare parts are shelved, used and old parts disposed of, cannibalized, or refurbished. Consumables are used and replenished. Methods must be found to keep track of these movements of materials and objects within the habitat or undue time will be spent looking for lost items or modifying procedures when a tool cannot be located. Crew time will be allocated for maintaining this system, which will no doubt be computer-based and will be shared with Mission Control on Earth so that other eyes can follow the internal status of the system. The status of this system will be updated regularly and particularly in advance of a new crew appearing from Earth.

### 3.1.8 Operations Demonstrations

A crew at an early long-duration lunar outpost will likely perform experiments that are operations-oriented, testing the operation of equipment with procedures that have been developed with the requirements of long-duration Mars missions in mind (see Section 2.4.11). Examples targeted toward demonstrations of crew autonomy could include experiments, where either in a simulated mode or in fact, communications with Earth are totally interrupted (in Mars exploration there may be periods of days when Mars is on the other side of the sun from Earth and no direct communications are possible). These demonstrations would be scheduled in advance as part of the mission advanced planning. Typically, this type of demonstration would aim at accomplishing mission objectives as well as demonstrating operations.

### 3.1.9 Planning

Most planning for either short-duration missions or 30 day stays on the Moon will be done on Earth. However, in anticipation of long-duration trips to Mars, where the link to Earth is not available in real time and may be ponderous in general, an increased level of autonomy of longer-duration lunar crews should be investigated. Detailed planning, in the sense of deciding specific sites to visit, how much time to spend there, what types of materials to collect, how many cores to obtain, etc. should, fundamentally, be done by the crew that is doing the investigations. However, the amount of time available to the crew for such planning is limited, especially as the level of activity will be hectic if one of the crews is to be on EVA each day. Therefore, new mechanisms for planning will have to be developed, at least for 30-day lunar missions. These mechanisms will include several elements: (1) Preparation of mission goals in advance of the mission (these will also be used as a basis for training); (2) General plans for the completion of the essential mission goals; (3) Feedback from the crew to Earth as mission activities are undertaken – locations visited, samples collected, pictures taken, experiments deployed, etc. – as well as the crew's personal observations and interpretations; (4) On Earth, assessment of the degree to which mission objectives are being accomplished, integration of the crew's observations, extrapolations to those observations to identify potential new targets and modifications of the general plan; (5) Discussion between the Earth and the crew to verify that changes to initial plans are appropriate and feasible; (6) updating of planning in cycles, such as one week, three days, one day. Planning techniques should achieve a balance between providing direction from Earth and autonomy of the crew, while off-loading routine or time-consuming tasks from the crew.

The crew will also want to keep track of their resources – time, consumables, etc. – and should have provision to do so, though these also will be monitored and assessed by Earth operations. Earth operations can maintain a virtual model of the lunar spacecraft or habitat, and will be able to guide the crew when new resources (e.g. a spare part or new tool) need to be accessed, or to provide a backup for the crew when a tool has been used and stowed. Over a long period of time, the configuration of a habitat can become confused, and it will be unfortunate if time is lost to science activities as a result of poor configuration control. In the context of planning, the data provided by the configuration control system may be more readily available to Mission Control on Earth and can be incorporated into forward planning. Of course, this information will be critical at the point where crews are exchanged.

Planning for communications between Earth and Moon should also be a cooperative activity between the crew on the Moon and controllers on Earth. A crew on the Moon will have a great deal to communicate with Earth. Some of it can be in real time, some of it will have to be planned in order to accomplish objectives with high quality. For example, public release video may require production time. A producer on Earth will develop a plan for the session and discuss it with the crew, the crew will determine the amount of time required to prepare for the session, and the session will be scheduled accordingly.

### 3.1.10 Training

The majority of instruction on all subjects should occur before the mission and must cover anything mission-critical that the crew might encounter early in the mission. Some amount of training and review will take place continuously throughout the mission. It is anticipated that several hours per week per crewmember will be spent in training activities.

Perhaps the most important training will involve maintaining proficiency and preparing the crew for contingency events and to work together to handle unforeseen events that arise during their mission. During past space missions, ground support personnel employed several different methods for exchanging information with crewmembers. Because the Moon is close enough to Earth for direct communication (with a short time lag), the ground controllers can participate in real time decision-making. However, for immediate response to anomalous conditions, the crew must be trained to respond autonomously when necessary and to have a means of maintaining their response skills throughout the mission. Training approaches in the future must allow for the accurate and timely interchange of information between the remote crew and support personnel. This section discusses the advantages and disadvantages of several methods used in the past to support training for long-duration missions comparable to long-duration lunar missions, and suggests several topics that pre- and mid-mission training must address.

Crewmembers traveling to remote locations prepare for months and sometimes years before their excursions. Most, if not all, of this training involves face-to-face contact with an instructor. Training classes, computer lessons, and printed manuals are the most common methods currently used to instruct crewmembers before and sometimes during a mission. Scaled mockups are also used to simulate actual hardware. These methods involve constant supervision from trainers, or at least periodic interaction. Crewmembers then continue training at their remote destinations by employing similar methods, materials, and ongoing dialogue with support personnel. Comparable programs may be suitable for the training for lunar missions. However, because of the additional burden of taking cumbersome printed information to the Moon (or the paper to print on while on the Moon), some form of electronic storage will be necessary to hold this information and updates. A crew within the Life Support Systems Integration Facility[2] evaluated the performance of virtual reality tools, information stored on CDs, prerecorded videos, and

[2] The Life Support Systems Integration Facility (LSSIF) is a vacuum chamber configured by the Johnson Space Center and used in a series of closed tests with people in the chamber between 1995 and 1997. While the basic

interactive Internet sites in accomplishing remote training. The results of its investigation will provide valuable insight into a favorable method for use in the future (Woolford et al., 2002). The most effective and practical form of training materials requires further investigation.

Another area requiring more investigation is the set of topics on which pre- and mid-mission instruction should focus. Technical skills are obviously important. However, training in interpersonal skills, conflict resolution and team development will be essential to complete a successful mission. Without the ability of ground personnel to intervene, crewmembers must learn to cultivate a strong team environment and solve or avoid interpersonal problems. Crewmembers must also learn to effectively interact with each other so that they can creatively solve mission-related problems on their own. Crewmembers traveling to the South Pole and those who stayed inside the Life Support Systems Integration Facility practiced activities designed to improve these skills both before and during their missions (Holland and Curtis, 2002). Crewmembers in the Life Support Systems Integration Facility also participated in several pre-mission discussions focusing on what to expect during their isolation test (Tri, personal communication). Crewmembers inside the Mars Desert Research Station (Snook and Burbank, 2002) employed other creative mechanisms for alleviating interpersonal conflict and tension. Experts suggest that this sensitizing of crewmembers to living and working together in close quarters for long durations is a worthwhile activity, especially since most minor problems tend to become magnified in an isolated environment (Stuster, 1996).

Operation of analytical and experimental equipment, maintenance procedures, emergency operations, and system knowledge requirements are among the technical skills for which training is required. Most of this training will involve a review of previously learned material. Crewmembers will need periodic group sessions to review the appropriate response to contingency activities such as rapid cabin depressurization or equipment fires. Some material, such as an emergency workaround to an unexpected failure, may be new. In order to deal with unplanned situations effectively, the crewmembers must continually practice their creative problem solving and efficient communication skills. This applies especially to drills for procedures that will be used infrequently, or never. Other activities that may be the focus of mid-mission training include those that occur later in the mission. For example, the crew should review initial surface procedures shortly before it lands on the planet, and study ascent plans in preparation for departure. New technologies intended for use on the planet such as propellant manufacturing or rover operation will also need frequent review as their planned usage time approaches.

All of the crews that visit the lunar facility will be under significant pressure to communicate their experiences and lessons learned both for analysis by ground support personnel and to train future crewmembers. They must practice appropriately and thoroughly describing events and have ample supplies and equipment to allow for the recording and storage of these details. Time must be available soon after critical events and following EVA or IVA exploration activities for personal reflection and rechecking of their records. Automated camera or observation systems could be used to decrease the amount of documentation work necessary for individual crewmembers. A balance will have to be struck between the amount of time spent in documenting previous observations, that needed to train for new investigations, and training for unexpected events.

These areas will receive more attention, as the requirements for a lunar mission are refined. Training for the lunar mission can be used as preparation for missions to Mars when it becomes possible for crews to spend from a few months to a year and a half at the lunar facility.

Summary:

Important items regarding the time and facilities necessary for training include:

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intention of the tests were to demonstrate closed life support system technologies, including plant growth, as they interacted with human crews, the later tests of 30-days and 90-days with a crew of four also provided an opportunity to study a range of the problems associated with long-duration stays in isolated spacecraft environments.

- Further investigation into preferred training techniques and easy ways to store associated materials within the habitat.
- The importance of providing training on both sociological and technical issues.
- Further investigation into the amount of time required during the flight for training to take place.

#### 3.1.11 Technical Communications

Communications of three types are envisioned for lunar missions. The first is purely technical, in that information is exchanged between the crew on the Moon, astronauts in an L1 facility, and operators back on Earth. This information will consist of data from the Moon regarding investigations, including real time video from EVAs, voice messages between crewmembers, data from instruments and monitoring systems (e.g. crew health monitors), and specific reports on experiments and observations from the crewmembers. The second is personal communication between astronauts and their families and friends back on Earth. The third is communication of astronauts and the general public back on Earth. This latter will be a significant element in conveying to the public the accomplishments and challenges of lunar exploration. It may be accompanied by video presentations from the lunar surface.

Communications from Earth are expected to include the mirrored equivalents of the astronaut's communications from the Moon. In addition, communications links will provide system updates, news from Earth, and educational and entertainment packages from Earth.

The communications bandwidth should be high to allow continuous communication. The capabilities for live video both to and from the Moon are likely to be the driving requirements.

Significant time for communications with Earth should be budgeted in each astronaut's daily/weekly work plan. It should be apparent that time should also be allowed to the crew in preparation for personal, private communications to Earth.

### 3.2 Crew-Sustaining Activities

#### 3.2.1 Health and Performance Maintenance

Current reference missions for the Moon involve relatively short stays on the Moon, from 4 to 30 days. However, a basic premise for the long-duration missions is that the initial facilities could be augmented, allowing longer stay times. As the stay time grows, the need for medical facilities will increase, due to the probability of encountering a medical problem and the time and expense required to return a crewmember to Earth before his or her tour of duty is complete. The question of when to incorporate advanced medical facilities into the architecture is a function of lunar outpost development strategy. Should the expected mission duration remain at 30 days, it may be possible to limit the medical capability on the surface. To be fully representative of a long-duration mission, including providing a baseline for Mars exploration, a more expanded medical facility would be required. The medical facilities suggested below are associated with this long-term stay possibility.

The capability to deliver clinical treatment is required due to the stochastic nature of medical illness. The unusual environmental characteristics of space travel, with its commensurate occupational hazards, predicate the development of a robust clinical capability for the maintenance of astronaut health and performance. The mission profile of a lunar surface mission is one primarily of exploration, with vigorous and highly complex activities. The crew will be actively involved with a variety of tasks, both internal and external to their pressurized habitat. Keeping the crew healthy and productive in this environment will undoubtedly involve routine activities such as health monitoring, but with a capability to handle more serious situations.

The remoteness of the Moon will prevent or delay any medical evacuation to Earth due to the limited number of launch windows, the transit time, and the difficulty of delivering medical care en route. Evacuation to L-1, where more robust medical facilities could exist, would be more straightforward, but would require at least a day and the termination of other mission activities. The primary treatment of illness and injury must therefore occur on the Moon's surface. Medical equipment and crew training will be kept basic and general purpose to deal with a wide range of potential events. However, there are certain mission-specific risks that could precipitate potentially catastrophic events that will require medical treatment (e.g., radiation exposure, effects of working in pressure suits, etc.) for which precautions can be taken and procedures prepared. With this combination of known and unknown sources for medical treatment, the general philosophy for delivery of medical care to the crew will use an appropriate combination of prevention, countermeasures, and clinical treatment (Hamilton, 1998) (see Figure 3.13).

The most effective and least expensive method of delivering medical care is through prevention. Thus, the medical care of the crew on the surface of the Moon actually begins prior to the mission. This is achieved by applying previous epidemiological knowledge about space travel and potential known and predicted risks of the proposed mission to select the necessary characteristics of the crew. The prevention of illness and injury is the most important aspect of medical care of any space crew.

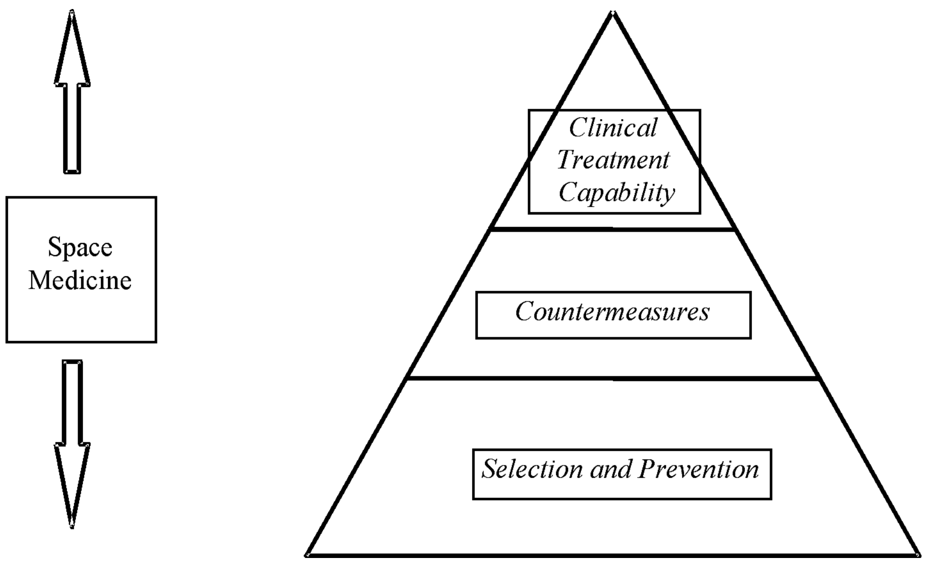


Figure 3-13. Medical Operations Clinical Hierarchy. The surface space medicine health care system embodies the philosophy of minimizing clinical treatment requirements through a preventative medicine and countermeasures approach to health care.

There are, however, risks and risk factors associated with surface exploration that may not be mitigated through preventative measures. Those risks, and/or associated risk factors, must be mitigated through the use of countermeasures. Countermeasures are a secondary preventative medical care method that mitigates a particular risk or risk factor by changing the crew environment or prescribing a medical intervention on a crewmember.

Illness or injury that cannot be prevented or mitigated by countermeasures will require clinical treatment. Clinical treatment is a medical endpoint where intervention is required to mitigate illness or injury. The resources required to treat unexpected illness and injury are dependent on the mission profile and the success of prevention and countermeasures. Medical care on the Moon's surface will thus be a continuum of prevention, countermeasures, and clinical treatment. An example of this tiered medical care philosophy can be illustrated by considering radiation exposure.

- Prevention. One of the many criteria used to screen candidates for crew selection may be an individual's natural resistance to the effects of radiation.
- Countermeasures. Drugs may be provided to the crewmembers to enhance their resistance to radiation effects. In addition to the suite of countermeasure drugs that may be available, engineers will examine the design implications of increased shielding, at least in selected areas (e.g., the "storm shelter" concept), to provide the crew with increased protection from radiation sources. Warning of radiation events is a part of this prevention architecture.
- Clinical treatment. In those cases where crewmembers fall victim to the effects of radiation, advanced life support for acute radiation sickness will be provided. The type and sophistication of the treatment capability will be the subject of study, taking into consideration the probability of this kind of event in light of the other factors (i.e., prevention and countermeasures) that have already been used to protect the crew.

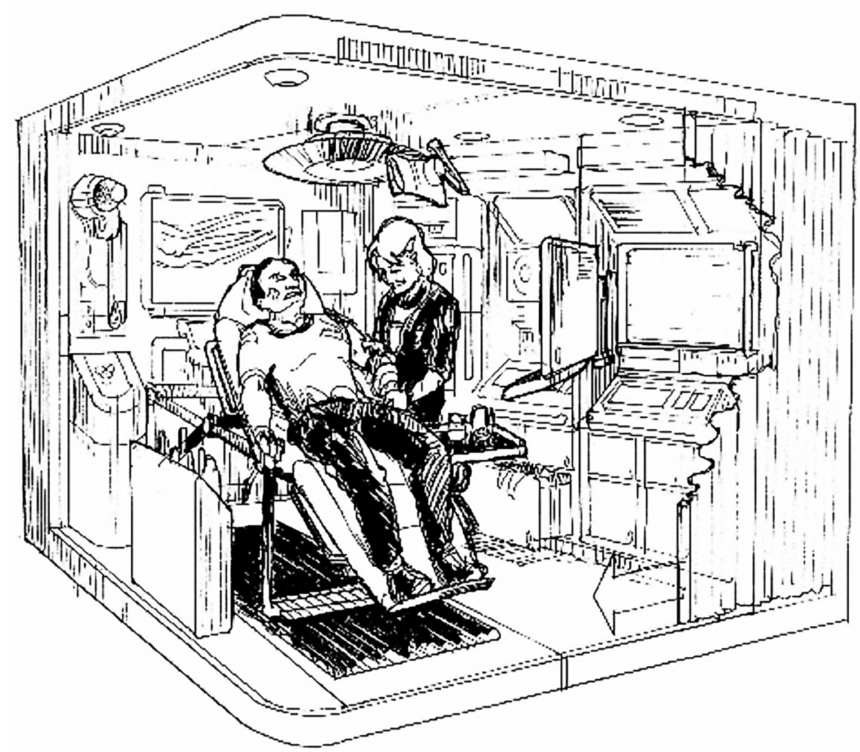

Figure 3-14. An artist's concept for a centralized medical/dental support facility. For a long-duration lunar mission. The facility will be located in the pressurized habitat. This facility will support both medical and life sciences activities associated with the mission.

There are several approaches to providing medical support on the Moon, including:

- Low to minimal level of care on the surface, accepting the commensurate risk.
- Maximal level of care, accepting lower risk but higher mass/volume penalties.
- Intermediate level, targeted toward the most likely problems encountered.

Current planning would favor the latter approach, balancing the level of crew care with risk factors as well as the mass and volume constraints that will be placed on all systems carried to the Moon. As a lunar facility becomes more sophisticated and tours of duty are extended, the medical facilities may be augmented. The facilities to care for the crew's medical needs will be concentrated in a single location in the habitat, but with provisions for emergency care distributed throughout the rest of the habitat and those systems used for EVA and pressurized rover activities. The central medical facility will contain most of the consumables and mass intensive medical equipment for the lengthy surface mission. These facilities should be able to deal with both routine and emergency medical problems, which can be reasonably expected given the mission profile. These problems include:

- Routine illness, such as colds or flu
- Decompression sickness
- Radiation sickness
- Laceration, requiring stitches
- Bone fractures
- Trauma
- Deconditioning
- Stress, depression, and acute psychosis
- Infection
- Dust and toxic exposures

This list indicates that the medical facilities should be capable of handling up to and including surgical procedures. (The extent or level of sophistication of these surgical procedures will be the subject of ongoing study for some period of time, taking into account the advances made in medical science both on Earth and in space over the next several years.) Sensors in the crew quarters will be capable of monitoring sick or injured crewmembers as they recover.

To illustrate how the philosophy of prevention first may be implemented, consider the following example. The crew may wear miniature sensors to allow early detection of potential medical problems (e.g. Hirt, 2000). These sensors are currently capable of continuous, real-time monitoring of the crews' individual physiological vital signs and may, with further technology development, track other important data such as blood chemistry or the rate of bone loss in the reduced gravity environment. Continuous monitoring of these sensor readings combined with wireless transmitter technology will allow these data to be automatically stored for historical trending of individual crewmembers' vital signs. The crew's physician member and Earth-based support personnel will monitor these trend data (these data will be transmitted to Earth in real time or periodically for detailed study and archiving in a manner consistent with patient medical privacy) to identify potential medical problems among the crew before they become serious enough to warrant clinical treatment. These sensors can also be programmed with alarm limits so that other crewmembers can be alerted to an individual experiencing some sort of medical distress. A position location system tied into the local navigation/position determination system (see Section 2.3.5) will inform the rest of the crew as to the location of the sick or injured crewmember. Measurements generated during both routine and emergency activities in the medical facilities and the data gathered by the miniature sensor system will be coordinated with the life sciences experiments also taking place on this mission. An onboard medical library will be available to assist with diagnoses and for review of specific procedures. The physician crewmember will consult with colleagues on Earth for specific assistance that cannot be found from other sources available to him.

Operations in the field, on an EVA or while operating the pressurized rover, will complicate the delivery of medical care. The majority of the medical facilities and supplies available to the crew will be concentrated in the pressurized habitat. Those members of the crew operating in the field will carry a subset of this equipment, with the focus on stabilizing injured or ill crewmembers so they can be transported back to the habitat for more extensive care. The medical sensor system worn by each crewmember will transmit vital sign data that the physician, and other crewmembers in the field, can display on workstations within pressurized structures (e.g., the pressurized rover or the habitat) or directly to EVA suit display systems (e.g., a heads-up display inside the helmet). If the physician is not present with the field party, data received from the medical sensors should be sufficient for the physician to direct the field crew's efforts regarding the best procedures to use (such as is presently done in many remote medical situations). The data provided by these advanced monitoring technologies will require a commensurate development of a set of clinical skills, knowledge, and experience among the crewmembers on the Moon. The development of advanced medical technology and the clinical diagnostic and treatment capabilities for the crew must be compatible with the "standard of care" expected for lunar mission, considering its duration and the probability of returning the crewmember to Earth.

Figure 3-15. A crewmember injured in the field is cared for by other members of the EVA crew. Sufficient equipment will be carried on EVAs to allow an initial assessment to be made of such injuries and to stabilize the crewmember for transport back to the pressurized habitat.

An assumption in many mission designs, particularly for Martian exploration (see Section 1.4), is that one member of the crew will be a trained physician and this person will be responsible for the basic medical care of the crew. However, all crewmembers will carry a responsibility for assisting the physician as the situation warrants. All of the members of the crew may need to be trained in other medical skills, such as nursing, emergency medical technician, or physiotherapy. An onboard electronic medical library will contain training information that the crew will use for maintaining these first aid and other medical support skills throughout the mission. This library and the training information it contains can be updated from Earth as necessary during the mission. Improvement of technology to assist crewmembers in medical tasks will be rewarding in terms of the level of treatment as well as in the reduction of demands on astronaut time. Appropriate preventative techniques and counter-measures to mitigate these risks need continued development. Research on Earth and at the ISS can be an effective means of expanding this knowledge. For those stochastic events that will undoubtedly occur, additional study is required to determine which are most likely to occur, given other preventative procedures and countermeasures, and thus require the development of equipment, procedures, and crew training. Examples of technology development areas related to these medical support areas include:

- Development of clinically essential noninvasive procedures and diagnostics.

- Development of medical therapeutics and diagnostics.
- Miniaturization of medical equipment, particularly imaging and analytical systems.
- Recycling of resources, particularly invasive instruments, sterile cloth, and biohazard containers and tubing.
- Development of extended shelf life capability for medications and other medical consumables.

### 3.2.2 Diet, Food, and the Wardroom/Galley

#### 3.2.2.1 Wardroom

Previous long-duration, isolated missions have shown that a space large enough for the entire crew to interact with each other can be beneficial for individual emotional and crew morale purposes (Stuster, 1996). In the past, wardrooms served this purpose by providing the crew with crew entertainment, eating and briefing area[s] (Connolly, 2002). To satisfy this need, the lunar surface habitat for long-duration missions will have a wardroom sufficiently large to accommodate the entire crew at one time. However, the habitat will have limited amounts of usable volume. Thus, rooms designed to provide multiple functions will be essential. A wardroom combined with a galley will be one area where crewmembers can accomplish several mission-critical activities. The area will provide room and equipment for food preparation, eating and associated activities, some food storage space, and a general office or entertainment area for the whole crew. Wardroom/galley activities are both an essential element of the lunar mission, but also an experiment that will provide important data for future exploration of Mars.

The most relevant analogs available for study of wardroom activities and functional capabilities, as used by small crews in isolated environments for relatively long-duration missions, are experiences from Skylab, the Shuttle, the Amundsen-Scott South Pole Station, and inside the Life Support Integrated Test Facility at the Johnson Space Center (JSC). Plans for the ISS and the BIO-Plex/Integrity facility at JSC also offer valuable insight.

The wardroom and galley areas should share one room or two connecting rooms centrally located in the habitat. The wardroom area will be large enough to hold the entire crew at one time. This layout is desirable in cases when the crew needs a place to talk in person, such as in the event of an emergency, important meeting, or celebration involving the full crew. The room design will accommodate the most likely users: groups of three or more people. It will also meet the needs of two people or a single person wanting to study or relax, so long as the traffic through such a high-use area is not bothersome. The wardroom should contain at least one window. Skylab crewmembers and designers fought hard to include a window in that wardroom and found it to be a popular feature of this space (Compton and Benson, 1983). During the Skylab missions, crewmembers spent a great deal of time using the window provided. Similarly, Shuttle crews spend a great deal of their free time looking out of various windows in the crew module. Whereas for Earth orbital missions the crew could watch the ever-changing Earth below, the lunar surface vista will be relatively constant. The window should be positioned to be able to view the Earth, which will be approximately fixed in position.

Skylab had a wardroom area containing a versatile central table with spaces for all three crewmembers (Belew & Stuhlinger, 1973). Similarly, the Life Support System Integration Facility has a large, popular wardroom table with a rolling chair for each crewmember. Thus it is reasonable to assume that the crewmembers in the lunar surface habitat will want a large table for meals, as a place for meetings or discussions, as a workspace or desk, or as a site for Public Affairs opportunities. A long line-of-sight fosters the impression of larger space and diminishes feelings of claustrophobia.

An “information wall” will incorporate one or more large projection screens and bulletin boards. With this and other equipment the crew can display information including surface images, watch videos, make presentations, or carry out other group functions. The wall can publicize information interesting to the crew such as the current date and time, a weekly menu, schedule information, a task list, and a variety of statistical information, such as the cumulative hours of EVA time or distance traveled to various sites. If the crew uses an intercom system to communicate with each other inside the habitat, the information wall is a suitable location for any main controls. The wall can also display decorative images or artifacts, as research shows that teams in remote and isolated locations need and enjoy the ability to look at large and/or colorful pictures, especially outdoor landscapes and holiday scenes (Stuster, 1996). Certain colors that are pleasing to the eye, and posters that show familiar scenes of home will put the crewmembers' minds at ease during their stay on the surface (Compton and Benson, 1983). Postings should be generic and acceptable to all crewmembers; nothing shown in public areas should be offensive to any crewmember to help maintain crew cohesion and morale (Stuster, 1996).

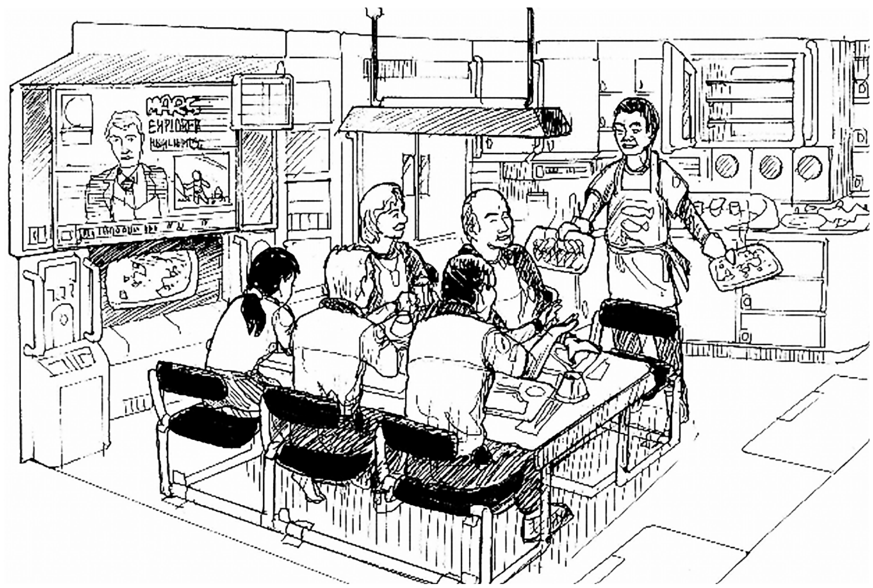

Figure 3-16. Artist's concept of the wardroom and galley area. This will be a space large enough to accommodate the entire crew for meals, meetings, or other special events.

#### 3.2.2.2 Meals and Food

Proper nutrition and palatable food are keys to maintaining long-term human performance for both physical and psychological reasons (Lane and Rambaut, 1994). Food selection and menu preparation will be a collaborative effort involving the crew and dietitians. Specific nutritional requirements for long-term activities in 1/6 g are unknown, particularly in the absence of detailed timelines for the missions, which will determine required energy content of the food. Crewmembers will identify specific foods they like and dislike. Dietitians will review crewmembers' lists of likes and dislikes and take into account nutritional requirements in an attempt to create a set of meals acceptable to everyone. Pre-mission taste tests will be conducted in which crewmembers may record personal preferences or make suggestions for changes. A joint review with everyone involved will produce a final menu plan. Crewmembers' tastes can and will change over the duration of the mission, so some complaints about the food are likely regardless of the level of preparation.

To provide International Space Station crews with nutritionally better meals and combat weight loss problems faced in the past, there is currently an attempt to move towards cyclic menus. Isolated crews in tests up to 91 days successfully used 10- to 12-day menu cycles. Experts must determine a suitable interval for the lunar mission based on variety and volume of food available. Each meal should offer a few choices for crew selection (Stuster, 1996). Menu planners may choose to sort foods into the food groups and allow crewmembers to select one item from each group to make up a meal. Shuttle menus currently allow each crewmember to select a unique combination of foods for each meal, none of which necessarily come from their own preflight selections. Another option used in the Life Support System Integration Facility tests is to serve a standard main course and offer a choice among several drinks, side dishes, and desserts. Snacks between meals will also be available. This modularity will provide necessary variety for crewmembers. Menus may include vitamin supplements to ensure that crewmembers meet their daily nutritional requirements, no matter what foods they select for their meals.

Meals eaten “on the run” will be common. Menu and schedule planners should not force crewmembers to use short meal periods. However, crewmembers may sometimes prefer to eat quickly or while performing other duties. Simple meals that require little or no preparation will be useful in these situations. More elaborate meals will occur when the entire crew eats together. Most isolated crews try to maintain a common, mutually agreeable dinnertime, no matter how hectic schedules become. Group meals provide necessary team bonding, as well as desired social interaction and organizational opportunities (Stuster, 1996). The responsibility for preparing a meal for the group will rotate periodically.

There will also be milestones to celebrate during the mission such as birthdays, holidays, significant accomplishments or other special occasions. Theme dinners will help mark these events, provide variety, and assist the crew in acknowledging the passage of time (Stuster, 1996). Preparing meals from scratch in a more traditional manner may be one way to set these meals apart from everyday provisions. Meals that are more elaborate than usual or provide foods traditional for the occasions are also suitable.

Menu and schedule planners, along with dietitians, must ensure that crewmembers performing EVAs receive adequate nutrition, especially if plans call for long or strenuous activities. Development is in progress that will allow suited crewmembers to eat during an EVA, as Apollo astronauts did while walking on the Moon. This will become useful to crewmembers if meal times before an EVA are short.

In addition to space provided for large group meals and other group activities, the wardroom and galley areas will provide a meal preparation area, accommodations for some food storage, and utensil and area cleaning equipment and supplies. Food storage space will house food for use in the near future, with long-term storage elsewhere in the habitat. This space will accommodate shelf-storable items as well as temperature-controlled equipment such as a refrigerator or freezer. This equipment should be near meal preparation areas for easier use. For long stay time missions, utensils for meal preparation and consumption are assumed to be reusable as opposed to disposable, to conserve both mass and volume. This implies that cleaning supplies and facilities will be required to sanitize these utensils to avoid possible health risks to the crew. Examples for storage for these items might include moveable racks, overhead cabinets, or under-the-counter bins.

Each of the different types of meals discussed will require different amounts of time, space, and equipment to prepare. Those in the “on the run” category will obviously require the least amount of all of these resources; the evening meals for the entire crew will require the most resources and will define accommodations located in the galley area. These evening meals will typically involve heating some portion of the food. Multiple small heating units or one large unit will be useful to reduce preparation times. A crew of four used two microwaves in the Life Support System Integration Facility with minor problems (Bourland et al., 2002). On the other hand, crews on the Shuttle complain that the oven warmer is too small and takes too long to heat food. During docked periods, Shuttle astronauts often used the faster heater on the Russian space station *Mir*. Redesigning and repackaging new machines to be smaller, faster, and capable of performing several different tasks will assist crewmembers in speedy meal preparation and will save both space and mass in the limited food preparation areas. The galley also needs hot- and cold-water dispensers for meal preparation since a few meals will include dehydrated foods that require water for reconstitution. These dispensers might be part of a small sink, or simply ports on the galley wall, as is the case on the Shuttle (MSFC, 2000). Another useful tool to have, in addition to dispensers, is a water heater. Shuttle crews use a water heater (JSC, 2002) and there are plans to provide one on the ISS. To avoid food contamination and the associated risks to crew health, there will be ample facilities and supplies to sanitize all areas and equipment involved in meal preparation, meal cleanup, eating, and food storage. At present it is unclear if commonly used cleaning supplies pose a risk to the biological life support system that is used to recycle water within the habitat. Alternatives exist (e.g., steam sterilization) and will be investigated, as the biological life support system technology and habitat design evolve.

Current experience suggests that frozen and dehydrated foods will be the most likely food forms available to lunar surface crewmembers, because of their long shelf lives, superior nutritional value, simple packaging, and the extensive experience using them. Current Shuttle flights rely on about 50% dehydrated foods and about 50% intermediate moisture foods, with limited amounts of fresh food. Food in these portions was tested in the Life Support System Integration Facility tests and proved satisfactory (Bourland et al., 2002). These numbers reflect mass and volume constraints in the Shuttle; although different values will apply to a lunar mission, constraints will also exist. Dehydrated foods offer mass and volume advantages over frozen or shelf storable foods that retain most if not all of their original water content. The drive toward a higher percentage of frozen foods is due to the fact that frozen foods are higher in nutritional value than dehydrated foods. In the future, menu planners hope to use more frozen or microwave meals, similar to those commercially available today. They are easy to prepare, and there is a great variety obtainable. However, frozen and microwave meals require more development before they are ready for use. Currently microwave dinners have a shelf life of about three to six months. This should be satisfactory for early missions, but may have to be extended as the tour of duty at a permanent facility is increased. Irradiated steak and turkey are now available for astronauts to consume on the Shuttle, and both have a shelf life of around three years. Further development in this area, particularly in commercial applications, may raise acceptance levels and provide readily available technology that will allow crewmembers to eat irradiated foods in the future. These activity modes clearly require equipment such as freezers and ovens in order to be possible. Food storage technology should continue to be pursued.

Dairy products are another nutritionally important food group usually missing from astronaut diets. Vitamin supplements are one solution, but others should be investigated. Finally, there is an ongoing complaint that space food is too bland. The addition of condiments to meal plans was helpful[3], but experts should consider other solutions to this problem. One option to overcome the bland food complaint is to grow fresh herbs or other small edible plants in a small garden. Experience from the Life Support Systems Integration Facility tests show that the inclusion of a garden will greatly enhance meal quality, as well as meal acceptance by the crew (Bourland et al., 2002). This crew enjoyed wheat grown inside a variable pressure growth chamber and fresh foods from a small garden inside their habitat. American astronauts aboard the Russian space station *Mir* performed plant growth cycle experiments to occupy their time. There are also plans to include a small garden in the habitat module of the BIO-Plex in addition the planned Biomass Production Chambers. Truly fresh food will be scarce and certainly provide a treat for crewmembers if available. Dinners for special occasions might include fresh foods grown in the garden. Growing and nurturing the plants presumably also will become a recreational activity. However, menu planners should not rely on the garden to produce any significant percentage of food during early missions.

Meal preparation itself can also serve as a welcome diversion from other daily activities for every member of the crew. For those members of the crew that enjoy cooking, this also could become a means to satisfy a personal need for creativity while providing the entire crew with variety during this shared activity. However, meal preparation should also not require an excessive amount of the crew’s time. Crewmembers on the surface will need and want to devote a large portion of their time to science and work-related activities. Meal preparation times cannot conflict with or constrict these activities. Schedules will allow plenty of time for actually consuming each meal, and meal preparation must not cut into this process either. Inside the Life Support System Integration Facility a crew of four

[3] An exception is sodium. There must be a reduction in the use of sodium to preserve foods. Sodium cuts down on the amount of calcium bones can store, and calcium loss is currently a large concern during long-term spaceflight (communication)(Bourland et al., 2002).

had an average meal preparation time of 22 minutes during the 91-day Phase III test (Edeen, personal communication). However, limitations on available facilities made cleanup nearly impossible, and this function was handled by transfering dirty items out of the facility (Bourland et al., 2002). Most of the meals consumed (60%) were microwave meals similar to those proposed for use on Earth. Considering this, the process for one person to prepare dinner for the whole crew should take no more than 30 minutes. Times will be much faster for other meals, except for special occasion meals that might be more elaborate. Individuals will prepare their own meals when crewmembers choose to eat separately. Any large-scale food processing will need as much automation as possible. The meal preparation time was also found to be a function of the capability of the facilities, such as the size and power of the microwave ovens (Bourland et al., 2002).

As the capability for long-duration stays grows, more use of "home-grown" foods may occur. This will also require counter space for food processing, storage space, and associated equipment. . Experiments performed in Analog facilities (Snook and Morphew, 2003) have shown that a diet of meals prepared primarily from fresh vegetables and fruits as those such as have been proposed for a long term Mars mission is too cumbersome, requiring up to 18 man-hours of labor for preparation per day. The overall incorporation of locally grown food is a research issue that can be addressed as an experiment in preparation for Mars missions.

Crewmembers will be responsible for cleaning up their own wastes after each meal. This will include finishing the entire portion of food served, compressing food packages, wiping clean all trays, utensils, and food preparation areas used, and storing all equipment and wastes. The whole cleanup process should only take about ten minutes. Shuttle meal cleanup takes about five minutes for up to seven crewmembers, and Phase III meal cleanup took an average of 17 minutes over 91 days for four crewmembers (Edeen, personal communication). One part of the cleanup process that needs major investigation is the consolidation and storage of food packaging wastes. Dehydrated food packaging currently accounts for 40%-50% of the total mass (Bourland et al., 2002). ). Large amounts of waste from food packaging materials is a problem on Shuttle flights, and will be a much greater obstacle during long-duration missions. Section 3.2.6 discusses the storage of trash within the habitat in more detail. Planning and packaging menus together by meal, rather than separately for each individual person, will help solve this problem to some extent.

Table 3-1 shows the average times used by past crews for meal preparation, meal consumption, and meal cleanup

Table 3-1. Average Daily Total Meal Times for Past Isolated Crews

| Mission or Test | Meal Preparation (minutes/day) | Meal Consumption (hours/day) | Meal Cleanup (minutes/day) | Number of Crewmembers |
|---|---|---|---|---|
| 90-day test, 1970 (Pearson and Grana, 1970)) | NA | 2.1 | NA | 4 |
| Skylab 2* | NA | 5.7 | NA | 3 |
| Skylab 3* | NA | 5.5 | NA | 3 |
| Skylab 4* | NA | 5.5 | NA | 3 |
| Shuttle (generic) | 10-60 (actual) | 3.0 (planned) | 5 (actual) | 2-7 |
| Phase III LSSIF test | 22 | Unknown | 17 | 4 |
| Mars Desert Research Station food experiment† | 80-1140 | 5.3 | 40-100 | 6 |
| ISS | 10-60 | 3.0 | 5-10 | 3-10 |
| BIO-Plex (plan | 45 | 2.0 | NA | 4-7 |

*Recorded as "Pre/Post-Sleep & Eating" Note: All preparation and cleanup times listed as "NA" were recorded and are included in "Meal Consumption" times.

†Preliminary results from the Mars Desert Research Station (Snook and Morphew, 2003)

### 3.2.3 Personal Hygiene

The crew activities collectively referred to as personal hygiene include body cleansing and grooming, elimination of bodily waste, and cleaning of clothing. Maintenance of good personal hygiene by all crewmembers will be important not only for obvious health reasons, but also as a means of maintaining individual and group morale (Stuster, 1996). The importance of this area is such that the mission commander or other leader should enforce the regular use of hygiene equipment and time allocated for these activities. Skylab had only one bathroom that could accommodate one person at a time. All three crews complained about waiting to use the facilities, and how it interfered with their schedules (Compton and Benson, 1983). Therefore, the long-term lunar surface habitat should contain space for two bathrooms. One bathroom will be larger, with space to contain several people at once. This will allow multiple crewmembers to perform hygiene activities, such as shaving or brushing their teeth, simultaneously. A second smaller bathroom will accommodate at least one crewmember. The large bathroom will most likely be close to the crewmembers' private quarters.

In addition to ample volume, the large bathroom should include a sink and countertop, storage, a large mirror, a urinal, and a full-body cleansing system. Just outside the big bathroom will be a personal storage area including some form of cubbyholes or lockers. For more convenient use, crewmembers can then keep bathroom supplies in close proximity to the bathroom and obtain them while the facilities are in use. A large mirror will "help reinforce crewmembers' personal image of themselves" (Stuster, 1996). There will also be a solid waste collection device in the large bathroom.

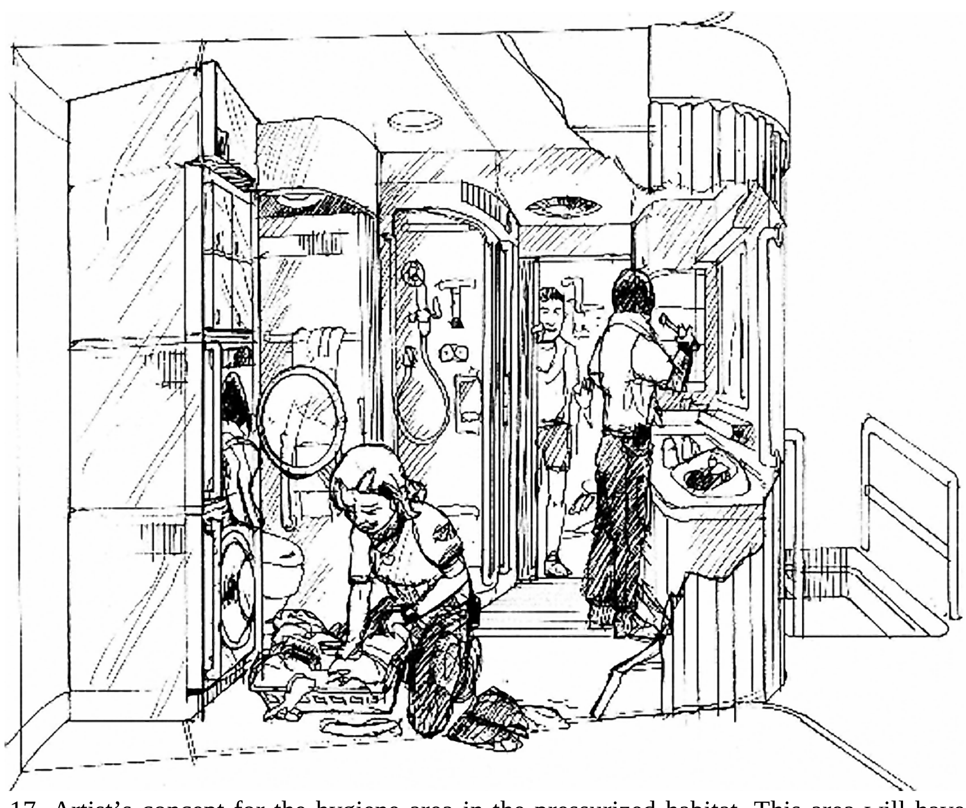

Figure 3-17. Artist's concept for the hygiene area in the pressurized habitat. This area will have accommodations for body cleaning and grooming, elimination of bodily waste, and cleaning clothing.

The second, smaller bathroom will be in a different section of the habitat than the larger bathroom, perhaps closer to a main work area, or next to the airlock. This bathroom will include a sink and countertop, a urine collection device, and a small mirror. The addition of a second solid waste collection device in the smaller bathroom is desirable, provided the life support systems can accommodate it.

The design for a full-body cleansing system within the habitat will be influenced by previous flight experience. Crewmembers rarely used their shower on board Skylab and Shuttle astronauts manage with only sponge baths during their missions. Although these may seem like arguments against including a full-body cleansing system, they are not. Skylab and other isolated crewmembers stated several times the desire to have full-body cleansing facilities for use after daily exercise periods or long durations without any personal hygiene (for example, after EVA). The process was either unavailable, or avoided because it was too cumbersome. Crewmembers in the Life Support System Integration Facility were allotted one shower per day, following their exercise period (Connolly, 2002).

There are several problems with past shower designs to correct in future full-body cleansing system plans. First, it is advantageous to provide a way to measure and restrict the amount of water used. This is different from limiting the actual time spent bathing. In other words, flow might stop after a crewmember uses two gallons of water, rather than after two minutes of using the system. Crews in the Life Support System Integration Facility successfully used the first method, while crews on submarines and at South Pole stations still endure the time limit technique (http://www.southpole.com/log.html). Another problem the Skylab crews mentioned was the lengthy setup of shower-related equipment. Preparations sometimes took nearly an hour, and crewmembers skipped many showers simply because this process was too drawn-out. Thus, space should be allocated for a permanent facility. Adjustable water temperature is important with hot water available. After the water shut off, Skylab crewmembers spent up to ten minutes using a vacuum hose to extract all remaining water out of the shower and off their bodies. They avoided showers because of the uncomfortable nature of the method (Compton and Benson, 1983). This process should be less burdensome in a gravity field as opposed to free space; however, complete removal of residual water after a shower is desirable as a hygienic measure and to reduce growth of molds.

Each crewmember will have a personal hygiene kit. Shuttle crewmembers currently receive one full-body towel and two washcloths for use each day during their missions. Similar supplies in a long-term lunar surface habitat must be washable, as the mass of taking disposable clothes and other supplies for the entire mission can surpass the mass of a washer and dryer system and associated water recycling. The articles in the personal hygiene kit allow for shaving, as well as hair, scalp, skin, teeth, and nail care, and feminine hygiene supplies for female crewmembers (http://spaceflight.nasa.gov/shuttle/reference/shutref/ crew/hygiene.html). Based on current plans for providing some common hygiene items to the first ISS crew, Table 2.13-1 provides an estimate of the mass and volume associated with personal hygiene items (Watson, 1998) for a long-duration mission. The three-person crew is all male and will be aboard the vehicle for 143 days. During early short-duration missions, this amount of supplies will not be needed, however, in planning for long-duration missions, account should be taken of the eventual need in terms of space allocated for storage and for the logistics system needed to keep crew supplies separated.

Table 3-2. Estimated Mass and Volume per Crewmember for Personal Hygiene Items (not including clothing)

| **Totals** | |
|---|---|
| Total mass for 18-month surface stay | 48.46 kg |
| Total volume for 18-month surface stay | 0.1549 m^3 |

Another important part of maintaining good personal hygiene is the availability of fresh clothing. Both expert opinion and past experience express the crew's need for several types of clothing (Compton and Benson, 1983). They also state that these clothes should be colorful and allow crewmembers to exhibit individual personalities to some extent. These clothes include items for use inside the habitat while performing regular activities, garments to exercise in, and clothes to wear to bed. In addition, crewmembers will need undergarments, socks, and slippers or shoes for use inside the habitat. Crewmembers should have enough clothing to change outfits regularly. Disposable clothes are not practical for a long-duration missions, but might be utilized during buildup of infrastructure at a lunar outpost. Some experts suggest that the crewmembers receive a new set of outer garments every two weeks and different undergarments every other day. Crewmembers inside the Life Support System Integration Facility had a variety of clothing and were able to do a personal load of laundry every four days (Connolly, 2002). The first ISS crewmembers will receive one pair of shoes per four months, new undergarments every two to three days, and a change of outer garments about every week to ten days. Their exercise and sleep clothes will be good for three to seven days. Other items such as sweaters and jackets will last the entire 143 days (Watson, 1998). Crewmembers on the Moon can expect to change their clothes at rates similar to those mentioned above.

A washer and dryer system is desirable to allow crewmembers to clean their clothing on a regular basis. Some extra clothes will allow for anticipated wear and tear, and a basic sewing kit will permit crewmembers to mend their clothes. Crewmembers may hand wash clothes in bathroom sinks occasionally, but a more automated process would be better. In addition to the personal laundry loads allowed in the Life Support System Integration Facility each week, crewmembers did one common load of towels, washcloths, and sheets each week. Crewmembers may also choose to use this method in the lunar habitat. However, water supply levels will also determine the frequency of washer use.

Each day crewmembers will have some time to perform personal hygiene. Schedules now include a standard 30-minute hygiene period in the morning as part of post-sleep activities and another 30 minutes at the end of the day as part of pre-sleep activities (Belew and Stuhlinger, 1998). These numbers were suitable in the past and should be adequate in the future. The schedule will also include additional time for personal hygiene after routine exercise periods. Crews that had the facilities usually preferred their routine full-body cleansing immediately following exercise periods, and this will most likely be the case in the lunar habitat. Also, immediately before an EVA crewmember exits the habitat, they will perform any necessary personal hygiene. A bathroom near the airlock will be very convenient for this purpose.

### 3.2.4 Exercise

The long-term effects of microgravity and partial gravity (i.e., the 1/6 gravity on the lunar surface) on the human body are not well understood. Previous studies have shown that regular exercise is one means of providing adequate countermeasures for most negative results of long-term space flight. From a medical standpoint, exercise should retard muscle atrophy, cardiovascular deconditioning, and bone demineralization. For these reasons, it will be a requirement for crewmembers to continue to practice some type of routine exercise while in a lunar surface. This may be modified by the amount of EVA activity carried out by the crew, though the effect of EVA on crew conditioning will have to be determined by measurements on the Moon. A NASA "Workshop on Exercise Prescription for Long-Duration Space Flight" identified the following other essential functions that exercise provides (Harris and Stewart, 1986):

- Preserve the appropriate level of aerobic capacity and muscular strength and endurance to facilitate crewmembers' ability to perform demanding physical work such as repetitive EVAs.
- Maintain general physical fitness as it benefits the individual's health and sense of well-being.
- Sustain the ability to accomplish end-of-mission unaided egress.
- Minimize the time required for post-mission reconditioning. The last two items are especially important to a crew arriving at a planet after a relatively long period in microgravity.

The limited experience available from the Skylab, the Shuttle, and some Russian space stations suggests a certain exercise regimen and recommended equipment, which will probably be applicable on the Moon. The Life Support System Integration Facility was equipped with a treadmill, bicycle ergometer and a resistive exercise device (Lee et al., 2002). Crewmembers need several pieces of equipment offering some amount of variety. This is necessary since often there will be several people wanting or needing to use equipment at one time. Also, if crewmembers find pieces of equipment they enjoy using, they are more likely to take advantage of exercise periods. Treadmills are beneficial because crewmembers enjoy them and they can provide varying levels of exercise. Equipment must be easy to use, unlike the Skylab bicycle that required a large, awkward harness.

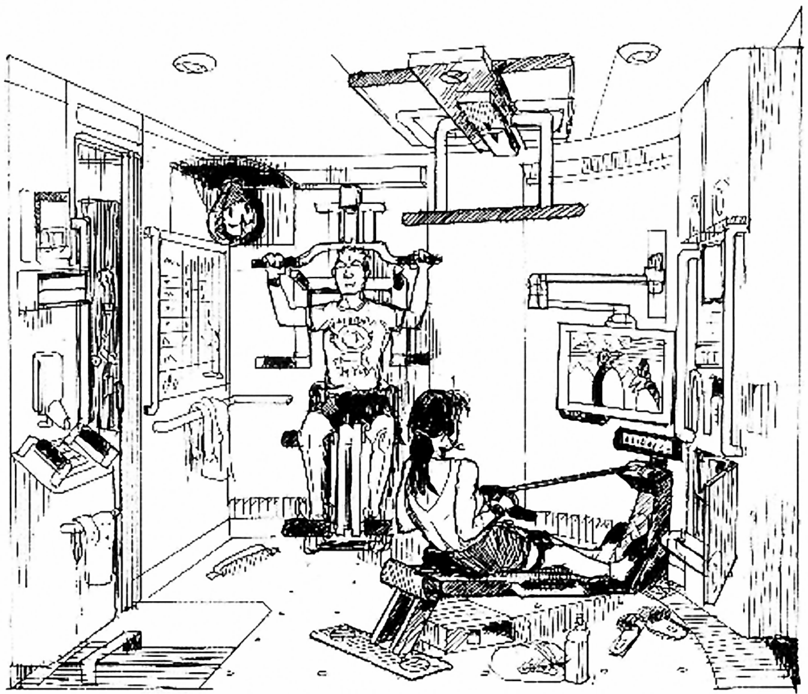

Figure 3-18. Artist's concept of the exercise area. Several pieces of equipment may be available to the crew to allow more than one person to exercise at a time and to provide individuals a variety of exercises.

(Compton and Benson, 1983). Development of other machines and equipment will be profitable. A resistive exercise machine, used in the Life Support Systems Integration Facility, might be effective with a few design changes. Isolated crews on the ground have also used step aerobics and workout videos in the past, which, with a few alterations, might also be a possibility. Experts suggest a rowing machine of some type will also aid in reducing the loss of upper body strength (Harris and Siconolfi, 1989). There will also be some spare parts to allow crewmembers to make necessary repairs. Each crewmember will have a scheduled time in the day for exercise, as opposed to a block exercise time for the whole crew (there will simply be insufficient amounts of equipment to allow the entire crew to exercise simultaneously). Most crews in the past scheduled one hour of actual exercise on the machines. Skylab and Shuttle crewmembers required up to 30 minutes before and after the exercise periods for setup and tear down of equipment (Belew and Stuhlinger, 1973). Preparations for exercise periods in a lunar habitat should take no more than 15 minutes. For convenience and to promote more frequent usage, equipment must already be in place or require minimal setup. Most schedules require six days of exercise per week; EVAs will replace daily exercise periods for crewmembers exiting the habitat. Previous isolated crews performed various physiological and medical checks on themselves that often involved exercise time and equipment (Compton and Benson, 1983). Crewmembers in a lunar habitat must have sufficient supplies to accomplish these tests as well. Some experts suggest that crewmembers monitor at least one workout period per week. Everyone will record their activities and progress for personal review, as well as for evaluation by doctors on Earth. Using these records, crewmembers may set personal goals for the trip. For example, a crewmember might attempt to travel a certain cumulative distance on the treadmill over the course of the mission. Crewmembers would have personal exercise prescriptions and goals to work toward, which should encourage them to work out.

Almost every Skylab crewmember expressed the desire for a full-body shower immediately following exercise periods (Compton and Benson, 1983). If the facilities are available, the schedule should allow for this. Section 3.2.3 discusses a smaller bathroom that contains a sink, toilet and mirror. It is desirable to locate this bathroom near the exercise room to allow crewmembers to refresh themselves during or after their exercise periods. Skylab crewmembers chose to workout in their underclothes so that their disposable workday clothes stayed clean for longer periods of time (Compton and Benson, 1983). Crewmembers on the Moon will wash their workday clothes regularly, avoiding this problem. However, crewmembers may receive lighter or thinner exercise clothes so they do not get unnecessarily hot.

One thing missing for the Skylab and Shuttle crews was the entertainment side of exercise. Crewmembers in the Life Support Systems Integration Facility had workout videos and music to accompany their workouts. Displays on or near equipment might provide these distractions to crewmembers in a lunar habitat. The screens might show video scenes to simulate a run in the park or a bike ride through the mountains. Crewmembers could also listen to music using headphones, or watch video newscasts from Earth. Displays could also show statistics about a crewmember's performance such as distance, average speed, or time elapsed. Some type of virtual reality interface could also provide these diversions. Simple methods of entertainment such as these will make the exercise process more appealing. Crewmembers in both the Life Support Systems Integration Facility and the Mars Desert Research Station have complained in the past that workouts were monotonous and they often skipped their assigned times (Compton and Benson, 1983, Snook and Morphew, 2003). This was sometimes due to lack of time, other times simply due to lack of desire. It will be necessary to avoid excuses such as these on a long-duration mission where exercise is fundamental in keeping the crew healthy. The location of exercise equipment within the habitat is another important factor. The gym area needs to have good air circulation. This circulation will cool crewmembers during their workout, as well as cool and dehumidify the area after its use. The collection of equipment needs to stay out of the way of general traffic, which may prompt the design of a dedicated fitness area. Another option is to stow all equipment out of sight, and only bring it out for periods of use. The problem with this is the time necessary for setting up the equipment, as well as finding suitable locations for storage and use.

#### 3.2.5 Off-Duty and Recreation

To remain productive and proficient during a long-duration mission, crew habitats will need to have facilities and equipment for ample sleep, privacy, and personal space. A long-term surface habitat must contain crew quarters and associated supplies to suitably accomplish these aspects of crew support. This section suggests several functions and configurations of crew quarters, taking into consideration lessons learned from Skylab and Shuttle designs and positive changes evident in JSC's Life Support System Integration Facility tests, as well as ISS and BIO-Plex plans.

Crew quarters designed for long-duration missions should balance the individual crewmember's need for privacy and the desirable strategy for mutual psychological and emotional support among the crew. The rooms should provide a place to sleep, relax, or work in private; simply closing a door or raising a partition should accomplish this, so long as other crewmembers recognize and respect these simple signs. Some amount of withdrawal into a private area, away from the rest of the crew, is normal and even necessary for individuals under these confining circumstances. However, if a crewmember is excessively withdrawing into his or her room (a potential indication of depression; Stuster, 1996), other crewmembers should properly identify and address this problem. In one technique that was applied in such circumstances in the Antarctic, two people (same gender) share some portion of their room "as a form of enforced buddy system to help ensure physical and psychological survival in a hostile environment"

(Stuster, 1996). Some type of removable partition can be used to separate the room into two distinct sides. People at the South Pole Station and other U.S. stations in the Antarctic choose to hang curtains from the ceiling to separate rooms shared by four crewmembers into private areas. The long-term lunar surface habitat may employ this or other comparable methods to separate crew quarters.

Without adequate amounts of sleep, crewmembers' efficient performance of daily activities decreases (Stuster, 1996). A space-efficient bed design will be useful. These surfaces will be used for sleep and they may be used for limited visitor seating during other times of the day. Soundproofing or noise reduction for the walls will also be important. Skylab crewmembers complained that it was hard to sleep with only thin walls separating them from noisy equipment. Many other isolated crews had similar complaints. Soundproofing can also be a part of providing privacy. Locating these rooms away from the galley and its loud machines will help solve the problem. Positioning a bathroom near the crew quarters will allow for easier access during the night. However, the bathroom may also contain some loud equipment forcing habitat designers to include some noise reduction there as well. It may be wise to schedule "quiet hours" before major mission milestones to ensure the crew has adequate sleep and preparation time. The crew can decide for itself the necessity and exact rules and times of these periods.

Designers should also consider Skylab crewmembers' comments regarding the location of crew quarters near an exit; several commented that sleeping was sometimes difficult because private sleep chambers were too far from an easy exit and thus subject to noise as other crewmembers moved past (Compton and Benson, 1983). Shuttle astronauts each receive a sleep kit, which includes earplugs and eye covers, to provide better quality sleep (http://spaceflight.nasa.gov/ /shuttle/reference/shutref/crew/sleep.html, 1998). The lunar surface habitat will contain similar kits for each crewmember. Sleep intervals should remain the same during the mission, except in the event of an emergency. Many isolated crewmembers in the past chose to stay awake past planned bed times, but this was a personal choice, not a necessity.

Besides providing a place where they can sleep and be alone, the crew quarters should give crewmembers a sense of home. The room itself will provide each crewmember with the capability for personalization. Crewmembers conducting long-duration tests in the Life Support Systems Integration Facility selected and decorated their rooms ahead of time (Tri, personal communication). On the other hand, settling in and organizing personal belongings might provide a useful distraction during the beginning phase of the mission. To help in selecting miscellaneous items to bring as decoration, crewmembers will receive a mass and volume limit before the mission. The crew may bring anything, as long as all items pass materials inspections and are not offensive in content. There will be personal storage available inside the room for clothing, books, music, video recordings, supplies, or other personal items. Overhead lights with several settings will be desirable so that crewmembers can adjust their personal space to their liking. Skylab crewmembers complained that their interior lighting did not provide enough light or lighting flexibility to adequately perform some duties within the habitat (Compton and Benson, 1983). One or two moveable lights per individual room will provide extra lighting wherever and whenever necessary. If an intercom system is available for use by crewmembers, each individual crew chamber will have an interface using the latest technology. A space-efficient desk with writing area and some type of personal workstation was part of every room in the Life Support Systems Integration Facility (http://advlifesupport.jsc.nasa.gov (LMLSTP Overview). A seat will be useful at the desk and to accommodate visitors. Most socializing will likely take place away from the crew quarters, as these rooms will be too small to comfortably hold more than two or three people at a time.

The proper size for crew rooms needs to be studied further. Table 3-3 lists sizes of several crew chambers in past remote area habitats, the results of several habitability studies, and indicates the wide variation in volume assigned to members of various crews for what can be considered long-duration, isolated missions. Overcrowded rooms can reduce productivity, as on submarines where crewmembers complain about the lack of personal territory (Stuster, 1996). On the other hand, providing separate chambers for each crewmember may be impossible in limited habitat volumes. The space should be larger than the cubicles in Skylab where crewmembers' major complaint was that the accommodations only served sleeping purposes (Compton and Benson, 1983). Crew quarters must be of acceptable size and contain sufficient equipment to function as a sleeping space, an office area, and a refuge during off-duty time. Habitat designers may configure equipment in any reasonable fashion.

Table 3-3. Isolated Habitat Crew Quarters Volumes per Person

| **Mission, Test or Study** | **Size (m^3)** | **Crew Per Room** |
|---|---|---|
| Skylab -- Commander's Room (Stuster, 1996) | 1.8 | 1 |
| Skylab -- Crew Room (Stuster, 1996) | 1.4 | 1 |
| South Pole Base (www.southpole.com/log.html, June 1998) | 14.3 | 2 - 8 |
| Life Support Systems Integration Facility (pet.jsc.nasa.gov/alssee/demo_dir/lmlstp.html, May 1998) | 9.2 | 1 |
| BIO-Plex (plan 1) (Adams, 1998) | 8.0 | 1 |
| BIO-Plex (plan 2) (Adams, 1998) | 12.5 | 1 |
| Submarine (Stuster, 1996) | 1.0 | * |
| Tektite I & II (Stuster, 1996) | 1.0 | * |
| Lovelace intangibles study; “long duration” (Stuster, 1996) | 3.7 | ** |
| Earth orbital station (Stuster, 1996) | 4.8 | ** |
| Lunar habitability system (Stuster, 1996) | 7.2 | ** |
| | average = 5.9 | |

*This size reflects the volume allotted per person, not crewmembers per room. Varying numbers shared one room.
** Specific figures on number of crewmembers per room not given

Figure 3-19 illustrates one possible means of incorporating these various features into the crew quarters. Individual sleeping areas can be closed off to control light, sound, or other distractions. Partitions allow crewmembers to have privacy when the divider is up, or obtain more space if taken away. This variation in configurations is desirable for several reasons. Crewmembers will need a place to dress or think in private, and experts suggest that sleeping may be easier if crewmembers have their own rooms. However, additional space will help crewmembers avoid feelings of claustrophobia experienced by several people in cramped remote habitats. Crewmembers should be able to achieve total privacy while in their own rooms (no cameras to monitor crew activities within crew quarters). However, if roommates choose to remove the partition, significantly more shared volume will be available. The rooms should be similar in size and shape to permit crewmembers to switch rooms mid-mission without a problem. This may be necessary should serious conflicts arise or simply for a change of atmosphere. Each side of the room will have its own door. The inclusion of locks does not seem to be important. Doors inside the Life Support Systems Integration Facility did not have locks, and other isolated habitats studied did not either.

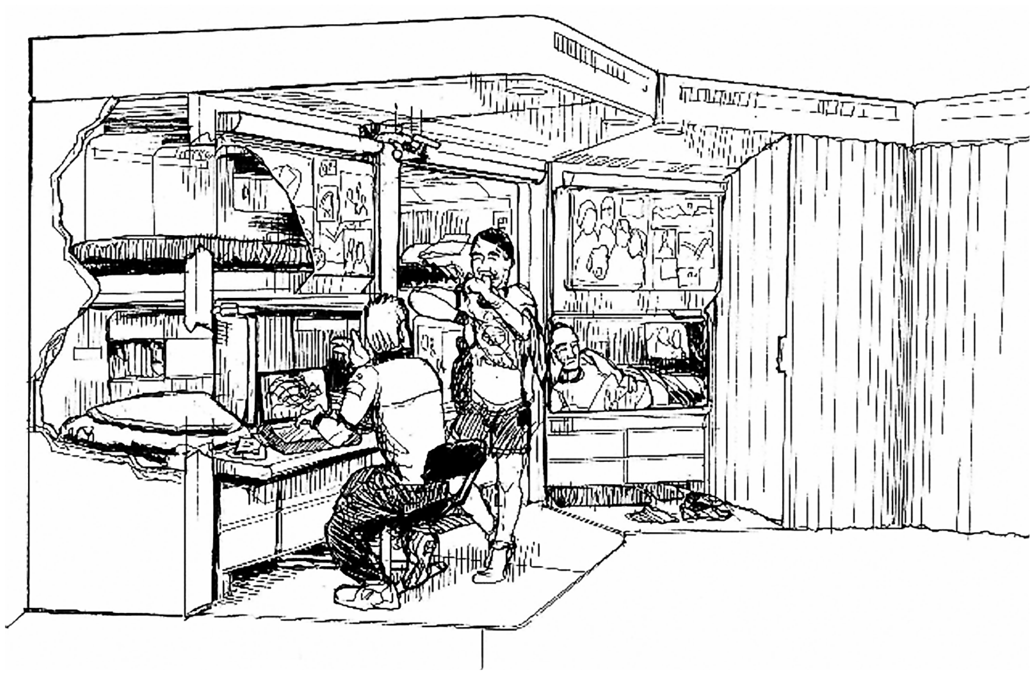

Figure 3-19. Artist’s concept of crew quarters in the habitat. These quarters will accommodate sleeping and personal work space. Partitions will allow individual areas to be closed off when desired, or opened to provide more space.

Past experience with long-duration missions on Earth and the growing level of experience with extended missions in space indicate that the crew will encounter two extremes in its activity schedule – periods of time with too much to do and times with too little to do. They may also be faced with extended periods of time during which their activities will be largely repetitious, which can lead to feelings of monotony and boredom. These situations are not unusual for most people and the solution is equally well known - provide ample off-duty time and adequate entertainment options to provide the entire crew and individuals with relaxation, distraction, or amusement (Rasmussen, 1973). There is a drastic difference in performance from crewmembers that have had sufficient relaxation time and those who had overbooked schedules allowing no free time. Also, excessive amounts of free time with insufficiently planned activities produce unnecessarily bored and underutilized crewmembers. Dealing with these situations will provide a challenge for the planners of long-duration lunar missions.

Past isolated missions such as the Skylab missions, Shuttle missions, Life Support System Integration Facility tests, winters at South Pole bases, and specific experiments at other analog facilities provide valuable insight into popular off-duty activities, the most effective scheduling methods, and estimations of off-duty time for crewmembers. Off-duty activities involving a majority of the crew, including mandatory daily or weekly group dinners, will most likely take place in the wardroom (see Section 3.2.2) because it can hold the entire group. A library or lounge area away from the wardroom is desirable to allow some amount of privacy for smaller groups, such as two or three people. Depending on the activity, private crew quarters might also be a place for two or three crewmembers to enjoy their off-duty time. Anyone participating in free-time activities must be considerate of noise levels, as not all crewmembers will be relaxing at the same time. Groups should be able to take advantage of games in their spare time; almost all isolated crews in the past enjoyed board games to help pass the time (Stuster, 1996). Crewmembers will want to avoid games that cause conflict among crewmembers, as the game Risk did for one isolated crew (Stuster, 1996). Off-duty entertainment should bring crewmembers closer together, not prompt arguments. Card games were also a fairly popular distraction for isolated crews, and have the additional advantage of being small, light, and easy to use almost anywhere. Games taking advantage of the reduced or nonexistent gravity will also be fun for crewmembers, if adequate space is available.

Another popular form of entertainment is video material, especially movies. Section 3.2.2 discusses large screens that may be present in the wardroom. The entire crew could fit in the room for a group movie night, or a few people might choose to watch something in their spare time. The surface habitat will have a wide variety of video available, and will include as many pre-selected crew favorites as possible. Because movies showing large, sweeping landscapes or outdoor scenes were extremely popular with isolated crews in the past, the library will include many movies or shows with this feature. Isolated crews at the South Pole also repeatedly requested tapes of recent commercial TV programming, so there will be a supply of recordings of some crew favorites. Blank media and an adequate communications bandwidth will allow crewmembers to upload a variety of recent programming (sitcoms, sports, news, etc.) on a regular basis.

Music will also provide groups with some needed relaxation. A public collection of music will accompany the crew on its journey. The type, variety, and volume of music should be agreeable to all crewmembers, as the music selection has caused conflict in the past (Stuster, 1996). Individual crewmembers also will bring musical selections as part of their personal equipment. In addition to listening, crews may engage in creative group activities, such as playing and recording music, both with each other, and collaboratively via electronic media with other musicians on Earth. This type of activity has been shown to be effective in amusing, challenging, and unifying the crew aboard the Mars Desert Research Station during the ICOMP experiment (Snook and Burbank, 2003).

Individual free time entertainment may be more common than group off-duty activities. Crewmembers may spend personal off-duty time anywhere within the habitat that they feel comfortable and are not disrupting another crewmember’s activities. Crew quarters will provide a quieter place for individual entertainment, and the library or lounge area will cater to small groups. There will be several forms of recreation available to occupy an individual’s off-duty time. As in the Life Support System Integration Facility, each crewmember will have a personal workstation for email, letter writing, or recording of observations and thoughts, in his/her crew quarters. Submarine crewmembers often express the inability to communicate with persons in the outside world as their biggest concern, and worry for the welfare of family members ashore (Stuster, 1996). To avoid these feelings, the schedule will allow for personal communications with family and friends at home. The frequency of these communications will somewhat depend on the type of transmissions. For example, the exchange of simple text messages will occur more often than swapping video clips with voice attachments. Personal, private voice communications with Earth should be possible.

Members of isolated crews at the South Pole and elsewhere were unable to stress enough the importance of receiving physical care packages and real mail (astro.uchicago.edu/home/web/cbero/mainmail.html) from friends and family. While it will be impossible for crewmembers on the Moon to receive a box of goodies or a present in the mail, it may be possible to arrange a different sort of care package. Ground personnel and family members could provide small surprises or gifts to celebrate a birthday or special anniversary. These items could be left for the crew to discover on their own, or ground support personnel could direct them to them. Crewmembers at the South Pole also find hidden goodies throughout their habitat left by previous researchers or other members of their teams. These small surprises brighten crewmembers’ days and help break the monotony of long-duration isolated missions. Mission planners and habitat designers should consider this an important off-duty activity when planning the lunar missions.

The World Wide Web has also provided many isolated crews with interesting diversions in the past. For example, web sites allowed crewmembers at the South Pole station and inside the Life Support System Integration Facility to answer questions from curious members of the public. Internet connections should be available to astronauts at a lunar outpost. Other established forms of entertainment available using the personal workstations include reading books, watching movie clips, listening to music, and playing games. Any of these are achievable using information stored on CD, disk, or other methods using the latest technology. As with group entertainment activities, crewmembers must always consider noise levels. Headphones will ensure that sound does not distract others. Crewmembers will be able to request and bring their own literature, music, and videos in addition to the supplies for the entire crew. Other off-duty activities will not need personal workstation equipment. Reading is always a popular activity among isolated crewmembers (Stuster, 1996). “Paperbacks” (some of which are likely to be printed on paper, but most will use an electronic book format) are a familiar medium that crewmembers can take anywhere in the habitat. “Magazines” (probably exclusively using an electronic format) will be valuable for the same reasons, but also because they can provide current news. Portable music equipment such as CD players is another popular and lightweight distraction and will be part of the crews’ personal equipment.

Most members of isolated crews choose to keep a journal of events during their time away from home. Their entries provide valuable information about the hardships and triumphs of long-duration or isolated missions. Certainly crewmembers on the Moon will keep logs of science and official work activities, but time and space for personal writing and reflection are also important (Stuster, 1996) and will be encouraged. Crewmembers may also use off-duty time and personal quarters for their religious activities. Mission planners should consider both sleeping and eating as acceptable off-duty activities. However, if any crewmember performs either of these activities in excess, others must note the problem and take appropriate corrective measures. Exercise will be a necessary activity for crewmembers during the mission.

External viewing time is another important free-time activity. Submarine crews greatly enjoy this pastime (Stuster, 1996) and it was popular on Skylab as well (Compton and Benson, 1983). Submarine crewmembers often have a hard time dealing with the drab interior of their habitat. The dark, plain environment barely visible through the portholes only makes things worse. However, periscope viewing-time for each crewmember is an activity that always lifts spirits and is now part of daily routines (Stuster, 1996).

Crewmembers will most likely want to spend some amount of free time viewing the external environment, although it will be relatively unchanging except for shadows cast as the day progresses. Astronomical observations from a small telescope might prove to be of recreational interest to the crew and might also contribute scientific data. Cameras outside the habitat will show crewmembers performing EVAs, or give insights into local weather conditions. Images like these will project easily onto a wardroom screen. In addition to being an enjoyable activity, looking out the window also allows crewmembers to exercise their eyes. If they are not able to use the periscope regularly, members of submarine crews often suffer from vision problems when they return to the surface. This results from not having far away objects to focus on, either inside the habitat or in the outside environment. Crewmembers can avoid eye problems by spending time looking out the windows.

The amount of free time available for the crew and its placement in daily schedules is very important for productivity. Mission and schedule planners as well as the crew itself must develop a standard routine that balances free time with work. Daily schedules will typically leave at least one hour of uninterrupted time before bedtime for relaxation and sleep preparations. Crewmembers perform routine personal hygiene and prepare for sleep, but may not perform any mission-critical tasks during this time (Alibaruho, 1998). Also, most experts suggest that the establishment of a regular workweek will help crewmembers organize their time and stay on schedule. A specific workweek template has not been established for this mission, although a generic workweek template has been suggested (Griffith, 1999, pages 16–18). However, several examples of similar space missions or long-duration missions on Earth can illustrate the likely range of possibilities.

- Current Space Shuttle crews accumulate off-duty time in proportion to the length of the mission at a rate of approximately ½ day per week (NASA, 1998d). They use this off-duty time in four-hour blocks. Due to the relatively short duration of Space Shuttle missions, these off-duty times are scheduled at an appropriate time within the other activities of the mission; there is no fixed number of days-on/days-off that is used across all Space Shuttle flights.

- The *Mir* space station uses a nominal schedule of five days on followed by two days off (Watson, 1998). However, the large number of repair activities typical of the later years of the *Mir* used up a portion of this off-duty time on a regular basis.
- The ISS agenda nominally plans for the crew to work for five days followed by two days off (NASA, 1998a). However, during these two days off, the crew will have housekeeping and activity planning for the upcoming week to accomplish. The ISS crew will also get eight holidays per year, which will be allocated at a rate of approximately two holidays per quarter. The crew will select which holidays it will observe. (Actually the eight holidays will probably be spread over 3-4 crews per year.)
- Crews working at U.S. South Pole bases work six days of the week and rest on the seventh

Free time should be as flexible as possible, giving crewmembers some say in when and how they use their off-duty hours. Also, scheduling and time constraints should protect this off-duty time. A reasonable balance of purposeful work and relaxation time is important to the success of a mission of this duration. After problems with falling behind schedule on Skylab IV, the crew moved to a looser schedule format. Each crewmember made more choices about what they did and when they did it. The crew enjoyed this and became much more productive (Compton and Benson, 1983). Crews in the Life Support System Integration Facility also practiced loose scheduling (Tri, personal communication). The crew aboard the Mars Desert Research Station facility found adhering to detailed time and task plans difficult, and documented their actual schedules as compared to those planned. Appropriate scheduling models for long-duration Mars missions will require additional research (Snook and Morphew, 2003). Mission planners should avoid adding too many new tasks to the schedule if the crew does not ask for them, since this caused most of the problems on Skylab IV. These past experiences show that schedules should remain flexible and allow the crew to select for itself as many of its duties as possible. Maintaining a task list helped keep the Skylab IV crew informed of future chores. Crewmembers could post a similar list on the wardroom information wall in the lunar habitat, or any other prominent place, to keep crewmembers aware of current objectives.

### 3.2.6 Housekeeping

Past experience indicates that habitat interior cleanliness is important not only for the health of the crew but also to maintain a positive collective image by the crew as reflected in the environment in which it must live and work (Stuster, 1996). This subject pertains primarily to keeping the habitat clean, as opposed to maintaining configuration control, which may require significant crew time due to the complexity of the facilities. Housekeeping, as it relates to long-duration, isolated missions, has few suitable analogies available for study due to the fact that most isolated missions are short enough in duration as to avoid these duties. Some missions survived longer isolation periods, but had an exterior support network in place to dispose of any wastes created, which a lunar surface mission will obviously not have available to it. This section discusses the facilities and supplies available for the routine cleaning of a lunar habitat's interior. Suggestions made in this section take into consideration experience from the Shuttle, Life Support Integration Facility tests, and the ISS. Keeping a surface habitat interior clean will require certain equipment and supplies, as defined by the cleaning activities that are likely to occur. For example, experience with the *Mir* space station indicates that molds, mildew, and other biological matter can easily grow on the interior surfaces of inhabited spaces; experience from Apollo surface EVAs indicates that dust and soil are difficult to remove from suits and thus are inevitably introduced into a habitat's interior. The Shuttle now carries a biocidal cleanser, disposable gloves, and general-purpose wipes for cleaning activities (http://spaceflight.nasa.gov/shuttle /shutref/crew/housekeeping.html). Similar resources may be sufficient to cleanse surfaces and equipment throughout a lunar habitat. At present it is unclear if these cleaning supplies pose a risk to a biological life support system that might be used to recycle water within the habitat. Alternatives exist but their impact to the biological life support system must be assessed as this life support technology evolves. If this means of cleaning interior surfaces is retained, it will be important to develop reusable resources, for instance gloves and wipes, to avoid serious mass and volume limit violations.

A vacuum cleaning system will be essential. The very fine-grained and gritty lunar dust will inevitably be brought into the habitat. Collection and removal of this dust will certainly be a unique process. Apollo astronauts walking on the moon spent some small amount of time brushing dust off their partner's suit before returning inside their vehicle, but this approach did not remove all of the dust. A vacuum system should improve the ability to manage the dust problem. The Life Support System Integration Facility included a small handheld vacuum while the Shuttle includes a vacuum hose and several attachments. A small vacuum was found to be useful on *Mir* (Thomas, personal communication). Comparable systems may be useful in cleaning lunar dust. It is possible to test the cleaning systems using dust from lunar samples currently being stored on Earth. Future testing must also examine the effects of dust on items inside the habitat, as well as procedures to prevent large amounts of dust from ever entering the habitat.

Past experience shows that several types of trash will accumulate inside the habitat. Wet trash, including food and hygiene products are especially messy, so disposal locations should be available near food preparation and cleanup areas, as well as in each hygiene facility. Dry trash includes items like paper and dry food packaging. Biohazardous trash may be generated by test procedures and can include blood or blood cleanup items. Chemical hazards may be payload-generated, or come from the environmental control and life support system. Advanced life support systems will recycle most human wastes produced during the mission, however, the system cannot be 100% efficient, and so some portion will need storage. This trash falls under the category of waste containment system trash. Other types of trash include batteries, packing materials, and sharps (items like needles or syringes). Efforts to reduce, reuse, or recycle waste should be employed at all levels. A collection system will be available to temporarily collect and store trash. The Shuttle currently uses two different kinds of bags, one for wet trash and one for dry trash. Future investigations will show if different types of storage are more applicable to a long-duration mission. Making the collection devices themselves reusable will save mass and volume. Multiple trash collection locations will be available throughout the habitat. The capability to seal waste is necessary due to odors produced by trash. Another large problem to solve is where to store accumulated trash during the mission. Unfortunately, there is no adequate analogy to examine when looking for answers to this question. All isolated missions in the past found ways to avoid this obstacle. In past isolated tests on the ground, trash often passed through an airlock for external support personnel to dispose of elsewhere (Mount, 2002). Other tests included a compactor to collapse trash that crewmembers then stored and disposed of at the end of the mission The Shuttle contains eight cubic feet of wet trash storage, which is sometimes full at the end of a two-week mission, but can be configured for more if it is expected (http://spaceflight.nasa. gov/shuttle/shutref/crew/housekeeping.html, 1998). If an adequate way to store trash is unavailable, the habitat will quickly become cluttered and unsanitary. The long-term effect of this problem is obvious. Advantage will be taken of every available location for trash storage, such as in empty propellant tanks, similar to the method used on Skylab, and in the empty food storage area after crewmembers consume the food. A compaction system is one possibility to manage trash. In all cases, trash will be either recycled, reduced (i.e., compaction or incineration), or contained.

Regardless of the form or containment used, storing hazardous wastes near the crew's food is undesirable for safety reasons and will be given special consideration during disposal. Reusing as many things as possible is another way of managing trash during the mission. For instance, sanitizing and reusing items, or making items durable enough to last through several uses, will reduce the volume of trash. Habitat designers should take special care when determining the number of locations and permanent positions available for trash storage. Proper ventilation or remote location of some of these areas will ensure that odors do not offend the crew. Also, it is unsafe and unwise to store harmful substances near spaces the crew frequently uses, such as food preparation or personal hygiene areas. Experiments should be performed to investigate destruction of wastes and disposal on the lunar surface. For example, solid wastes can be largely reduced to carbon and gaseous products by incineration. The ash could be disposed of in a special surface storage area, making provision to recover and reprocess the metallic constituents should the amount become large enough to merit the expense of reprocessing system hardware. Alternatively, it may be possible to integrate trash disposal with in situ materials production systems, turning waste into useful products. For example, the terrestrial processing to produce elemental silicon typically uses wood chips to provide the reductants, so burnable wastes might also be utilized as reactants in the silicon production process.

The crewmembers will share the cleaning duties within the habitat. Crew schedules will allow some amount of time at regular intervals for general housekeeping to take place. Every crewmember will have the opportunity to perform the associated housekeeping tasks in all the public areas of the habitat. For example, everyone will use the bathroom and it will require some amount of routine cleaning to remain sanitary. Alternatively, this cleaning may involve collecting trash bins from different parts of the habitat and consolidating the contents, or removing dust from equipment. Some cleansing of the habitat will take place daily, such as after meals. Crewmembers must sanitize the food preparation and eating areas regularly to avoid contamination. In this case, crewmembers will be in charge of cleaning up after themselves. Section 3.2.2 of this document addresses some of these procedures. In the past, crewmembers used anywhere from 5 to 15 minutes of their off-duty time to tidy their personal quarters and belongings. Skylab crewmembers and those inside the Life Support System Integration Facility used free time or off-duty days for major cleaning of personal areas (Compton and Benson, 1983; Tri, personal communication). It was each person's responsibility to keep his/her own rooms clean. This method worked well and crewmembers can easily follow similar routines in the lunar habitat. The recycling of human wastes, on the other hand, must be a totally automated process. These systems and pieces of equipment need more development, but their final configurations cannot require constant human intervention. Crewmembers may perform periodic checks of the systems, but the machinery should be capable of running continuously on its own. Some human assistance may occur when it becomes necessary to store leftover wastes.

## 3.3 Post-Arrival and Pre-Departure Activities

In the period immediately after landing on the Moon and just before returning from the Moon to Earth or to a facility at Earth-Moon L1, there will be special activities that will be required of the crew. During the period of time immediately following a successful landing on the lunar surface, several key events must occur to allow the crew to transition from an in-space mode to a ground safe mode and finally to a ground operational mode. Interspersed with these key events will be a number of other non-time-critical activities that the crew must perform before normal operations can occur. This section discusses these various events and their implication for crew operations and safety.

### 3.3.1 Activities After Landing

The very first event that will occur after touchdown is to safe the landing vehicle. This will include purging the engines, shutting down the landing systems, and securing the various other systems involved with flight. This process will be carried out by automated systems on the vehicle with status information displayed to the crew and sent to Earth-based support teams. The crew will have an override/manual backup capability for this safing process that may be used in contingency situations. Direct crew involvement in activities other than contingency situations is not anticipated due to the uncertain nature of their functional capabilities.

The "Lunar Gateway" architecture for human missions beyond Earth orbit has been discussed recently (NExT, 2002). The Gateway is a station at Earth-Moon L-1, which provides a habitat and other services for crews to remain for a few days. The Gateway is significant because it provides access to the Sun-Earth L-2 point, for astronomy, can be a way station on a human mission to Mars, and can provide the opportunity to land spacecraft anyplace on the Moon at practically any time with similar energy requirements. If the Gateway architecture is utilized, people landing on the Moon may have been in space for 12-14 days, including time at the International Space Station and at the L1 facility, as well as somewhat longer travel times than experienced by Apollo astronauts. Astronauts arriving at the Moon may, therefore, be less capable of strenuous exertion in the Moon's gravity field, so the development of tasks and procedures should keep this in mind. Some conditioning time on the lunar surface may be required, although that time was short during the Apollo missions. Nevertheless, some reduction of capability in the first day might be expected for short-duration missions.

The availability of significant facilities in 0-g (the ISS and an L1 station) would allow a complete simulation of a Mars mission by spending several months in space, then descending to the lunar surface (e.g. Stafford, 1991). In that case the time required for accommodation to the lunar surface gravity environment could be extended. "Observations on Shuttle crewmembers indicate that post flight recovery takes about the same length of time as the flight duration, at least for flights of about two weeks. Long-duration *Mir* crewmembers undergo rehabilitation (including prescribed exercise and physical therapy) for at least one to two months post-flight before they are released to continue readaptation to Earth's gravity during their regular routine," (Stegemoeller, 1998). Additional research will be needed in this area to understand and mitigate the effects of extended flight in a microgravity environment on functions in the 1/6 g environment. This could be an area of significant operational utilization for a lunar base in preparation for Mars exploration.

For long-duration missions, the crew's initial task, after safing, will be to perform an EVA that takes them from their lander to a pre-installed habitat. Because the resources of the lander will be limited, this activity is likely to be taken as soon after arrival as possible. This action would be done differently if the crew had been in space for 180 days in microgravity conditions. In that case, a high degree of automation may be necessary for nominal activities during at least the first several days, or possibly longer, to carry out necessary functions while the crew adapts to the lunar gravity field. Designers of the lunar missions will decide on the basis of priorities of mission objectives, including obtaining data relevant to Mars missions, whether to build this kind of automated capability into the lunar missions at their start.

Because the landing vehicle and the ascent vehicle will be integrated on the lander and will be operating on internal power (i.e., batteries or fuel cells) during entry and landing, it may be necessary to provide a power source for the lander to maintain its systems for the period it is on the Moon. Nominally, the lander will be connected as soon as possible to the surface power, thermal control, and data systems by a robotic system operated from Earth. Status information during this process will be displayed to the crew and sent to Earth-based support teams. The crew will also have override control of the robotic vehicles that will be used to connect power and thermal control should that contingency be necessary.

Once these activities have been completed, the crew can assess the status of the habitat and supporting systems. The crew would check out any systems that have been shut off or were operating in stand by mode. When all of these systems are operating normally, the crew can consider it safe for routine operations and capable of surviving on the surface for a long period of time given no failures.

### 3.3.2 Preparation for Departure

When crew stay times are 30 days, the ascent vehicle will have been on the surface for at least that amount of time (In some cases, a backup ascent vehicle may have been landed automatically previously and could have been on the surface for even longer). This system will need to be powered-up for departure, inspected and finally disconnected from any ground system connections. In addition, if the crew is not to be replaced immediately, certain parts of the habitat may be placed in standby condition or turned off. Much of this can be done by remote control from Earth, with participation as needed by the crew. Certain systems may require more intensive preparation for the crew's departure. For example, a biological-based life support system might be shut down while waiting for the next crew that will supply the raw materials it needs to function. Shutdown of a biological-based life support system may require an extended period of time (i.e., several hours or possibly days) to place it in a mode for subsequent startup by the next crew. During this time the crew will use the backup, open loop life support system with cached air and water supplies.

Throughout the surface mission, the crew will have been collecting data and samples associated with various experiments it has conducted or gathered from various sites visited. Some samples may be biological samples associated with health-monitoring activities. Throughout the surface mission, the crew will have gone through a process to determine which samples and data (i.e., data that could not otherwise be sent electronically to Earth) should return to Earth. Initial design studies (NExT, 2002) suggest that the ascent vehicle may be sized to return 50 kg of materials to Earth. This would make the selection criteria very stringent. The lunar crew will consult with colleagues on Earth to make the final selection. It will then package the selected samples and data appropriately and make them ready for the transfer to the ascent vehicle. The crew will check scientific experiments and monitoring equipment that will be in operation while no crew is present, and verify that it is in good working order—or, if it is not, repair it—and will perform an inventory and corresponding status check of all surface resources before departure. This will serve as a benchmark for determining the resources available for use by subsequent crews as well as input to planning for future cargo missions.

A much more thorough checkout of the ascent vehicle will take place as the date for departure approaches. Most of this will be done from Earth, but the crew on the Moon may perform visual inspection of the vehicle and provide backup if there is some problem with automated operation from Earth. The “go/no go” decision for launch of the crew will be based on a determination by Earth-based support teams that the ascent vehicle is in a healthy state. Consistent with the spares and maintenance philosophy discussed earlier, the surface crew will also remove any remaining surface equipment from the ascent stage that has not been previously transferred to the surface facilities. All other non-essential surface systems and equipment will be shut down and placed in a safe area (e.g., moved away from areas of potential flying debris caused by the ascent vehicle, sealed against dust infiltration, etc.). The surface crew’s final activity will be to shut down the closed-loop life support system and place the habitat in a quiescent mode.

The crew, along with the samples and other payloads being returned to Earth, then move to the ascent vehicle using the rovers. Once all personnel and equipment have been transferred, the rovers are moved to a safe location (moving the rovers could be an automated activity or a manual activity by an EVA crew. Any umbilicals attaching the ascent vehicle to surface systems will be disconnected and the crew will enter the ascent vehicle for their ride back to space.

### 3.4 Autonomous Deployment of Surface Systems and Experiments

In current planning for lunar missions, the crew lander/ascent vehicle and the surface habitat elements will be delivered by different vehicles in support of long-duration lunar missions. This strategy implies that system exist to unload elements, move them significant distances, connect them to each other, and operate for significant periods of time without humans present. In fact the successful completion of these various activities may be part of the decision criteria for launch of the first crew from Earth. The elements that could be landed robotically include:

- A backup ascent vehicle that the crew could use to reach the L1 transportation node, should the vehicle they arrive in become unusable.
- An ISRU plant that would make breathing gases and water to increase stores brought from Earth or to make propellants for use by surface transportation vehicles or by the ascent vehicle.
- A power plant to provide the energy needed to operate other surface systems.
- A thermal control system to support the heat-rejection needs of various surface systems.
- Navigation aids
- A high volume communications system

- Other supporting infrastructure that is either needed to support the landing of the crew or that is not needed until after the crew reaches the surface, such as unpressurized or pressurized rovers.

These systems could be autonomously deployed and operated in roughly the following scenario: After landing, a power plant will be unloaded, moved to its operating site, and made operational. The power plant is connected to a power distribution system that will deliver power to an ISRU plant (if used), the habitat, and any other surface system requiring electrical power. A thermal control system is also deployed. This system is separate from the power plant, with the primary responsibility of supporting the other systems needing a means of rejecting waste heat; a decision has not been made regarding this requirement. The ISRU plant is then placed into operation and begins producing commodities for use by the crew. The navigation aids communication system. Failure of any of these systems to be deployed or to be operational before the launch of the crew will be an element in the decision process for the launch of this crew. The successful deployment and operation, including maintenance and repair, of these systems places a significant burden on autonomous or supervised systems that will accompany the first cargo mission. The design of these various surface systems and the robots that will support deployment, operation, maintenance, and repair must proceed concurrently and should allow for the eventual interaction by EVA crewmembers.

### 3.4.1 Power System Deployment

One of two options will be used to provide power for surface infrastructure: a solar array/fuel cell system or a nuclear system. In either case, a certain amount of autonomous or supervised activity will be required to deploy these systems and place them into operation. For the solar array option, the deployment is likely to occur in two phases. In the first phase, which will occur shortly after landing, a portion of the complete system, solar arrays and thermal radiator, will be deployed by automated/robotic systems. The exact amount of the total system that will be deployed will be determined by the amount of power needed to keep the crew and critical systems at a minimal operational level. Once the crew is able to conduct EVA activities, the remainder of the system can be deployed either using the same automated devices or by an EVA crew. Studies carried out to estimate the total amount of power that must be delivered by this solar array system, particularly in an off-nominal situation indicate that a large surface area will be needed, potentially covering thousands of square meters. The selected landing site cannot be guaranteed to satisfy all of the deployment constraints needed by this system (these constraints vary depending on the specific type of solar collection system, deployment procedure, and final configuration selected). This implies that a robot should also be prepared to do some amount of site preparation. This could include clearing debris or leveling surfaces.

If a nuclear power plant is selected, it is assumed that the power plant must be unloaded and moved approximately one kilometer away from both the lander that delivered it and from the eventual landing site of the human crew. The separation distance requirement results from the need to minimize the radiation exposure to the crew and other vulnerable systems. In addition to the distance requirement, it also may be necessary to place additional shielding material between the reactor and the crew. This will depend on the reactor design and site-specific conditions. If needed, this material could come from naturally occurring terrain such as low hills or ridges, or the siting of the reactor in the bottom of a small crater. If this additional shielding cannot be provided naturally, then it must be provided by another means. As an example, a robotic vehicle could be used to dig a small hole or build small berms or both, in order to create a shield between the reactor and the crew. With this requirement in mind, a number of events must occur prior to the reactor's deployment. First, a robotic vehicle will be needed to locate the most suitable site within the distance and siting constraints of the reactor. This site cannot be guaranteed to meet all of the previously stated constraints, particularly the shielding requirement, implying that a robot must also be prepared to do some amount of site preparation. This could include clearing debris, leveling a surface, digging a depression, or constructing berms. Once a suitable site has been located and prepared, the reactor will be off-loaded from its lander and moved to the site.

The reactor will then be placed in its operating position and any necessary appendages (e.g., thermal radiators) will be deployed. Once in operation the reactor may need periodic inspection, maintenance, or repair.

These tasks could be scheduled or unscheduled and will be highly dependent on the reactor design. Components known to require some sort of inspection, maintenance, or replacement (or those components for which a random failure could disable the reactor), such as valves, pumps, or control electronics, should be designed for easy accessibility and robotic compatibility. It is assumed that these inspection, maintenance, or repair activities will be accomplished through automated or teleoperated robotic devices. Because of the radiation environment involved and the type of tasks to be accomplished, it may be necessary to dedicate one robotic vehicle to operations within close proximity of the active reactor, especially as a contingency against an extensive, high-radiation-exposure repair. The final activity associated with the power system (this applies to either the solar or nuclear option) prior to its activation is the deployment of a power transmission and distribution system. This will be a system of power cables of appropriate capacity for the distributed users of electrical power on the surface. Such a cable will connect the power system to the ISRU plant (potentially the largest single user if large-scale commodities production is planned), to the surface habitat, and to the ascent vehicle. Finally, a secondary distribution handling system will be used to meet the needs of other surface systems. Little specificity was made regarding this distribution system in Mars mission studies (NASA, 1997 and NASA, 1998c) and additional study is needed to refine the concept.

#### 3.4.2 Deployment of Other Systems

If a robot is available that is capable of deploying the power system, it is likely that other uses will be found for it. These could involve autonomous or teleoperated deployment of the other systems suggested above before the crew comes to the station, or use as a utility vehicle capable of hauling and deploying experiments, once the crew has arrived. For example, at a long-term lunar outpost is will be desirable to locate a geophysical sensing package at considerable distance from the outpost, perhaps 10 km, to avoid interaction with human activities. This utility vehicle could be used to haul the equipment to the site and participate in its deployment.

### 3.5 Orbital Support for Surface Activities

It is assumed that the Lunar Gateway architecture will be utilized for the lunar missions defined in this study. This can provide important logistical support to the lunar outpost. As the L1 point will always be in a similar position with respect to the outpost, it may be useful to make observations from that location that can help document surface activities. Although it is a long way from the lunar surface, it would be possible to locate a telescopic imager there that could provide meter scale resolution of the area surrounding the outpost and could document changes to the surface as they occurred. In principle, it is possible that some services required only occasionally could be provided from L1; however, the propulsion requirements are significant for landing a payload on the Moon, so L1 support could be expensive. When propellant production is achieved on the Moon, it would be possible to operate a reusable transportation vehicle between the lunar surface and L1 without importing propellants from Earth to L1. This should make the Moon-L1 transportation leg less expensive and could open operational uses for L1 that heretofore have not existed. For example, L1 might house an inventory of spare parts that are infrequently needed on the Moon. This would be particularly attractive if the L1 station is also supporting other activities.

## 4.0 Surface Reference Mission Options

### 4.1 Operational Strategies

#### 4.1.1 Selection of Priorities and Experiments

Any mission will have resource constraints within which the mission operations must be carried out. The principal constraints on human missions will be: (1) mass of systems carried to the Moon and to some extent their volume and complexity; and (2) crew time available to explore, conduct experiments and maintain crew functions. Because the lunar missions will have complex goals and diverse objectives, the selection of the optimum mix of objectives/experiments/exploration will be a difficult problem. The reluctance of scientists to discuss priorities between scientific objectives can be a hindrance, so it will be necessary to develop a mechanism by which priority decisions can be made. Iron fisted program managers can make such decisions, but will not win support of the scientists and technologist who will be their customers in this activity. The best approach may be to begin to develop a broad scientific/technical/practical community well before the missions are expected to be flown and letting them work out processes with which the integrated communities can select activities to be carried out.

#### 4.1.2 Site Selection

The selection of sites for detailed surface investigations and for long-term human occupation is of great importance. Historically, locations for lunar exploration have been selected through a process that considers: (1) the scientific or technical objectives that can be accomplished at the site and (2) operational considerations, including access to the site (particularly with respect to contingency operations) and the safety of operations, particularly landing. During the Space Exploration Initiative development period, two workshops were held at the Johnson Space Center to discuss the process by which landing sites could be selected (Morrison, 1990). The reports from these workshops were never formally published; however Taylor and Taylor (1996) summarized the results of the workshops.

A large number of prospective sites for exploration activities have been identified (e.g. Taylor and Spudis (1988); LExSWG (1995); Taylor and Taylor (1996)), based on their scientific and technical merit. At the time of the earlier work, the possibility of ice deposits at the lunar poles was not as clearly defined, which adds specific value to polar sites. In addition, the South Pole-Aitken Basin was not recognized as such an important feature, which adds some far side landing zones to the list. Figure 4-1 captures a view of the Moon, showing prospective landing sites based on the previous reports.

In the 1990 workshops, consideration was given to criteria of suitability of sites for various scientific investigations. Some criteria that may be considered are summarized in Table 4-1, not including criteria that are common to all locations. These criteria were developed in particular for the case of a lunar outpost; however, many of them will be important for short-duration stays, in which it is probable that the scientific objectives will have the overriding priority.

Not all of the sites identified in Figure 4-1 require detailed human exploration. Some can be adequately studied robotically at the current state of lunar knowledge, others would benefit from Apollo-like short-duration exploration. Still others would benefit from intensive study of the scale that would be made possible by a lunar outpost. In addition to lunar studies, sites may have to meet other technical requirements, such as resource availability, viewing conditions for telescopes, interference with Earth’s magnetosphere RF background, etc. From a large list of sites (Taylor and Taylor, 1996, Figure 4-2), the workshops in the 1980s identified six target sites to study in greater detail for their suitability, which are listed in Table 4-2. (Almost certainly, similar groups studying the problem today would identify one or more locations in the South Pole – Aitken Basin as a potential site for long-term occupancy). In the end, the workshops concluded that there was insufficient data to distinguish readily between the value of different sites, basically a statement that the objectives of a lunar outpost were not well enough known to discriminate between various sites. A major recommendation of that era of lunar exploration was to complete the remote sensing of the Moon, particularly for mineralogical and chemical variations across the lunar surface. Now, this has been done, largely by the Clementine and Lunar Prospector missions, but landing site considerations have not been discussed by the interested scientific and technical communities since that time.

Table 4-1. Selection Criteria for Lunar Base Siting (Taylor and Taylor (1996)

| Exploration Theme | Criteria |
|---|---|
| Lunar Geosciences | Ability to address specific major science issues<br>Geological diversity in region<br>Access to enigmatic features |
| Lunar Geophysics | Access to large features of major importance for regional geophysical surveys<br>Suitability for heat flow (away from mare/highland Boundaries<br>Geological diversity<br>Geometrical relation to deep moonquake epicenters<br>Near magnetic anomalies |
| Astronomy | View of the celestial sphere<br>Local topographic impediments<br>Out of sight of Earth (for radioastronomy and mm wavelengths |
| Space Physics | View of Earth and magnetosphere<br>Radioactivity of regolith |
| Resources | Access to resources<br>Access to solar energy |

Table 4-2. Lunar Sites Suitable for Long-Term Human Exploration (Taylor and Taylor, 1996)

| ***Site*** | ***Objectives*** |
|---|---|
| Mare Tranquillitatis (24.9N, 39.4E) | Crust and Mantle, Impact Processes, Regolith, Resources |
| Mare Ingenii (35S, 165E, far side) | Crust and Mantle, Impact Processes, regional geophysics, magnetic anomaly, |
| Riccioli (3.5S, 74W, limb site) | Impact history, regional geophysics, astronomy, resources |
| Amundsen (88S, 60E, pole site) | Impact history and processes |
| Aristarchus (23N, 48W) | Crust and Mantle, Impact processes, Regolith, Pyroclastics |
| Mare Smythii (1.7N, 85.8W) | Crust and Mantle, Impact history, Regolith, Pyroclastics, Astronomy, regional geophysics |

Space infrastructure architectures utilizing Earth-Moon L1 as a staging point may lessen the importance of some of the operational considerations encountered in previous site selection exercises. The availability of a human-rated facility at L1 relieves some of the concern for crewmember safety and health that favored the selection of either equatorial or polar sites for previous exploration programs. In the approaches considered at that time, mid-latitude sites were not as favorable because the times at which contingency could launch from the Moon to rendezvous with an orbiting spacecraft were few. Launches to L1 can be done equally well at any time. Therefore, L1 becomes an important backup facility for the lunar surface.

Buildup of surface infrastructure at a long-term surface outpost also changes the site selection strategy to some extent. For example, creation of a dedicated launch/landing facility nearby a lunar outpost reduces some of the risks of landing and departure from the Moon. The development of lunar resources that would attend any long-duration lunar outpost reduces the risk and the cost of the program, but may lead to focusing on sites that are amenable to resource production.

The selection of sites may be influenced also by the availability of reliable surface transportation. Scientific productivity can be enhanced by providing long-range surface mobility for selected sites, as is illustrated in Table 4-2. As the range of mobile systems increases, the selection of a specific location for an outpost can be made easier by allowing the specific site to be selected based primarily on safety and operational considerations.

For a permanent lunar facility and particularly for advanced facilities such as lunar telescopes, sites will need to be surveyed in detail prior to establishing the facility. Products that should be available in the immediate area of proposed locations for detailed site selection and certification include detailed topography (at sub-meter resolution), soil mechanics properties, information about the location and grade of any resources, and, for polar regions, detailed illumination models.

### 4.1.3 Crew Work Day and Work Week

Crew workdays are likely to be different for short-duration and long-duration missions, due to the anticipated higher cost/hour of astronaut work time on short-duration missions and the ability of humans to put forth extraordinary effort for short periods of time. Work on short-duration missions is likely to be totally preplanned, as it was during Apollo, whereas work efforts on long-duration missions will provide more capability for variety, to take advantage of discovery and follow-up, and crew-originated tasks.

Estimated work days can be derived from the standard crew workday used in the International Space Station is (Griffith, 2000):

- 1.0 hours post-sleep activities
- 3.0 hours for meals
- 0.5 hour for uplink message review
- 7.0 hours for mission operations support
- 2.0 hours for exercise (includes setup and teardown)
- 0.5 hour for report preparation and planning
- 2.0 hours for pre-sleep activities
- 8.0 hours for sleep period

Current analog studies are specifically testing these proposed time allocations.  Preliminary results suggest that more time is required for activities such as report preparation, planning, uplink message review, and other group consultations and preparations for work than those derived from ISS schedules (Snook and Morphew, 2003). Further research is needed to develop new operational models, especially for longer duration science-driven mission scenarios.

For short-duration missions to the Moon, with minimal support capabilities, meal times are likely to be significantly shorter and exercise other than that experienced during EVAs will not be required. This would extend the useful workday to 10-11 hours. EVAs will be from 6.5 – 8 hours, depending on the capabilities of suit technology and crew capacity. For four-person crews on a long stay mission, with EVAs every other day, this will leave some crew time for IVA activities, although with any given EVA team scheduled for every other day, data analysis and planning tasks will dominate the time of the IVA crew, possibly compromising their ability to devote sufficient attention to the activities of the other EVA crew. On the other hand, for short-stay missions with only a few days of EVA possible, it is likely that the entire crew will go out each day, leaving no one inside. Very little, if any, time for IVA activities will be available. This scheduling approach should be closely examined to ensure that it indeed affords maximum scientific return for a short term mission.

For long-duration missions, the ISS workday may be acceptable; however, longer duration EVAs may be cost-effective. The availability of two members of the crew to conduct IVA activities when the other crew is on EVA will provide significant amounts of IVA capability. The amount of IVA activity may be increased in near-polar locations, as it may not be possible to conduct effective EVAs in portions of the lunar night.

Crew exercise in 0-g (e.g. ISS) is scheduled for six days a week. On the Moon, EVA activity will count toward fulfilling the exercise requirement. If strenuous enough, every other day EVAs may become the norm for fulfilling the exercise requirements.

One scheduling model proposes activity blocks that occur at the same time every day (Griffith, 2000). The pre-sleep, sleep, and post-sleep periods are considered off-duty time for the crew with no scheduled activities. The sleep period may be shortened or the work/rest cycle shifted to accommodate the mission critical events. Time for crewmembers to prepare and review personal messages will usually occur during their daily or weekly off-duty periods. This may not be sufficient if the crew are required to respond to outreach or public e-mails during their off-duty periods. MDRS studies have shown that the crews spend significantly more time than expected on e-mail and other electronic file transfer tasks, both personal and scientific. In some cases (e.g. exercise), where facilities are limited, the daily activity blocks will differ between crewmembers.

A standard crew workweek during a long-duration space mission (e.g. ISS) consists of (Griffith, 2000):

- 5 days for mission support activities
- 0.5 day for habitability activity and maintenance
- 1.5 days off duty time
- Off-duty time allocated in equally spaced four-hour blocks throughout the IV days of the surface mission. Current practice is to allocate four hours of off-duty time per crewmember per week.

Mission critical events may cause the regular schedule to be adjusted.

Within the relatively restricted space available to a lunar crew, 1.5 days of off duty time may not be effective, particularly if interspersed with other activities in 4-hour intervals. A flexible approach to the expenditure of this time should be taken. Crewmembers should have significant opportunity for reflection on their experience, communicating with Earth, conducting personal experiments, or other activities that are in categories somewhere between work and relaxation.

The day/night cycle on the Moon is unnatural in terms of human wake/sleep cycles. For early missions to a lunar polar area, missions can be planned so that the amount of time that the sun is actually visible is maximized. As the utilization of a facility becomes long-term, there may also be times when the sun is not visible for more than 14 days at a given location. The general approach to operations will be to maintain a normal terrestrial diurnal cycle, probably synchronized with Mission Control shifts on Earth. For long-duration missions, habitat operation should be maintained so that there are specific lights on/lights off schedules that will simulate the terrestrial diurnal cycle.

### 4.2 Robotic Surface Missions

There are many places on the Moon where further exploration can yield answers to significant scientific questions as well as emplace experiments that can have importance for technical aspects of space exploration and development that do not require extended stay times on the surface. Some of these can be conducted using robotic missions; others will require or will be most effective if undertaken with humans.

Robotic missions are of use for scientific reconnaissance of an area, for certification of a site prior to initiating intensive human activities, or for the emplacement of distributed instruments, such as seismometers, on the surface.

#### 4.2.1. Sample Return Missions

There are a number of places on the Moon where the analysis of samples in terrestrial laboratories can address significant questions of scientific interest. For example, samples from selected areas of the South Pole – Aitken basin could provide first order information on the apparent compositional uniqueness of this region of the Moon, including information on the early impact history of the Moon and its early crustal formation. Both of these questions have relevance to the early history of the Earth. In another example, analysis of the most recent basalt flows on the Moon, identifiable from orbital imaging, could provide fundamental information on the thermal history of the Moon.

It is possible to provide important information with simple robotic sample return missions because the impact history of the lunar surface has broken up and mixed to some extent the rocks to be found in a particular area. Most of the rock fragments in the lunar regolith are locally derived, but others have been thrown in from afar. The improvement in remote sensing capabilities allows better inferences to be drawn about the origin of those that have been thrown from a distance. Small rock fragments are suitable for a wide variety of chemical, mineralogical and isotopic analysis to determine their origin and age.

Simple robotic missions, capable of delivering 200-400 kg payloads to the lunar surface are sufficient for the purpose of returning a few hundred grams of sample to the Earth. Samples also would be collected on human missions, but robotic sample return missions should be used where: (1) the questions to be addressed do not require the sampling and analytical capabilities of on-site humans (e.g. collection of samples from a specific lava flow; (2) there is a question of whether humans should be sent to a location, which can be answered by a robotic mission (the further sampling of the South Pole – Aitken Basin, a very complicated feature, may be an example), or (3) or as precursors to a human exploration mission (for example, in advance of a lunar polar mission, where few relevant surface data are now available).

Simple sample return missions can be carried out in a few days on the lunar surface.

#### 4.2.2 Robotic Rover/Sample Collection Missions

Mobility on the lunar surface of 10’s to 100’s of kilometers could allow the collection of a wider variety of rock fragments from the regolith that overlies geological units that can be characterized based on remote sensing. A sampling technique similar to the sample return mission could be utilized, with samples brought back to a robotic or human Earth return system. In the case of an intended human sortie mission, robotic rovers emplaced a few months or perhaps a year prior to human landing could collect and bring samples to the human landing site for inspection, selection and return to Earth.

### 4.2.3 Robotic Instrument Emplacement Missions

The elucidation of the internal structure of the Moon requires emplacement of scientific stations, particularly seismometers and heat flow experiments, at up to 8 widely distributed locations on the Moon. The Apollo missions installed the Apollo Lunar Surface Experiment Package, which contained geophysical instruments and a radioisotope power source. The Japanese are intending to emplace two seismometers on the Moon with their Lunar-A mission. Additional instruments could be emplaced using robotic or human missions. It is possible that instruments emplaced by astronauts can have longer lives and higher performance than those emplaced robotically.

## 4.3 Short Stay Human Missions

The Apollo 15-17 missions to the Moon were capable of significant exploration. Astronauts were able to undertake three 2-person EVAs, supported by a rover, utilized complex sampling equipment such as a 3-meter drill, and emplaced the ALSEPs. New missions of similar scale (e.g. 4 people, 4 days) could carry out twice as much or more exploration activity and obtain a more diverse sample collection from each site. They may also be utilized as the first step in a campaign where humans will stay for longer periods in a second or following mission.

Surface mission planning for short stay time missions must consider the interplay between two crews; one may occupy the base habitat while a second crew is out of the habitat working in the field (EVA). An option that may be considered is to have all crewmembers on EVA simultaneously, as was done in the Apollo program, albeit with a smaller crew. The correct balance between safety and productivity must be achieved. If one crew is on the surface and the other in the habitat, it is anticipated that the EVA crew will receive the highest operational priority at any time and will be monitored by the crew in the habitat as well as from Earth. However, operations should be set up so that the crew in the habitat does not have to spend much time in monitoring the EVA crew, as their time can also be spent conducting experiments and performing housekeeping duties, as well as carrying out whatever activities are needed for health and performance maintenance. If that is done, substantial periods of time should be available for IVA experiments. As this is a new capability, compared to previous human missions to the Moon, it deserves careful thought. Mission planning should be designed to optimize the productivity of both crews. This will become more pronounced in the long stay time missions, where the proportion of highly effective EVA time to the total mission will be smaller. For short missions, the timing can be such that, like Apollo, both nighttime and high noon thermal conditions are avoided; however, for longer stays, there may be several hours around lunar midday and at night that will not permit full EVA operations.

Figure 4-1 depicts locations on the Moon where relatively short-duration missions could accomplish significant scientific objectives. Three are characterized here, as examples. Because these are short-duration missions, experiments are delivered to the Moon that must either be completed in the course of the surface stay or be left to run in automated mode following departure of the crew. These could include scientific stations or technology experiments.

### 4.3.1 Aristarchus Plateau

#### 4.3.1.1 Science Objectives

Taylor and Spudis (1988) developed a rationale for the detailed study of the Aristarchus Plateau from a lunar outpost. The Aristarchus Plateau region is geologically complex, consisting of highlands (relatively old) material adjacent to more recent mare basalts (Figure 4-2). The region shows high thorium concentrations associated with KREEP compositions, which may be represented in breccias, melt rocks or perhaps KREEP-rich volcanic flows. Volcanic features such as the Cobra Head and Schroeter's Valley, as well as pyroclastic deposits, indicate an extensive magmatic history. The pyroclastic materials are believed to be similar in origin to the orange glass found at the Apollo 17 site, representing samples of the deep mantle underlying the region. The crater Aristarchus, believed to be less than a billion years old, has penetrated both highlands and mare units, the distribution of which in its ejecta can provide information about the cratering process. Thus, several fundamental processes can be investigated in this region. The pyroclastic deposits may also be a good source for oxygen if resource utilization is intended.

An initial short stay at the Aristarchus site could lay the basis for subsequent, more intensive exploration. An initial investigation could be carried out to a location on the rim of Schroeter's Valley, where pyroclastic volcanic rocks could be sampled, as well as ejecta from Aristarchus, which should include melted materials from which the age of the crater could be determined as well as rocks from the highland and mare terrain that the crater penetrated. With sufficient mobility or aided by robotic rovers, a geophysical traverse across Schroeter's Valley might be conducted, which could address the process by which sinuous rilles were formed on the Moon. The initial investigation could lay the basis for longer term, more detailed investigations.

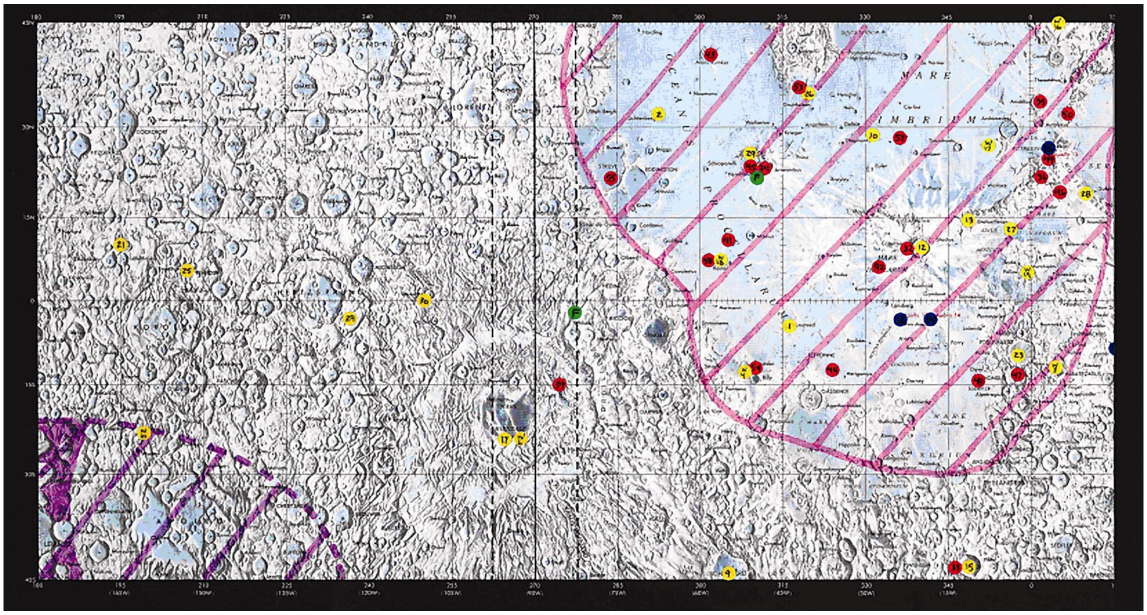

Figure 4-1 (a)

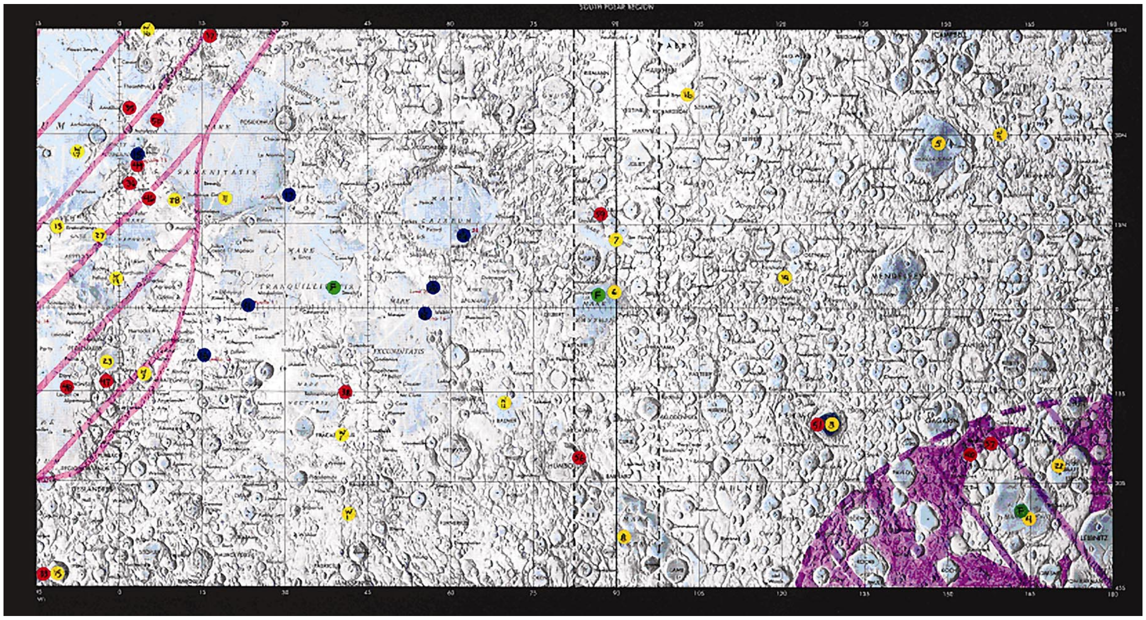

Figure 4-1 (b)

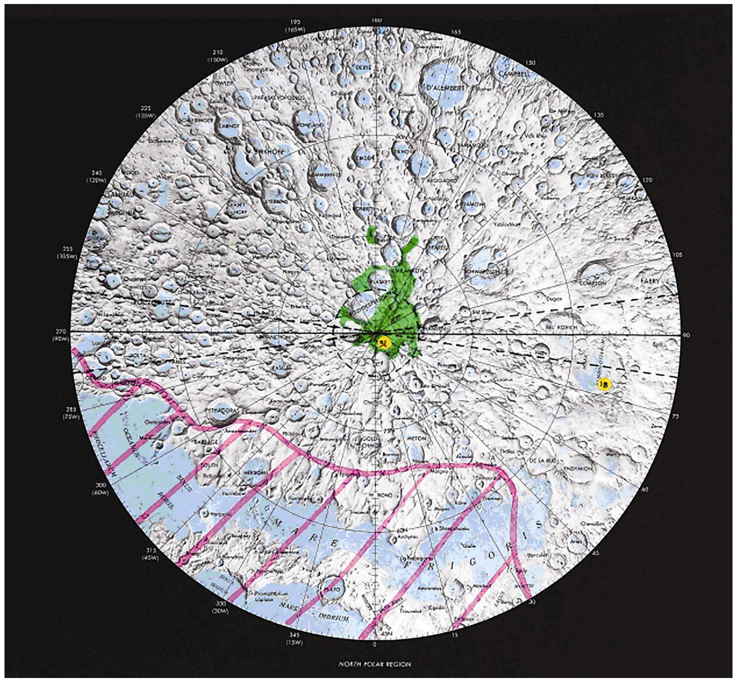


Figure 4-1 (c)

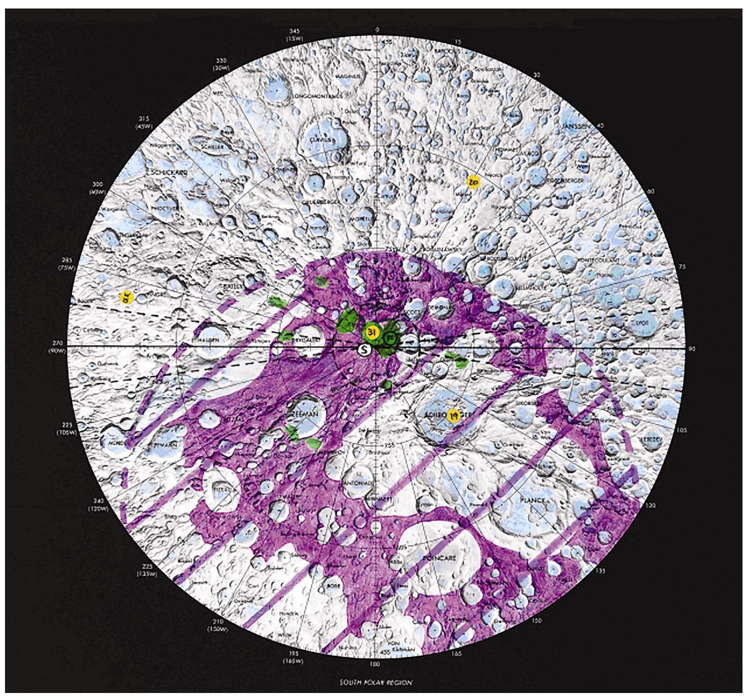


Figure 4-1 (d)

Figure 4-1. Potential investigation sites for future lunar missions. This compilation was produced by John Gruener, Lockheed-Martin Co., Houston, Texas. Figure (a) Western Equatorial Region; Figure (b) Eastern Equatorial Region; Figure (c) North Polar region; Figure (d) South Polar region. The designations for the numbered sites are: Blue dots = Apollo and Luna sites; Green "F" dots = First Lunar Outpost (FLO) study sites; Yellow dots = sites 1-31, robotic sites, from Taylor and Spudis (1988); Red dots = sites 32-59, human sites, from Taylor and Spudis (1988); Yellow "W" dots = Wilhelms (1985)

Figure 4-2, in conjunction with Table 4-2, can be used to demonstrate the value of longer missions and the availability of a pressurized rover. Table 4-2 defines the full scientific objectives of the exploration of the Aristarchus Plateau by defining nine different areas of scientific interest. In a four day mission, with four 6.5 hour EVAs supported by an unpressurized rover, assuming a maximum range of 10 km from the landing point (which would be located close to feature 6 on the illustration), it should be possible to address the objectives identified in the preceding paragraph. Other features of importance are located 40 km to 100 km away, and several are on the opposite side of Schroeter's Valley, which may require a much longer surface traverse to reach. Assume that the crew has access to a pressurized rover, that the rover can operate for extended periods of time at a speed of 5 km/hr, and that straight line pathways are possible from an outpost to the point of interest, and that the vehicle can be driven for 6 hours during a typical traverse day. In this case, it will take a traverse of 3-4 days to achieve the farthest point. Assuming that 2 days will be spent exploring the area and 3-4 days to return, the total traverse would last 8-10 days. It would be possible, perhaps to do three such traverses during the course of the mission, which means that the five objectives identified could not be achieved in a single 30-day mission. It might be possible to combine more than one important site on a single, longer duration traverse, reducing the total travel time, but the above scenario does not account for stops made along the way, which would increase total travel time. It also assumes that EVAs done in daylight and at night are equally effective. The inference from this qualitative analysis is that to accomplish the full set of objectives at the Aristarchus Plateau it would take more than one 30 – day visit, and possibly up to 90 days at the outpost. The quality of the work done on these traverses would be comparable to the quality of work done on 3-4 day sorties to the surface, essentially reconnaissance with a limited amount of detailed study. Additional investigation of features of the Plateau, based on feedback from observations made in initial traverses, could well require several months of additional investigation.

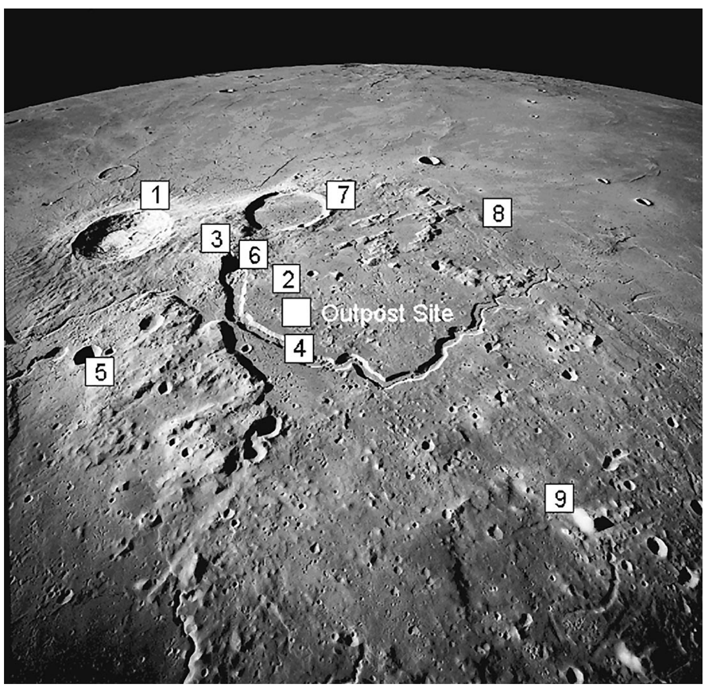


Figure 4-2. Region of Aristarchus Plateau (from Morrison (1990)) with proposed outpost location indicated. (NASA Photo AS15-M-2611)

Although the surface travel time is a significant overhead on the time of crewmembers, the surface traverse strategy would appear to be significantly less costly and expensive than conducting an equivalent number of sorties to the Moon from Earth or from L1. Those missions, too, have significant crew overhead time requirements. The amount of propellant required on the Moon to return a single crew to L1 is comparable to the mass of a reasonable pressurized rover (3,000-4,000 kg), which would be capable of conducting many sorties. A detailed comparison should be undertaken. However, the analysis also shows the limitation of use of a pressurized rover. If it is required that a surface traverse be completed in a single lunar day, the pressurized rover could reach points approximately 180 km from the outpost with the assumptions adopted above. Beyond that range, provisions for overnight driving or stays in the field would have to be provided. With knowledge of the terrain, longer distances might be traversed if the speed of the rover can be increased. Long rover ranges also put additional burdens on the reliability/repair/rescue elements of surface operations.

Table 4-3. Distribution of Exploration Targets at Aristarchus (Adapted from Morrison (1990))

| Site | Name | Distance from Outpost | Objectives |
|---|---|---|---|
| 6 | Outpost site* | 0 | A secondary crater from Aristarchus is nearby, which will provide a window to the subsurface as well as information on Aristarchus ejecta and the secondary cratering process |
| 1 | Aristarchus Crater (40 km diameter) | 42 km | Study of Imbrium ejecta, pre-imbrium crustal material, the age of the crater and the cratering process |
| 2 | Aristarchus Plateau | 10 km | Study pyroclastic volcanic material that may represent magma generated in the lunar mantle |
| 3 | Cobra Head Crater | 12 km | The apparent source crater for the flow (lava tube?) that now forms Schroter’s Valley |
| 4 | Schroter's Valley (the valley can be sampled near Cobra Head, rather than at the point marked here | 2 km | One of the largest and most conspicuous of lunar rilles. Conduct sampling and geophysical studies |
| 5 | Aristarchus A Crater | >60 km | This location is within the ejecta blanket of Aristarchus. Studies around this location will help understand the distribution of ejecta from Aristarchus and the nature of secondary craters |
| 7 | Herodotus Crater (35 km) | 20 km | An older crater, flooded with lava |
| 8 | Eratosthenian mare | 80 km | A younger volcanic flow has flooded this area |
| 9 | Herodotus chi | 110 km | Olivine-rich mountain that may expose pre-Imbrium crustal materials |

* The site selected is somewhat different than that depicted on the illustration. It is close to the location identified on the illustration as site 6. This is the reason for the differences in distance between this table and the original table A-2 in Morrison (1990).

#### 4.3.1.2 Activities Required

To undertake the scientific objectives at Aristarchus, the following activities should be undertaken:

1. Surface traverses to map and sample areas where remote sensing indicates concentrations of pyroclastic deposits and ejecta from Aristarchus. Sampling techniques can include shallow trenches or drive tubes, rocks collected from the regolith using a rake, and specimens from large boulders that represent Aristarchus ejecta. Trenching may be a particularly important approach to determine whether volcanic sequences can be distinguished and sampled. An initial trench excavated on the first traverse

2. Geophysics traverse (active seismic, gravity, radar sounding) across Schroeter’s Valley and to delineate depth of pyroclastic deposits. The traverses could be aided by the use of robotic rovers, capable of carrying instruments across the relatively steep walled valley, where slopes of approximately $30^o$ exist. Operation of these rovers could benefit from direct observation by astronauts from the valley rim.

3. The geological traverses in an initial visit could be limited to distances of 10-15 km from a central landing site. More detailed investigations were defined in Morrison (1990) that could require traverses reaching as much

as 100 km from a central location.

4. For more complete reconnaissance sampling of the region, it would be possible to deploy sample-collecting rovers in advance of the arrival of astronauts. A wider sampling would help in decision-making for subsequent human exploration of the area.

5. For any site of human exploration, a long-term geophysical station and heat flow probe should be established.

6. Technology and other science experiments that could be associated with a short visit to this site include: (1) ISRU demonstration experiments, including excavation and oxygen extraction; (2) EVA and mobility experiments; (3) Environmental sensors; (4) Radiation shielding experiments.

#### 4.3.1.3 Timeline

The timeline for the science activities for this mission consists of four days of surface exploration. They would be carried out by one or two crews, utilizing procedures similar to those used by Apollo, probably including a lunar rover. Each of the traverses would be planned in advance, to accomplish the objectives outlined above. An initial trenching experiment would provide information from which to determine the extent of trenching to be done on subsequent traverses. The geophysical traverse of Schroeter's valley might be divided between two astronaut EVAs, depending on the capabilities of the robotic systems. Ancillary experiments should be largely done with IVA.

### 4.3.2 Lunar South Pole

#### 4.3.2.1 Science Objectives

The lunar South Pole lies geologically in ancient lunar highlands at the edge of the South Pole – Aitken Basin (SPA), the oldest, largest and probably deepest well-preserved impact crater on the Moon (perhaps in the solar system). A near-polar site would be appropriate (Figure 4.3). Geoscience objectives include understanding the ancient highlands crust of the Moon, the dynamics of large basin forming events (smaller multi-ring basins exist within SPA), the age of the SPA event, and the nature of post-basin volcanism. The special properties of the lunar poles, particularly the characterization of volatile deposits in permanently shadowed craters, need to be explored. Characteristics of the lunar polar environment relevant to the utility of large telescopes can be addressed.

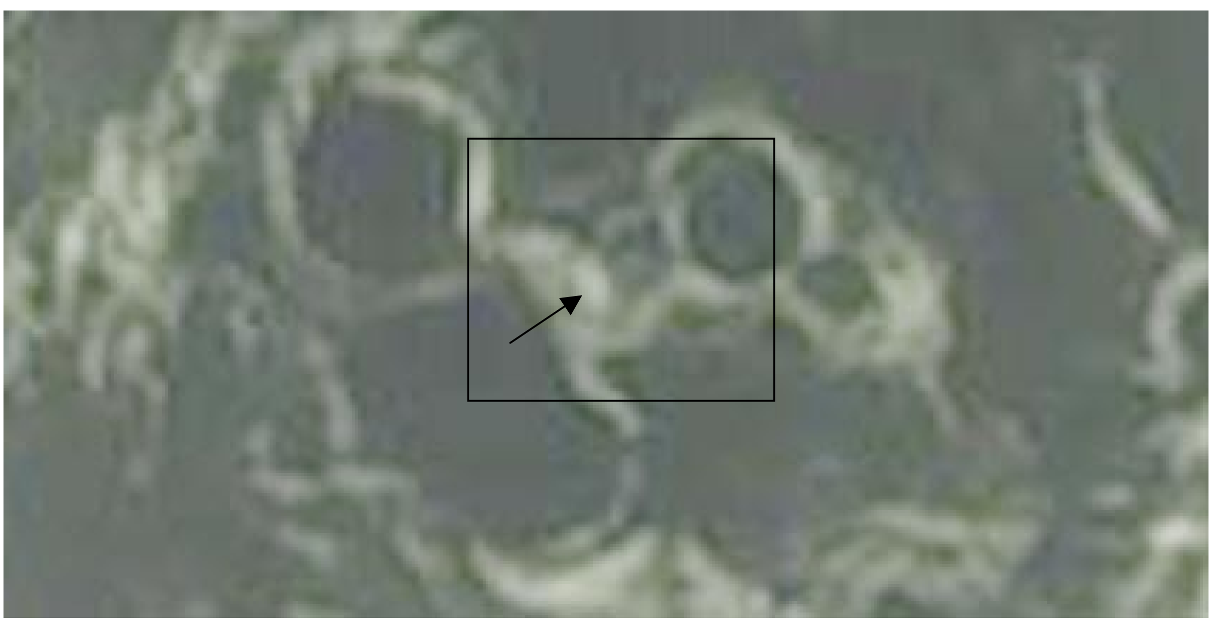

Figure 4-3. Lunar south pole. Constructed from Clementine mosaic of lunar south polar region. The light region at center of the image is an area where the relatively high point is sunlit more than half of the time.

#### 4.3.2.2 Activities Required

The activities envisioned for a short visit to the lunar south pole include:

1. Regolith sampling. A visit to an ancient highland site provides an opportunity to statistically sample the rock types in the original lunar crust by concentrating a large number of pebble-sized fragments, using a tool such as the rake carried by the later Apollo missions. It may be possible to conduct initial analysis on the Moon, using an automated analysis and sorting mechanism to select the range of chemical compositions included in the sample fragments. Such a collection should include old highland crust rocks as well as impact breccias and melt rocks generated by the SPA and younger multi-ring basins.

2. Robotic exploration of permanent shadow. Small, teleoperated rovers can be utilized to conduct geophysical and geochemical surveys within areas of permanent shadow. These can include electromagnetic sounding and hydrogen sensing to discover areas where volatile deposits are most highly concentrated. Humans could be sent to do detailed characterization of areas of high interest

3. Surface and subsurface characterization of ice deposits. The data of interest are the form, quantity and distribution areally and with depth of ice or volatile deposits. The sampling of subsurface deposits in shadowed craters will be a complex undertaking because the act of removing the sample may alter the character of the material. An astronaut entering the area will bring heat and possibly alter surface deposits. Cores or drills inserted into the regolith are likely to heat the regolith and drive away some volatiles. If volatiles are released, they may freeze out in parts of the system where they can cause damage. A human exploration campaign will be iterative, starting perhaps with on-site inspection and testing of the surface physical properties to determine the differences between regolith in and outside of the permanent shadow. If the surface is similar to regolith elsewhere, a drive tube can be utilized to insert a probe designed to determine subsurface physical properties and the content and type of volatiles. Volatiles might be determined with an attached mass spectrometer. The probe could be inserted to different depths by pushing or hammering, or if the material is like the lunar regolith elsewhere, a drill may be required. Once the properties of the regolith are understood in general, a number of such tests should be made. In general, the depth of testing does not need to be deeper than 1-2 meters, though in some places, ice could exist at deeper levels.

4. Installation of surface physical properties and environmental monitoring sensors, to establish the parameters that could affect a variety of future uses of the permanent shadow. These measurements could include temperature sensors to understand diurnal variations as well as dust and seismic sensors to determine the natural particulate and vibrational behavior of the site. Sensors could be installed to determine the long-term lighting conditions of the site.

5. A heat flow probe system installed within a permanently shadowed area will provide a direct and rapid measurement of the heat emerging from the Moon in this terrain, a measurement of the radioactivity of the lunar interior and the amount of original heat still escaping from the Moon. Installation of a long-lived seismic station is also important, as it is at any site visited on the Moon. These sites will require nuclear power sources for long-term operations.

6. Packaging of samples for return to Earth.

#### 4.3.2.3 Timeline

Four sorties are envisioned for this mission. One will generally acquaint the crew with what will be perceived as a strange place, to find their way around, etc. Two sorties would be used to explore a permanently shadowed area, which might be several kilometers from the landing site. A fourth would sample the regolith and emplace experiments. The fourth sortie would

### 4.3.3 Taurus-Littrow (Apollo 17 Site)

#### 4.3.3.1 Science Objectives

The Apollo 17 site in Taurus-Littrow was a particularly productive site and can be considered for a revisit (Figure 4-4). Such a revisit would provide additional time to investigate features not reached in the Apollo 17 mission and to investigate in more detail findings begun by Apollo 17, such as the discovery of orange glass deposits, which became the type materials for pyroclastic volcanic deposits that now have been recognized many places on the Moon. In addition, a special effort was made on the Apollo 17 mission to create a lunar Long Duration Exposure Facility by documenting components and materials and retaining coupons of these materials in the Houston curatorial facility. These materials are available for comparison to pieces of the Apollo 17 hardware that could be sampled and returned, in the same manner that Apollo 12 sampled the Surveyor III camera mission. In that case, however, the period of exposure was relatively short, compared to the 30+ years that will have passed between Apollo 17 and renewed lunar exploration. Exploration of this site would provide a test of the premise that revisiting a lunar site can be an effective way of studying the Moon. A great deal of information is available from the Apollo 17 mission, which could be used to define the scientific objectives of a new mission and resample, if desirable, locations that were studied by Apollo 17.

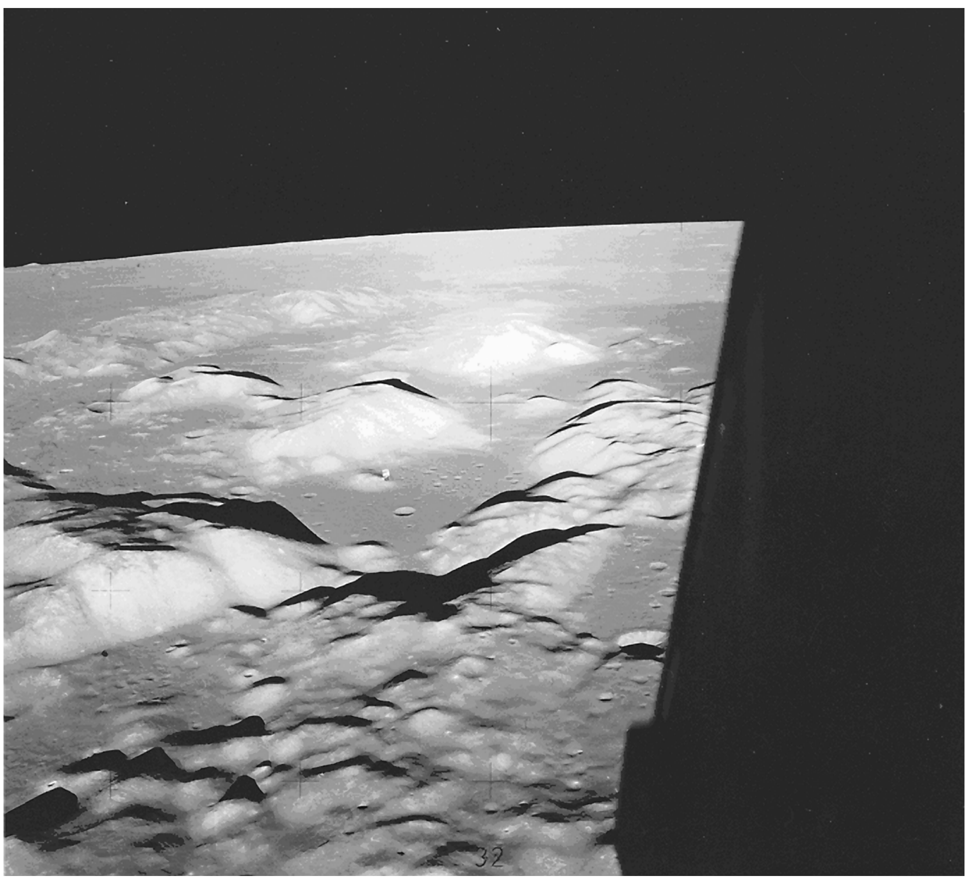


Figure 4-4. Image of the Apollo 17 landing site. Bright object in the center is the Apollo Command and Service Module (in flight), not the lander. A revisit of this site could provide more intensive study of terrain originally sampled by the Apollo 17 crew. (NASA Photo AS17-147-22464)

Specific objectives of a lunar mission to Taurus-Littrow could include:

1. More intensive study of the distribution of pyroclastic material by collecting samples and conducting an active geophysics (seismic) study of the thickness of the pyroclastic units and their possible layering. Cores and trenches in the deposits could yield important information on the sequence of formation of the deposits, including evidence of the evolution of the magmas from which the pyroclastic materials were derived.

2. Traverses at Apollo 17 could be designed to obtain better sampling of the basin impact breccias exposed there as boulders. A special drill system might be utilized to sample a large number of distinctive rock fragments in coarse breccias (Figure). Perhaps an entire traverse could be spent on a single large breccia fragment.

3. Emplacement of surface environment and geophysical stations.

4. Sampling of Lunar LDEF pieces for return to Earth.

#### 4.3.3.2 Activities Required

The following activities could be carried out at this site.

1. Scientific traverses with collection of rake samples and special sampling of fragments from large breccia boulders. Consider hand held rock drill (similar to automated Mars drill designed for the Athena rover) as a sampling tool for breccia fragments.

2. Rapid screening analysis for fragments collected in rake.

3. Packaging of samples for return to Earth.

4. Emplacement of geophysical and environmental instruments.

5. Sampling of the Apollo 17 spacecraft for long-duration exposure studies. Tools for collecting pieces of spacecraft TBD. The site of the Apollo 17 landing might be studied also for other features related to the landing and ascent of the Apollo 17 spacecraft. This would also be a good site to exploit historical activities as part of an education and outreach program.

6. Emplacement of geophysical traverse line (geophones) and conduct of traverse geophysics (gravity, magnetometer, ground penetrating radar).

#### 4.3.3.3 Timeline

Four sorties. The first will conduct site reconnaissance and a geophysical traverse across orange soil deposit. One will collect and separate rake fragments, one will sample breccia boulders more thoroughly than was possible on Apollo 17, and one will collect specimens from the Apollo 17 spacecraft.

### 4.4 Long-Duration Human Missions and Infrastructure Development

The maximum duration of a lunar mission conducted by Apollo was 3 days. Longer crew stay times allow for broader surface exploration, more intensive special sampling, and a range of technological and operational experiments and demonstrations to be performed. The opportunity may also exist to revisit a site if the initial sortie finds something that would benefit from a follow-up visit, or if the initial goals could not be accomplished in the first EVA. Two possible locations for an extended stay time mission are defined. Each mission is described in two steps, an initial 30-day mission and a follow-up 30-day mission, utilizing in part the infrastructure delivered for the initial mission. These could form the basis for establishing a permanent outpost on the Moon.

### 4.4.1 South Pole Station

#### 4.4.1.1 Science and Technology Objectives

The objectives of a long-duration mission to the lunar South Pole are:

1. Thoroughly investigate the properties of permanently shadowed areas, including characterizing the volatile content outside of and inside permanent shadow and studying volatile dynamics within the permanent shadow;

2. Assess the resource potential. This goes beyond the initial characterization discussed for the short term mission and is aimed at discovering deposits of volatiles that are high enough in concentration and extensive enough that they can support an operational volatile production facility. Demonstrate the production of water and propellants;

3. Conduct long-term tests that demonstrate the suitability or lack of suitability of polar locations for astronomical observatories;

4. Establish long-duration test beds to demonstrate exploration technologies for long-duration stays on the Moon or visits to Mars;

5. Explore the effects of reduced gravity on humans and animals;

6. Conduct experiments in reduced gravity fluid flow, heat transfer, the mechanics of granular materials (including regolith), combustion and other properties that are fundamental to the design of operational systems;

7. Evaluate the problems associated with longer-term missions to a lunar polar site;

8. Conduct surface explorations of increasing range and scale to areas of geological importance, to address questions of the origin of the ancient crust and the early impact history of the Moon;

9. Conduct experiments in space physics, solar wind, and other radiation phenomenon;

10. Explore the range of possibilities for construction on the lunar surface that are essential if the initial outpost is to be expanded;

11. Demonstrate techniques that can be used to expand the capabilities of a permanent human outpost utilizing adaptable equipment (such as surface mobility systems) in a variety of ways.

#### 4.4.1.2 Activities Required

The following tasks and activities will be necessary in this scenario:

1. Robotic systems operating extensively within the permanent shadow, conducting geophysical traverses and sampling the regolith.

2. Conduct human sorties into the permanent shadow at a number of places, conducting subsurface sampling and analysis of volatiles to assess the volatile resource potential of the area.

3. Conduct long-range (10-20 km from base in initial visit; up to 100 km when pressurized rover is available) sorties (outside of the permanent shadow) to areas of geological importance for sample collection.

4. Establish and maintain instruments for environment monitoring and geophysics and space physics measurements.

5. Set up long-duration technology test bed experiments.

6. Conduct physical and biological experiments within the habitat.

7. Monitor the health of astronauts over the duration of the mission

8. Teleoperate systems for inspection, maintenance and external site preparation and construction demonstrations

9. Analyze samples collected by robotic and human sorties to select materials for return to Earth.

10. Communicate findings and discuss with colleagues on Earth.

11. Maintain operational systems; demonstrate capability to repair failed pieces

#### 4.4.1.3 Timeline – First 30-Day Mission

A lunar polar mission has significant constraints on EVA activity. Although there may be some areas where sunlight is available close to the base up to 70% of the time, these areas will be restricted and the lighting will always be at a low angle, leading to shadows behind topographic features. As the sun drops to the horizon, light will become limited, so EVA traverses in full sunlight will only be feasible on a few days of each month. On other days, Earthshine will provide some illumination; however, the light also will be striking the surface at a low angle. It is likely that artificial illumination will be required on most traverses. Traverses have been suggested in the table below (Table 4-4) based on the assumption that the mission will begin just as day breaks on the Moon, though light may not come immediately to the outpost site, depending on topography. Human traverses into permanently shadowed areas are preceded by robotic traverses. It is assumed that there are two crews, each of which can conduct a traverse on alternate days. While one crew is on traverse, they will be supported by the other crewmembers in the facility; however, the IVA crew may undertake other tasks. It is assumed that ventures into the permanent shadow will require the full attention of the IVA crew. In this case, the number or frequency of EVAs may need to be reduced to allow for reasonable workloads on both EVA and IVA crews.

#### 4.4.1.4 Timeline– Second 30-Day Mission

The timeline (see Table 4-5) assumes that two long-range pressurized rovers, designed to be capable of trips of several Earth day duration, have been delivered to the outpost. These are thoroughly checked out and utilized for sorties up to 50 km from the outpost site. It is assumed that enough experience has been obtained by this time that suited EVAs can be conducted at night (or into the permanent shadow) when they are required.

Table 4-4. Timeline for Lunar Polar Mission – First 30-Day Mission

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 1 | | | Acclimate and checkout |
| 2 | Dawn | Deploy instruments; nearby science | Set up inside experiments |
| 3 | Dawn | Local traverse; experiment setup | Set up inside experiments |
| 4 | Sun | Geology traverse in sunlit area | Operate telerobotic systems in shadow |
| 5 | Sun | Geology traverse in sunlit area | Operate telerobotic systems in shadow |
| 6 | Sun | Traverse into shadow | Monitor EVA |
| 7 | Sun | Rest | |
| 8 | Sun | Traverse into shadow | Monitor EVA |
| 9 | Sun | Geology traverse in sunlit area | |
| 10 | Sun | Geology traverse in sunlit area | |
| 11 | Sun | Geology traverse in sunlit area | |
| 12 | Twilite | Traverse into shadow | Monitor EVA |
| 13 | Twilite | Traverse into shadow | Monitor EVA |
| 14 | Dark | Rest | |
| 15 | Dark | EVA- nearby base – deploy instruments | |
| 16 | Dark | EVA – demonstrate repair techniques | |
| 17 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 18 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 19 | Dark | EVA - Earthshine traverse | Monitor EVA |
| 20 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 21 | Dark | Rest | |
| 22 | Dark | EVA – Dark traverse | Monitor EVA |
| 23 | Dark | EVA – Dark traverse | Monitor EVA |
| 24 | Dark | EVA – Dark traverse | Monitor EVA |
| 25 | Dark | EVA – Dark traverse | Monitor EVA |
| 26 | Dark | EVA – Prepare samples for return | |
| 27 | Dark | EVA- Secure external systems | |
| 28 | Dark | Rest | |
| 29 | Dark | Prepare for return | |
| 30 | Dark | Prepare for return, depart | |

Table 4-5. Timeline for Lunar Polar Mission – Second 30-Day Mission

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 1 | | | Acclimate and checkout |
| 2 | Dawn | Check out facility, deploy long-range vehicle(s) | Set up inside experiments |
| 3 | Dawn | Practice contingency operations | Set up inside experiments |
| 4 | Sun | 8-hour traverse in long-range vehicle | Monitor EVA |
| 5 | Sun | 8-hour traverse in long-range vehicle | Monitor EVA |
| 6 | Sun | 24-hour traverse in long-range vehicle | Monitor EVA |
| 7 | Sun | Rest | |
| 8 | Sun | 24-hour traverse in long-range vehicle | Monitor EVA |
| 9 | Sun | 48-hour traverse in long-range vehicle | Monitor EVA |
| 10 | Sun | | Monitor EVA |
| 11 | Sun | Vehicle inspection and maintenance | |
| 12 | Twilite | EVA- Erect garage for vehicle | |
| 13 | Twilite | Traverse into shadow | Monitor EVA |
| 14 | Dark | Rest | |
| 15 | Dark | EVA- nearby base – deploy instruments | |
| 16 | Dark | EVA – demonstrate repair techniques | |
| 17 | Dark | EVA – Earthshine traverse – instrument and experiment monitoring | Monitor EVA |
| 18 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 19 | Dark | EVA - Earthshine traverse | Monitor EVA |
| 20 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 21 | Dark | Rest | |
| 22 | Dark | EVA – Dark traverse | Monitor EVA |
| 23 | Dark | EVA – Dark traverse | Monitor EVA |
| 24 | Dark | EVA – Dark traverse | Monitor EVA |
| 25 | Dark | EVA – Dark traverse | Monitor EVA |
| 26 | Dark | EVA – Prepare samples for return | |
| 27 | Dark | EVA- Secure external systems | |
| 28 | Dark | Rest | |
| 29 | Dark | Prepare for return | |
| 30 | Dark | Prepare for return, depart | |

### 4.4.2 Mare Smythii

#### 4.4.2.1 Science and Technology Objectives

Mare Smythii was considered to be a high priority site by the site selection strategy workshop reported by Morrison (1990) for its geological interest, equatorial location viewed as good for astronomical observations, and for access to the far side (Figure 4-5). Scientific issues that could be addressed at a Mare Smythii site include: (1) highland and crustal processes; (2) mare units and lunar volcanism; (3) cratering processes and history; (4) determine constraints and opportunities for a large lunar telescope; (5) survey the region for accessible resources among mare and highland lithologies (pyroclastic deposits occur in the area). This 30-day mission also will address technology demonstrations for long-term lunar missions and eventual human missions to the surface of Mars. Therefore, the establishment of a technology test bed, resource utilization experiments and other activities that could precede the establishment of a permanent lunar outpost should be undertaken.

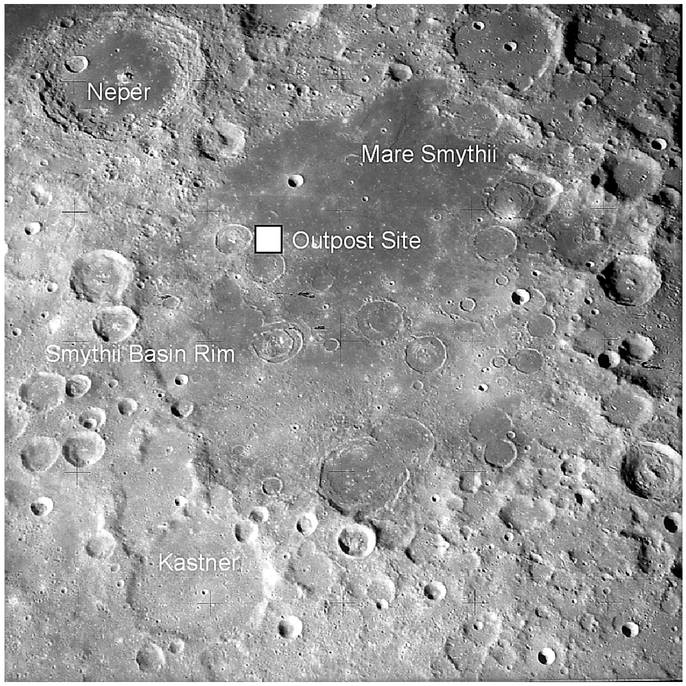


Figure 4-5. Mare Smythii with a proposed location for a surface outpost (from Morrison (1990)). (NASA Photo AS15-95-12991)

4.4.2.2 Activities Required

The activities to be carried out at the Mare Smythii outpost include:

1. Geological traverses. The site selection strategy workshop identified 16 sites within 100 km of a central outpost location in Mare Smythii as high priority places for geological investigation. A location can be selected where several of these sites are within 20 km of the outpost and can be investigated in an initial 30-day mission, while all of them could be accessible on a subsequent mission when long-range vehicles are available. Traverses from the outpost would undertake observations of terrain and regolith features, detailed studies and sampling of specific features, and collection of samples for return to the outpost.

2. Analysis of samples. Initial analysis of samples from the regolith could be used, in conjunction with remote sensing data, to further identify features of interest for subsequent EVAs. Subsequently, on-site sample analysis can be used to select samples for return to Earth, as will as to characterize resource deposits.

3. Emplacement of a lunar surface technology test bed (outside the habitat). Once installed, these experiments will be teleoperated from Earth or from the habitat. For experiments using local materials, crewmembers may provide materials to the experiments.

4. Emplacement of long-lived geophysical, space physics and environmental monitoring instrumentation.

5. Installation of a modest lunar telescope, to allow the determination of suitability of the site for larger telescope facilities.

6. Astronaut physical and psychological monitoring; experiments in gravitational biology.

7. Installation and operation of elements of biological life support systems.

8. Teleoperate systems for inspection, maintenance and external site preparation and construction demonstrations

9. Analyze samples collected by robotic and human sorties to select materials for return to Earth.

10. Communicate findings and discuss with colleagues on Earth.

11. Maintain operational systems; demonstrate capability to repair failed pieces

#### 4.4.2.3 Timeline – First 30-Day Mission

The timeline for the Mare Smythii mission involves near-outpost and extended distance traverses, to establish the geological setting of the outpost site and investigation of the major features. The assumption that each crew will stay in the habitat on alternate days puts a premium on organizing the investigations so that the IVA crew is able to spend the time analyzing materials from their previous sortie, before they embark on a subsequent field traverse. The Smythii outpost, lying on the relatively flat mare terrain, will be a good place to develop field exploration techniques and gain experience for even longer crew stays on the Moon.

Table 4-6. Timeline – Mare Smythii – First 30-Day Mission

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 1 | | | Acclimate and checkout |
| 2 | Dawn | Deploy instruments; nearby science | Set up inside experiments |
| 3 | Dawn | Local traverse; experiment setup | Set up inside experiments |
| 4 | Sun | Geology traverse | Operate telerobotic systems in shadow |
| 5 | Sun | Geology traverse | Operate telerobotic systems in shadow |
| 6 | Sun | Geology traverse | Monitor EVA |
| 7 | Sun | Rest | |
| 8 | Sun | Geology traverse | Monitor EVA |
| 9 | Sun | Geology traverse | |
| 10 | Sun | Geology traverse | |
| 11 | Sun | Geology traverse | |
| 12 | Twilite | Traverse into shadow | Monitor EVA |
| 13 | Twilite | Traverse into shadow | Monitor EVA |
| 14 | Dark | Rest | |
| 15 | Dark | EVA- nearby base – deploy instruments | |
| 16 | Dark | EVA – demonstrate repair techniques | |
| 17 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 18 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 19 | Dark | EVA - Earthshine traverse | Monitor EVA |
| 20 | Dark | EVA – Earthshine traverse | Monitor EVA |
| 21 | Dark | Rest | |
| 22 | Dark | EVA – Dark traverse | Monitor EVA |

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 23 | Dark | EVA – Dark traverse | Monitor EVA |
| 24 | Dark | EVA – Dark traverse | Monitor EVA |
| 25 | Dark | EVA – Dark traverse | Monitor EVA |
| 26 | Dark | EVA – Prepare samples for return | |
| 27 | Dark | EVA- Secure external systems | |
| 28 | Dark | Rest | |
| 29 | Dark | Prepare for return | |
| 30 | Dark | Prepare for return, depart | |

#### 4.4.2.4 Timeline – Second 30-Day Mission

This exploration scenario assumes that at least one pressurized rover has been sent to the Smythii outpost. It is assumed that, during its first use, a maximum period for the rover to be away from the outpost is 72 hours. This could allow the pressurized rover to move 100 km from the outpost, if suitable rescue capability is available.

Table 4-7. Timeline for Mare Smythii – Second 30-day mission.

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 1 | | | Acclimate and checkout |
| 2 | Dawn | Check out facility, deploy long-range vehicle(s) | Set up inside experiments |
| 3 | Dawn | Practice contingency operations | Set up inside experiments |
| 4 | Sun | 8-hour traverse in long-range vehicle | Monitor EVA |
| 5 | Sun | 8-hour traverse in long-range vehicle | Monitor EVA |
| 6 | Sun | 24-hour traverse in long-range vehicle | Monitor EVA |
| 7 | Sun | Rest | |
| 8 | Sun | 24-hour traverse in long-range vehicle | Monitor EVA |
| 9 | Sun | 72-hour traverse in long-range vehicle | Monitor EVA |
| 10 | Sun | Continue 72-hour traverse –Intensive exploration of site 30 km from outpost | Monitor EVA |
| 11 | Sun | Continue 72-hour traverse | Monitor EVA |
| 12 | Twilite | Vehicle inspection and maintenance | |
| 13 | Twilite | Prepare system for nighttime operations | |
| 14 | Dark | Rest | |
| 15 | Dark | EVA- 8 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 16 | Dark | EVA – 8 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 17 | Dark | EVA – Earthshine traverse – 8 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 18 | Dark | EVA – Earthshine traverse 8 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 19 | Dark | EVA - Earthshine traverse – 16 hour traverse, if rover capabilities, particularly power, are sufficient | Monitor EVA |
| 20 | Dark | EVA – continue traverse | Monitor EVA |

| Day | | EVA Activity | IVA Activity |
|---|---|---|---|
| 21 | Dark | Rest | |
| 22 | Dark | EVA – Dark traverse - 16 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 23 | Dark | EVA – Continue Dark traverse | Monitor EVA |
| 24 | Dark | EVA – Dark traverse - 16 hour traverse in pressurized rover to test nighttime operations near base | Monitor EVA |
| 25 | Dark | EVA – Continue dark traverse | Monitor EVA |
| 26 | Dark | EVA – Prepare samples for return | |
| 27 | Dark | EVA- Secure external systems | |
| 28 | Dark | Rest | |
| 29 | Dark | Prepare for return | |
| 30 | Dark | Prepare for return, depart | |

Development of concepts for IVA is not as complete as specifications for EVA. This must be remedied in subsequent planning. The amount of time available for IVA will probably be greater than that for EVA, because EVAs may be restricted at night and because some IVA operations will be possible as fill-in work by one crew during EVAs by the other crew. Some of this time will be taken up by housekeeping, exercise, and maintenance operations. Consideration should be given to lengthening the stay time to approximately six weeks for the nominal mission. That would increase the amount of daytime EVA that is possible. Daytime EVAs at a polar site need to be planned particularly carefully, due to the low angle solar illumination. It will be critical at a polar outpost to develop the capability for nighttime operations, because the amount of daylight available at most sites during the day will be restricted.

### 4.5 Discussion of Timelined Activities

Significant issues related to timelined activities are associated with the mission architectures adopted for this report:

1. The split of time between EVA and IVA activities for a 4-person crew is not particularly effective on a short stay mission, if the crew is limited to every-other-day EVA. If a short stay mission spends four days on the surface, each crew will be able to conduct two EVAs. One EVA every other day seems a good target for crew health and performance issues; however, it leaves a great deal of time of the other two crewmembers to conduct IVA activities. IVA capabilities for short-duration missions are likely to have lower priority in terms of resources such as mass and space available. Reducing the crew to three astronauts on the surface and allowing each crew members to perform two EVAs in a 3-day stay could more effectively utilize crewmember time. Alternatively, it may be possible for two crews to be on EVA on some days. Two crewmembers could be conducting experiments in the vicinity of the habitat while the other two were on an extended EVA. A detailed study of the balance of effort required for EVA and IVA are required to allow the various options for crew deployment to be understood adequately. Some studies have shown a larger amount of IVA time is required to support EVA activities than previously thought. However, for short-duration missions with small light-time communications delays with Earth, this will be less pronounced than for longer term surface stays.

2. For extended duration missions of 30-days, the ratio of IVA to EVA is high if it is assumed that nighttime EVAs will be somewhat restricted. The IVA to EVA ratio might be further increased due to the demanding IVA schedule in support of each EVA. During the nighttime period of about 14 days, much of the time all crewmembers will be in the habitat and available for IVA tasks. As spending the night is a major design issue for systems (particularly power levels and energy storage), it would seem appropriate to plan to spend 45 days

on the surface to take advantage of two lunar days and one night, as was the plan in the First Lunar Outpost studies carried out in the early 1990s. In either case, significantly more effort must be put into the design of important scientific and technical experiments that can be carried out by the crew during the lunar nighttime in the immediate vicinity of the habitat or within it. This problem may be exacerbated for long-duration stays near the lunar poles.

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13. ABSTRACT *(Maximum 200 words)*

The goals and objectives of future lunar exploration are defined in terms of science, preparation for long-duration stays on the Moon, preparation for human exploration of Mars, exploring the possibility of economic uses of the Moon, and maintaining the health and performance of humans and machines on the Moon. These objectives can be met by carrying out a set of functional activities on the Moon such as scientific field investigations; sample collection and analysis; deployment of surface scientific instruments such as seismometers and telescopes; teleoperation of exploration and technology demonstration systems; intravehicular activity, maintenance and repair; and other activities. These are combined into a set of surface exploration mission options. Short-stay missions (e.g., 4 people for 4 days) that principally address scientific and technology verification are defined for three different types of sites, and long-stay missions (e.g., 4 people for 30 days), which can build up infrastructure for longer duration stays, are defined for two sites, including a south polar site. Representative timelines for crew surface activities are presented.

This document is considered to be a snapshot that will be revised as the nature of human lunar missions become better understood.

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