

**Advanced Extravehicular Activity
Systems Requirements Definition Study**

NAS9-17779

**PHASE II
EXTRAVEHICULAR ACTIVITY AT A LUNAR BASE**

Final Report

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FOREWORD

This report, Extravehicular Activity at a Lunar Base, is submitted under NASA Johnson Space Center contract NAS9-17779, Advanced Extravehicular Activity Systems Requirements Definition Study. This document addresses EVA requirements for remote operations from a lunar base.

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ACRONYMS AND ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ACTS	Advanced Communications Technology Satellite
ADS	Altitude Decompression Sickness
ADVEVA	Advanced Extravehicular Activity
AGC	Automatic Gain Control
AI	Articulation Index
AIAA	American Institute of Aeronautics and Astronautics
Al	Aluminum
AL	Anomalistically Large
ALARA	As Low As Reasonably Achievable
AM	Ambulance module
ANSI	American National Standards Institute
Ar	Argon
ARAMIS	Automation, Robotics, and Machine Intelligence System
ASAP	As Soon As Possible
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ATA	Atmospheres, Absolute
ATM	Apollo Telescope Mount
ATV	All-Terrain Vehicle
ax	X-Axis Acceleration
ay	Y-Axis Acceleration
az	Z-Axis Acceleration
BFO	Blood-Forming Organs
BHS	Body Heat Storage
BIB	Built-In Breathing
BIG	Biochemical Isolation Garments
BITE	Built-In Test Equipment
BTPS	Body Temperature and Pressure Saturated with Water
Btu	British Thermal Unit
C	Celsius
cal	Calorie
cc	Cubic Centimeters
CCITT	Consultative Committee for International Telegraph and Telephone
CCTV	Closed-Circuit Television
CD	Compact Disk
CERV	Crew Emergency Return Vehicle
CFU	Colony-Forming Units
cm	Centimeter, (also) Center of Mass
CNS	Central Nervous System
CO ₂	Carbon Dioxide
Comm	Communications
CRS	Cosmic Ray Source
CRT	Cathode Ray Tube
cSv	Centi-Sievert
CUM	Cumulative
C&W	Caution and Warning System
D	Absorbed Dose
DACT	Disposable Absorbent Containment Trunk
DARPA	Defense Advanced Research Projects Agency
dB	Decibels
DB	Dry Bulb Temperature
dB(A)	Decibels Using an "A" Weighing Filter Characteristic
dBm	Decibels Above 1 Milliwatt

DCS	Decompression Sickness
DE	Dose Equivalent
DEMUX	Demultiplexer
dia	Diameter
DIPS	Dynamic Isotope Power System
DoD	Department of Defense
DOF	Degrees of Freedom
e	Electron
E	Energy
ECG	Electrocardiograph
ECLSS	Environmental Control and Life Support System
ECS	Environmental Control System
ED10	10% of the Population Showing Physiological Response to Ionizing Radiation
EDK	Electric Dynamic Katathermometer
EEG	Electroencephalograph
EEU	Extravehicular Excursion Unit
EIRP	Effective Incident Radiated Power
EITP	Extravehicular Inflight Training Package
EKG	Electrocardiograph
EL	Exposure Limits
ELF	Extremely Low Frequency
EM	Electromagnetic
EMI	Electromagnetic Interference
EOMV	Enhanced Orbital Maneuvering Vehicle
EMU	Extravehicular Mobility Unit
E/R	Extender/Retractor
ESSA	Environmental Sciences Services Administration
ET	Effective Temperature
eV	Electron Volts
EV	Extravehicular
EVA	Extravehicular Activity
F	Fahrenheit
FDA	Food and Drug Administration
FDP	Fatigue Decreased Proficiency, (also) Flight Planning Document
Fe	Iron
FMEA	Failure Modes and Effects Analysis
FSS	Flight Support System
FSW	Feet of Seawater (33 FSW = 1 Atmosphere)
ft	Feet
g	Gravitational Acceleration
GC/MS	Gas Chromatograph/Mass Spectrometer
GCR	Galactic Cosmic Radiation
GEO	Geosynchronous Earth Orbit
GeV	Giga (billion) Electron Volts
GFK	Generic Fabrication Kit
GIAG	Government Industry Advisory Group
GT	Global Temperature
gx	Vibrational Acceleration in the Direction of the X-Axis
gy	Vibrational Acceleration in the Direction of the Y-axis
Gy	Gray (radiation dosage unit of measure)
gz	Vibrational Acceleration in the Direction of the Z-Axis
H	Hydrogen
He	Helium
Hg	Mercury
HMD	Helmet-Mounted Display
HPA	Holding and Positioning Aid
hr	Hour

HUD	Heads-Up Display
HUT	Hard Upper Torso
H ₂	Diatomic Hydrogen
Hz	Hertz (cycles per second)
HZE	Ultra-Heavy Nuclear Particles
Icl	Insulation Value of Clothing
IDB	In-Suit Drink Bag
IEEE	Institute of Electronics and Electrical Engineers
in.	Inch
INIRC	International Non-Ionizing Radiation Committee
IR	Infrared, (also) Ionizing radiation
IRPA	International Radiation Protection Association
ISO	International Standards Organization
ISSS	International Symbol/Signal System
ITMG	Integral Thermal/Micrometeoroid Garment
IV	Intravenous
IVA	Intravehicular Activity
JSC	Johnson Space Center
K	Kelvin
KA	(Band) 26.5 to 40.0 Gigahertz (one billion Hertz)
KB	Kilobit
kbps	Kilobits Per Second
kcal	Kilocalories
KeV	Kilo Electron Volts
kg	Kilogram
km	Kilometer
Kmh	Kilometers Per Hour
kPa	Kilo Pascal
Kr	Krypton
KU	(Band) 12.4 to 18.0 Gigahertz
kw	Kilowatts
KSC	Kennedy Space Center
Laser	Light Amplification by Stimulated Emission of Radiation
Lb	Pound
LBNP	Lower Body Negative Pressure
LCD	Liquid Crystal Display
LCG	Liquid Cooled Garment
LCVG	Liquid Cooling Ventilation Garment
LD50	Lethal Dose of Ionizing Radiation for 50% of the Population
LED	Light-Emitting Diode
LEM	Lunar Excursion Module
LEMU	Lunar Extravehicular Mobility Unit
LEO	Low Earth Orbit
Leq*	Equivalent Continuous Noise Level (4 db exchange rate)
LET	Linear Energy Transfer
LiOH	Lithium Hydroxide
LMISTC	Lunar Man-Inside-the-Can
LOS	Line of Sight
LP	Load Package
LRD	Litter Recovery Device
LRV	Lunar Roving Vehicle
LTA	Lower Torso Assembly
LURU	Lunar Replacement Unit
μ	Micron
m	Meter
MAKS	Medical Aid Kit/Station
Maser	Microwave Amplification by Stimulated Emission of Radiation
Max	Maximum

mb	Millibar
MDAC	McDonnell Douglas Astronautics Company
METS	Modular Equipment Transporter System
MeV	Mega Electron Volts
MFR	Manipulator Foot Restraint
mg	Milligram
Mi	Mile
MIL	Military
Min	Minimum, (also) Minute
MISTC	Man-Inside-the-Can
MHz	Megahertz
MLI	Multilayer Insulation
mm	Millimeter
mmHg	Millimeters of Mercury
MOLAB	Mobile Laboratory (Apollo era concept)
MOTV	Manned Orbital Transfer Unit
MPAC	Multipurpose Application Console
mph	Miles Per Hour
MSC	Manned Space Center (JSC)
MSFC	Marshall Space Flight Center
MSIS	Man/Systems Integration Standard
MTBF	Mean Time Between Failure
m μ	Millimicron
MUX	Multiplexer
mw	Milliwatts
MW	Microwaves
N ₂	Nitrogen
NASA	National Aeronautics and Space Administration
NAV	Navigation
Nc	Convective Heat Transfer Coefficient
NC	Noise Criteria (curve)
NCRP	National Council on Radiation Protection and Measurements
Ne	Neon
NIOSH	National Institute for Occupational Safety and Health
NIR	Non-Ionizing Radiation
nm	Nanometer, (also) Nautical Miles
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense
NTU	Nephelometric Turbidity Units
O ₂	Diatom Oxygen
O	Oxygen
OASPL	Overall Sound Pressure Level
OB	Octave Band
OBS	Operational Bioinstrumentation System
OMV	Orbital Maneuvering Vehicle
OR	(Event) Ordinary Proton
ORU	Orbital Replacement Unit
OSHA	Occupational Safety and Health Administration
OTC	Over-the-Counter
OTV	Orbital Transfer Vehicle
oz	Ounces
P	Proton
P _A	Partial Atmosphere
P4SR	Predicted 4-Hour Sweat Rate
PCM	Pulse Code Modulation
PEO	Polar Earth Orbit
PFR	Portable Foot Restraint
pH	Potential of Hydrogen

PLSS	Primary Life Support System, (also) Portable Life Support System
PNL	Panel
psi	Pounds of Static Pressure Per Square Inch
psia	Pounds of Absolute Pressure Per Square Inch
psig	Gauge Pressure
PSIL	Preferred Speech Interference Level
Pt/Co	Platinum/Cobalt
PTS	Permanent Threshold Shift
PTZ	Pan/Tilt/Zoom
Q	Quality Factor
QPSK	Quadrature Phase Shift Keying
qs	Body Heat Storage Index
r	Radius
Ra	Radium
RAB	Rigidizing Attachment Boom
rads	Radiation Dose Absorbed by Tissue
RBE	Relative Biological Effectiveness
Rcl	Total Heat Transfer Resistance
RDA	Recommended Dietary Allowance
R _e	Earth Radii
R _{EM}	Roentgen Equivalent Man
RF	Radio Frequency
RFI	Radio Frequency Interference
RFPG	Radio Frequency Protection Guide
rms	Root-Mean-Square
RMS	Remote Manipulator System
RTG	Radioisotope Thermoelectric Generator
SAA	South Atlantic Anomaly
SAE	Society of Automotive Engineers
SAFE	Solar Array Flight Experiment
SAT	Satellite
SAR	Scientific Absorption Rate
SBADPCM	Sub-Band Adaptive Differential Pulse Mode Modulation
SCR	Solar Cosmic Radiation
SD	Standard Deviation
SDMS	Standard Database Management System
sec	Second
SEP	Solar Energetic Particles
SIL	Speech Interference Level
SMF	Space Medical Facility
SNR	Signal-to-Noise Ratio
SPE	Solar Particle Event
SPF	Specific Pathogen Free
SPL	Sound Pressure Level
sq	Square
Sr	Strontium
SS	Space Station
SSA	Space Suit Assembly
SSEMU	Space Station Extravehicular Mobility Unit
Stbd	Starboard
STD	Standard
STL	Suppressor T Lymphocyte
STP	Standard Temperature and Pressure
STS	Space Transportation System
Sv	Sievert
sys	System
tb	Weighted Mean Body Temperature
TBD	To Be Determined

TBT	Total Body Temperature
tc	Core Temperature
TDMA	Time Division Multiple Access
TDRSS	Tracking and Data Relay Satellite System
THURIS	The Human Role in Space
TLV	Threshold Limit Value
TM	Telemetry
TMG	Thermal Micrometeoroid Garment
Tmrt	Mean Radiant Temperature
TOC	Total Organic Carbon
TON	Threshold Odor Number
torr	(A unit of pressure equal to) 1.316×10^{-3} atmosphere (Torricelli)
TPAD	Trunnion Pin Attachment Device
Tr	Skin Temperature
TTN	Threshold Taste Number
TTS	Temporary Threshold Shift
TTS2	Temporary Threshold Shift Measured 2 Minutes After Exposure
TV	Television
UCD	Urine Collection Device
USRA	Universities Space Research Association
UV	Ultraviolet
UVR	Ultraviolet Radiation
VCR	Video Cassette Recorder
VDT	Video Display Terminal
VOX	Voice-Operated Transmission
W	West
WASK	Work Area Safing Kit
WBT	Wet Bulb Temperature
WBG	Wet Bulb Globe Temperature
WD	Wet/Dry Index
WFI	Water for Injection
WS	Workstation
Xe	Xenon
Z	Ultra Heavy Nuclei
ZPS	Zero Prebreathe Suit

CONTRACT OVERVIEW

This document reports final progress in the second phase of a 24-month, three-phase study for the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC). The study focuses on extravehicular activity (EVA) systems requirements definition for three advanced space missions: in geosynchronous orbit (Phase I), at a lunar base (Phase II), and in Mars surface exploration (Phase III). The Phase I study was conducted from May 1987 through January 1988; the Phase II effort began in February 1988 and was completed in September 1988, after which the third phase will commence.

The technical team collaborating on this study comprises experts from Essex Corporation, Lovelace Scientific Resources, Incorporated, and CAMUS, Incorporated. Essex, represented by Nicholas Shields, Jr., and Dr. Valerie Neal, has primary responsibility for human factors, hardware design, and interface requirements, as well as production of the study documents. Lovelace, whose team led by Arthur Schulze includes Apollo astronaut Dr. Harrison Schmitt, is responsible for biomedical requirements and incorporation of lunar experience into the study. Skylab astronauts Dr. Gerald Carr and Dr. William Pogue, the CAMUS members of the study team, are responsible for crew systems requirements.

In our deliberations, we have been guided not only by the outline specified in the contract but also by our team members' first-hand experience on the moon, in low-Earth orbit, and on the ground in all aspects of the space program. Their insight has been both practical and imaginative. Proposed requirements have been discussed and analyzed by the entire team to ensure that all relevant perspectives are considered. We have put all suggestions to the test of experience in order to validate the systems design requirements presented in this study.

APPROACH TO DERIVING REQUIREMENTS TO SUPPORT EVA AT LUNAR BASE

At the outset of Phase II, the team received direction from JSC to focus our study on remote-from-main-base extravehicular activity on the moon. Considerable attention is already being given to lunar base construction scenarios with associated EVA to prepare the surface, erect the habitat, deploy the power system, and establish other necessary facilities. Our consensus was that it would be useful and instructive to assess remote EVA forays at some distance from the comforts and shelter of the main base. We have, therefore, assumed the existence of an established main base and have not concerned ourselves with construction-phase EVA scenarios.

Our team consulted with the JSC technical team for this study to select a set of candidate scenarios for our reference mission. We also jointly agreed to a set of assumptions that focused our options; for example, we assume an EVA suit pressure of 8.3 psi, lunar rover mobility rather than "flight," and a minimum base complement of four crewmembers. These initial assumptions are presented in Chapter 1.

Led by our astronaut team members, we then developed six remote EVA scenarios in considerable detail. These nominal and contingency scenarios are presented in Chapter 2. Input for the scenario development was derived from creative thinking by the team, reviewing the literature of lunar base studies, and assessing the statement of work in light of actual experience. The experience database we consulted includes Apollo and Skylab crew debriefing transcripts, Apollo lunar EVA videotapes, Apollo environmental and biomedical data, and our astronaut team members' own recollections.

In addition to these historical records, we also reviewed the advanced planning studies for future Space Station and lunar base operations to see where technology appears to be headed, what we can reasonably expect to be available, and what is probably beyond the scope of near-term EVA systems. At the request of the contract monitor, we have matched some of our assumptions to Space Station era technologies and considered how these may be adapted or superseded for lunar base EVA. Within our report, we identify such technology issues and present the rationale for solutions other than the Space Station's. Our study is compatible with NASA's current man-systems standards and EVA design guidelines.

Our technical approach blends pragmatism and imagination. We have looked at practical problems and concerns in each of the scenarios, and we have raised the relevant human factors, biomedical, and hardware design issues. In some cases, we suggest novel solutions rather than the usual ones to illuminate design tradeoffs. All of our discussion is set in the context of the unique lunar environment, a dusty, harshly lighted terrain sometimes subject to lethal radiation and other hazards — an inhospitable place where humans soon intend to set up industry and housekeeping.

1.0 Introduction

Men have walked and worked, eaten and slept, driven around and explored, felt elated and tired, joked and complained on the moon. Already, we have made it a temporary workplace and home, proving the feasibility of eventual lunar settlement.

In the late 1960's, in response to our nation's commitment to send a man to the moon and safely return him, 12 men pioneered the way. For various reasons, their missions did not lead to immediate settlement. Now, two decades after the Apollo program, we are making plans to return to the lunar surface, this time to stay. NASA's tentative plans for a lunar settlement call for the start of activities around the turn of the century and for establishment of the first operational settlement around the year 2010.

As we plan for the establishment of a self-sustaining base on the moon, we must look both to past experience and present technology to determine what resources the colonists will need to carry on day-to-day life there. In particular, we must look at their probable "outdoor" activities to determine what kinds of support technologies they will require.

This study examines the unique lunar environment, biomedical considerations, appropriate hardware design criteria, hardware and interface requirements, and key technical issues for advanced lunar extravehicular activity (EVA). The reference mission for this study is derived from six probable EVA scenarios — three nominal operations and three contingency situations that represent a spectrum of workloads from heavy duty manual labor to concentrated mental effort and a variety of environmental, technological, and biological emergencies.

This study does not address EVA during the establishment of the main base nor does it address routine proximity EVA. Rather, it focuses on remote EVAs — excursions to other worksites or scientific stations several kilometers away, forays that may preclude a quick walk or drive back home in the event of emergency. Just as the pioneers of the American West set up base camps and then set out on exploratory expeditions, just as camps are the hubs for remote mining and timber operations, just as scientists in the Antarctic go "out into the field" to conduct their research, so the lunar colonists will roam away from the main base to do their work.

Ranging far afield from the shelter and resources of the main base raises many technical and philosophical issues pertinent to the EVA systems design requirements for life support systems, transport vehicles, tools, crew health and well-being, communications, and protection. This study presents those issues, considers the relationship of human needs and hardware design, considers how humans and their technology will function in the lunar environment, and recommends further study of certain issues as planning progresses toward a return to the moon.

It is important to recognize, even at this early stage of analyzing advanced lunar EVA requirements, that the operational environment of such EVAs will be very different than that during the Apollo program. The routine nature of day to day, week to week activities at a nearly autonomous lunar base will inevitably lead to generalized plans for each EVA, consistent with the constraints imposed by safety and consumables. Some special activities will require detailed plans and timelines and others will incorporate standard timelines for normal complex tasks, but activities such as mining, drilling and sampling, and exploration will depend more on the experience and judgment of the EVA crew than on timelines and checklists. Thus, in general, we should set aside the Apollo concepts of minutely detailed and rehearsed timelines for each EVA.

To focus this study, the sponsors and authors agreed to make several assumptions about the lunar base and probable technology in use there. These assumptions were made not to bias the study toward any particular hardware design solutions but to narrow the field of variables to a manageable set. Table 1-1 reflects this consensus.

Table 1-1. Assumptions

TOPIC	ASSUMPTIONS
Locale	Existing main base; remote EVA required Main base and remote sites located on Earth-facing side Network of safe havens and/or shelters
Crew	Minimum complement: 4 Fully acclimated to 1/6-g EVA crew autonomy In contact with each other and main base
Suit	Advanced Space Station era model Nominal operating pressure: 8.3 Zero-prebreathe based on suit and habitat pressures Water-cooled garment 8 hour EVA duration
Mobility	On surface, by foot or rover; no flight
Technology	Some automated systems/subsystems Multi-use rover Mining machine independent of rover Explosives for excavation and seismic purposes

In the course of discussing these assumptions, we readily identified several areas for design requirement trade-off analysis. These trade-offs, listed in Table 1-2, are mentioned in the following scenario discussions and at appropriate places in the report.

Table 1-2. Trade-Offs

Suit:	Standard suit vs wardrobe of different suits Reconfigurable suit vs custom-fitted suits Hands-in capability vs no hands-in capability Hard vs soft Anthropomorphic vs "man-inside-the-can"
Vehicle:	Standard rover vs reconfigurable rover vs special purpose vehicles
Tools:	Manual vs power vs automation Vehicle-mounted vs stand-alone vs set-up systems
Sensors:	Radiation, biomedical, locator, environmental sensors Attached to body vs integral to suit vs attached to suit
Logistics:	Active vs passive
Shelters:	Portable vs stationary Structure vs vehicle vs excavated trench Safe haven vs logistics depot

Several environmental issues that cannot be ignored drive all considerations of lunar EVA system design requirements. These are listed in Table 1-3.

Table 1-3. Environmental Issues

Absence of atmosphere
Reduced gravity (1/6 Earth's)
Dust and soil
Boulder-strewn and cratered terrain
Radiation hazards
Range of mobility, navigation, & communication

2.0 Lunar EVA Mission Requirements Survey/Task Definition

2.1 LUNAR EVA TASK DEFINITION

EVA tasks near an operational lunar base encompass a range of activities that differ in some ways from those required to operate a remote base on Earth. The major differences are associated with a hard vacuum, extreme monthly temperature variations, solar radiation storms, ubiquitous permeating abrasive dust, total absence of water, and a highly reducing soil environment. These conditions dictate environmental control and life support systems, with suits configured to allow the successful completion of tasks with a productive workload and a high degree of safety.

The mission scenarios presented in section 2.2 describe lunar EVA tasks in considerable detail. Defined tasks reflect a blend of operational needs, human capabilities, and environmental constraints. The questions to be asked are, "What needs to be done?" "What do the crew need to do the job?" "Can the crew do each task?" and (if not) "Why can't they do it?"

At the EVA site, the crew engage in a variety of activities appropriate to the task at hand. Typical generic tasks are listed in Table 2-1; more detailed applications are presented in the timelines, Tables 2-2 through 2-7.

Table 2-1. Generic EVA Tasks

Activate, deactivate
Adjust
Assemble, disassemble
Calibrate
Check and confirm
Clean
Collect
Communicate
Connect and disconnect, electrical
Connect and disconnect, mechanical
Define
Display
Encode
Inspect (visual)
Label and encode
Load, unload
Manipulate
Monitor
Navigate
Observe and detect
Perform maintenance
Position
Set up
Stow, unstow
Test
Transfer
Traverse
Verify (visual)

2.2 LUNAR EVA REFERENCE MISSION SCENARIOS

Six EVA scenarios form the basis of the reference mission for this study. Three scenarios explore representative nominal operations, the everyday work of drilling and sampling, mining, and attending to science stations. Three other scenarios explore potential contingencies that cause the crew to interrupt their EVA work and take shelter or rescue action: solar flare, suit failure, and sickness.

These six scenarios were developed to demonstrate a spectrum of workload from heavy duty to light duty, a variable balance of manual and mental effort, and different types of environmental, technological, and biological emergencies. Other candidate scenarios were identified and discussed (agricultural operations, oxygen production plant operations, and vehicle breakdown) but were not specified in this report because many of the associated tasks are already included in the six chosen scenarios.

The **drilling/sampling scenario** represents the most repetitive physical effort and the most urgent physiological demands. The EVA crew are manually setting up large and small equipment, changing drill bits, stringing together drill stems, extracting and bagging soil and rock samples, transferring equipment and samples, and moving about on foot. These operations require good balance, both upper and lower body mobility, manual exertion and dexterity, and clear near vision and mental concentration for visual inspection, computer encoding of an automated drill, and decision making. A fairly flexible EVA suit and gloves are desirable to allow bending, reaching, handling, climbing, and maintenance of balance at each of the worksites and over uneven terrain.

The **mining scenario** imposes the greatest system workload but, because it is amenable to automation and mechanization, it represents a medium level of physical effort as the crew set up, activate, and supervise the system. The crew may orient and align and start the equipment, but the hard work is done by the machine. Less suit flexibility and mobility are required for this workload, but greater protection from the environment is necessary. At the mine site, dust contamination and flying debris are potential hazards. A protective shield may be desirable here to isolate the EVA crew from these hazards.

The **science scenario** generally represents the lightest physical effort, the most precise manual and mental activity, and the most demanding visual tasks. This workload includes inspection, observation, procedures verification, calibration, data collection, reporting, and rudimentary workbench activity for servicing, maintenance, or data analysis at solar and astronomical observatories, biological and materials science research sites, geoscience analysis stations, and seismic stations. The equipment handled is more fragile and the crew's actions more delicate than in the other work scenarios. A flexible suit and gloves permitting fine dexterity are extremely important to enhance the capability and efficiency of the crew.

The contingency scenarios explore conditions that put the EVA crew at risk. The most extreme case is a **solar flare emergency**. Depending on solar particle acceleration, the crew have less than 30 minutes (Bufkin, 1988) to 1 hour (McCormick, 1987) to reach or construct a safe haven that not only protects them from the onslaught of radiation but also sustains them for a minimum of 36 hours until the hazard abates. Responses to this environmental emergency require ready access to adequate shelter with sufficient breathing air, food, and water for the duration of their confinement, plus safety margins in case a rescue operation is required.

Suit failure may be either a recoverable contingency (slow leak) or a catastrophic emergency (rupture or shutdown). When the life support technology fails, the crew must restore suit integrity or move to shelter. Response to this technological emergency requires ready repair capability, auxiliary life support systems, and transportation. Should the suit depressurize, immediate access to a sustaining environment is critical.

Sickness on duty is worse than a nuisance when one is enclosed in an EVA suit and perhaps hours away from the base. Besides causing general discomfort and debility, nausea and

diarrhea are major waste management and contamination problems. Response to these biological emergencies requires a capacity for clean-up and treatment and access to transportation.

The following narratives briefly raise the critical issues and design requirements suggested by these reference mission scenarios. Detailed scenario timelines are presented in companion tables. Specific issues and requirements are discussed more thoroughly elsewhere in the report.

Scenario definition requires assumptions for the pressurization of the lunar base habitat, EVA suit, and work sites. It has been assumed that pressure regimes enabling zero pre-breathe EVAs will be maintained. Facilities such as a mine, however, may operate non-pressurized, or an agricultural site may operate at a different pressure and with a higher level of carbon dioxide mixture than the main base habitat. Other important considerations in specifying pressure and breathing air composition are physiology, oxygen toxicity, equipment cooling, and flammability. These issues are addressed in section 3.2.3, Suit Operational Pressure Level.

NASA's baseline EVA period is 8 hours, which includes donning and doffing the pressure suit and transit to and from a remote worksite. This "overhead" activity leaves only 4 to 6 hours of productive work time. Such a short EVA period for routine, remote operations at a lunar base may not be cost-effective.

Present planning for advanced EVA seems to be constrained by logistics rather than human performance considerations. Apollo experience indicates that a longer EVA work period is feasible. Therefore, for the purpose of this study, the scenarios assume that 8 hours are available for EVA work, that suit donning and doffing require an additional hour at each end of the EVA work period, and that suit cleaning, life support system recharge, and similar "overhead" tasks are not included in the EVA period. For increased crew productivity and effectiveness, these "housekeeping" functions might be performed by dedicated suit technicians at the lunar base rather than the EVA crew. Similarly, consumables for the "overhead" activities of travel and preparation could be supplied from the rover rather than the LEMU to preserve EVA provisions for use during the actual work period. The rationale for extended duration EVA to permit 8 hours of productive labor is presented in sections 2.4.3 (Lunar EVA Workday Length) and 2.4.4 (Lunar EVA Duration Optimization). The 8-hour work period timelines assume a less fatiguing suit than the Apollo EMU and include brief rest breaks as necessary.

Before departure, the EVA expedition party will have reviewed the plans for remote-from-base operations. Their training and familiarization were conducted within the base training facility, and equipment configuration and supplies were readied. The equipment for any remote expedition includes all of the provisions to support a specific mission objective, such as mining, as well as a complete set of equipment to support general mission activities and emergency situations. For transport of large equipment and supplies, it may be necessary to use a trailer or cart.

The EVA crew depart the main base with a fully equipped rover and supply carrier. At prescribed distances or time intervals, the crew set out communication beacons or antennas to establish a communications link with the main base. These markers also can be used as triangulation sources and as rescue aids if a rescue party must be dispatched. Periodic communications checks between the rover and the base verify the continuity of the communications link. Backup communication is direct to Earth with relay to base. Following a preplanned navigation route of the surface or previously installed markers, the EVA expedition proceeds to the first site of interest.

2.2.1 Drilling and Sampling Operations

At this site, samples will be taken to determine the feasibility of future mining operations. As the rover is guided into the area, considerable attention is focused on the exact location of the site to be drilled and the relative location of the rover. With the similarity of terrain, colors, and boulders, there is some probability of error in having a single system determine the precise location of the desired sampling site and getting the rover to just that location. Guided by orbital communications satellites, onboard locators, electronic maps, or main base direction, the crew should be able to verify the exact location of the rover with respect to the sample site, but they should not have to make that determination alone. Once the desired location has been verified, the tasks of drilling samples can begin.

With the rover at the correct site, the crew deactivate any power systems not required for the current operation while at the same time applying power to the drilling and sampling systems. This power switching leaves essential services on board the rover. Adjusting the external power sources and calibrating them is the responsibility of one crewmember, while the second (or other) begins unstowing the sampling equipment and systems. The small equipment and tools needed to support the sampling system are laid out on the rover workbench, and the larger equipment is set up at the drilling site. With precise location, the rover and the drill site should be right next to each other, making the rover a convenient work support center.

The EVA crew make the necessary connections to the mechanical and electrical subsystems of the drill, check that all interfaces are correct and secure, and perform a test. Any special equipment calibration, such as drilling speeds or depth gauges, is performed; when all subsystems have been verified, the crew activate the sample drill. For deep drilling, the rover should support the drill fixture, leaving the crew free to make adjustments to the equipment and saving them from expending great effort to stabilize and drive the sample drill into the lunar surface. For even shallow drilling, the sampler should be supported in a fixture that frees the crew from heavy manual labor.

During the drilling operation depicted in Figure 2-1, the crew monitor the drill status and progress, change drill bits as required, and add drill rods to the equipment if it is a deep bore. This involves extracting the drill from time to time for equipment changeout as well as for sample collection. The operations of drilling, extraction, and sample collection are automated and supported from the rover. The EVA crew encode the parameters to the drill computer to manage these functions.

During sample extraction, the crew manage the coding of the samples for future analyses, or they can take them to the onboard sample analyzer for on-site analysis. The requirement for on-site analysis is not certain unless there are specialized crews responsible for locating promising sites and other crews and mining system vehicles responsible for extracting the minerals. In this case, on-site analysis would allow rich sites to be marked immediately for future mining, saving the time required for samples return and analysis and reducing location error probabilities.

If samples are collected for later analysis, they are bagged, labeled, and stowed in a collector bag or bale. When the bale is full of labeled samples, it can be stored on the lunar surface for future pick up if the expedition plan calls for visiting several sites on the outbound leg; these bales would be collected later on the inbound leg of the expedition.

When the correct quantity of samples has been gathered from one drill hole, the crew command drill extraction; as the drill rods come up, the crew can disconnect them and stow them on the work bench. The bit is checked and replaced if necessary. A visual inspection of the equipment is performed before traversing and setting up for the next drilling at the site. The equipment is stowed by the crew if traverse to the second location is a significant distance.

Most of the mechanical and physical tasks are assigned to the rover systems and subsystems, to reduce crew fatigue, while the cognitive tasks and the fine manipulation and adjustments are left to the human crew. As always, contingency training must reflect the fact that if a mechanical support system fails to operate properly, then the EVA crew has to fix or take over the operations of the mechanical system. However, the EVA systems to support lunar operations should concentrate on enhancing the manipulative and visual capabilities of the crew to take full advantage of their strengths in these areas.

The sample collection and return scenario is based on experiences during the Apollo missions. We can rely on these experiences to plan clearly feasible activities. New opportunities, such as mining lunar material, offer us the chance to greatly expand on Apollo experiences. The probabilities of success for mining activities will have to be derived in part from our surface mining experiences on Earth.

Requirements derived from the drilling and sampling scenario include:

- ▶ Automation of repetitive tasks (e.g., drillings, assembly of drill rods and bits, sample analysis)
- ▶ Multiple location aids for precise navigation and site selection
- ▶ Rover-supported drill fixture
- ▶ Rover-mounted workbench
- ▶ Onboard sample analysis
- ▶ Portable (LEMU-mounted or tripod-mounted) remote control and display workstation
- ▶ Crew safety guards/protective barriers against dust and hazardous operations
- ▶ Extended-duration EVA.

Figure 2-1. Drilling and Sampling Operations

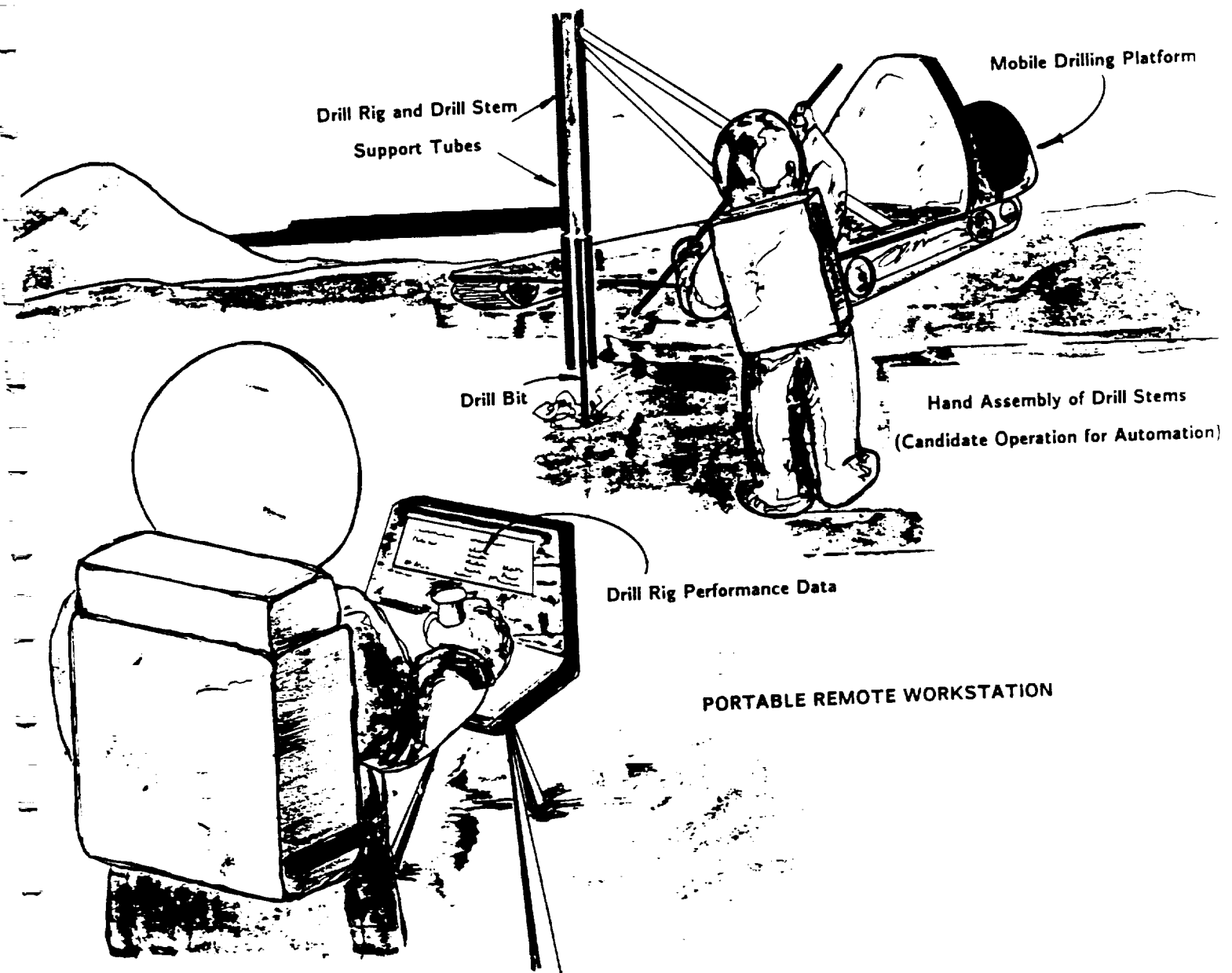


Table 2-2. Drilling and Sampling Operations

TIMELINE	TASKS
Hrs/Min	
-4:00	Support crew loads and configure rovers
-1:30	Define schedule for drilling and sample operations
-0:30	Don suit
0:00	Egress habitat
0:10	Check equipment required for drilling and sampling operations
0:20	Activate rover
	Disconnect rover from recharge power
	Activate rover power systems
	Test and adjust power systems
	Activate rover navigation systems
	Test and adjust navigation systems
	Activate rover communications systems
	Test and adjust communications systems
	Activate rover control systems
	Test and adjust control system
	Test and adjust drive system
	Initialize rover navigation systems
0:25	Position rover for drilling systems attachment
0:30	Secure drilling systems to rover
	Connect mechanical interfaces
	Connect electrical interfaces
	Verify integrity of drill
	Adjust bit components
	Adjust rod components
	Adjust rod joints
	Test and adjust gear box
	Adjust sample retrieval system
	Test and adjust drill motor
	Test and adjust drill mechanical components while in operation
	Test and adjust sample retrieval system while in operation
	Replace appropriate modules and components
1:00	Test and adjust sample analysis system
	Test and adjust interface between sample analysis system and sample retrieval system
	Adjust calibration of instruments
	Adjust ilmenite quantity measuring system
	Adjust total gas quantity measuring system
	Adjust particle size/frequency measuring system
	Test and adjust operation of preserved sample selector train
	Adjust selector system
	Adjust bagging system
	Adjust baler
	Replace appropriate modules and components
1:30	Transport loaded rover to drilling and sampling initial point
2:00	Adjust rover for automatic operations
	Position rover at initial point
	Encode drilling, sampling, and navigation parameters into rover computer
2:05	Initiate drill and sample operations
	Activate automatic drilling, sampling, and navigation mode
	Adjust automatic operation
2:10	Confirm drill and sample operations

- Adjust rover traverse line as required
 - Position rover if obstacles are encountered
 - Position drill as required
 - Position and re-initialize auto-mode if drill encounters large boulder
 - Adjust sample analysis calibrations
 - Encode map position of large boulders
 - Encode boulder fields and other obstacles to mining
 - Encode locations of sample bales
 - 5:35 Terminate rover drill and sample operations
 - Deactivate automatic drilling, sampling, and navigation mode
 - Confirm closure of automatic navigation system
 - Confirm calibration of sample analysis instruments
 - 5:45 Gather sample bales
 - Traverse to bale positions
 - Place bales onto rover cargo bed or trailer
 - 6:15 Transport loaded rover to base
 - 6:45 Terminate shift operations
 - Unload and store sample bales
 - Position rover at drill storage site
 - Disconnect drill from rover
 - Disconnect electrical interfaces
 - Disconnect mechanical interfaces
 - Clean and inspect drill and sampling components
 - Communicate information on drill status
 - Position rover at recharge site
 - Clean and inspect rover components
 - Inspect power systems
 - Clean and inspect drive systems
 - Inspect navigation systems
 - Clean and inspect control systems
 - Inspect communication systems
 - Communicate information in rover status
 - 7:25 Deactivate rover
 - Deactivate rover navigation systems
 - Deactivate rover control systems
 - Deactivate rover power systems
 - Connect rover to recharge power supply
 - 7:30 Store equipment, tapes, etc., at base as required
 - 7:40 Clean rover surfaces as required
 - 7:50 Ingress habitat
 - 8:00 Doff suit
 - 8:00+ Support crew performs suit and rover maintenance
-

2.2.2 Surface Mining Operations

Mining of critical energy and life sustaining resources will be essential for the long-term economic survival of the settlement. Although aluminum, magnesium, and chromium are abundant, it is the oxygen-containing and fusion-fuel-containing ores that will be most important. Proposals call for regolith to be mined for ilmenite to produce oxygen and for helium-3 to produce fusion fuel for export to Earth. By currently envisioned processes, reducing ilmenite to obtain oxygen will require a continuous hydrogen source that could be provided as a by-product of helium-3 production.

Mining the regolith for minerals for export from the moon or to support lunar base operations will require larger and more complex equipment than that involved in the drilling and sampling operations. Because mining is inherently dirty work and the mechanical stresses of extracting and transferring large quantities of mined material are great, the miner will have to be a major system rather than a component attached to, and operated from, the rover. The rover should not have to be designed to accommodate either the stresses or the dust protection from mining and still provide good service as a support platform and transport vehicle for crews. As shown in Figures 2-2 and 2-3, the miner should be an independent system, possibly incorporating some rover subsystems, that is brought to the site and activated or is assembled there and then activated.

The regolith miner has been installed at, or transported to, a site that earlier was geologically studied, sampled, and found to be relatively rich in the desired material. The EVA crew orient and position the miner before initiating the extraction of material. This involves verifying the location of the miner, moving it into final position, and stabilizing it using the miner's mobility. The crew perform checkout and verification of the miner's systems and subsystems, make any mechanical or electrical connections, encode the operating computer and, as in the case of drilling, perform the cognitive, visual, and manipulative tasks.

Since the miner is a major subsystem that is monitored by the EVA crew, it should be possible to use the mining platform as a utilities and consumables source for support of the EVA crew. This is in keeping with the philosophy of reducing the amount of equipment which the crew are required to carry around and relying more appropriately on the major systems for crew support. In this case, the crew would connect their LEMUs to the miner consumable stores, the electrical power source, the communications subsystem, and the gas and water supply. The crew could then move about the miner, attached to it by umbilicals, and perform all preparations and set-up activities without exhausting their portable life support and power supplies. The crew would disconnect from the supply either at the end of the shift or prior to the actual mining operations, depending on safety considerations and operating protocols.

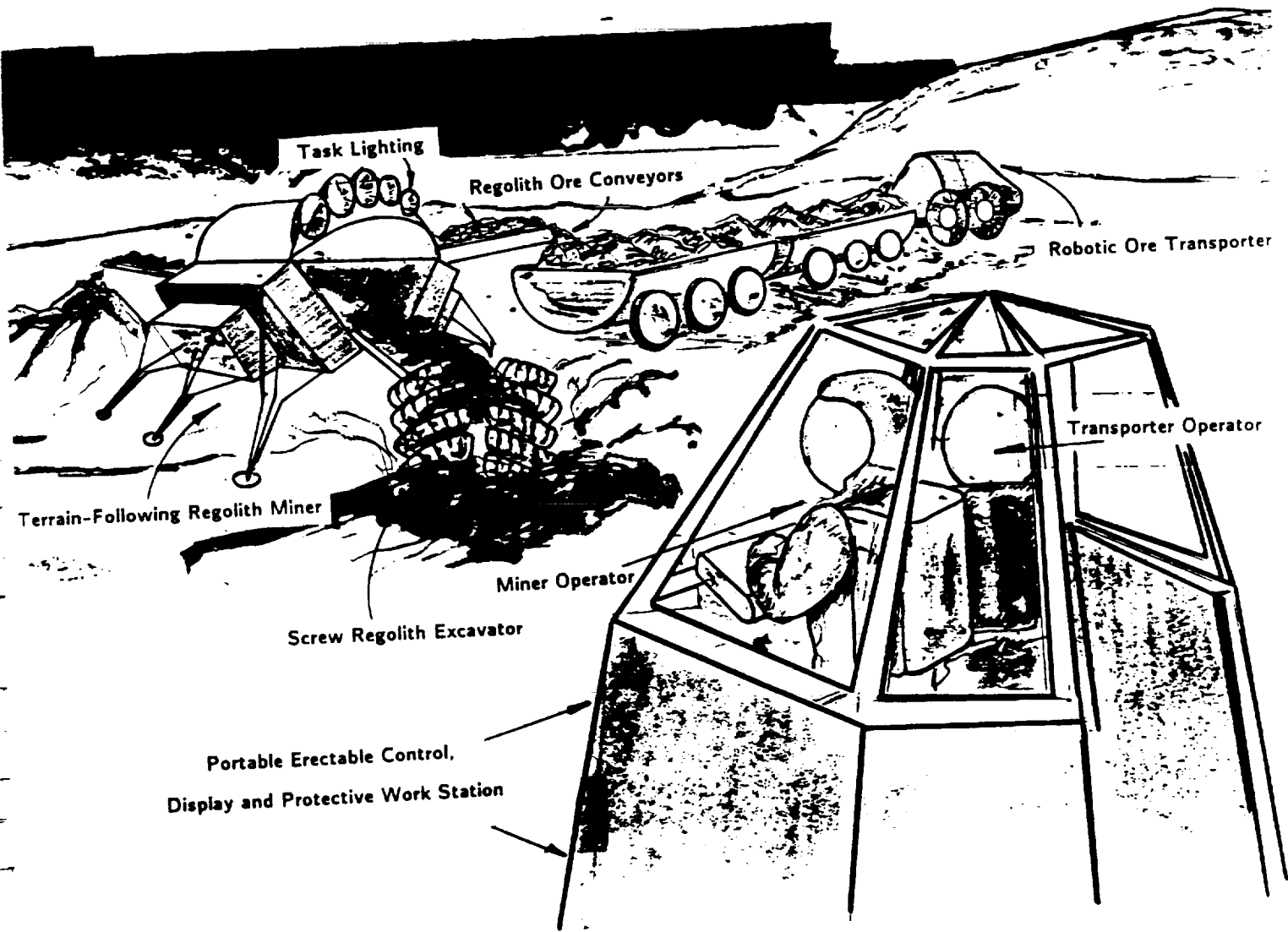
In order to move about the mining site and perform the operations, the EVA crew must have the advantages of mobility and flexibility afforded by a dexterous suit. However, this is not necessarily the most desirable type of protection for mining operations. As large amounts of material are moved in mining operations, there will be considerable dust in the immediate area. The disturbed regolith is a source of surface contamination for equipment and personnel in the vicinity. Small blocks and stones may be kicked up by the mining equipment, which in the reduced gravity could be propelled considerable distances. To protect sensitive equipment, personnel, and their life support equipment in and around the mining site, it will be necessary either to restrict access to the area during operations, develop a harder suit for protection against the dust and ejecta, or provide a protective enclosure from which crewmembers may observe or control operations. The protective enclosure, as shown in Figure 2-2, would not provide life support or a pressurized environment but would serve to isolate the crew from the local dust and debris produced during regolith mining. The cab of the rover or the miner might also provide this protection.

The majority of the physical work is assigned to the miner system, while the EVA crew are responsible for fine tuning the system and monitoring its progress. This division of labor corresponds to the relative advantages of humans and machines.

Requirements derived from the surface mining scenario include:

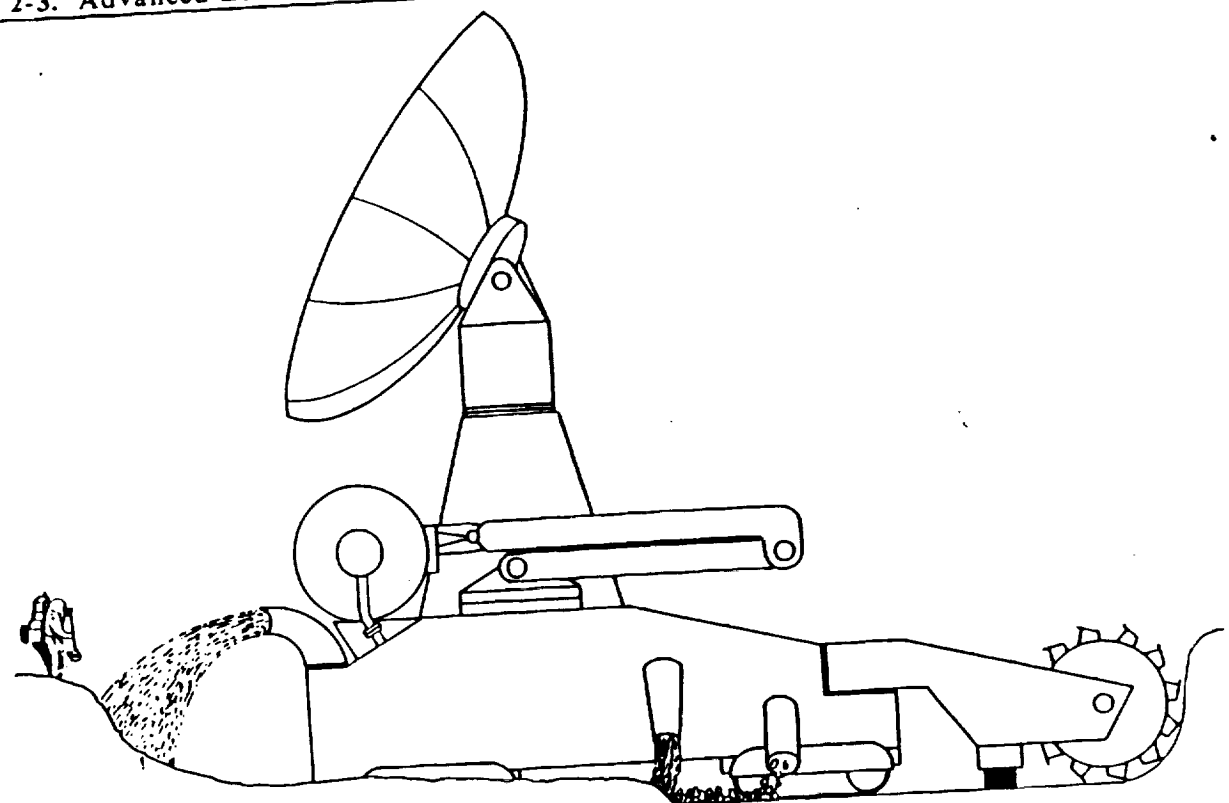
- ▶ Independent miner system
- ▶ Automated miner system
- ▶ Look-ahead radar
- ▶ Use of explosives for boulder removal
- ▶ Additional protective shielding against debris (supplied by rover, suit, or protective enclosure)
- ▶ Extended duration EVA.

Figure 2-2. Protective Enclosure for Surface Mining Operations



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Figure 2-3. Advanced Lunar Miner Concept (Sviatoslavsky, 1988)



SIDE VIEW OF LUNAR MINER MARK-II

TOP VIEW OF LUNAR MINER MARK-II

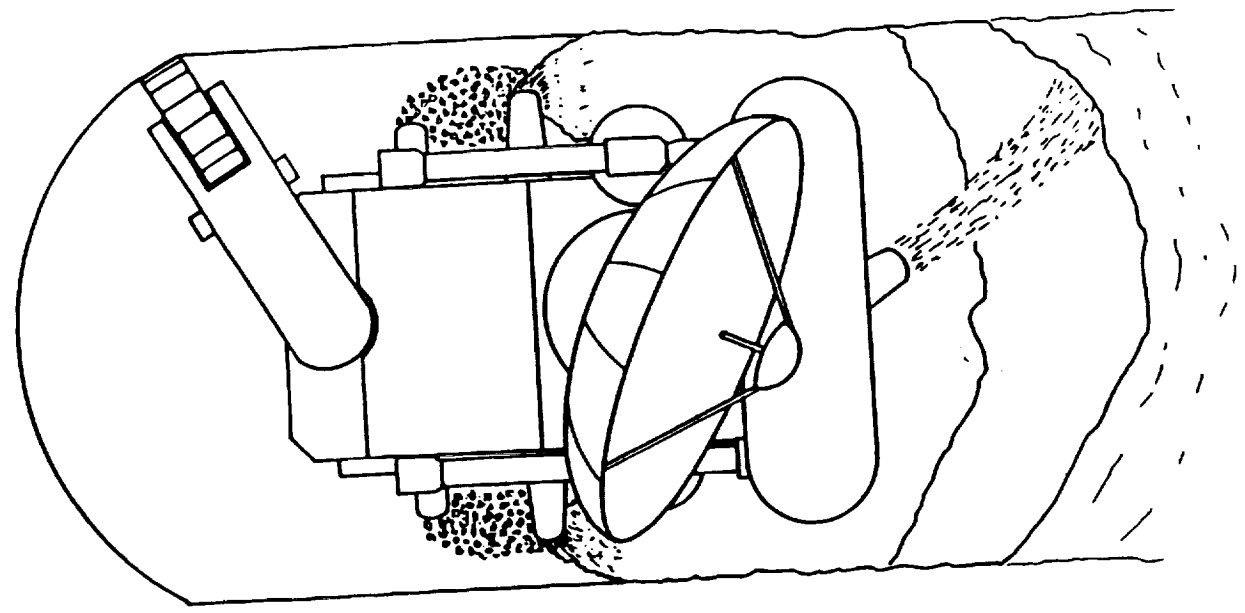


Table 2-3. Surface Mining Operations

TIMELINE	TASKS
Hrs/Min	
-4:00	Support crew loads and configure rover
-1:30	Define schedule for shift activity
-0:30	Don suit
0:00	Egress habitat
0:10	Check equipment required for shift activities
0:20	Activate rover
	Disconnect rover from recharge power
	Activate rover power system
	Activate rover communication systems
	Activate rover control systems
	Activate rover navigation system
	Initialize rover navigation system
0:25	Transport loaded rover to mining locations
0:55	Deactivate rover
1:00	Position equipment on regolith miner
1:05	Activate regolith miner start-up power system
	Activate regolith miner communications system
	Ingress regolith miner
	Test and adjust communication system
	Place communications in operational configuration
	Activate regolith miner control computer
	Test and adjust control computer
	Place control computer in operational program
	Activate system and system test and adjustment routine
	Activate regolith miner primary power systems
	Test and adjust power system
	Place primary power system in operational configuration
	Activate regolith miner drive system
	Test and adjust drive system
	Place drive system in operational configuration
	Activate regolith digging system
	Test and adjust regolith digging system
	Place digging system in operational configuration
	Activate look-ahead radar
	Test and adjust look-ahead radar
	Place look-ahead radar in operational configuration
	Activate concentrate off-loading system
	Test and adjust concentrate off-loading system
	Place concentrate off-loading system on stand-by
	Activate secondary concentrator
	Test and adjust secondary concentrator
	Place secondary concentrator in stand-by
	Activate primary concentrator
	Test and adjust primary concentrator
	Place primary concentrator in stand-by
	Activate coarse reject off-loading system
	Test and adjust coarse rejects off-loading system
	Place coarse rejects off-loading system in stand-by

- Activate grade analysis system
 - Test and adjust grade analysis system
 - Place grade analysis systems in stand-by
- Implement required maintenance procedures
- 1:35 Connect lunar extravehicular mobility unit (LEMU) to miner consumables
 - Connect LEMU communications system to miner communications system
 - Confirm communications
 - Connect electrical system to miner power supply
 - Connect LEMU gas system to miner gas supply
 - Connect LEMU water system to miner water supply
- 1:45 Position regolith digging system at mining face
- 1:50 Activate regolith miner
 - Observe systems come on-line in proper sequence
- Observe regolith miner systems performance
 - Detect changes in systems performance
 - Adjust system elements as required
- Observe performances of regolith digging systems at mining face
 - Detect changes in systems performance and regolith lithology
 - Adjust mining schedule as required
- Observe grade analysis system data
 - Detect adverse change in regolith grade
 - Adjust mining schedule as required
- Observe look-ahead radar data
 - Detect out-sized regolith boulders
 - Adjust mining schedules as required
 - Communicate information to base as required
- 2:00 Remove large boulders (see detailed timeline)

LARGE BOULDER REMOVAL

- 0:10 Configure rover for boulder removal
Attach large borehole drill bit, rods, and casing to rover
Attach and test acoustical profiling system
Stow boulder removal explosive system
Connect all power corrections
- 0:40 Transport loaded rover to detected location of boulder
- 1:10 Determine size and shape of boulder
Visually (or with drill) verify indication of boulder
Obtain and analyze acoustical profile
- 1:40 Plan removal procedures
Position shot holes for desired boulder trajectory
- 2:00 Drill and case shot hole(s)
- 2:30 Deploy boulder removal explosives
Gather explosives
Confirm initiator safety pins in place
Place explosive canisters in shot hole(s)
Pull safety pins on initiators
- 3:00 Transport rover to monitoring locations or protective enclosure
- 3:15 Detonate explosives
- 3:30 Transport rover to boulder location (former)
Verify removal successful
- 3:35 Transport rover to next boulder location or to base

- Communicate information on shift activity
Activate high data rate communications system
Compute data as required
Encode data as required
Transmit data
- 6:00 Communicate shift information to next shift
Compute shift data
Display shift data as required
Plot shift data as required
Define changes in mining schedule as required
- 6:25 Confirm shift change
Disconnect LEMU from miner consumables
Disconnect LEMU water system from miner water supply
Disconnect LEMU gas system from miner gas supply
Disconnect LEMU electrical system from miner power supply
Disconnect LEMU communications from miner communications
- 6:35 Confirm communications
Gather equipment, tapes, etc., for return to base
- 6:40 Egress regolith miner
- 6:45 Position equipment, tapes, etc., on rover
- 6:50 Activate rover
- 6:55 Transport loaded rover to base
- 7:25 Deactivate rover
Deactivate rover navigation system
Deactivate rover control system
Deactivate rover power system
Connect rover to recharge power supply
- 7:30 Store equipment, tapes, etc., at base as required

7:40 Clean rover surfaces as required
Clean rover thermal protection surfaces
Clean rover camera lens surfaces
7:50 Ingress habitat
8:00 Doff suit
8:00+ Support crew performs suit and rover maintenance

2.2.3 EVA Science Activities

If hand and arm fatigue are eliminated, the lightest physical workload is the setup, calibration, and operation of science packages and experiments for research in geology, astronomy, biology, and other disciplines. However, the workload for installation of observatories and large antennas is physically strenuous. The precision and dexterity requirements, along with the visual and mental tasks associated with scientific data collection, may well be more demanding than in any of the other scenarios. The use of visual aids for analysis, the use of small tools and the crewmembers' gloved hands for precise operations, and the exercise of precise control required for scientific operations will illuminate EVA requirements which might not be evident in other scenarios.

The EVA crew go through the training and review required of any remote operation, and the required scientific equipment and tools are loaded into/onto the rover. Special packaging and stowage may be required for some of the equipment. Various equipment packages are available for research in different disciplines. With the rover loaded and checked out, the expedition crew leave the main base and proceed to the first scientific station or location.

Again, as in the other scenarios, the rover is required to serve as more than a transport vehicle to support the mission. It must also serve as a source of consumables, a scientific workbench, a maintenance workstation, a data collection and storage point, and possibly a sample characterization laboratory for some missions.

The expedition follows the preplanned route to the first science station using distributed communication markers or lunar orbit communications and navigation satellites. The crew then verify the exact location of the science site and their position relative to the desired site.

For seismic investigations the crew perform a visual inspection of the equipment package, unstow and deploy the equipment, and transport it to the prescribed location. The active seismic explosive package is set up and activated, the locations noted, and with all of the packages in place the crew notify base that the first experiment has been readied. The requirement for crew safety means that the active seismic data collection takes place only when the crew are at a safe location. The charges are detonated by remote radio command having a finite temporal and physical window for activation. Crew safety is ensured by having the charges inactive before this window opens and after it closes. This precedent was set in the Apollo seismic experiments.

Having set up and activated the timers for active seismic experiments, the crew stow miscellaneous equipment and proceed to the next science station. There, they replace an existing deep regolith thermal and seismic sensor with an updated module. The EVA crew locate the site of the old sensor package, using careful visual inspection or the assistance of locator aids; they move the rover to this position and unstow the deep drilling rig used to bore the hole for the science package. This task requires manual assembly of bits and drill stems and places a considerable demand on the manual dexterity of the crew during assembly and feeding of the drill string.

These tasks have been accomplished on prior missions; however, if they remain in the category of manual tasks, mission planners will need to attend to finger, forearm, and hand fatigue that

develops within an hour. This fatigue arises from working against the pressure in the glove for all finger motion and from repeating operations. Because the assembly and insertion of drill stems requires repetitive manual alignment, screwing, and manual positioning of the string in the bore hole, these tasks are prime candidates for automation to reduce crew workload and the potential for finger, hand, and arm muscle cramps and fatigue. The crew could monitor and adjust the automated process of building drill stems while the physical work would be accomplished by machines.

The crew set up the drilling rig on the rover and encode the drill computer for rate of bore and depth. While the drill is operating, the crew monitor the progress and make adjustments as necessary. These activities require careful visual analysis and inspection on the part of the crew, and some local area lighting may be required, especially for night operations. At the appropriate depth, the drill is extracted, the crew install the science pack on the drill string, and they insert the package into the bore hole. The crew verify that the package is at the correct depth and release it in the bore hole, withdrawing the string and any science cables that may be required for calibration, equipment verification, or data collection. The crew verify the correct operation of the equipment package, make the necessary connections to the data recording and transmission devices to be left at the site, and then break down the drilling jigs and equipment.

When they repackage and stow the equipment on the rover, the crew communicate to the base that they have completed this task and are ready to proceed to the next site. The base will verify the remote crew's location and the route to the next site. The crew activate the onboard stereo cameras and the active navigation system and proceed to the next science site, where they perform maintenance and repair on scientific packages.

Upkeep and maintenance of science packages is necessary for the accurate collection of remote science data. For this reason, the rover is equipped with a workbench capability to permit the crew to conduct on-site repair, maintenance, and upgrade, at least to the lunar replacement unit (LURU) level, as depicted in Figures 2-4 and 2-5. The crew navigate to the science site, locate the package in need of repair, retrieve the science package, transfer it to the maintenance workstation, and activate the diagnostic and the repair and maintenance programs on the workbench computer. Following the program guide, the crew remove and replace old or failed components with new or updated ones using tools at the workbench.

These types of procedures require the greatest dexterity, precision and cleanliness; if the suit technology limits the degree of precision that can be exercised in the field or if the unit contains hazardous materials that prevent on-site repair, then it may be necessary to return the unit to the main base for refurbishment. As this will result in a loss of data between remote missions, it is desirable to accommodate repair at the LURU level "in the field." If the rover is large enough to support shirt-sleeve operations, the science package could be passed in through an airlock and repaired in this environment or in a glove box.

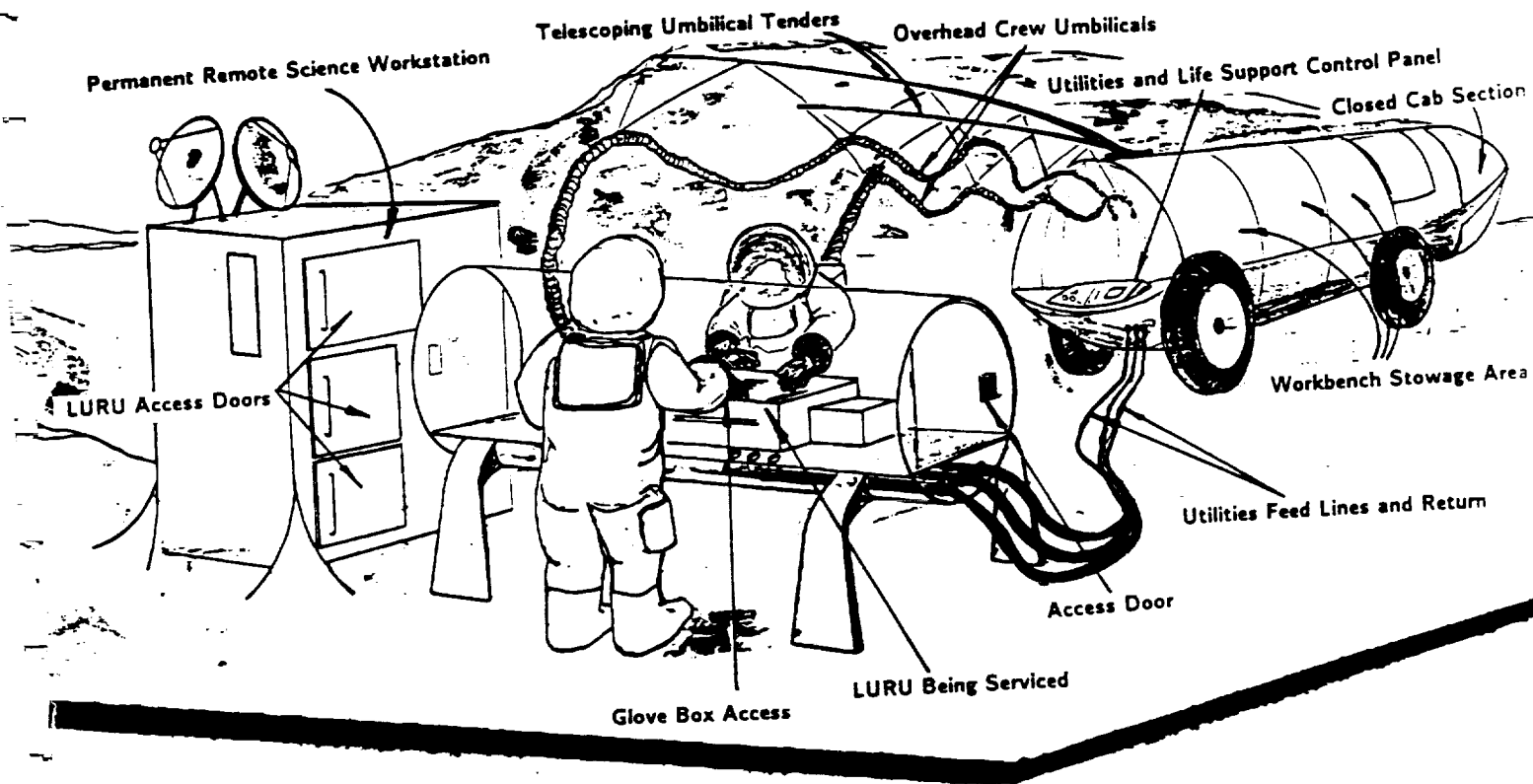
The issue of completely modular change-out in the natural environment versus LURU servicing at a glove box should be subject to analyses and trade studies. The glove box is a potential solution to the dust problem for servicing in the field. However, a crewmember would have to use the gloves in the glove box while wearing the LEMU gloves as well, and manipulative performance may be too restricted to perform servicing and repair in situ.

After replacing the failed LURU, the crew verify the correct operation of the unit and return it to service. The crew stow the maintenance and repair equipment and the maintenance workstation. Then they proceed to the next science station or return to the main base.

Requirements derived from the EVA science activities scenario include:

- ▶ Rover-mounted drill fixture
- ▶ Rover-mounted workbench
- ▶ Rover-mounted or portable glove box
- ▶ Use of explosives for seismic experiments
- ▶ Extended duration EVA.

Figure 2-4. Portable Glove Box and Servicing Workbench for Science Activities



PORTABLE MAINTENANCE AND SERVICING WORKBENCH
CLOSED CAB PRESSURIZED ROVER

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Figure 2-5. Rover-Mounted Mobile Work Station for Science Activities

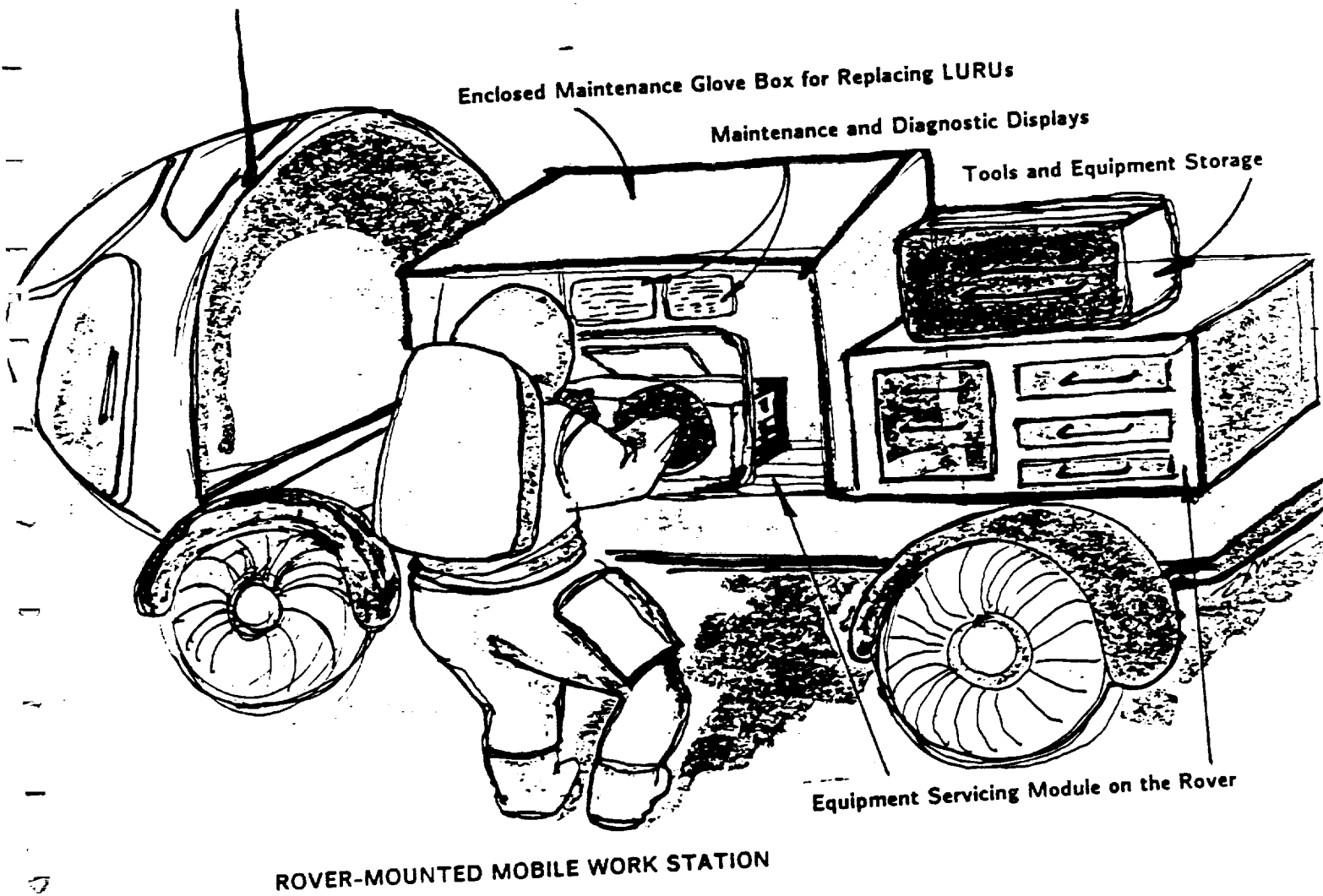


Table 2-4. EVA Science Activities

TIMELINE	TASKS
Hrs/Min	
-4:00	Support crew loads and configure rover
	Gather science station equipment from storage location at base
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Gather science station replacement modular from storage location
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Gather biological equipment from storage location
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Connect electrical interfaces as required
	Gather active seismic equipment from storage location
	Confirm safety pins in place
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Gather active gravimetry equipment from storage location
	Disconnect storage interfaces
	Transport to rover
	Connect to rover storage interfaces
	Connect electrical interfaces
	Activate and observe system self-test
	Adjust calibration as required
	Gather active radar equipment from storage location
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Connect cooling interfaces
	Connect electrical interfaces
	Activate and observe system self-test
	Adjust calibration as required
	Gather active regolith analyses equipment from storage location
	Disconnect storage interfaces
	Transport to rover
	Connect rover storage interfaces
	Connect electrical interfaces
	Activate and observe system self-test
	Adjust calibration as required
	Gather deep-drilling equipment from storage location
	Position rover for deep drilling system attachment
	Disconnect storage interfaces
	Connect rover storage interfaces
	Connect electrical interfaces
	Connect cooling interfaces
	Confirm proper system performances
-1:30	Define procedures and schedules for science operations
-0:30	Don suit
0:00	Egress habitat
0:10	Disconnect rover from recharge station

- Disconnect electrical interfaces
- Disconnect oxygen interfaces
- Disconnect water interfaces
- 0:15 Activate rover
 - Activate and adjust rover power system
 - Activate rover computer system
 - Activate and adjust rover communication system
 - Adjust rover control system
 - Activate and adjust rover drive system
 - Activate and adjust navigation system
 - Display rover computer self-test data
 - Display active EVA crewmember riding position
- 0:20 Drive rover to first science stop
 - Confirm initialization of navigation system
 - Activate stereo camera system
 - Verify active geophysical data recording
 - Operate rover along preplanned route
 - Correlate observation with active geophysical data
 - Inspect targets of opportunity as appropriate
 - Display active geophysical data as appropriate
 - Display active regolith analysis data as appropriate
 - Correlate active data sources with observations
- 1:30 Rover arrives at first science stop
 - Inspect science objectives
 - Deploy active seismic explosive package
- 2:00 Drive rover to second science stop
 - Confirm initialization of navigation system
 - Activate stereo camera system
 - Verify active geophysical data recording
 - Operate rover along preplanned route
 - Correlate observations with active geophysical data
 - Inspect targets of opportunity as appropriate
 - Display active geophysical data as appropriate
 - Display active regolith analysis data as appropriate
 - Correlate active data sources with observations
- 2:30 Rover arrives at second science stop
 - Inspect science objectives
 - Deploy active seismic explosives package
- 3:00 Drive rover to third science stop
 - Confirm initialization of navigation system
 - Activate stereo camera system
 - Verify active geophysical data recording
 - Operate rover along preplanned route
 - Correlate observations with active geophysical data
 - Inspect targets of opportunity as appropriate
 - Display active geophysical data as appropriate
 - Display active regolith analysis data as appropriate
 - Correlate active data sources with observations
- 3:30 Rover arrives at third science stop
 - Inspect science objectives
 - Deploy active seismic explosive package
- 4:00 Drive rover to science station
 - Confirm initialization of navigation system
 - Activate stereo camera system
 - Verify active geophysical data recording
 - Operate rover along preplanned route
 - Correlate observations with active geophysical data
 - Inspect targets of opportunity as appropriate

- Display active geophysical data as appropriate
 - Display active regolith analysis data as appropriate
 - Correlate active data sources with observations
 - 4:30 Rover arrives at science station
 - Position rover at deep-drilling site
 - Deactivate active gravimetry equipment
 - Deactivate active radar equipment
 - Deactivate active regolith analyzer
 - 4:35 Activate deep-drilling system
 - Test deep-drill protective system
 - Activate drill
 - Verify automatic drill stem feed
 - 4:45 Replace science station modules as required
 - 5:00 Adjust and align science station modules as required
 - 5:30 Deploy science station upgrade equipment
 - Deploy active seismic geophone array
 - 6:00 Terminate deep drilling system operations
 - Activate drill stem recovery system
 - Verify automatic storage of drill stem
 - Cap drill stem as required
 - Deactivate deep drill system
 - 6:40 Drive rover to base
 - Activate active gravimetry equipment
 - Activate active radar equipment
 - Activate active regolith analyzer
 - Confirm initialization of navigation system
 - Activate stereo camera system
 - Verify active geophysical data recording
 - Operate rover along preplanned route
 - Correlate observations with active geophysical data
 - Inspect targets of opportunity as appropriate
 - Display active geophysical data as appropriate
 - Display active regolith analysis data as appropriate
 - Correlate active data sources with observations
 - 7:10 Rover arrives at base
 - Position rover at deep-drill storage site
 - Replace deep-drilling system in storage station
 - Disconnect rover interface
 - Connect storage interface
 - Replace active regolith analyzer in storage location
 - Replace active radar equipment in storage location
 - Replace active gravimetry equipment in storage location
 - Replace geological equipment in storage location
 - Connect to rover recharge station
 - Deactivate rover
 - 7:50 Gather science samples and tapes
 - 8:00 Ingress habitat
 - Doff suit
 - Implement procedures for storage of science samples and tapes
 - 8:00+ Support crew performs suit and rover maintenance
-

2.2.4 Solar Flare Emergency

The absence of a protective atmosphere in the lunar environment leaves the surface of the moon exposed to the ambient solar and galactic radiation environment. The fiercest short-term environmental hazard for humans on the lunar surface is solar storm radiation. Left exposed to some intense solar storms, humans would receive a lethal dose several hours after such events occurred at the sun. The ability to predict solar storm events is not perfect, but the detection of X-ray bursts at the solar surface can be used as a warning aid to alert the EVA crew on the lunar surface of a potential solar storm. From the time of X-ray burst detection to the arrival of the highest density of heavy nuclei there is a one to two hour period, about half of which can be used to hurry back to the base, to reach an existing shelter, or to prepare and enter protective shelter.

The requirements for protection are clear, and the design solutions can take several forms: emergency return to base, supplemental shielding in the suit or rover, prepared safe havens, portable shelters, or in the case of this scenario, an emergency excavated trench shelter.

While the lunar EVA expedition crew are performing tasks away from the main base, they are notified that an X-ray burst has been detected. The alert may be issued from the lunar base, Earth, or the EVA crew's own radiation detection system. They are too far from the main base to execute an emergency return, and the nearest hardened shelter is at a mining site that is also too remote to assure a safe return. The crew terminate the current activities; after a review of potential sites in the vicinity (already identified in pre-planning), the crew transfer to a location that affords a field of large blocks and deep regolith.

The rover is maneuvered to a position near two of the larger blocks and the crew unstow an explosive trenching system from the rover. The system is checked to verify that all safety devices are in place and that initiator power to the charges is ready. The crew then deploy the trenching system between the two large boulders, orienting the charges to excavate a deep, narrow trench upon detonation. The safety pins are removed and the system is checked one final time by the crew. They drive the rover from the vicinity of the explosion site, seeking shelter behind other boulders or sufficiently far away to preclude being struck by ejecta, and remotely arm the trenching system. After final verification of the safety requirements, the crew remotely detonate the explosive trenching devices. The explosive control system accounts for the detonation of each charge. The crew then drive the rover back to the trench site, verify the system's performance, emplace trench support walls (if required), and maneuver the rover over the excavated trench.

In order to carry out the next measures, some design requirements must be postulated for the rover system. First, the rover equipment has been uniformly packed and distributed over the rover chassis, or during an emergency the equipment can be uniformly distributed to cover the top of the rover; similarly, the water supply is carried uniformly under the rover. Second, the rover has been designed with side curtains or side walls that can be deployed during an emergency. The side walls might form the undercarriage of the rover and be deployed in much the same manner as a storage box wherein the box flaps rest on one another and are extended one at a time to open the box. The side curtains might be a hardened fabric deployed from the side of the rover. The requirement is for five-sided protection (top, both sides, and both ends) afforded by the rover as it rests over the trench. The protection is not necessarily radiological; the deployed walls or curtains can be covered with loose lunar soil to provide the necessary material thickness to stop radiological penetration to the crew. The rover system protection then keeps the trench walls from falling in on the crew, while the piled up lunar soil actually provides the radiation protection. A soil piling tool or regolith blower machine would be a useful crew aid for this emergency.

The rover is positioned over the trench and the crew now deploy the side and end walls of the emergency shelter. Locking the walls together to form a secure "box" under the rover, the crew then cover the sides and one end of the box with lunar soil to a specified depth.

The boulders on either side of the rover also afford some protection; in areas where there are no large boulders the depth of loose soil piled around the rover would have to be greater.

The rover must serve as both a protective shelter and a consumables source during the solar flare emergency. With utility connections in the undercarriage of the rover, the crew have access to the life support and communications provisions installed on the rover. Otherwise, the crew must bring into the shelter emergency provisions such as communications, command and control computers, locator beacons, possibly a self-contained life support utility, lighting and similar subsystems that can be operated by an EVA-suited crewmember.

Before entering the trench shelter, as time permits, the crew perform a final inspection to verify the integrity of the soil back fill and the distribution of protection on top of the rover. They then deploy radiation monitors to measure the amount and duration of solar flare radiation, so they know when the emergency is over and what level of radiation exists both outside and inside the shelter. This will enable the crew to stand down from the emergency at the appropriate time and, in the event of radiation exposure inside the shelter, to take the necessary countermeasures. The crew then enter the shelter, pulling down the last side wall and securing it.

Once inside the shelter, depicted in Figure 2-6, the crew perform systems and subsystems checks of life support and communications, radiological monitors, and any command and control functions available to them from within the shelter. They remain in the shelter until they have determined that the storm is over or that the initial X-ray burst was a false alarm. The false alarm would be indicated within two hours of the initial burst and the subsequent absence of solar particle radiation. The storm would be confirmed by detection of radiation, and the crew would remain in the shelter until safe levels of radiation were indicated by their monitors a day or more later. Terrestrial experience suggests that during the storm the radiation might degrade communications with the main base or with Earth, so the monitoring system would have to be independently reliable. However, current opinions are that such a storm would not appreciably affect either point-to-point communications on the surface of the moon or between moon and Earth. Laser direct communications with the near side of Earth would not be affected.

The crew would be able to stand down from the emergency based on its own monitoring data, but the preferred approach would be to verify safe exit conditions with the main base. With such verification the crew could exit the shelter and stow the emergency provisions, clean and retract the side walls, and mount a return to base for medical evaluation and care if necessary.

Requirements derived from this solar flare emergency scenario include:

- ▶ Shelter in the field if crew cannot quickly return to base
- ▶ Solar flare alert/warning system
- ▶ Radiation sensors (on-suit and ambient) and dosimeters
- ▶ Use of explosives to excavate a trench
- ▶ Soil-moving tool to make protective banks of regolith against shelter
- ▶ Rover-supplied consumables (power, O₂, fluids)
- ▶ Uniformly packed rover, designed to serve as emergency shelter
- ▶ Extended duration EVA.

Figure 2-6. Emergency Shelter - Rover and Excavated Trench

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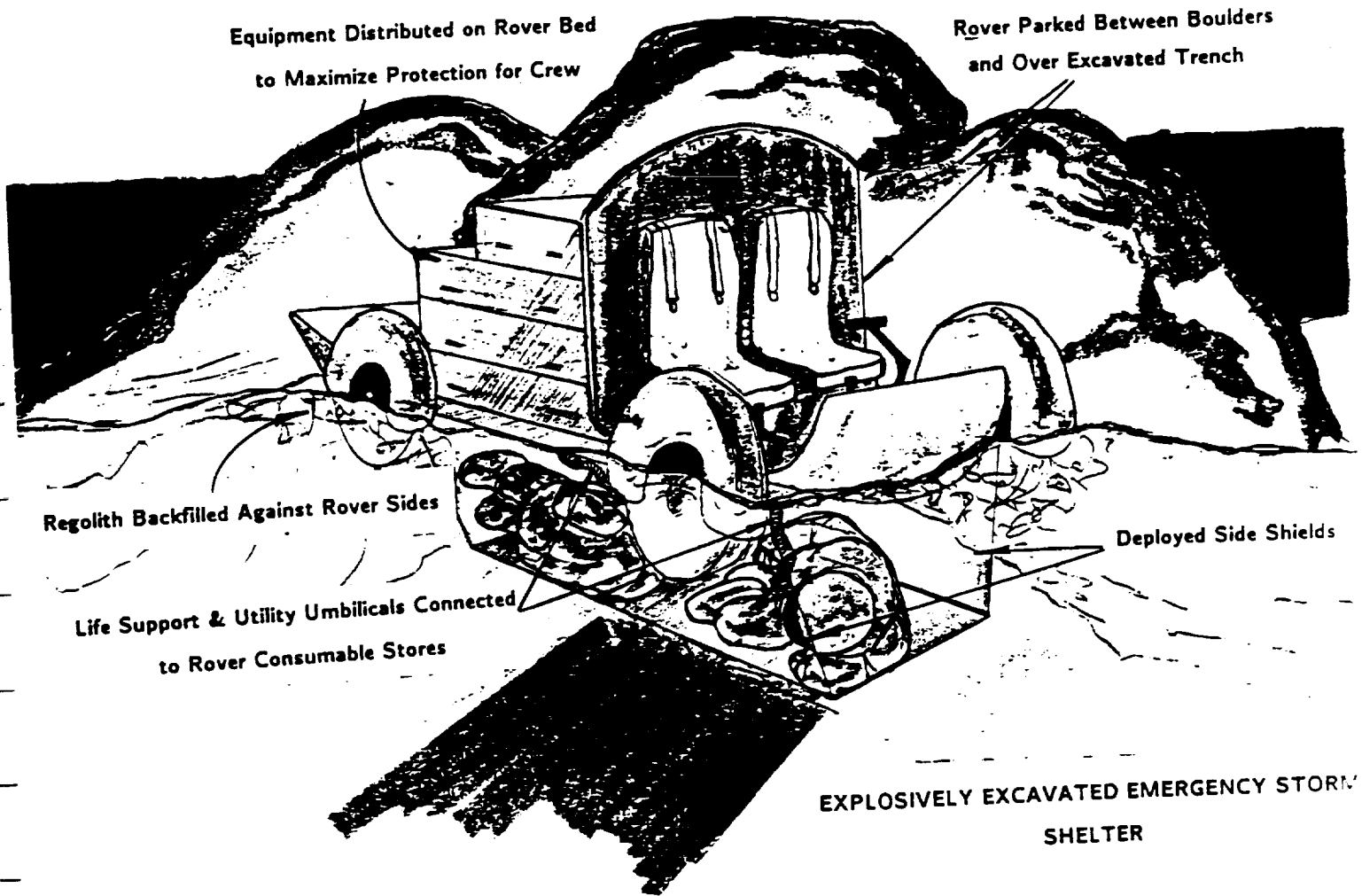


Table 2-5. Solar Flare Emergency

TIMELINE	TASKS
Hrs/Min	
0:00	Confirm solar flare detection
0:01	Terminate current operations
0:05	Select site for solar flare trench Priority for site selection: <ol style="list-style-type: none"> 1. Flat area between two large boulders 2. Flat area next to large boulder 3. Flat area in bottom of accessible crater 4. Flat area
0:10	Prepare trenching explosive system Remove explosive trenching system from rover Verify safety pins in place Verify initiator power
0:15	Deploy explosive trenching system Deploy explosive trenching system in desired orientation for trench Remove safety pins
0:20	Move to safety to monitor explosion
0:25	Detonate explosive trenching system Deploy protective shield as required Activate detonation signal system
0:30	Traverse to solar flare trench location
0:35	Verify solar flare trench is adequate Check width, depth, and wall stability
0:40	Modify solar flare trench as necessary Deploy reinforcing walls as required Backfill against reinforcing walls as required
0:45	Position rover over solar flare trench Drive rover into straddling position Deploy side and rear shields Gather regolith moving equipment Bank regolith against side and rear fenders as required Fill front shield with regolith
1:00	Ingress solar flare trench Deploy front shield Connect lunar extravehicular mobility unit (LEMU) systems to rover consumables Connect LEMU communications to rover communications system Connect LEMU electrical systems to rover power supply Connect LEMU gas systems to rover gas supply Connect LEMU water systems to rover water supply Monitor radiation levels Define post-emergency operations
36:00+	Confirm safe exterior radiation levels Disconnect LEMUs from rover consumables Disconnect LEMU water system from rover water supply Disconnect LEMU gas system from rover gas supply Disconnect LEMU electrical system from rover power supply Disconnect LEMU communications system from rover communications system Egress solar flare trench Retract front shield Egress trench Reposition rover off solar flare trench Clean and stow side and rear shields Empty regolith from front shield

2.2.5 Suit Failure Emergency

The crew goes to a region shown to be rich in minerals in order to survey the area for the installation of a mining and processing plant. Upon arrival, the two crewmembers unstow the surveying equipment and begin setup. While the first crewmember is adjusting the sighting devices, the second crewmember ventures out with the sighting stakes and a hammer to set them in the regolith.

The LEMUs worn by the crew are near the end of their service period, still within the operational range but subject to failure under extraordinary stress. While the crewmember is hammering one of the stakes, the right wrist joint on the LEMU is stressed; with additional pounding and turning of the joint, the seals fail and the LEMU begins to leak at the joint. The in-suit alarms for loss of pressure indicate to the crew that there is an emergency depressurization and that the rate is significant but not catastrophic. The suit emergency pressure system increases the flow rate of oxygen to the crewmember, while the communication network announces an alarm to the system.

The crewmember with the leaking wrist joint applies pressure to the joint with his left hand glove but is only partially successful in restricting the leak rate. The other crewmember retrieves the splint and patch kit stowed in the emergency provisions locker on the rover. He quickly joins his EVA partner and removes an external pressure patch kit from the emergency bag. As shown in Figure 2-7, the pressure cuff is placed over the damaged seal and inflated to a pressure greater than the internal pressure of the suit, thereby closing off the leaking wrist joint. With the suit leak stopped and the internal pressure returned to normal, the two crewmembers return to the rover and execute a quick return to base.

There are other ways to handle suit failure emergencies which are not of a catastrophic nature. With vacuum umbilical connectors it would be possible for two crewmembers to share a common life support system through a "buddy system"; the crewmember with the faulty LEMU plugs into his or her partner's LEMU through a life support connector and umbilical. Another approach is to envelop the crewmember with the faulty LEMU in a pressure bag inflated with an attached emergency canister and providing breathable air under pressure. Either of these approaches would mitigate a minor to moderate suit failure and allow time for contingency operations preparation. Each has its drawbacks, too. The buddy system does not in and of itself correct the failure, and the pressure bag makes mobility and translation either impossible or extremely difficult. The translation and transportation problem can be solved with the litter device, and the buddy system can be used in conjunction with a splint and pressure patch.

Requirements derived from this suit failure scenario may include:

- ▶ Rover consumables adapter kit for direct suit supply (may be different from recharge)
- ▶ Emergency Enclosure
- ▶ Ancillary Emergency Enclosure equipment/provisions
 - Trailer/rover bed (carrier for the Emergency Enclosure occupied by EVA crewmember)
 - Internal instrumentation and control (if required in addition to suit instrumentation/controls)
 - Adapters/cables/hoses to supply Emergency Enclosure from rover
 - Restraint system for Emergency Enclosure

- ▶ Buddy system capability (harness, hoses, portable stowage)
- ▶ Emergency suit failure patch/wrap/seal, devices ("finger in the dike" implementation)
- ▶ Rover capability
 - Single crewmember operation
 - Instrumentation to monitor Emergency Enclosure as well as rover consumables status
 - Capability to visually monitor Emergency Enclosure while driving the rover
 - Capability to recharge/replenish rover consumables from other rover (rover "Buddy System") or from shelter
- ▶ Safe haven huts or "igloos".

Figure 2-7. Suit Failure Emergency

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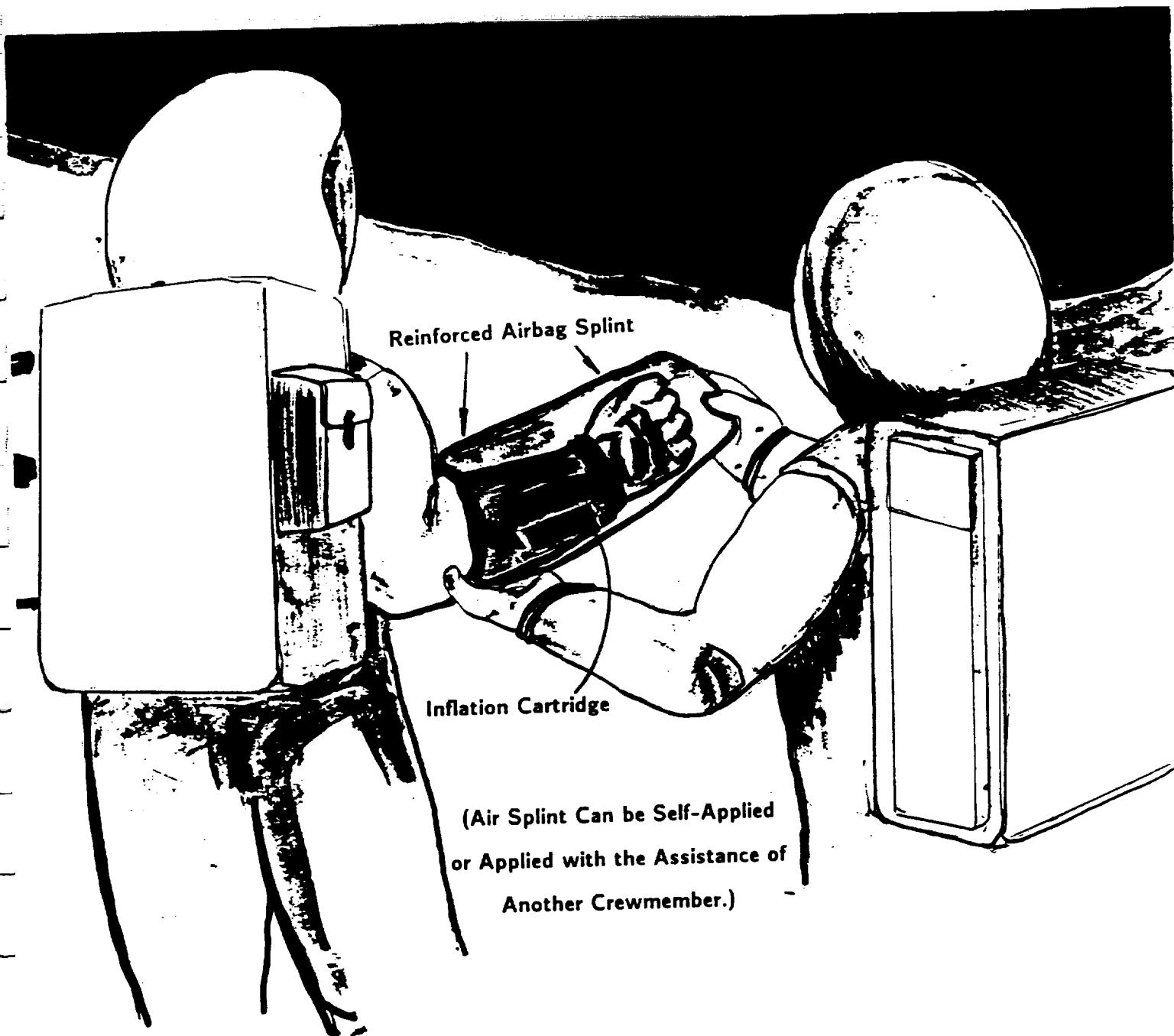


Table 2-6. Suit Failure Emergency

Note: EV-1 is crewmember with suit emergency. EV-2 is other crewmember. Suit configuration is assumed to be generally the same as the Shuttle suit; that is, an anthropomorphic LEMU and PLSS with a limited contingency oxygen source.

Detect/verify/report suit leak emergency:

- ▶ Caution and warning (C&W) system
- ▶ Overt physical cues
- ▶ Other
- ▶ Notify base of situation

Immediate action options:

- ▶ Reduce severity
 - Patch
 - Wrap
 - Seal
- ▶ Exploit additional resources to sustain pressure above redline
 - Buddy System (slow but progressive loss toward redline with possibility of reaching redline before getting to rover)
 - Rover: Move to rover (possibly using Buddy System en route) for better consumables support, refined diagnosis/troubleshooting, less urgency

Classify emergency to determine return mode:

- ▶ **Contingency Return** to base with EV-1 attached to rover consumables, if pressure stabilized is greater than 3.2 psi (or other acceptable level) and/or flow rate stabilized is less than emergency O₂ flow makeup by rover
- ▶ **Emergency Return** with EV-1 in Emergency Enclosure, if pressure stabilized is less than 3.2 psi (or other acceptable level) and/or flow rate stabilized is greater than emergency O₂ flow makeup by rover

Contingency Return to base (EV-1 normal passenger seating, connected to rover consumables supply):

- ▶ EV-1 and EV-2 move to rover as soon as possible (ASAP)
- ▶ Reconfigure from buddy setup to rover support of EV-1
- ▶ EV-2 verify EV-1 pressure and flow rate within guidelines
- ▶ EV-2 configure site operations to safe/secure contingency status (optional)
- ▶ Gather and restow equipment and tools for return to base (optional) on rover
- ▶ Configure/prepare rover for **Contingency Return** to base
- ▶ Notify base of status and intentions; request backup rover preparation and standby for dispatch to intercept/assist. Coordinate return route.

Contingency Return mode assumes that EV-1 is self-tended and unable to assist EV-2 during return trip. (EV-1 is a passive passenger.)

Emergency Return to base (EV-1 secured in Emergency Enclosure, with Emergency Enclosure connected to rover consumables and communication):

- ▶ EV-1 and EV-2 move to rover ASAP using Buddy System
- ▶ Reconfigure from buddy setup to rover support of EV-1; EV-1 attach to rover consumables; EV-2 assist EV-1 verify pressure and flow rates from rover in limits
- ▶ EV-2 unstow, deploy, attach/restrain, configure Emergency Enclosure for EV-1 transfer
- ▶ EV-2 assist EV-1 transfer from rover system to Emergency Enclosure and ingress, seating/restraint in Enclosure

- ▶ Verify satisfactory pressure and communication
- ▶ Notify base of status and intentions; request base dispatch backup rover to intercept/assist; coordinate with base on return mode
- ▶ EV-2 configure site operations to safe/secure contingency status (optional)
- ▶ Gather and restow tools and equipment for return to base (optional)
- ▶ Configure/prepare rover for Emergency Return to base
 - EV-1 in Emergency Enclosure, restraints secured
 - EV-2 starts Emergency Return
 - EV-2 monitoring EV-1 using visual assessment and communication reports from EV-1
 - EV-2 monitoring rover consumables trends from standard rover instruments
 - EV-2 (rover -1) and backup rover crew (rover -2) coordinate route and rendezvous for final stage of trip to base

Note: There is no mention here of a "safe haven" or intermediate station between worksite and base. In cases where worksites are a considerable distance (an hour or more) from the main base, the need may arise to construct way points or safe haven facilities where a stash of consumables, supplies, spare suit, etc., could be maintained and which could provide repair/refurbish facilities. In such cases, base would not dispatch rover -2 unless the situation dictated (need for additional consumables, spare suit, etc.)

2.2.6 Sickness Emergency

Radiation exposure, an allergic reaction, toxic contamination, or a bacterial infection that causes a systemic reaction may result in an EVA crewmember's becoming ill while in the LEMU, with episodes of diarrhea, vomiting, and fever. The ability to handle these emergencies must be built into the LEMU, but the contingency operations will involve significant limitations. The first limitation is that either an episode of vomiting or diarrhea must be dealt with without the use of the hands inside the suit, which means probable contamination from wastes expelled during an episode. The second limitation is that the equipment to accommodate this contingency must not interfere with the normal and usual tasks of the crew. The equipment must be out of the way until needed, and the need may be sudden and overwhelming.

During an episode of sudden sickness, all of the EVA and LEMU systems are required to function normally and some are required to function at an accelerated rate. The head to toe airflow should be increased to take solids, liquids, and noxious gases away from the head and face to filters or traps in the lower body area; lunar gravity will facilitate this process. The LCG should be able to compensate for an increase in body temperature due to infection. The neck ring on the LEMU should provide enough room for the crewmember to expel vomitus to the collection bag or other such device, or to expel it to the lower portion of the suit and not have it in the helmet area. Emergency purge air flow could then transport the waste away from the upper torso. To prevent cyclic response to vomitus in the suit, filters and airflow would have to keep the vomitus gases from recirculating to the crewmember's breathing air. The same would be true of bowel gases associated with diarrhea.

An episode of diarrhea could more easily be contained through the use of undergarments and absorbent pads or an Apollo-type fecal containment system, but it would be no less frustrating. The physiological response to acute episodes is generally overriding, with all of the individual's attention focused on the bodily problems, which gives rise to the requirement that another crewmember come to the assistance of the ill crewmember as soon as possible to aid him or her in getting back to the rover and returning to the base. This assistance is required to prevent the sickness episode from being compounded while the crewmember's attention and concentration are focused on the acute aspects of the illness. It is assumed that neither an episode of diarrhea nor vomiting in itself constitutes a life threatening condition as long as the equipment performs as required; that is, purge air flow, coolant, and evacuation of solids

to the lower portion of the suit all function effectively. Release of a deodorant into the suit air flow also should be considered.

Once the ill crewmember has been aided by the other crewmember and placed on the rover, the expedition can make a return to base or a nearby safe haven for cleanup and medical care. The rover should be supplied with a first aid kit containing fresh medications/injections.

If a crewmember is in dire need of medical treatment, an additional provision could be a portable pressurized litter compartment or ambulance module (AM). The ambulance could be dispatched by base upon notification of emergency return mode to intercept the rover en route to base. The ambulance module should accommodate two crewmembers and have sufficient space to unsuit the ill/injured crewmember for emergency treatment. In the unlikely event that two crewmembers are ill or injured and the ambulance is dispatched to rescue both, the ambulance would have to accommodate three people. Such a capability becomes more important as the population of the lunar base increases.

Requirements derived from the sickness scenario include:

- ▶ Non-intrusive biomedical monitoring devices that can be worn by crewmembers performing physically demanding work
- ▶ Medical aid kit/station (MAKS), including interfaces to suit and rover communication system to allow biomedical sensing (suit interface), display of biomedical parameters (MAKS panel and rover driver's panel), and transmission to base
- ▶ Telemetry of biomedical data to base
- ▶ Litter recovery device (LRD) operable by one crewmember with or without mechanical aid
- ▶ Rover winch and cables for mechanical assist transfer of LRD
- ▶ LRD restraint system in the rover or rover trailer
- ▶ Non-voice emergency communication system (NECS) to allow an ill/injured crewmember to communicate via hand signals, keyboard, etc.
- ▶ Rover-ambulance module
- ▶ Contaminant-sensitive patches worn on the suit exterior to aid in diagnosis and to prevent contamination of the ambulance
- ▶ Enhanced capability of LEMU to tolerate and neutralize the adverse effects of external toxic contaminants and internal biological contaminants
- ▶ Biochemical isolation garment (BIG) to allow a crewmember to provide medical treatment without exposure to an ill/injured crewmember who may be contaminated. The BIG should be a dedicated piece of equipment for medical treatment stations and for the ambulance module.

Table 2-7. Sickness Emergency

Confirm sick-in-suit detection
Activate caution and warning (C&W) system
Travel to ill/injured crewmember
Administer immediate treatment as required
Assess severity of illness/injury

1. Crewmember can walk, talk, and perform simple tasks

Escort crewmember to rover or drive rover to crewmember (judgment by assisting crewmember)
Access rover medical aid kit/station (MAKS)
Perform additional diagnosis
Provide additional treatment
Coordinate activities with base
Configure suit for contingency return
Clean up as practicable
(Release in-suit odor absorbents)
Verify life support systems operation
Aid crewmember ingress to rover
Configure site operations to secure contingency return to base
Gather equipment
Prepare rover for contingency return to base
Notify base of status

2. Crewmember can walk, but cannot talk or perform simple tasks

Confirm crewmember capable of self-tending during travel to rover and return to base
Escort crewmember to rover or drive rover to crewmember (judgment by assisting crewmember)
Access rover MAKS
Perform additional diagnosis
Provide additional treatment
Coordinate activities with base
Configure suit for contingency return
Clean up as practicable
(Release in-suit odor absorbents)
Verify life support systems operation
Aid crewmember ingress to rover
Configure site operations to secure contingency return to base
Gather equipment
Prepare rover for contingency return to base
Notify base of status
Establish method of monitoring crewmember during return to base
Monitor rover medical status displays
Use base-monitoring of status if medical telemetry is available

3. Crewmember is unconscious

Notify base of prep for emergency return
Request dispatch of rover with ambulance module (AM)
Walk back to rover
Drive rover to crewmember
Deploy one-man litter recovery device (LRD)
Secure crewmember to LRD
Execute manual or mechanical assist transfer of crewmember to rover bed or trailer
Secure crewmember in LRD transport restraints
Configure rover for emergency return to base
Notify base of status
Coordinate return route and rendezvous point with AM

2.3 UNIQUE LUNAR ENVIRONMENTAL CONSIDERATIONS

The human need for life support in an alien environment is the principal driver of EVA systems requirements. However, the design of EVA systems is influenced principally by characteristics of the environment in which they must operate. The environment of the moon presents several critical issues for lunar EVA. These critical issues guide our thinking as we develop requirements to support advanced EVA on the lunar surface. They are the guard rails that we bump as we consider design criteria and requirements.

Having been to the moon and worked there, we already understand how to adapt EVA technology (suits, rovers, tools, etc.) to this unique environment. Table 2-8 is a brief review of the characteristics of the lunar environment; Table 2-9 summarizes the lunar radiation environment. Table 2-10 presents some significant considerations for lunar EVA. Further information on the lunar environment appears in sections 3.2.15, Radiation Tolerance, and 3.2.17, Sand, Dust, and Surface Terrain.

Table 2-8. General Physical Characteristics of the Moon

Mean distance from Earth:	384,405 km 238,858 statute miles 207,562 nautical miles 60.3 Earth radii
Lunar diameter:	3476 km 2160 statute miles 1877 nautical miles
Orbital velocity:	1.03 km/sec. 0.64 miles/sec. 2001 knots
Escape velocity:	2.38 km/sec. 1.48 miles/sec. 4627 knots
Surface circular satellite period:	-2 hours
Gravity: equator)	0.165 g (1.62 m/s ² at lunar
Atmosphere:	nil
Surface gas density:	2×10^5 molecules/cm ³
Surface terrain: (maria)	Slopes from 0-10 degrees and 0-23 degrees (highlands)
Surface temperature:	102 °K to 407 °K -171 °C to 134 °C -276 °F to 273 °F

2.3.1 Absence of an Atmosphere

The moon is void of any substantial atmosphere, but surface molecules of gas have been measured at densities of 2×10^5 molecules/cm³ (10^{-12} Torr). This value could increase modestly with major activities on the surface and subsurface mining in support of lunar base operations.

Besides driving the requirement to provide breathing air and air pressure to the EVA crew, the lack of an atmosphere on the lunar surface also affects the visual perceptions of the crew. There is no attenuation and scattering of sunlight as it arrives from the sun. Solar illumination at the moon is approximately 10,000 foot candles, and the mean albedo is about .07. Consequently, there are sharp gradients in lighting on the lunar surface, with bright light in one spot but adjacent dark shadows, as shown in Figures 2-8 and 2-9. However, solar illumination falling on the lunar surface is backscattered into shadowed areas, so it is possible for the crew to see and work there. Actual contrast is not as crisp as the photograph (Figure 2-8) implies.

At close quarters, this chiaroscuro can affect task lighting; at longer ranges, it masks surface terrain features and compromises the crew's ability to judge the size, depth, and distance of craters. The textural gradient component of our learned distance estimation is affected, and distances are estimated with error due to the lack of feature softening with increasing distance. This is especially true for new crews working on the lunar surface. Visual research suggests that after two or three days of experience in the new visual environment, humans will accommodate to the new visual cues, provided they have sufficient opportunity to learn distance estimation in the stark environment. Artificial lighting, even in full sun situations, may be required in order to provide the crew with full visual apprehension and comprehension of the environment. While the Apollo films show the crew benefiting from reflections of sunlight off their suits and the down-sun lunar surface to illuminate shadowed areas (see Figure 4-3), an active illuminator that does not depend on the sun angle and crew position is a more predictable approach, particularly for lunar night.

The lack of atmosphere means that there is no natural help in cleaning surfaces of lunar dust contamination. One possible remedy is to use some form of canned air to blow surfaces clean, provided this technique does not abrade those surfaces.

The absence of an atmosphere also means that there is no overhead protection from space radiation and no atmospheric friction to slow or burn up micrometeoroids. Consequently, precautions must be taken against exposure to these hazards.

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Figure 2-8. Sharp Light/Dark Contrast (NASA AS16-106-17413)

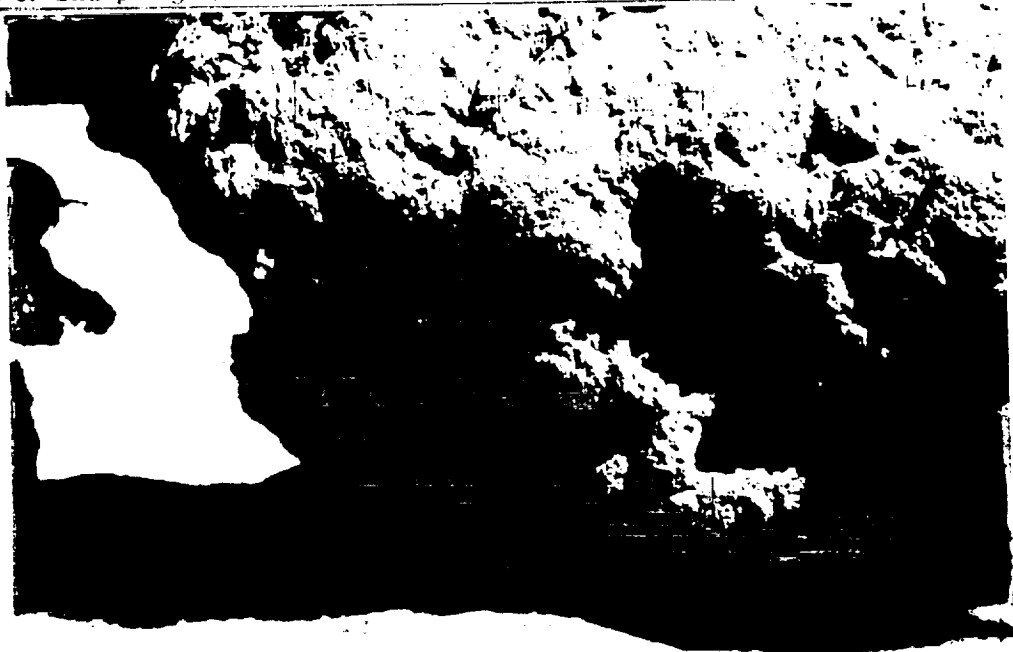


Figure 2-9. Surface Features Obscured by Shadow (NASA AS11-40-5954)



2.3.2 Reduced Gravity

The lunar gravity is about 1/6 that of Earth (0.165 g), or 1.62 m/s^2 gravitational acceleration at the lunar equator as compared to 9.78 m/s^2 at the Earth's equator (Bufkin, 1988). This low-gravity environment produces a kinesthetic and proprioceptive perception of up and down; it causes things to "fall down" but at rates different than on Earth. Nonetheless, in the design of lunar equipment, the center of gravity must be considered, especially in equipment worn by the EVA crewmember.

The one-sixth gravity on the moon provides humans with a visceral sense of up and down and can be used to keep tools and equipment in place, unlike the floating environment of microgravity, but it also permits humans to fall down in the regolith should they lose their balance. It permits humans to handle larger masses with ease and reduces the energy required to move these masses. It enables humans to leap and stride, but it also permits soil to be kicked in long trajectories above the surface. Human sensitivity to radiation may be affected by the reduced gravity environment. We should take advantage of this environmental feature in our designs for equipment and procedures to support long term lunar activity, just as we design to take advantage of microgravity in orbit.

2.3.3 Dust and Soil

The lunar regolith is mostly composed of extremely fine debris. (See section 3.2.17 for detailed properties.) This dust penetrates very small openings, clings to equipment, and loses its natural bearing strength and cohesiveness along routes and paths with repetitive traffic. Dust is an omnipresent fact of life on the moon; it is the most serious environmental problem for routine operations.

The dust and soil must be kept from the living spaces and shirt-sleeve environment of the main base and remote stations. It must be kept out of joints and off fabric, out of tools, and off radiators. Where it cannot be eliminated, it must be controlled; and where it can be used to benefit humans, it should be used, as a source of oxygen and other gases and as radiation protection piled up over shelters.

Dust carried into living spaces soon settles to the floor or is trapped in filters and represents only a temporary respiratory irritant. Nonsmokers are little affected by dust in terrestrial environments due to natural respiratory clearing processes. Unprotected bearings and other parts moving in contact, however, soon lose their functional characteristics.

The issue of how to control and compensate for the soil must be the subject of a thorough series of investigations. Can it be precipitated electrostatically? Can it be washed by water or other fluid? Can it be vibrated, blown, or brushed off effectively? Can it be isolated by the use of protective covers and garments? Can we derive design solutions from our clean room experience and use slight positive pressure, forced air circulation, grid floors and the like? What are the cumulative consequences of living and working in the regolith?

2.3.4 Terrain

The lunar surface terrain is divided into two characteristic regions: the smooth maria that account for about 17% of the surface, and the highlands that make up the remaining 83% of the surface. In the maria regions, the slopes are from 0 to 10 angular degrees with a standard deviation (SD) of 3.7 degrees; in the highlands, the terrain slopes from 0 to 23 degrees with a SD of 4.5-6 degrees and higher. Sloped, crater-pocked, and boulder-strewn terrains are shown in Apollo photographs (Figures 2-10, 2-11, and 2-12, respectively).

The ridges, craters, slopes, blocks, and regolith present some design constraints for equipment and life support systems. During the Apollo missions, the limited mobility afforded by the EMU ankle design posed problems in negotiating the crater rims and slopes found on the moon. However, crews worked for an hour or more on slopes up to 20 degrees. The absence

Figure 2-10. Sloped Lunar Terrain (NASA AS15-90-12187)

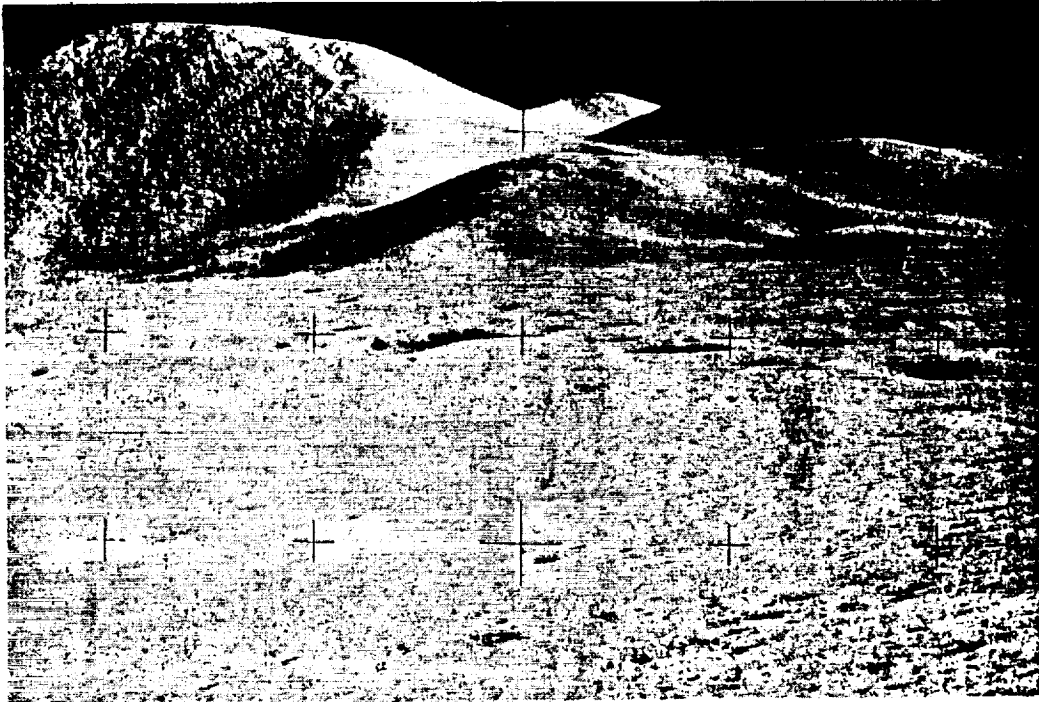


Figure 2-11. Crater-Pocked Lunar Terrain (NASA AS15-87-11748)



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Figure 2-12. Boulder-Strewn Lunar Terrain (AS14-64-9103)



of a light diffusing atmosphere made the identification of subsurface craters very difficult in the down-sun direction. The large blocks pose problems for some line-of-sight communications, such as visual and microwave, while the smaller blocks pose problems for lunar surface vehicles and ambulatory EVA crewmembers. These are not insurmountable problems, and our equipment for the long duration exploration of the moon must account for these features of the terrain.

2.3.5 Day/Night

The lunar day and night period is approximately 28 Earth days. The sidereal period is slightly longer than 27 days and the synodic period is slightly longer than 29 days. The day/night periods offer some cyclic protection from solar non-ionizing radiation and also make artificial lighting for EVA a requirement.

2.3.6 Temperature

The variable lunar surface temperatures are a function of solar illumination and shadows. The range of temperatures has been reported to be from 102 °K to 384 °K by Bufkin (1988), and from 102 °K to 407 °K by Bova (1987). The roughly 300 degree temperature differences can be experienced at the same time on a piece of equipment depending on its orientation with respect to solar illumination and deep space.

2.3.7 Radiation

The radiation environment of the moon is harsh. The lunar surface is exposed to the continuous flux of galactic cosmic radiation (GCR) and to infrequent periods of intense solar energetic particle activity. Particle fluxes on the lunar surface are about 1/2 of their intensity in free space because they are blocked below the horizon. Crewmembers are not protected from these ionizing particles by either an atmosphere or a magnetosphere.

The GCR flux is between 1 and 2.5 particles $\text{cm}^{-2} \text{s}^{-1}$, depending on solar activity. It consists of about 90% protons, 9% helium nuclei, and 1% heavier nuclei. GCR dose is difficult to shield; approximately 5 to 10 m of lunar soil reduces the GCR dose to terrestrial levels.

Solar protons pose a significant risk to inadequately shielded crewmembers. Very large energetic particle events, which can cause acute radiation effects, occur at intervals of 7 to 10 years. Intermediate events, which can limit mission activities, occur several times each year. For nominal flares, build-up to peak radiation intensity occurs within a few hours or less. Monitoring of X-ray precursors may provide 30 minutes to one hour of additional warning.

We must contend with life threatening radiation hazards on the lunar surface. The galactic cosmic radiation and the intense particle radiation from solar flare events are potentially significant problems for the EVA crews exploring the lunar surface, remote from the main base. It has been suggested that the radiation hazard may be aggravated by other factors in space, including stress and low gravity. In addition to the natural radiation environment, we must consider the introduction of non-ionizing radiation associated with communications systems. High atmospheric nuclear explosions on Earth, currently banned by international treaty, might also contribute to the radiation hazard on the lunar surface. (Radiation hazards and shielding requirements are considered in detail in sections 3.2.15 and 4.5)

Table 2-9. Charged Particle Environment at the Lunar Surface

Source	Energy (MeV/nucleon)	Flux ($\text{cm}^{-2} \text{s}^{-1}$)	Penetration Depth (cm of aluminum)	Max. Dose
Solar Wind	10^{-3}	10^8	10^{-6}	~0
Solar Energetic Particles				
Protons	1 to 10^3	$<10^5$	1 to 10^2	<10 Gy
Helium Nuclei	1 to 10^3	(~1%)	1 to 10^2	(~1%)
Galactic Cosmic Radiation				
Protons	10^2 to 10^4	2	1 to 10^3	0.02 Sv/yr
Heavy Nuclei	10^2 to 10^4	0.2	10^{-1} to 10^2	0.23 Sv/yr

2.3.8 Range of Mobility, Navigation, and Communication

How far we can go beyond the protection and comfort of the main lunar base will depend on the portability of our life support systems and the distribution of our communication systems. With portable and distributed safe havens having medical and life support capabilities and with a communication system that allows full-time contact with the main base, EVA remote expeditions should be able to explore anywhere within walking or driving distance of a safe return to shelter. Lunar orbiting communications and navigation satellites could provide freedom to set up remote sites anywhere on the lunar surface. A network of distributed safe havens could permit us to leap-frog great distances on the surface, much as we did in exploring the American West, going from fort to fort and then establishing new forts at the "end of the line," or as we have done in the Antarctic with distributed shelters. (Section 4.7, Shelters, and sections 3.1.7 and 4.9, Communications, address these matters in more detail.)

Table 2-10. Environmental/Physiological/Operational Considerations for Lunar EVA

- ▶ Exposure to radiation
 - Ionizing (solar flare, natural background, nuclear power installation)
 - Non-ionizing (exposure to communications antennas)
- ▶ Low gravity (0.165 g)
- ▶ Changing physiology due to extended stay in reduced gravity
 - Reduced muscle mass
 - Bone demineralization
 - Decreased cardiovascular condition
 - Loss of red blood cell mass
 - Suppressed immunological function
- ▶ Lunar dust exposure and control
- ▶ Sharp thermal gradients
- ▶ Rugged and sloped terrain (maintaining upright stability)
- ▶ Sunlight/Earthlight
 - Angles subtended (vary with respect to crew position/orientation)
 - Perception of stellar space
 - Lunar night/lunar noon
- ▶ Exposure to space debris (micrometeoroids and ejecta)
- ▶ Exposure to contaminants and occupational hazards in plant operations
- ▶ Effect of absence of Schumann Electromagnetic Resonance
- ▶ Communications routings on links with Earth and Space Station
- ▶ Automated systems in LEMU to preclude requirements for "hands-in" capability
- ▶ Operational monitoring of EVA crewmember at remote sites from lunar base

2.4 LUNAR EVA MISSION OPERATIONS REQUIREMENTS

Extravehicular activity will be part of the normal daily routine at a lunar base, and the job descriptions of some long-term residents there will include regular EVA assignments. The Apollo, Skylab, and Shuttle programs have established the precedents for intermittent EVAs. Space Station planning for EVA is derived from that experience database and from new requirements and technologies. Lunar base planning gives us an opportunity to think about extending the range of crewmembers on the moon by extending the duration of EVA. This report considers current EVA philosophy in light of prior experience on the moon and suggests some different ways to meet lunar mission operations requirements.

The Space Station EVA Systems (EVAS) User and Interface Guidelines (Kosmo, 1986) provides for an 8-hour per crew work period every 24 hours. The 8-hour period includes pre-and post-EVA operations in support of the actual EVA. (Unique pre-EVA operations for lunar activities might include donning a protective garment to reduce soil and dust contamination; post-EVA operations might include the removal of such a garment or the necessity of thoroughly cleaning the LEMU after the EVA.) Some estimates of the pre- and post-activities in support of lunar EVA place a 4-hour overhead on EVA; this would reduce the productive EVA work period to 4 hours. The "overhead" time associated with donning, doffing, cleaning, and drying will make short periods of EVA (4 hours or less) impractical. Work plans and crew inclinations will probably tend toward longer duration EVAs.

2.4.1 Lunar EVA Work Period Parameters

The work periods for EVA to support remote lunar operations are determined by several interrelated factors. Chief among these are the tasks that the EVA crews undertake, and the geography and surface features of the area where the tasks are performed. For tasks that demand traversing slopes to install manually transported equipment, the workload will be quite high; consequently, the crew may become fatigued early in the EVA period. In video tapes of Apollo 16 and 17, the crew stop every once in awhile to rest from the strenuous science and sample-taking tasks. Although they continue to stay within set timelines, they sometimes appear to have to rush or discontinue tasks to remain on schedule, largely because of unexpected demands from discoveries or hardware malfunctions. The work periods should allow sufficient rest between strenuous tasks. Planners should consider the target-of-opportunity schedules for science missions. The surface topography over which the EVA crews have to work should be considered in determining work periods.

Systems technology for lunar EVA is also a determining factor in the definition of work period parameters. The EVA suit design and capabilities, the rover support capabilities, and the degree of automation available to support operations will influence, if not determine, the duration of work periods. With a baseline design similar to the Space Station extravehicular mobility unit (SSEMU), the work periods would be limited to the requirements imposed by that hardware and be similar to Apollo EVA work periods.

Significant environmental factors must be considered in determining the work period. The exposure to radiation on the lunar surface, the day and night cycle, and the thermal extremes have a limiting effect on the work period. Although Earthlight will be significant, EVA conducted during the lunar night requires artificial lighting, and the power requirements to support continuous operations influence how long, or even if, EVA is conducted at night. Exposure to GCR and solar radiation influences the work periods according to the amount of radiation protection afforded by the most vulnerable part of the lunar extravehicular mobility unit (LEMU). In the SSEMU, the arms and legs are most exposed.

A major limiting parameter of the EVA work period is the amount of consumables provided within/on the suit. The supply of oxygen, food, and cooling must be sized to the anticipated metabolic expenditures. As an alternative or supplement to on-suit supplies, the use of umbilicals attached to stationary, portable, or rover-mounted stores of consumables should be

considered. Consumables replenishment via umbilicals is predicated on a safe, reliable vacuum transfer system.

A summary list of parameters that will influence or determine the work periods of remote lunar EVA includes the following:

- ▶ EVA tasks and sub-tasks
- ▶ Geography and surface features of the task site
- ▶ Radiation exposure, ionizing and non-ionizing
- ▶ Day and night cycles of the moon
- ▶ Temperature and thermal extremes
- ▶ Design and capabilities of the LEMU
- ▶ Number of EVA crewmembers involved in a remote task
- ▶ Degree of automation available to support EVA
- ▶ Design and capability of rovers and other mobility vehicles

2.4.2 Lunar EVA Workday Length

The Apollo program has proven the feasibility of consecutive EVAs involving a "full-day's work." According to Dr. Charles Berry in "Biomedical Results of Apollo" (1975, page 591),

"We learned from Apollo that man can perform very nicely in a one-sixth gravity environment. One-sixth of the gravity to which he is accustomed proved to be sufficient to give man a feeling of near normalcy for performing functions with at least the same ease as he does on Earth and, in some cases, with greater ease. The astronauts adapted quickly to movement in the lunar gravity environment and traversed the surface of the moon rapidly using many gaits..." "Apollo lunar surface activity also demonstrated that the metabolic costs of working in that environment were completely acceptable."

The radiation exposure limitation to lunar EVA (without significant shielding) has been set by Silberberg, Tsao, Adams and Letaw (Mendell et al., 1985, page 663) at 10 hours per 24-hour interval for the two-week-long lunar day. Their conclusions were that:

"Permanent residents on the Moon can spend about 20% of the time (or 40% of the two-week daylight time) without significant shielding. Most of the time should be spent in shelters of $> 400 \text{ g/cm}^2$ or about two meters of densely packed lunar soil, either below the surface or at the surface beneath a shielding mound. At the time of rare gigantic flares, shelters $> 700 \text{ g/cm}^2$ are needed; such a protection is particularly important for radiation-sensitive fetuses."

The longest lunar surface EVA was just over 7 1/2 hours on Apollo 17. It is reasonable to plan on an EVA workday that is 6 to 8 hours long under conditions similar to those existing on the Apollo missions. With donning, doffing, and cleaning, the EVA workday could be 10 to 12 hours per day on a 6-day per week basis.

2.4.3 Lunar EVA Duty Cycles

The lunar EVA duty cycle (shifts on/off or EVA/IVA) is influenced by mission operations requirements, physiological constraints, and technological factors.

If there is a requirement for continuous remote operations (e.g., at a mining site), provisions will be made for EVA shifts. There may be no inherent need, however, to adhere to a standard weekly work schedule based on 5 days on/2 days off or 6 days on/1 day off; other options might be 3 on/1 off or 2 on/1 off, depending on physiological and technological considerations. The Space Station Program Definition Requirements Document (JSC-31000, Covington, 1987) limits EVA to 18 hours/week per crewmember.

Shift rotation may be determined on the basis of permissible radiation exposure, both incremental and cumulative. Individual crewmembers may need to alternate EVA and IVA work periods to avoid exceeding their dose limits.

Physical fatigue is not expected to be a significant limiting factor for EVA duty. Apollo crews generally did not report being tired. Forearm muscle fatigue from compressing the glove in repeated manual operations disappeared overnight with normal rest. Fingernail soreness associated with prolonged use of the EVA gloves lasted for several days and would have made consecutive EVAs painful. However, fingernail trauma or chafing of other parts of the body can be avoided by suit design, and many improvements have already been incorporated in Shuttle and Space Station era suits. Articulated finger joints or mechanically assisted finger bending would help to reduce forearm fatigue.

Technological constraints on the lunar EVA duty cycle include the LEMU recharge and servicing requirements, rover recharge and servicing, and availability of any other EVA-critical hardware.

2.4.4 Lunar EVA Duration Optimization

With an advanced version of the SSEM as the baseline for the LEMU, lunar EVA duration is 8 hours. The baseline EVA work period fits plans for prior missions and experiences in the workplace and places minimal requirements on food, water, and personal hygiene. However, this 8-hour EVA period includes a requirement to prepare for EVA and to clean the LEMU following EVA, which tasks are estimated to take about 4 hours, leaving only 4 hours for productive EVA labor. If travel to and from the site is subtracted, the EVA work period becomes very brief. It is not practical to have EVAs of 4 hours or less in support of remote site operations.

The average EVA duration for lunar astronauts on Apollo was 5.77 hours, with a maximum experience of 7.62 hours. Longer EVAs can be accomplished by humans in good physical condition. Apollo crewmembers indicate anecdotally that 10- to 12-hour EVAs would not be physically prohibitive, if the suit and glove design and the consumables would support longer duration EVAs.

The duration of lunar EVA might be extended and productivity might be optimized by preserving the 8-hour baseline period for actual labor. "Overhead" suit maintenance activities and transit time to the remote site need not reduce the effective EVA work period. If, for example, life support consumables are supplied through the rover while crewmembers are traveling to and from the worksite, the entire LEMU charge is preserved for the work period. Similarly, if suit inspection and cleaning procedures are simplified to take only 30 minutes or if those tasks are assigned to suit technicians rather than the EVA crew, the "overhead" burden on EVA time drops and more time is available to do work.

During the conduct of remote expeditions more than 4 hours from the main base or distributed shelters, it will be necessary to provide a habitable environment for the EVA crew. This may be a pressurized cab or habitat on the rover. The 4-hour requirement is derived from the half time of the 8-hour EVA permitted in a 24-hour period.

On the other hand, if we provide consumable or regenerable life support aboard the rover, it will be possible to drive to a remote location while on rover life support, conduct a full 8-hour period of EVA at a remote site using portable life support systems, and then reconnect

to the rover life support for the trip back. This permits more time of productive EVA by treating the drive time as overhead, provided that the EVA crew remains within the established radiation exposure limits for the particular LEMU design.

The optimum resupply of EVA consumables will be from lunar base. A remote excursion might normally involve daily trips back to base for sleep, personal hygiene, and meals. Occasionally, however, an "overnight camping trip" might be envisioned during which the crewmembers sleep in their suits while connected to life support and consumables on the rover. Such an extended EVA would probably require special accommodations for sleeping, waste management, and some other functions.

Current EVA equipment will support EVA missions of up to 10-hour duration. Additional factors to be considered in optimizing EVA duration will be the workload, both mental and physical, the degree of automation to support EVA, and the expedition crew size.

2.4.5 Lunar EVA Translation Considerations

There are at least three means of translation on the lunar surface: walking, riding in a surface vehicle, and flying. Only the first two means are considered in this study. The assumed driving speed to a remote EVA site is about 10 km/hr, the typical speed of the Apollo lunar roving vehicle on level terrain.

In walking and riding, the considerations are regolith, blocks, slopes, craters, and the EVA safety parameters applied to the mission. The video tapes of the Apollo lunar missions reveal that walking about the lunar surface kicks up a great deal of soil and dust, thereby contributing to contamination problems.

Unaided walking appears to require some concentration and energy to move and maintain balance. The crewmember tries to maintain dynamic stability, achieving balance by continually making fine adjustments to stance and posture. One consideration might be to assist the EVA crewmembers with walking poles that would provide a means of balance and "propulsion," as shown in Figures 2-13 and 2-14. Resultant mobility would be comparable to cross-country skiing.

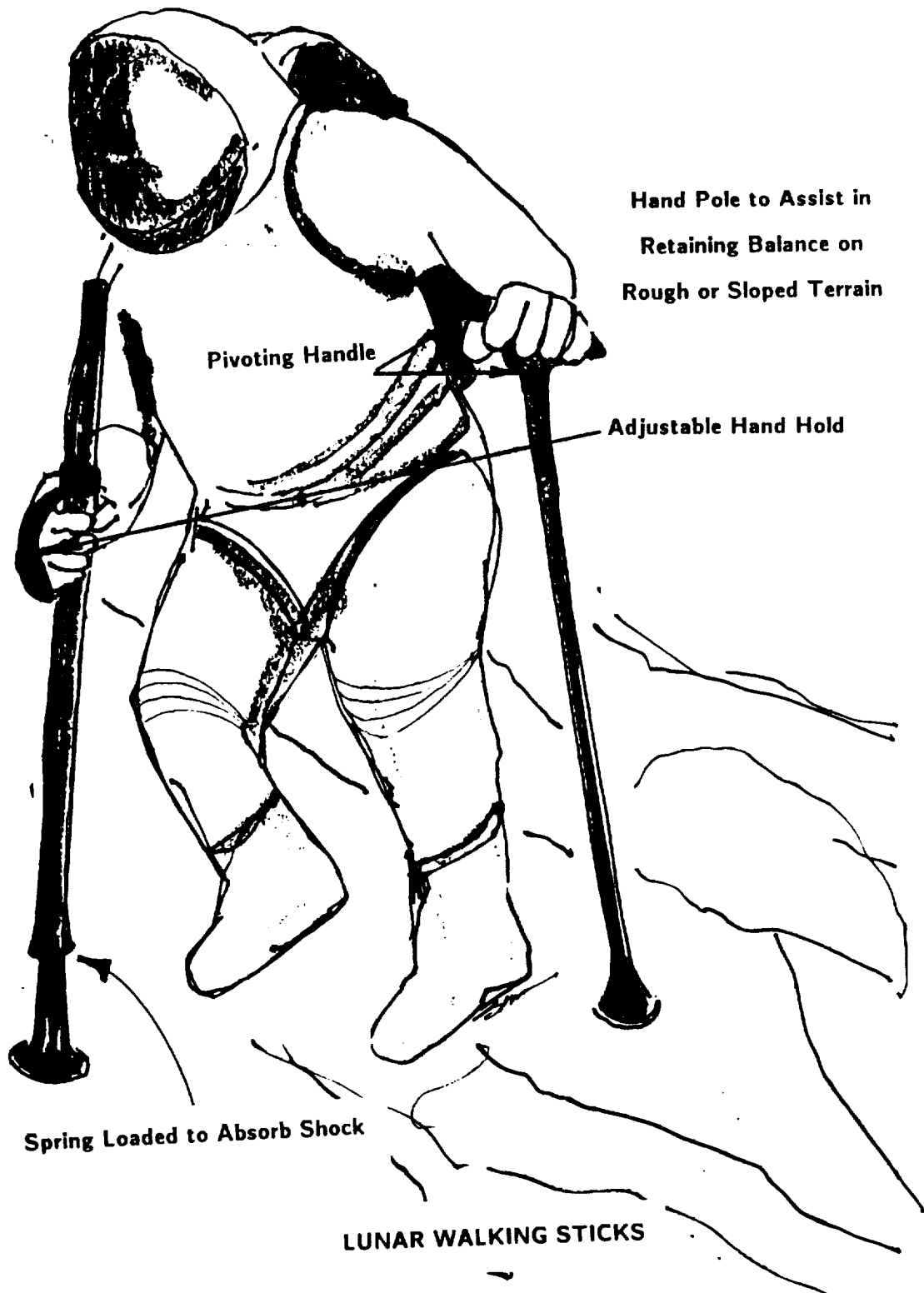
For vehicular translation, a lot of dust is generated by the wheels of the rover that might contaminate radiators, solar panels, the EVA crew, and other exposed items. The Defense Advanced Research Projects Agency (DARPA) has an ongoing program to develop multi-legged walkers for traversing rough terrain with payloads. These translation vehicles are modeled after insects, specifically the cockroach; they provide stable translation over a surface with little surface contact and disturb less soil than a wheel or track.

Large and small blocks of rock, slopes, and craters must be considered in lunar surface translation, whether walking or riding. Based on experience during Apollo 17, the crew cautions that distance with respect to these surface features is generally underestimated. The rover must be able to negotiate slopes and to avoid craters, and the ambulatory EVA crewmember must be able to ascend and descend slopes in the working area, or avoid them if they exceed the capabilities of the LEMU.

The safety parameters of the remote mission influence surface translation. The walk-back distance to the main base or shelters in the event of rover failure must be considered. Also, the ability to locate oneself, to be located, or to identify a landmark influences translation safety factors. Translation in any direction should be within visual or RF range of the last trail mark, and the distance of translation should allow a walkback to shelter.

For maximum stability under 1/6 g conditions, all suits should have a normal center-of-gravity that is close to the body's longitudinal axis. Boots that engage an optimized surface area of

Figure 2-13. Lunar Walking Sticks



LUNAR WALKING STICKS

Figure 2-14. "Ski Pole" for Crew Mobility/Stability

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**A Conventional Ski Pole Approach
to Translation Stability**

loose lunar soil should be used. Consideration should be given to the natural walking, running, or "skiing" motion promoted by the environment.

Rovers could be of several different types designed for various categories of activities and transportation needs; trailers also should be considered. Each rover must be equipped with navigation aids that enable the crewmembers to determine their exact location and the base operators to track the location and movement of each rover. Map displays with markers from locator beacons should be considered for use at the base and in each rover. Batteries recharged and supplemented by solar arrays will probably prove to be the most practical power source for small rovers. However, in the case of a large "Conestoga Wagon" or MOLAB (Apollo era concept for a Mobile Laboratory) type rover, a small high-energy/density power source such as a fuel cell may prove to be desirable.

The range of operation might be approximately 20 km from the lunar base. This would allow crewmembers to tend blasting operations located well away from base. Since this range might be out of the comfortable and safe walkback range, the use of buried consumables and shelters at way points along the longer routes should be considered. Safe havens in the form of caves, tunnels, or other excavations in the regolith might be placed at about 2-hour intervals along major routes; thus, EVA crews would usually be within an hour from shelter. It may be possible to build facilities that allow crewmembers to drive rovers directly into the shelters to escape solar flare events that might occur while en route from lunar base along established pathways. These excavations would not preclude the need for portable or emergency shelters.

2.4.6 Lunar EVA Rescue Capability

Design efforts for EVA rescue should emphasize having an ill or injured crewmember stay in his suit for most rescue procedures. Some consideration should be given to the probability or risk of sudden decompression during a remote EVA; if that risk is appreciable, provisions should be made to sustain and rescue the stricken crewmember. Contingency plans involving "buddy systems" to share life support consumables should be considered a part of the rescue system/capability.

The sickness scenario exemplifies the necessity to provide emergency rescue capability. Rescue assumes the availability of a backup rover and an ambulance module as well as a one-person litter recovery device (LRD). Availability of a hyperbaric chamber is another possible provision. Biochemical Isolation Garments (BIGs) might be provided to protect crewmembers engaged in a rescue from an injured or contaminated crewmember. However, sources of contamination requiring such heroic efforts might not exist in the lunar base environment.

2.5 CRITICAL SYSTEMS FOR LUNAR EVA

How do we best take advantage of humans in space, and how do we protect them from the environmental and technological hazards associated with space exploration? This question leads us into a consideration of critical EVA systems and ways to make our technology best suit the human and the mission. The issues discussed here are not strict requirements, but discussions of possible requirements, based upon what we have learned from our experiences on Apollo, Skylab, and Spacelab.

2.5.1 Pressure Suits

The underlying assumption for this study is that an advanced version of the Space Station EMU (SSEMU) will be available to support lunar EVA. This suit will be a basic SSEMU with design improvements in the joints and gloves and some additional protection from lunar soil contamination. In this study, the lunar suit is called LEMU. The lunar reference mission scenario points up the opportunity to increase human productivity by varying the LEMU design requirements to accommodate the environment, the range of anthropometric variation, and the variety of tasks envisioned for remote lunar operations.

A requirement derived from observation of the Apollo films is for mobility aids and stability of the EVA crewmember. The ambulatory modes employed by the several crews appeared to disturb large amounts of regolith, require large amplitude movements, and contribute to loss of balance in some circumstances. The Apollo suit design did not permit full radial and axial movement in the ankle and lower leg, so downhill movements and negotiation of slopes and grades appeared to be difficult and uncomfortable. Also, the large amplitude motions in decreased gravity did not always end in a precise and controlled stop. Apollo crews rapidly learned to anticipate such problems. Design changes to the ankle joints might permit greater control during ascent and descent of grades, ridges, and rims. A means of providing lateral and anterior/posterior stability while moving might aid in mobility, particularly in an emergency or recreational traverse, and in the control of surface contamination. Ski-type poles and an outrigger device are possible design solutions to the problems of motion and station. (See section 4.3.1, Crewmember Translation.)

The variety of tasks for the EVA crew on the moon lends itself to the argument that there should be a variety of LEMUs designed for accomplishing these tasks with the greatest degree of safety and productivity. The wardrobe of suits that might be available in the future could include the following:

- ▶ Hard armored, for working around mining and other heavy equipment
- ▶ Self mobile, for traversing the lunar surface in a self-contained life support and mobility unit
- ▶ Mechanically enhanced, with exoskeletal force enhancers for performing both arduous and dexterous manipulative tasks, or integrated enhancers built into the suit or gloves.

The idea to be explored is that the LEMU might reflect not only the basic life support function but also the job and task functions in a more specialized way.

Other items in the wardrobe might be an over-garment, cover-all, or easily replaceable outer layer to protect the LEMU from excessive exposure to lunar dust, soil, and possibly radiation and an easily donned intravehicular activity (IVA) pressure suit for use if integrity of the pressurized main base is violated.

Consideration was given to a hands-in-suit capability, which would afford a convenient way to attend to eating, drinking, waste management, and some communication functions. The primary reason for hands-in capability was to reduce radiation exposure to the crew through the arm and leg portions of the suit. For extended lunar EVA missions, increased protection from radiation hazards may be necessary. However, a hands-in suit with a unitary lower torso does not satisfy the lunar EVA requirements for mobility and a lightweight LEMU. Therefore, the functions of eating, drinking, waste management, and communications control are accomplished using a Space Station era EMU technology without the benefit of hands inside the suit.

Another consideration in suit design is custom fit and resizing. While logistics and cost may preclude a dedicated LEMU for each inhabitant of a lunar base, a suit that can be adjusted to fit individuals may improve crew comfort and productivity. A "tailored" suit (either by custom design or by interchangeable/adjustable parts) would give the individual maximum limb motion, postural range, and hand-eye manipulative envelope. It would also reduce the chafing, pressure points, and other discomforts and restrictions of an ill-fitted suit. Conceivably LEMUs might need to be adjusted for weight loss/gain or changes in the size of long-term lunar residents. It may be cost-effective to provide custom fitted suits for dedicated EVA crewmembers and shared suits for other lunar base residents who go outside rarely or only for local excursions. Another possibility is to custom fit only the crucial portions of the suit, such as the gloves.

The issue of suit fit and sizing raises questions about relevant anthropometric measurements for 1/6-g EVA: what are the critical parameters, and how do they correlate with 1-g and 0-g measurements?

Long-term use is a factor in LEMU design and maintenance. To date, orbital and lunar EVAs have lasted less than 20 hours. Lunar base EVA schedules may impose suit-useful-life requirements of hundreds of hours. Heavy use may cause suits to stretch or deform, develop worn or frayed spots, or fail at critical junctures. Suit maintenance considerations include regular inspection, replacement of heavy wear components, and repair techniques and standards. For ease of servicing, heavy wear components should be interchangeable and standard sized; an inventory of spares should be maintained to support the servicing schedule. Helmets, faceplates, and visors need regular maintenance to prevent degradation of their optical properties. Periodic servicing of the LEMUs will supplement routine cleaning of the suit interior and exterior after each EVA.

Two other general suit design topics are worth consideration at length. First, a specifically designed physiological monitoring undergarment to be used exclusively for the collection of biomedical research data would afford medical specialists the ability to collect data without interrupting and greatly inconveniencing the operational lunar crews. The biomedical research monitoring suit could be an integrated undergarment worn by medical test subjects while performing routine and specific tasks to collect physiological data. Second, anthropometric reconfiguration and functional reconfiguration should be evaluated as ways to accommodate the widest range of people undertaking the greatest variety of tasks in support of lunar EVA.

2.5.2 Rovers

The roles of vehicles in remote lunar operations can be as limited as providing a basic means of transporting personnel and material from the main base to a remote site or as varied as are our transportation vehicles here on Earth. During the early years of lunar colonization, the majority of attention and resources probably will be spent on the establishment of the main base and the support systems to maintain life on the moon. The near-term requirement for a sophisticated transportation system is not evident until the base is fully operational and populated, and subsequent remote stations are established for specific scientific and exploratory purposes.

During the establishment of the main base and early remote expeditions, there is, however, a requirement to support human productivity and safety by providing sufficiently sophisticated hardware systems to allow machines to do best what they can and humans to do best what they can. Without argument, machines can be designed to travel farther, carry more weight, go faster, provide more environmental protection, and be reconfigured with greater ease than can humans. This implies that where requirements exist for going long distances, carrying large masses, or proceeding with speed, these functional requirements be met with machines, specifically transporting machines.

Some of these transportation requirements do not blend well with others, such as transporting large masses and transporting with speed. In cases of competing requirements, we can either compromise our design for the best mix, or we can have several different design solutions which maximize specific capabilities of the machines. There are varied and sometimes conflicting transportation requirements to support remote lunar EVA:

- ▶ Transporting personnel on the surface
- ▶ Transporting material on the surface
- ▶ Transporting science laboratories to specific sites
- ▶ Transporting miners, ore carriers, and processors to mining sites

- ▶ Trailering large quantities of materials
- ▶ Carrying small habitats, safe havens, and portable shelters to distributed sites
- ▶ Carrying workstations to remote sites
- ▶ Providing emergency protection from environmental hazards
- ▶ Rescuing stranded EVA expeditions and returning them to base
- ▶ Rapidly returning to base
- ▶ Serving as communications and work platforms
- ▶ Supporting tools, jigs, and fixtures for remote EVA operations
- ▶ Negotiating rugged terrain.

For almost all of the activities in the lunar scenarios, the rover serves as more than just a means of transportation: it also serves as a source of consumables, work platform, shelter, and pack horse. We should consider a set of special purpose rovers to meet the requirements for lunar EVA remote operations, using a variable rover configuration atop a standard drive train and frame or chassis that supports several types of cabs and beds. One configuration probably will not be adequate for the many tasks envisioned for lunar surface vehicles.

The basic transportation functions could be handled by a standard vehicle for hauling people and equipment from site to site, but when additional tasks are assigned to this machine, such as tool handling, shelter, and rescue, the configuration and functions of the rover also change. With a basic drive train and chassis, the rover could be outfitted as an ambulance for the rescue and removal of sick or injured crew. It could be outfitted as an excavation vehicle for establishing remote camps, and it could transport the shells for the remote camps as we move to distribute way stations and safe havens on the lunar surface. It could also serve as a remote scientific laboratory for on-site material samples characterization, or it could be a mobile scientific workbench for minor maintenance and analysis activities. The rover could serve as a support platform for drilling operations and as a shelter in the event of solar flares. Equipped with a small habitat, the rover could support extended duration remote operations, or equipped with life support provisions it could support extended EVAs via umbilical while the crew travels on the rover. The rover cab might be open, closable, or pressurized. Figures 2-1, 2-4, 2-5, and 2-15 depict different rover concepts.

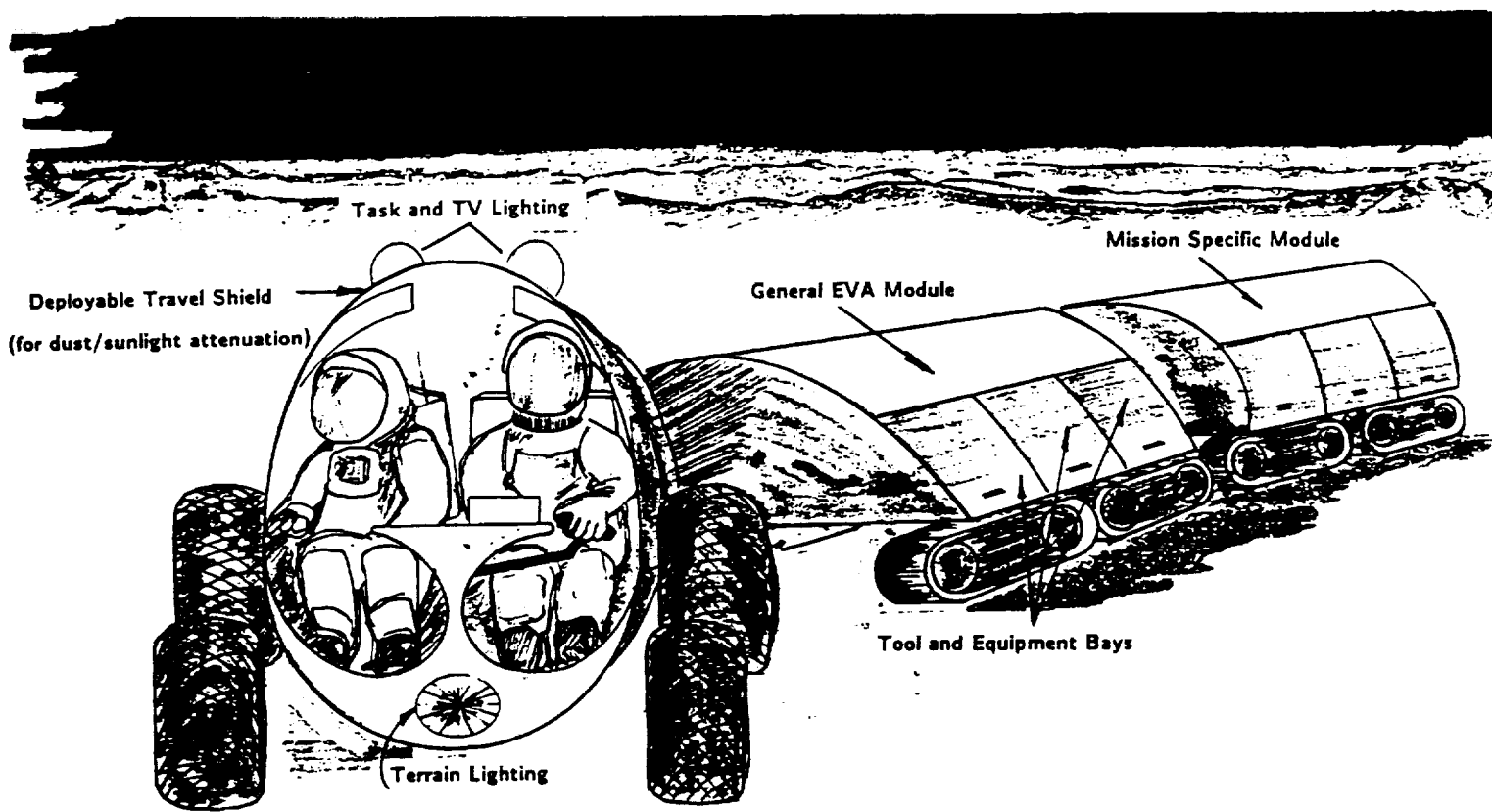
A corresponding transportation scheme is used on Earth, with pickup trucks and jeeps to move lightweight payloads to remote locations, all terrain vehicles for remote touring, and recreational vehicles and campers to support remote living. A similar potential exists to expand our transportation system on the moon as a function of varied requirements derived from operations.

The outfitting of the rover is such that the generic equipment common to all remote operations is stowed in the same location for all missions. Specialized equipment to support a particular mission objective or activity is stowed in mission dedicated areas aboard the rover. If a trailer cart is used, it should be loaded with equipment that is least needed in the case of contingency or emergency operations so that it may be temporarily abandoned for a rapid return to base.

All life support equipment, emergency provisions, communications, shelter, and rescue equipment should reside in dedicated areas on the rover, just as the generic equipment has a specified place for storage on the rover. This provides for positive transfer of training; reduced time to acquire, identify, and stow commonly used articles; and efficient operations under emergency stress.

Several different configurations of lunar rovers have been identified. These range from complete outpost facilities (motor home or Conestoga wagon concept) to miniature "All-Terrain Vehicles" (ATVs). Modules for special purposes, such as ambulance (Advanced Life Support) facilities should be considered. The generic use of the word "rover" in this study applies to all configurations and sizes of rover.

Figure 2-15. Open Cab Rover with Equipment Trailers



OPEN CAB ROVER WITH EQUIPMENT TRAILERS

Science Workstation

For remote science operations, the rover may be equipped with the following equipment and modules:

- Active seismic equipment
- Gravimetry equipment
- Science station upgrade equipment
- Science station replacement modules
- Active radar equipment
- Active regolith analysis equipment
- Deep drilling equipment
- Maintenance workstation.

Some of the equipment will be used to replace and upgrade previously installed scientific packages, while other equipment will be used to conduct operations at new sites or to conduct scientific investigations that can be moved from site to site.

The onboard systems to support the science expedition include stereoscopic TV, route planning navigation, geophysical data recording along the route, and active correlation of crew observations with geophysical data. The data are stored either on board for return to base or sent back via communication link for real-time analyses at the base laboratory.

The science maintenance workstation is equipped with restraints for tools and equipment, task lighting, computer data packs for maintenance procedures, computer diagnostic packs for on-site testing of functions, provisions for controlling contamination of the science pack during repair (such as a glove box device), and holding and positioning devices to assist the crew during repairs. The rover maintenance workstation also has LURU storage for old and new modules. Figures 2-4 and 2-5 depict rover-workstation concepts.

Visual inspection of equipment may well require workbench lighting and visual aids such as magnifiers if small parts must be carefully examined by the crew. Some type of air blower to blow off debris during inspection may be necessary. The Apollo films show that on several occasions that the crew attempted to do this by blowing within the helmet as a natural way of clearing debris from equipment.

Ambulance Module

An ambulance module could be attached on a rover or a trailer behind a rover to function as a remote urgent care vehicle. The capability required would be similar to that of a terrestrial mobile coronary care unit or an advanced life support vehicle with one major difference - the capability to supply and to control a pressurized atmosphere. This module should allow up to four people in zero pre-breathe suits (ZPSs) to enter a pressurized environment. As the number of crewmembers participating in EVA increases, provisions for transporting two crewmembers in ZPSs in supine position becomes important.

In addition, the cabin (or a portable, collapsible air chamber) should function as a multi-place hyperbaric chamber with pressure of a minimum of 2.8 ATA. Further studies of the need and feasibility to supply pressurization up to 6.0 ATA should be conducted. Although the need for a 6 ATA chamber has been emphasized in recent studies (Whidden and Horrigan, 1988), it may be possible during an emergency transport situation to start treatment of an emergency decompression with a chamber rated at 2.8 ATA and 100% oxygen by mask.

The entrance to the ambulance module should be outfitted with a dustlock and various dust control equipment. A detailed discussion of the required equipment and medical operating philosophy is given in Section 3.2.10 of this report. The ambulance module should be equipped with a source of supplies and consumables to allow life support for 4 crewmembers for approximately 4 hours. This would allow for stabilization of the patient or patients and

return to base plus time to dispatch other supplies, if needed. An analysis of the distribution of the water stored in this module and the thickness of the walls of the module should be made to determine the level of radiation protection that it affords and its feasibility for use as a form of safe haven.

Whenever EVA activities are taking place within a lunar colony, an ambulance module should be available at the lunar base for dispatch and rendezvous in contingencies, such as the need for additional supplies and for support in the event of remote-site malfunctions.

Back-Up Rovers

A back-up rover should always be kept in readiness at lunar base. This rover should have the capability to make a rapid excursion to the remote site for emergency rescue and transportation. Although a major function might be to deliver an ambulance module on a trailer, a series of trailers with different capabilities could be available to be towed behind this back-up rover. The availability of a back-up rover could extend the useful range of EVA beyond that of walk-back. A typical back-up rover might be considerably smaller and operate faster than a full-capability rover, although rovers of similar capabilities would prevent disruptions of base activities. Consideration should be given to the use of the back-up rover as a tow vehicle that could be used to return a disabled rover back to lunar base.

Rover Cab Configuration

There are numerous advantages (especially in ease and speed of ingress and egress) of the open cab concept of the Apollo lunar rover, which proved to be an efficient vehicle in its application. In the environment of an active lunar base, a closed cab configuration might be of advantage during certain remote operations that involve chemical or dust contamination. It is possible that a compromise cab configuration might be designed that would allow the crew to close or partially close a driver's cab temporarily for certain applications or for transit through certain zones of activity on the lunar surface. Such a cab might be fabricated in the form of clear partitions that telescope or deploy by drawing and extending like curtains. No clear requirement exists for a hard crew cab that would restrict and slow movement of the driver or passengers into or out of the rover. Ease of entry and exit are highly desirable, and design goals should ensure this capability to the same degree that it existed in the Apollo rover.

2.5.3 Shelters

Throughout this report, there are references to safe havens and shelters that provide sanctuary for the EVA crew during nominal and emergency operations. Table 2-11 presents various shelter and safe haven options and the provisions that might be available in each.

Generally, the shelter concept refers to a system that protects the crew from radiation exposure during a solar particle event. The shelter may be in place and fixed at a site of high activity or where EVA crews frequently visit, it may be a portable device that is taken along with the rover, or it may be a trench that is explosively excavated in an emergency. A shelter need not be a pressurized containment, and provisions for food and comfort are not implied. Such shelter is generally used in an emergency when the crew cannot safely return to base. It should support the full EVA crew (supplying air, water, and communications) for the longest anticipated duration of a major solar storm.

The safe haven concept provides for EVA crew protection and recovery from more general classes of emergencies, such as suit leaks, sudden illness and injury, isolation due to equipment breakdown, and other emergencies that might force the crew into a pressurized environment that could support them with or without the protection of the LEMU. These safe havens provide food and water, medical supplies, communications, and other necessities until the crew can make repairs or be rescued by the main base backup crew. Safe havens could be installed along major routes or worksites, transported with the crew, or integrated into a major system.

They would not have to be activated until they were needed, but all of their subsystems would be on standby in the event of a retreat to safe haven.

If a remote EVA site is beyond the range of a safe haven or other shelter, the crew may need to deploy (or partially deploy) a shelter there as the first order of business. Whether or not protection is provided depends on the risk philosophy adopted by mission planners. The issue of a shelter against solar flares may be resolved for any remote traverse as it was for Apollo EVA. That is, planning can be based on the statistical probability of a flare being so small for any one EVA that a flare can be ignored relative to other contingencies. In that case, no provision would be made for shelters; this approach probably will not be acceptable for long-term occupation and EVAs at a lunar base.

Tradeoffs should be made between the construction of shelters and alternate means of protection against solar flares. Options include supplemental shielding (hand covers, hardened visor) worn by the crew as they "make a run for it" back to base, established shelters along main routes, portable shelters, and explosively excavated emergency trenches.

If shelters are provided to support remote operations, their location may be determined on the basis of either population density or distance. For density, the shelters may be placed where high levels of activity are taking place, such as a mining site or a major science site, involving repeated trips to a single location or occupation of the site for extended periods. For distance, the EVA crew should always be within return distance of a safe haven, or they may take their safe haven with them. Table 2-12 shows shelter options suitable for various distance ranges and types of sites.

The shelters installed at remote locations where activity is concentrated should be able to accommodate the full complement of EVA crew at the site for emergency periods associated with solar flares, plus a margin for rescue from main base. The shelters should afford protection from solar radiation and provide for emergency life support and food and water. Shelters can be buried in the regolith to accommodate remote site requirements. When the activity at the site has become less concentrated, the shelter could be recovered and moved to some other site of heavy visitation or activity.

The shelters and safe havens that are provided for remote exploration either could be taken along with the expedition as an integral part of the rover equipment, or they could be distributed along the paths of exploration, or they could be a combination of both approaches. This assumes that our lunar exploration is not random, but progresses out from the main base with known direction and purpose much like the western U.S. and the Antarctic were explored.

A solar flare emergency while crewmembers are more than one hour from a habitat or adequately shielded safe haven represents a significant risk during lunar base operations. The current state of the art of producing appropriately shaped trenches by explosive excavation in uniform and cohesive rock debris (Dick et al., 1986) suggests that this technique may be a viable option for protecting crewmembers during solar flare emergencies. The safe deployment and detonation of explosive systems designed for rapid trenching of the lunar regolith can build on the precedent of explosive systems (up to 6-lb TNT equivalent) deployed for the Active Seismic Experiment by the Apollo 17 crew.

Figure 2-6 depicts an emergency shelter concept for an excavated trench under the rover. The incorporation of protective materials and water supply in the floor of the lunar rover would provide a readily available roof for the trench. Lunar regolith placed on this floor and banked against deployable fenders on the rover could be used for additional protection. Outlets for oxygen, water, and power through the underside of the vehicle would allow for conservation of LEMU consumables for the duration of a solar flare emergency.

Table 2-11. Shelter/Safe Haven Options for Lunar EVA

Features	Backup Rover	Excavated Trench	Excavated Safe Haven	Prefab Safe Haven	Trailer Safe Haven	Base Safe Haven	MOLAB
LIFE SUPPORT/PROTECTION							
Atmosphere							
Pressurized Volume	O	O	O	✓	O	✓	✓
Suit Dependent	✓	✓	✓	O	✓	O	O
Consumables Resupply							
O ₂	✓	✓	✓	✓	✓	✓	✓
CO ₂ Removal	✓	✓	✓	✓	✓	✓	✓
H ₂ O Cooling	✓	✓	✓	✓	✓	✓	✓
Food/H ₂ O	O	O	O	✓	✓	✓	✓
Power	✓	✓	L	L	✓	✓	✓
Thermal Control	L	L	L	L	L	L	L
Spare Suits	O	O	O	✓	O	✓	✓
Emergency Services							
Medical	✓	O	O	L	✓	✓	✓
Contamination Mgmt							
Human Waste	O	O	O	L	O	✓	✓
Toxic Chemicals	L	L	L	L	L	L	✓
Radiation Shielding							
Self-Contained	O	O	L	L	L	L	✓
Lunar Soil							
Trench	✓	✓	✓	O	O	O	✓
Cover/Berm	✓	✓	✓	✓	O	✓	✓
ANCILLARY FEATURES/SERVICES							
Communication							
Voice	✓	✓	✓	✓	✓	✓	✓
Data	✓	O	✓	✓	✓	✓	✓
Lighting							
Internal	O	O	L	L	✓	✓	✓
External	✓	O	O	✓	✓	✓	✓
Mobility							
Self-Mobile	✓	O	O	O	O	O	✓
Transportable Intact	✓	O	O	✓	✓	✓	O
Transportable/ Erectable	O	✓	✓	✓	O	O	O

✓ = provided
 O = not provided
 L = limited or partial provision

**Table 2-12. Operational Desirability of Shelter Concepts
(On a Scale of 0-10; BU=Backup)**

	Within 10 km	>10 km	>100 km	Major Remote Site	Minor Remote Site
Backup rover	10	0	0	0	0
Stand-by explosive system	0	10	BU	5	10
Explosively constructed safe haven	0	0	0	10	0
Prefab emplaced safe haven	0	0	0	3	0
Trailer- mounted safe haven	0	3	0	3	3
Backup rover at base, trailer- mounted safe haven	0	5	0	3	0
MOLAB	0	3	10	5	0

2.5.4 Dustlock

The people of the world have devised many physical and operational ways to exclude environmental contamination from their homes and buildings. The mud room serves the farmhouse as a place to deposit dirty boots and covers before coming into the house. The front halls of houses in the snow belt are hung with coats, boots, scarves and other snow-covered clothing. In the Orient, it is customary to remove one's shoes before going into the living quarters, to keep the outside dirt outside. These front halls and ante-rooms also moderate the environmental extremes of temperature and humidity as people enter and leave the building.

During the operation of the lunar base, people will be coming in and going out of the main habitat for a variety of purposes. A small, dedicated dustlock such as that shown in Figure 2-16 which is equipped to moderate the environmental extremes and control the transport of lunar dust into the habitat will be required. This requirement arises from the fact that the regolith covers and penetrates the outer garments of the EVA crew almost

immediately. The Apollo films show the bright white EMUs as men first venture out of the lunar module, and then, within minutes, the white turns grey below the knees, regolith covers the gloves, and with an occasional fall, dust covers the whole EMU. Figure 2-17 shows the soiled suit of an Apollo crewmember. The lunar dust also covers the equipment used on the surface; while an occasional journey in and out of a lunar habitat over a short duration mission will not lead to the accumulation of large amounts of debris, for extended missions the accumulation may present a substantial housekeeping problem unless it is accommodated in the habitat's design.

The dustlock must serve the dual purposes of isolating the lunar soil transported in from EVAs as well as disposing of it or allowing for easy disposition. A dedicated area for this purpose will ease the design burden on the habitat itself. It will also ease some of the housekeeping requirements for the main base crew. It was reported by the Apollo crews that dust was more than a surface presence in the lunar excursion module (LEM); it also caused temporary nasal and oral irritation.

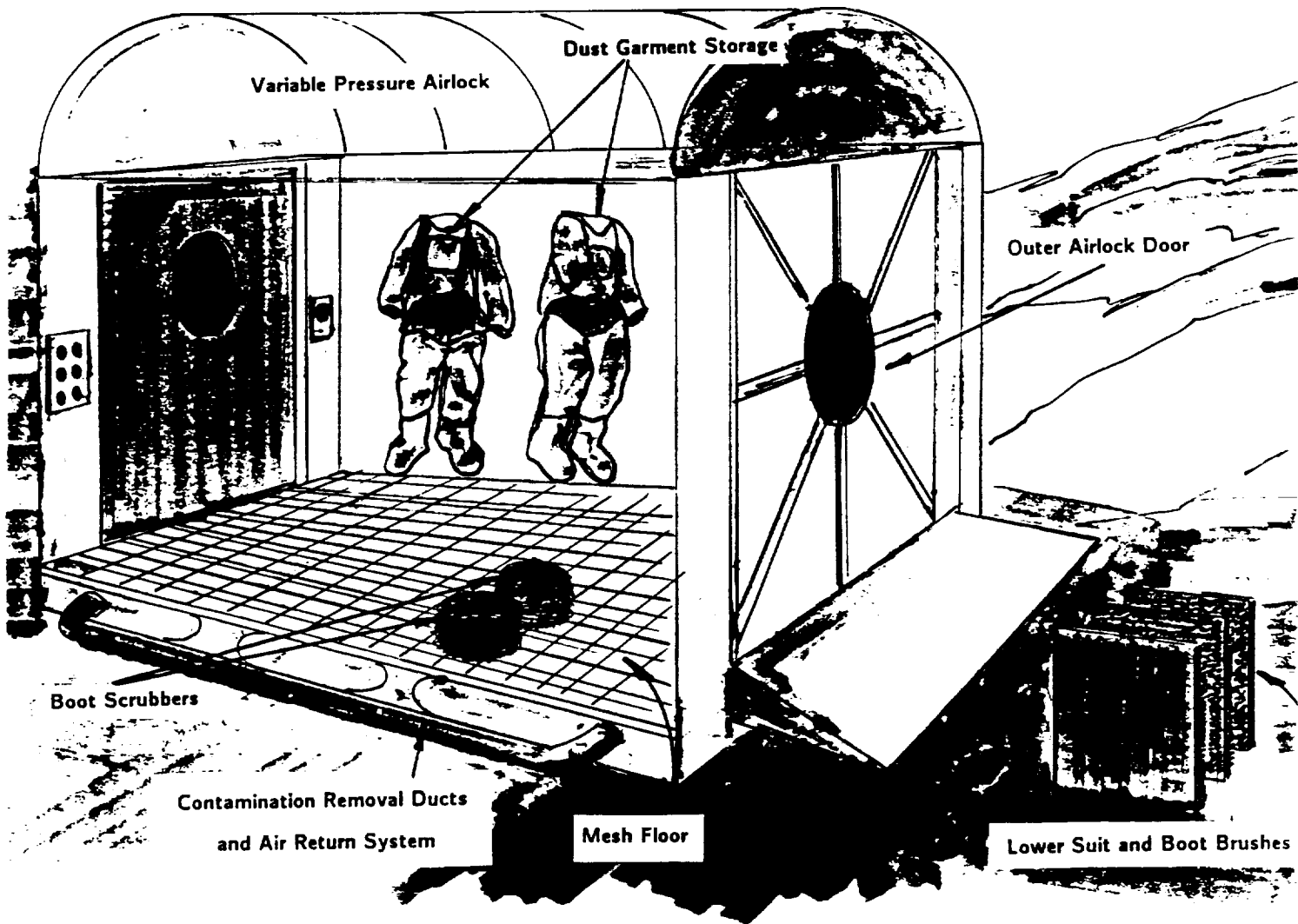
The dustlock should serve the primary requirements of isolating most of the soil contamination and providing a means of disposing of it, and it might serve other purposes, such as a storage room for EVA dedicated equipment that need not always be returned to the main habitat area for servicing or storage. If it is a combined air- and dustlock, it could serve as the don, doff, cleaning, and storage area for the LEMUs.

The design of the dustlock, especially the hatches, should acknowledge the abrasive soil characteristics and avoid the long-term build up of soil as EVAs are conducted over the life of the main base. The design should reflect the requirements to dispose of all soil and to eliminate the build-up of any soil around seals and hatches of the dustlock or airlock. The design also should accommodate necessary cleaning operations.

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 2-16. Lunar Dustlock

EVA AIRLOCK AND DUSTLOCK WITH COVER GARMENT
STORAGE AND DUST SCRUBBERS



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 2-17. Apollo Suit Soiled by Lunar Dust (NASA AS15-85-11514)



2.5.5 Major Equipment

The arduous tasks of mining and drilling and processing raw materials cannot be left to the delicate equipment used to transport, conduct science, or support human life. Major systems must be designed and developed to fully exploit our lunar operations. Miners and ore transporters should be highly automated, specially designed machines to meet the task objectives of recovering and processing large amounts of regolith. This is not work that humans do very effectively or productively; it is dangerous and dirty and repetitive, better suited for machinery, with human oversight.

Humans are much better at thinking and perceiving. To support these activities, another type of major equipment may be required: a portable science station that can be brought to a specific site of interest. Such a station could support examination and characterization of lunar materials and samples, or it could support far side astronomical observations. The technical team has considered a Spacelab type of operation, staffed by the EVA crew for both IVA and EVA in support of remote operations. The remote laboratory would enable activities that cannot be performed at the main base, such as far side observations, or activities to be performed in near real time rather than delayed until return to base, such as characterization of materials.

The use of explosives for trenching raises the need for an explosives control system to ensure crew safety. This system must include three elements: a detonation sensor to verify that all charges have exploded or are in a "safe" configuration, a locator to find any unexploded "duds," and a grapple tool to "safe" a dud if necessary.

3.0 Lunar EVA Hardware Design Criteria

3.1 LUNAR EVA MAN/MACHINE REQUIREMENTS

Under EVA conditions, humans will do what they do best — analyze real-time situations, predict consequences, devise alternative strategies, and select from these strategies. It is in the resolution of the unexpected opportunity, condition, or problem that the human clearly demonstrates superiority over the most advanced artificially intelligent robots. In a sense, the human exhibits instant and automatic reprogrammability in response to stimuli, such as those represented by problems, observations, and opportunities. The ability to improvise solutions to problems will be vital to the successful completion of the EVA scenarios.

3.1.1 Unique Human Capabilities in Lunar EVA

The majority of work for the lunar EVA crews will not be improvising but executing well-defined tasks for which they have trained. For these tasks, the unique human capabilities are observation, manipulation, and analysis. The Apollo tapes show the EVA crew engaging in observation and manipulation. With appropriate support equipment at the remote EVA sites, future crews should be able to perform on-site analysis of samples, make observations with telescopes, or manage large mining and processing plants.

As on Earth, people on the moon will manage and control machines that augment and complement their efforts. Humans should decide when, what, and where a machine executes a function and then monitor, evaluate, and redirect the machine.

Humans also have the capacity to repair machines and components should the hardware become worn or damaged. The Apollo experience affirms the importance of designing components to take advantage of this human capability.

The Apollo experience also demonstrates the unique human capability to persevere and exceed expectations. Despite some limits in mobility, for example, the Apollo crews had long and productive EVAs. The design of the Apollo EMU restricted some kinds of movement (e.g., bending over to pick up something, traversing slopes), but the crews adapted to such constraints and still achieved their objectives efficiently. Despite strenuous timelines, the crews did not report unusual fatigue in the lunar EVAs; in fact, they felt that longer EVAs would have been possible and desirable. In general, past lunar EVA experience indicates that humans perform well on the moon and are capable of performing a wide range of tasks with only marginal fatigue.

3.1.2 Logistics

For the away-from-base lunar EVA reference mission, an active logistics system should be considered. This would require that equipment loaded for an expedition be outfitted with radio frequency (RF) or another active device so that the equipment can be located, monitored, or otherwise "found" through a system inquiry rather than a personal search. Many times during the Apollo missions, the crew had to look for a piece of equipment or ask another crewmember where a particular item was located. The active logistics system should operate over some specified range so that the crew do not need physical possession of the article to "locate" it in the logistics inventory as with bar code readers. This requirement will reduce look-up time and ensure that equipment and productive time are not lost during a mission.

Concerning "lost" equipment during a mission, it was noted that on some of the Apollo missions equipment was discarded at the conclusion of a task or expedition. For future remote lunar operations, there should be a requirement to return all equipment, regardless of its status, to the main base or logistics stores area. No equipment should ever be discarded, except in an emergency. Debris around work areas can hinder operations and data-gathering. Discarded and partially-expended equipment and supplies may have value to the base at some future

date. Designated areas should be established at all worksites where equipment may be temporarily stored. Equipment logged out of the logistics stores for a remote EVA should be logged in at the end of the EVA.

Logistics stores should be transported in a separate vehicle pulled by the rover. In the event of an emergency or a rapid return to base, the logistics trailer could be detached from the rover and left at the remote site for later pickup. The EVA crew should not be required to transport equipment or logistic stores on their persons except to conduct specific tasks.

The logistics package for remote operations should have two components: general and mission-specific. A general core of logistical supplies should be taken on each remote mission. This general core should be supplied and configured the same way for each expedition and located on the trailer in a dedicated area. The mission-specific logistics also should have a dedicated location on the trailer. This will enable the crew to benefit from positive transfer of training with respect to the common logistics core, the equipment available from the common core, and the specific location of this equipment. This should increase productivity by decreasing the time necessary to familiarize the crew with the common logistics elements.

Common core logistics should include backup power and life support provisions. The life support provisions could be provided via umbilical to the crew.

All recharging of oxygen tanks should take place at lunar base. Replacement of oxygen supplies during EVA should be necessary only in an emergency and should be accomplished by replacement of an entire tank rather than by recharging a tank from an oxygen supply on the rover.

Logistic equipment should be provided in a modular form so that changeout can be accomplished by removing one module and plugging in a replacement. These modules are lunar replacement units (LURUs). To reduce the requirement to replace units frequently, regenerable and recycling systems should be considered.

It is reasonable to require the sensing of each item's presence in its stowage location and to input this information into a central logistics computer. In addition, it is reasonable to check tool/equipment transporters automatically before and after a work mission to ensure that all scheduled items taken out are brought back. This can be accomplished before leaving the remote worksite via the communications link and appropriate service request. The following automatic identification techniques should be considered:

- bar codes
- optical character recognition
- electronic vision and pattern recognition
- magnetic stripes
- speech recognition
- radio frequency identification.

Radio frequency tagging seems best to fit the stowage concept suggested above; the variations include active coded transmissions, coded responses to interrogation, passive-no code, and passive coded. There are already several products on the market and by the time these scenarios are realized, small, battery-powered coded transmitters and transponders that respond to RF interrogation signals may be available that would serve the lunar base requirements very well. Electromagnetic interference (EMI) will be a major problem that requires an extensive, deliberate effort to provide a stable system that overcomes limitations associated with operation in RF fields.

3.1.3 Maintainability

The permeating and abrasive qualities of the lunar dust are the overriding factors in increased maintenance activities associated with lunar EVA. Dust removal, coating application, and

lubrication will occupy the majority of the maintenance efforts unless precluded by initial design. A major maintainability requirement should be that equipment exposed to and used in the lunar regolith be protected from the abrasive character of the lunar soil or be designed to be serviced in that environment at a remote maintenance station. Patching material should be supplied for application to worn areas of the integral thermal/micrometeoroid garment (ITMG) and/or suit. Replacement of the garment with a spare is another option.

The lunar base and the Space Station should conform to the same level of maintainability requirements. For the Space Station, the design requirements for minimum achieved availability are 90%. "Achieved availability" is the probability that a system or equipment when used under stated conditions in an ideal support environment will operate satisfactorily at any given time. This includes active preventive and corrective maintenance down-time, but does not include supply, waiting, and administrative down-time (JSC Maintainability Working Group Requirements Memo, July 11, 1986). The maintainability requirements for lunar EVA should require an availability of 90% or better as determined by lunar-base-specific trade-off studies. Special skill requirements for maintenance should be minimized by automated checkout and module replacement wherever feasible.

The requirements memo also states that hardware should be designed to facilitate maintenance, inspection, and repair to the replacement unit (LURU) level plus the servicing and de-servicing of consumables, waste, and refuse. Based on crew experience, the most desirable features for system and subsystem maintainability are:

- Ease of disassembly and reassembly
- Modular design
- Commonality among different items and systems
- Ease of test, checkout, and verification after refurbishment
- User-friendly techniques to perform fault analysis and diagnostic and corrective procedures or actions
- Efficient workstation and restraints and appropriate tools and test equipment
- An adequate inventory of spare and repair materials.

Maintenance of the LEMU should be accomplished at a dedicated site at the main base by specially trained personnel. The LEMU should be maintainable at the LURU level for the replacement of parts and components. Scheduled maintenance should be performed following each lunar EVA and at intervals required by the LEMU designer, NASA, and experience. Maintenance specialists should visually inspect and functionally check the LEMU prior to each EVA to verify proper functions and pressure integrity (leak check). Any remote site maintenance of the LEMU should be limited to adjustments in the LEMU for personal comfort and task type.

3.1.4 Hardware Servicing

Automatic checkout and self-test will be major components of the EVA equipment. All vital functions of the suit and life support system should be self-tested at a minimum rate of twice per minute. The use of "press-to-test" functions should be allowed for EVA equipment parameters that are not life-critical.

Tools and equipment used by the EVA crews should be designed to limit the need for servicing during a mission to the greatest extent possible. The majority of planned servicing should be conducted at the base station in special servicing bays and workshops where there are means to control the abrasive lunar soil and remove it from equipment and the environment.

Where it is necessary to perform hardware servicing at the EVA site, it should be possible to isolate the hardware component from the regolith. This could be done at a clean workbench or in a glove box, if feasible. Appropriate tools, diagnostic equipment, task lighting, and solar illumination shading should be provided. Holding and orienting fixtures should be provided for the hardware to be serviced, and if necessary, more than one crewmember should be able

to work on the equipment at the same time. For the servicing of permanently in place hardware, such as a remote science station or observatory, the largest serviceable component should be removable and serviceable by a single crewmember. The largest serviceable component should also fit in the glove box or workbench for servicing.

Based upon our flight and lunar experience, humans have performed mission-saving operations through contingency servicing and repair. It would be sensible to design equipment to take advantage of this capability, even if no servicing is anticipated. This might be as simple as designing large equipment in modular fashion, so the EVA crew can remove and replace modules that have failed or have been updated. At the very least, the EVA crew should be able to return a unit in need of servicing to the main base without having to return the whole assembly.

Hardware with moving components will require servicing on a periodic basis to replace lubricants and clean bearing areas. The lubricants appropriate to the lunar environment must contend with a virtually hard vacuum and wide thermal extremes. Consideration of new solid lubricants is proposed for lunar base operations (Kimzey, 1988) rather than liquid or dry powder lubricants, which would degrade rapidly under operational conditions.

3.1.5 Cleaning and Drying

Cleaning and drying EVA hardware, especially the suits and outer coverings, is a major activity in these scenarios and requires detailed, innovative design work to minimize the time and effort involved.

The outside of the suit will require the ancillary use of a durable overgarment (ITMG) and/or specialized coatings to keep the lunar dust from impregnating and destroying the surface and fabric. Considerable effort should be expended in the formulation and development of coatings that will keep the dust from sticking to the exterior surfaces. Such coatings might be replenished by wiping, as demonstrated by the use of "wipes" on connectors and zippers during the Apollo program. The use of alpha emitters to neutralize static charges should also be explored.

Precautions must be taken to keep dust out of the lunar base habitat by removing as much dust as possible before the crewmember enters. One option (presented in section 2.5.4, Dustlock) is a combined dustlock/airlock at the entry to the habitat. This facility would be equipped with boot brushes, scrubbers, a grid floor, filters, forced air circulation, and a vacuum cleaner for mechanical dust removal. This facility would contain stowage areas for cover garments, tools, and expended equipment. It might also include recharge stations for batteries and compressed air equipment.

Another alternative might be a "shower stall" (using water or air) located between airlocks at lunar base; this area would be pressurized and heated if water is used. The use of recycled water in a hydraulically-pulsed shower with a grated floor can be envisioned. However, the wetting characteristics of lunar soil must be known in order to predict the effectiveness of water as a cleaning agent. It may be found that lunar dust repels water and will not become truly wet to cleanse the surface of the suit. If this is the case, then an air shower might be more effective. Ionization of the cleansing stream (either air or water) by the use of electronic or nuclear ionizers may be helpful in removing the dust. The airlock should contain a filtration system with electrostatic precipitators.

Cleaning of the interior of the suits should also be made as automatic as possible. Swabs and solvents with biocides should be used adjunctively to "soap and water" in the cleaning process. The service time to clean and resupply the suit should not exceed 1 hour, and each suit should be reusable for at least 100 times (800 hours) without extensive rework.

3.1.6 Caution, Warning, and Checkout

The caution and warning (C&W) systems of lunar surface EVA should be similar in all applicable respects to the systems used for the space suits and Space Station at that time. C&W tone and synthesized speech formats should be common with those of the Space Station for efficiency in crew cross-training and use.

The following requirements are quite specific since they are based on document No. EE-2-87-005 (U) Rev. A (Space Station Audio Systems Derived Requirements). If Space Station requirements are revised, then these requirements should be changed to maintain compatibility, especially as related to crew cross training in safety related systems.

- ▶ **Tone classes** - Signals shall be generated according to the following classes of events:

CLASS I (CREW EMERGENCY)

Siren tone (fire/smoke)
Klaxon tone (pressure decay)

CLASS II (HARDWARE FAULTS)

Dual alternating tones, 400/1024 Hz

CLASS III (SOFTWARE LIMIT FAULTS)

Single tone, 500 Hz

New classes - To be evolved during development of the base and proximity operations. Any faults having overall system implications related to safety must be CLASS II or III. New crew emergency conditions will probably be reflected back into Class I.

- ▶ **Distribution** - All classes of C&W tones should be distributed by the audio system. Class I tones should not be switchable. C&W for the suit should be autonomous and not depend upon processing in the lunar base central station for actuation of tones within the suit. An appropriate suit system reset should be provided on the suit.
- ▶ **CLASS I, hardwired** - The design should provide direct hardwired connection of CLASS I tones from the C&W system to a separate, non-switchable audio speaker coil located in at least two places within the helmet. The C&W tone volume should be controllable to permit voice communications at the same time but should have sufficient minimum level to ensure immediate attention.
- ▶ **Interfaces - EVA-Base** - A two-way hardwired interface should be provided when the EVA crew are under test in the airlock. A two-way radio interface should be provided when EVA is in progress.
- ▶ **Voice synthesis** - The system should provide the capability to synthesize voice C&W messages in addition to generic audio tones and provide the crew with the capability to enable/disable voiced messages. All message commands should originate in the C&W system and be distributed by the audio system.
- ▶ **Displays/indicators** - In addition to the tones and generated speech, C&W messages should be presented to the EVA crewmember via alphanumeric displays (including the HUD) and dedicated indicators.

- ▶ **Checkout** - The pre-/post-EVA checkout and the in-service monitoring should be under the supervision of the suit checkout and data management system. Fault conditions should be sensed, analyzed, and corrective action indicated to the crew. An expert system should be evolved as the data base grows. Typical functions to be evaluated automatically include:
 - Pressurization system integrity
 - Primary and emergency oxygen supply
 - Thermal cooling loop
 - Communication subsystem
 - Data, command, and display subsystems
 - Wiring and power continuity
 - Emergency purge or flush system
 - CO₂ removal system
 - Humidity control

- ▶ **Radiation warning**
 - Advance warning for solar flares and particle radiation arrival should be provided from a monitoring station on Earth or lunar base.
 - EVA crew should have a local detection/alarm system so they are not dependent on the communication system for a timely warning.
 - Real-time active dosimetry should be provided at several sites, both inside and outside the suit.

- ▶ **RF radiation warning**
 - Warning of RF fields into which the EVA crew are entering should be provided.

3.1.7 Communication Requirements

This section identifies requirements for EVA communication hardware that are driven by operations. These lunar base requirements are similar in many respects to those established for the Space Station. However, there are significant differences in the methods of routing and the additional functions accommodated by the much more advanced technology available in the later time frame.

The system should be built around a central station, located at lunar base, which controls an expandable network of local and remote users through dynamically selected direct and relay transmission links. Channels should be assigned in response to user requests and should automatically be sized in bandwidth, power, and processing to accommodate the user specified services.

The network should be transparent to the user and should incorporate reference/test signals that allow automated detection and analysis of a system malfunction. Automatically activated redundancy should maintain functional operation while repairs are being made. System failure should be graceful with the worst case still allowing simple manual operation or relayed transmission through alternate nodes. System operation should require a minimum of user insight into its mechanism. The number of redundancy levels available for a transmission should vary in accordance with the importance of its function. Several redundant signal paths should be provided for safety critical transmissions. Sortie or mission success communications should have some redundancy while enhanced capability functions may be single string.

IMPLEMENTATION:

► Routing/Capacity

A crewmember should be able to make a service request by voice or by using a keypad. The request, specifying the destination(s) and the types of service needed, shall cause the central base unit to configure the channel, directly or through relays, and provide the function and bandwidth necessary. The service request itself should not interfere with existing operations and should not be heard by other remote users. (See also "Access" and "Voice Privacy" in section 4.9, "Voice" in section 3.1.7 below, and "Voice Privacy" in section 3.2.12.)

Routing shall be through direct line of sight RF transmission, if possible; otherwise relays should be used as required. Transmission to or from shadowed or shielded areas, such as unpressurized work enclosures, should be through installed passive or active repeater antennas. Before resorting to a satellite relay, contact will be attempted automatically through a number of strategically placed local scanning beam antennas.

► Access

While every unit in the system should be technically accessible, inhibits shall be provided to protect specific channels if desired. Units typically accessible should include other EVAs, base consoles/individuals, teleoperated equipment, voice activated equipment, surface vehicles, remote stations, en route space vehicles, Space Station and Earth (via comm-platform, Tracking and Data Relay Satellite System (TDRSS), Advanced Communication Technology Satellite (ACTS), or other distribution networks available at the time).

► Frequencies

The frequencies used should be selected to minimize UHF-VHF interference from Earth and locally generated EMI to radio astronomy observations in microwave and HF-LF bands. Other considerations are discussed in section 4.9, Communications Interface Requirements.

► Signal Processing

Automatic level control, voice activation, digitizing, coding, multiplexing, demultiplexing, and packetizing are typical signal processing functions to be performed within the EVA communication system. While significant advances in the processing techniques and implementing hardware are expected, functions such as these will be required.

SERVICES PROVIDED:

► Voice

Each standard remote unit, such as that incorporated into the EVA suit system, should provide one operational voice channel having full duplex operation (simultaneous two-way operation). This is the requested/assigned channel already discussed.

An additional standard fixed channel should be provided for emergency use. A call for assistance made on this channel should be heard by all other units in any designated area, regardless of the assignment configuration. This channel should also be full duplex. Through this channel all crewmembers should be able to receive broadcast alerts, such as a warning of increased incident radiation hazard.

A duplex emergency backup channel should be provided for a minimum of EVA-to-EVA voice communication.

Multiple conversations and audio from various sources should be combined, if desired, so that persons can work together and so that voice documentation may contain all necessary inputs. This combined service should be full duplex.

The voice signal should be digitized using an algorithm dictated by the total system integration engineering. The digitized signal will be packetized, coded, and multiplexed with the other services prior to modulating the RF carrier. Address information contained in each packet will ensure proper destination regardless of node or relay routing used.

The option of encrypting the crew's conversation on the assigned channel to a level sufficient to ensure privacy should be provided.

▶ **Telemetry**

Suit systems and biomedical data shall be telemetered when required by the mission plan. The digital data should be multiplexed, packetized, combined, and processed with other services for transmission. These data can be routed to destinations other than those of the voice signal for processing by the health and safety monitoring systems. Consideration should be given to the possibility of routing tool or task-specific instrumentation data through the EVA communication system.

▶ **Commands**

Incoming commands that control critical emergency functions should be transmitted to the EVA where they are displayed and/or automatically acted upon. Noncritical commands may enable a supporting console operator to manipulate remotely the TV camera controls or some other sensor mounted on the EVA suit.

Outgoing commands may control functions such as teleoperations and text-and-graphics for the in-helmet display. Commands may be initiated by voice or a task-specific hand controller/input device. A specific voice command should be able to inhibit outgoing voice communication while voice commanding is in progress. Consideration should be given to incorporation of new techniques, such as command generation by head and eye motion and possibly even cortical activity, into teleoperations and positioning.

Like all other services in this integrated system, both incoming and outgoing commands should be digitized, packetized, interleaved, and processed prior to transmission.

▶ **Remote Sensors**

Numerous sensors including television, laser scanner, IR scanner, radar or others may be combined to produce enhanced video and other information. Such enhanced target information is especially valuable on the lunar surface where the absence of atmosphere-scattered light produces images of immense brightness contrast. The dynamic range of most optical sensors is greatly exceeded and it becomes difficult to see both the illuminated and unilluminated portions of the subject. Other sensors fill in the invisible portions. Combinations and "smart" sensors provide additional significant data. Range, range-rate, and angular change are typical.

A suit-borne sensor should be provided to monitor the radio frequency energy impinging on the suit. Information from the sensor should be displayed in the suit and should trigger an alarm if a safe level is about to be exceeded, allowing the crewmember to move out of the signal field or have it turned off.

Signals from the various sensors shall be multiplexed and processed into the composite which transmits the other services. Provision should be made to allow routing of the

various signal components, representing each sensor or combination, to different destinations as required for display, recording, computation, and teleoperation.

Combinations of selected voice sources and alphanumeric data should be routed to the video recording site where they will be mixed and integrated into the stored or transmitted video signal to prevent separation and loss.

► **Incoming Data**

Packetized data coming into the EVA shall be processed and delivered to the appropriate suit-borne systems such as the in-helmet-display. Telerobotic data should be provided to the EVA crewmember in various forms including audio, synthetic speech, video, graphic, alphanumeric, and tactile/force feedback.

► **Helmet Utilities**

The required video, text, graphic, suit, and life support data signals shall be routed to the heads-up display within the suit. Manual and automatic light attenuation should be considered for the visor/faceplate. Microphones and miniature speakers should be mounted on the helmet interior in strategic locations which allow free head movement. Special electronic and acoustic treatment are required to prevent interaction of the speaker and microphone signals. Careful attention must be paid to reduction of noise from air motion, pumps, fans, and other suit machinery. Similarly, noise due to suit motion, rubbing, and external vibration that is transmitted mechanically and through the suit air must be efficiently attenuated.

► **Reliability**

System reliability shall be achieved through proper design and fabrication of circuits and hardware as well as through redundancy of equipment and signal paths. As described, automated internal testing allows reconfiguration of components or paths with minimum user action. System failure shall be graceful with nonessential functions lost first and mission functions lost next, while safety critical functions are maintained.

3.1.8 Contamination

The most positive way of avoiding a toxic episode is to assure no exposure whatsoever to any toxicant or potential toxicant. Since zero concentration of contaminants is impossible, there will always be some exposure to chemicals, and it is necessary to have sufficient knowledge of the toxicity of those chemicals to be able to anticipate what effects will result from which exposure. With that knowledge, judgment can be used to formulate limits for exposures that are unlikely to result in immediate adverse health effects. There are some problems in exercising such judgment, however. Most available data on the toxicity of chemicals is based on either the results of experiments with animals utilizing relatively high concentrations of the chemicals and relatively short exposures or the results of human experiences with exposures to much lower concentrations.

A toxic effect of a chemical can be manifest in many ways. Most experimental animal exposures have studied frank, overt toxicity; e.g., gross effects on liver or kidney. In addition, many behavioral studies have been done, both with animals and humans. Elucidation of behavior modifications in experimental animals is frequently done in animal models that are much more crude than the human counterpart. This is because it is possible to use much higher exposure concentrations than would be acceptable with human test subjects. The same is true, of course, for determination of toxic effects in other organ systems. However, it is difficult to extrapolate from species to species in a quantitative fashion, even though knowledge of the human health effects is what is desired. Recently, the application of physiologically-based toxicokinetic models (Andersen, 1981; Andersen et al., 1980; Gerlowski and Jain, 1983; Himmelstein and Lutz, 1979) have shown utility in aiding that kind of

extrapolation by relating to physiological processes that form a sounder basis, for such extrapolations (Adolph, 1949; Dedrick, 1973; Dedrick and Bischoff, 1980).

The concept of criticality of function is applicable to contamination prevention in EVA activities. There is usually sufficient knowledge on the toxicity of chemicals that are likely to be encountered to be able to promulgate contamination limits that are not likely (to whatever level of statistical probability is desired) to evoke frank toxicity or mortality. However, that prediction may not be sufficient. When an astronaut is placed in a hostile environment, such as that on the lunar surface, it is possible that a small decrement of function (such as mental acuity) can result in a situation which renders the astronaut more susceptible to the hazards of the environment. Thus, a small decrement that would not be critical in a laboratory test situation can result in potentially dire consequences if it impacts his ability to cope with the hazardous environment. Consider the analogy of consuming several ounces of ethanol at a cocktail party with the subsequent operation of a motor vehicle. Lethality can result at a far lower blood alcohol concentration than would be encountered in direct ethanol toxicity. Nonetheless, inability to cope with the environment is a direct result of exposure to the toxicant (ethanol). Methods to assess neurotoxic effects on cognitive function are being developed, and instrumentation to perform such tests should be considered for possible installation and use at a lunar base.

Two sources of contamination are possible for EVA on the lunar surface: (1) materials that man has introduced into the environment (off-gassing from cabin and other habitat materials, components and equipment as well as thermal degradation of electrical equipment, plastics, hydraulic fluids, etc.) and (2) materials that are naturally present in the environment itself. In setting exposure limits, it is anticipated that information on existing materials will be available, information on new materials will be developed, and the effects of the lunar surface materials will be catalogued.

Decontamination procedures should take place as close as possible to the source of contamination and external to all airlocks, if possible.

The disposal of human wastes should be done through the lunar base sanitary disposal system only. The processing of such wastes will require major design effort. Established waste management/containment procedures and good personal hygiene procedures should always be observed.

Lunar gravity will help clear particulates from the work area but at a much slower rate than that on Earth. The widespread distribution of fine lunar dust will present a major problem, and slower clearance must be taken into account in scenario development.

Although the exact gaseous or liquid contaminants likely to create an exposure problem in lunar scenarios cannot be listed at this time, it is certain that several will ultimately be identified. Activities such as refueling might involve exposure to propellants and will require that a chemical control barrier be a part of the ITMG. It is suggested that selective trace contaminant detectors (patches that change color upon significant exposure) be placed on the suits and/or cover garments.

3.2 LUNAR EVA PHYSIOLOGICAL/MEDICAL REQUIREMENTS

The establishment and operation of a permanent lunar base with routine EVA require detailed attention to the requirements for physiological and medical support. Many unanswered questions about the adaptation of humans to long-term stays in the lunar environment must be answered. Our success in future space missions, including lunar habitation, will be determined, in large measure, by our ability to maintain and ensure the health of each of the crewmembers during the mission as well as upon his or her return to Earth.

The major physiological and medical requirements for EVA in a lunar base might be classified in five broad categories:

- ▶ Appropriate provisions for life support
- ▶ Accommodation of anticipated physiological and psychological changes
- ▶ Provision of countermeasures against long-term physiological and psychological changes
- ▶ Provision for medical treatment of natural disease processes as well as accidents
- ▶ Health assessment and maintenance.

These requirements have an impact on the design of almost all lunar base hardware and extend from considerations of methods for detoxifying, purifying, and recycling the environment to the development of dietary and exercise regimens.

3.2.1 Anthropometric Sizing Accommodations/Dimensional Limits

There is a requirement to size to the full range of the potential population given the colonization approach of bringing many people to the moon. If this requirement is not met, then the population performing EVA must be limited to the sizing range of the LEMU, and provisions will have to be made to supply others with emergency pressurized capsules to provide life support in the event of a system failure at the base.

The sizing of the LEMU will have to accommodate the changes in the physical stature of individuals in the 1/6 gravity environment that will differ from those on Earth and in microgravity. Anthropometric sizing should consider the following reported dimensional changes (Waligora, 1979) that occur at 1/6 g as compared to 1 g:

- ▶ Postural changes associated with changes in gravity
- ▶ Spinal curvature and dimensional changes
- ▶ Abdominal dimensional changes associated with fluid shifts
- ▶ Other anthropometric changes.

Of course, dimensional changes may occur in the opposite direction if the crewmember arrives on the moon after a stay on Space Station; thus, some planning is required to accommodate resizing changes that are dependent upon whether the crewmember is arriving directly from Earth or from a long-duration sojourn at Space Station. Dimensional changes associated with changes in gravity (from 1 g to 1/6 g or from 0 g to 1/6 g) should be considered.

If there is a major resizing capability by LEMU component, then a clean assembly and disassembly area must be provided to protect the components from lunar soil contamination during resizing. This should be carried out at the main base rather than at a remote site. There should be some capability to perform resizing at the remote site to accommodate adjustments as a function of tasks and workload; this might be limited to arm and leg adjustments to provide a more comfortable working envelope for the crewmember while walking or performing manual tasks.

3.2.2 Metabolic Profiles

The metabolic expenditures during Apollo lunar surface EVAs have been analyzed in detail using three independent, and somewhat indirect, methods of metabolic assessment. The data

contain no major anomalies and compare well with those anticipated by extrapolation from orbital EVA data and terrestrial studies.

Table 3-1 contains a summary of the data on metabolic expenditures for Apollo lunar surface EVA data (Waligora and Horrigan in "Biomedical Results of Apollo," 1975). These data demonstrate the approximate range of metabolic expenditures that might be anticipated for the activities contained in the scenarios of this study. The range of metabolic rates that occurred during the entire lunar EVA experience on Apollo was 229 to 351 watts (197 to 302 kcal/hr), with a range on selected tasks of 115 to 522 watts (99 to 450 kcal/hr). The exact suit design and configuration will have some impact on the numbers to be anticipated; however, the additional burden of increased suit pressure might well be offset by the increased mobility of better joints and flexibility that have been designed into the newer generation of suits. It is also anticipated that individual variations from crewmember to crewmember might be far greater than that which might occur from one type of suit to another.

Thus, the data contained in Table 3-1 will be taken as roughly typical of those to be expected for similar tasks in the advanced EVA scenarios. Of particular interest to this study are the lower metabolic rates associated with driving and riding the lunar rover and the higher rates associated with more strenuous activities. The data of Table 3-1 provide a significant level of confidence in the bounds of metabolic expenditures to be expected. It should be noted that peak work rates are more important in assessing the strain on the crewmember than are mean work rates (Astrand and Rodahl, 1986).

Based on previous NASA missions, the Environmental Control System should support the following approximate Liquid Cooled Garment (ECS) (LCG) metabolic rates:

- ▶ Average metabolic activity rate of 290 watts (250 kcal/hr, 992 Btu/hr) or 1.86 watts/lb (1.6 kcal/hr/lb, 6.3 Btu/hr/lb) for duration of EVA.
- ▶ Maximum metabolic activity rate of 581 watts (500 kcal/hr, 1984 Btu/hr) or 3.72 watts/lb (3.2 kcal/hr/lb, 12.7/Btu/hr/lb) for 15 minutes and 468 watts (403 kcal/hr, 1600 Btu/hr) or 3.02 watts/lb (2.6 kcal/hr/lb, 10.3 Btu/hr/lb) for 1 hour.
- ▶ Minimum metabolic activity rate of 75 watts (65 kcal/hr, 285, Btu/hr) or 0.49 watts/lb (0.42 kcal/hr/lb, 1.67 Btu/hr/lb) for 1 hour.

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**Table 3-1. Metabolic Expenditures During Apollo Lunar Surface EVA
(Biomedical Results of Apollo, NASA SP-368, 1975)**

Mission No.	EVA No.	Crewmen	Metabolic Rate, J/hr x 10 ³ (kcal/hr)					EVA Duration (hr)
			ALSEP Deployment	Geological Station Activity	Overhead	Lunar Roving Vehicle Operations	Total For Activities	
11	1	CDR	818 (195)	1023 (244)	899 (214)		949 (227)	2.43
		LMP	1267 (302)	1471 (351)	1269 (303)		1267 (302)	2.43
	1	CDR	864 (206)	1017 (243)	1232 (294)		1028 (246)	3.90
		LMP	1006 (240)	1028 (245)	1119 (267)		1054 (252)	3.90
12	2	CDR		913 (218)	902 (215)		922 (221)	3.78
		LMP		1058 (253)	1038 (248)		1054 (252)	3.78
	1	CDR	762 (182)	1230 (294)	920 (219)		843 (202)	4.80
		LMP	947 (226)	729 (174)	1084 (259)		980 (234)	4.80
14	2	CDR	494 (118)	996 (238)	895 (213)		959 (229)	3.58
		LMP	851 (203)	1120 (267)	894 (213)		1054 (252)	3.58
	1	CDR	1182 (282)	1153 (275)	1417 (338)	639 (152)	1159 (277)	6.53
		LMP	1369 (327)	778 (186)	1226 (293)	435 (104)	1033 (247)	6.53
15	2	CDR	1019 (243)	1227 (293)	1202 (287)	624 (149)	1054 (252)	7.22
		LMP	1110 (265)	792 (189)	1116 (266)	414 (99)	854 (204)	7.22
	3	CDR	1095 (261)	1013 (242)	1303 (311)	578 (138)	1086 (260)	4.83
		LMP	962 (230)	788 (188)	981 (234)	447 (106)	854 (204)	4.83
	1	CDR	869 (207)	905 (216)	1146 (273)	725 (173)	917 (219)	7.18
		LMP	1081 (258)	1125 (258)	1154 (275)	666 (159)	1065 (255)	7.18
16	2	CDR		933 (223)	1044 (249)	470 (112)	822 (197)	7.38
		LMP		1023 (244)	987 (236)	438 (105)	874 (209)	7.38
	3	CDR		966 (231)	983 (235)	518 (124)	854 (204)	5.67
		LMP		1013 (242)	1107 (264)	430 (103)	864 (207)	5.67
	1	CDR	1192 (285)	1094 (261)	1267 (302)	508 (121)	1150 (276)	7.20
		LMP	1166 (278)	1255 (300)	1193 (285)	472 (113)	1139 (272)	7.20
17	2	CDR		1094 (261)	1267 (302)	506 (121)	864 (207)	7.62
		LMP		1255 (300)	1193 (285)	472 (113)	874 (209)	7.62
	3	CDR		1094 (261)	1267 (302)	506 (121)	980 (234)	7.25
		LMP		1255 (300)	1193 (285)	472 (113)	990 (237)	7.25
Mean			1018 (244)	1018 (244)	1123 (270)	518 (123)	980 (234)	
Total time (hr)			28.18	52.47	52.83	25.28	158.74	

CDR = Commander
LMP = Lunar Module Pilot

It should be noted that metabolic rates required for activity on the lunar surface were accurately predicted for a suit pressure of 3.7 psia (25.5 kPa or 192 Torr). For example, during Apollo 14, walking traverses averaging 0.45 mph (0.2 m/sec) and 1.54 mph (0.69 m/sec) required 278 kcal/hr (323 watts) and 305 kcal/hr (355 watts), respectively (Waligora and Horrigan, 1975). The predicted values for numerous simulations were about 25% less than the measured values (Roth, 1968). An important question remaining is what a reasonable prediction might be for the metabolic cost of working in a particular type of suit pressurized to 8.3 psia (57.2 kPa or 429 Torr). Linear extrapolation of the earlier simulation data summarized by Roth in 1968 for 0 psig and 3.7 psig to 8.3 psia (57.2 kPa) suggests that metabolic rate during walking at 0.5 mph would be increased by 34% by the added suit pressure. At a speed of 1.54 mph (0.69 m/sec), the increase would be approximately 42%, and at 3.5 mph (1.56 m/sec) (speeds reached during Apollo 14), the added pressure would add about 50% (to 576 kcal/hr or 670 watts). Increasing this by 25% for the difference between previously measured and predicted values, a value of 720 kcal/hr or 837 watts is obtained for the higher pressure suits of a design similar to those used in prior lunar missions. It would seem imperative, therefore, that adequate simulation testing be performed with the Zero Prebreathe Suits (ZPSs) to determine that the increased mobility and flexibility do indeed reduce the metabolic cost below an allowable level of 500 kcal/hr or 581 watts. Other factors that influence metabolic rate, independent of suit pressure, are suit weight, suit flexibility, and astronaut training. Factors influencing metabolic rates that are unique to this scenario are:

- ▶ Deconditioning during Space Station sojourn or long-term occupation of lunar base
- ▶ Specific suit design parameters
- ▶ EVA equipment (tools, foot restraints)
- ▶ Lunar day/lunar night cycles
- ▶ Work tasks in rugged terrain at reduced gravity (1/6 g).

The following topics are recommended for further study:

- ▶ What impacts do age, gender, and degree of physical fitness have on EVA metabolic costs?
- ▶ What effect does a constant light cycle have on EVA metabolic costs? How does this relate to the overwork potential imposed by constant daylight?
- ▶ How does the suit affect individual metabolic costs; i.e., different fits, ratio of crewmember size to weight of suit, etc.

3.2.3 Suit Operational Pressure Level

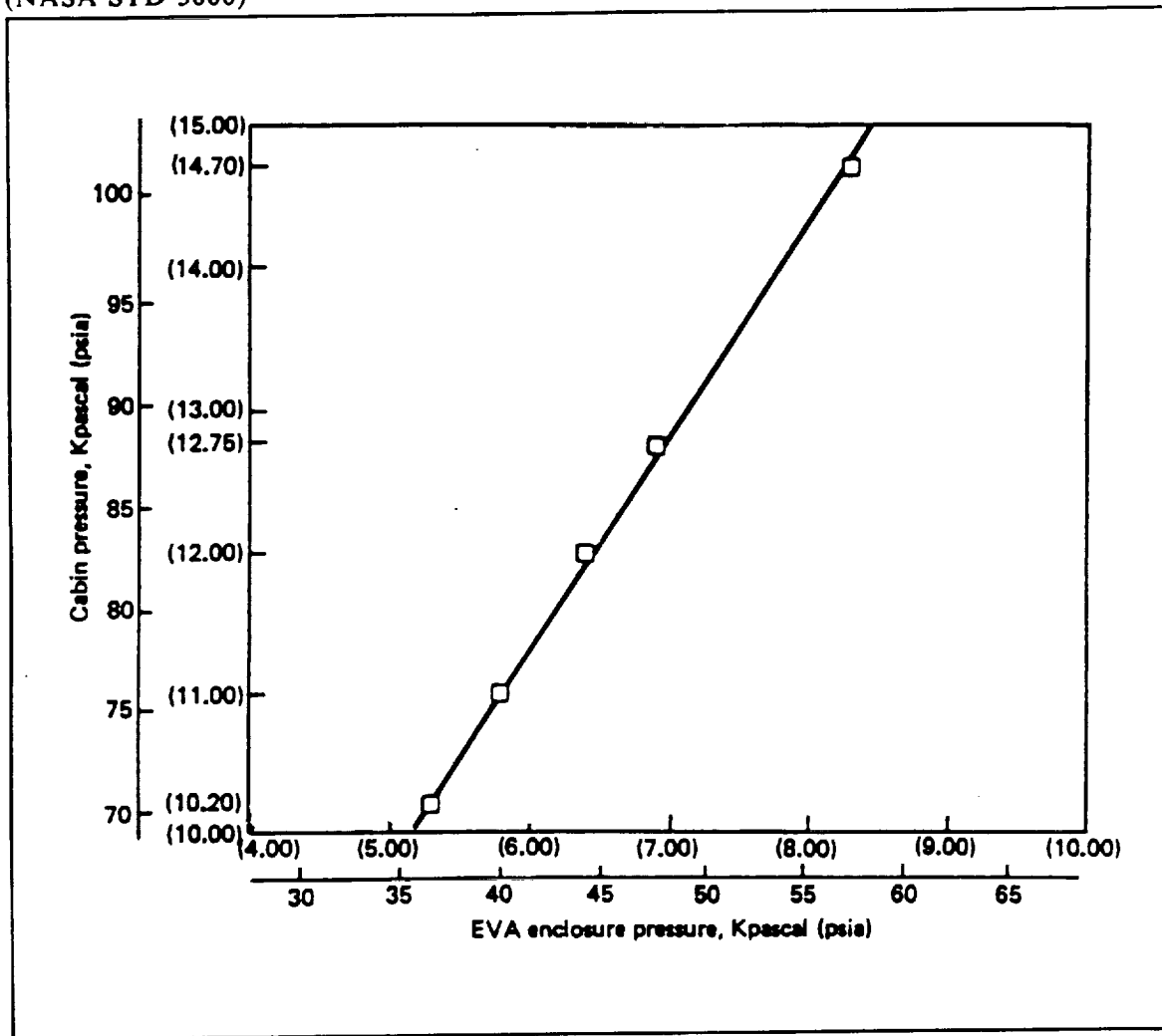
An operational lunar base, using normal Earth gas composition of 78% nitrogen and 21% oxygen, should be designed with cabin and suit pressure combinations that allow zero-prebreathe EVAs. The maximum feasible cabin pressure is that of sea level (101 kPa or 14.7 psia), but there are numerous potential advantages to reducing the cabin design pressure to the equivalent of approximately 4,000 feet altitude on Earth (87 kPa or 12.6 psia). There may also be some system advantages to the use of different gas mixtures.

The R value, the ratio of nitrogen partial pressures in tissues to the final total pressure, should not exceed 1.4. Figure 3-1 is a plot of cabin pressure versus EVA enclosure for $R = 1.40$ (no prebreathe requirement). The LEMU should be pressurized to 57 kPa (8.3 psia) to provide a "no prebreathe" capability when moving in and out of facilities pressurized to 101 kPa (14.7 psia). Tradeoffs can be made in suit pressures to achieve improvements in suit flexibility at lower pressures. If the condition that R is maintained at 1.4 is applied, the LEMU could be pressurized to 48 kPa or 7.0 psia in order to provide no prebreathe capability when moving in and out of facilities pressurized to 87 kPa or 12.6 psia. If the cabin pressure is allowed to be reduced for short periods of time to the equivalent Earth altitude of about 10,000 feet (70 kPa or 10.2 psia), then suit pressures as low as approximately 37 kPa or 5.3 psia might be utilized. The rate of change of pressure to which a crewmember is subjected shall be limited to 0.34 kPa per second (0.05 psi/sec) maximum under normal conditions of depressurization and repressurization.

Emergency pressurization shall be provided to maintain the suit at a minimum pressure of 41.4 kPa (6.0 psia) for a minimum of 30 minutes. Emergency repressurization shall be limited to 6.9 kPa/sec (1.0 psi/sec). (See NASA STD-3000.) Further studies of the feasibility of emergency pressurization of the suit to 2.8 ATA for potential use in hyperbaric treatment should be conducted. This type of overpressure may require defeating emergency "pop-off" safety mechanisms and probably will not prove feasible. However, it would be a highly desirable feature for expediting the emergency treatment of a crewmember experiencing barotrauma.

The composition of the atmosphere of the suit, if it is an oxygen/nitrogen mixture, shall meet all requirements for "zero prebreathe." The oxygen partial pressure shall be maintained above the minimum normoxic pressure level and below 41 kPa (6 psia). (See NASA STD-3000, pg. 14.2-6.) Some recent data report that oxygen toxicity may not be as significant a factor as previously thought (Webb, 1988). NASA is currently sponsoring oxygen toxicity measurements by the United States Air Force.

**Figure 3-1. Cabin Pressure Versus LEMU Pressure for R = 1.40
(NASA STD-3000)**



3.2.4 CO₂ Levels

The inspired level of carbon dioxide in a suit is composed of the ambient CO₂ partial pressure in the suit plus that rebreathed from the crewmember's expired gases. NASA STD-3000 states that the inspired carbon dioxide during EVA:

"Shall not exceed 1.03 kPa (7.6 Torr or 0.15 psi) at metabolic rates up to 465 watts (400 kcal/hr or 1600 Btu/hr). The inspired CO₂ shall not exceed 1.31 kPa (10 Torr or 0.19 psi) for periods up to 15 minutes at metabolic rates up to 581 watts (500 kcal/hr or 2000 Btu/hr), and shall not exceed 2.00 kPa (15 Torr or 0.29 psi) for periods of 5 minutes at metabolic rates up to 732 watts (630 kcal/hr or 2500 Btu/hr)."

It also states that the optimum value for the partial pressure of carbon dioxide is 0.04 kPa (0.3 Torr). Thus, it is imperative that the scrubbers in the suit maintain the carbon dioxide partial pressure below 1.03 kPa (7.6 Torr) for daily operation under the conditions of this scenario. A warning alarm shall occur for partial pressures above 1.33 kPa (10 Torr) and the crewmember should reduce activity and limit exposure to 15 minutes maximum. If the CO₂

partial pressure rises above 3.0 kPa (23 Torr), the EVA should be terminated as soon as possible or emergency methods should be used to reduce the carbon dioxide level while reducing metabolic activity.

Accumulation of CO₂ in a human habitat will result in two serious consequences, (a) a progressive rise in pulmonary ventilation resulting from the rise in P_ACO₂ and arterial PCO₂, stimulating the chemoreceptors (Figure 3-2) and (b) visual and auditory hallucinations, headache, nausea, asphyxic sensations, sweating, and loss of consciousness which occur with increasing prevalence as concentrations and time of exposure increase (Figure 3-3).

If the space around the crewmember in an enclosure pressurized to one atmosphere has a volume equal to the body, about 70 liters (Lovelace Foundation, 1975), a 10% level for a resting individual will be reached after approximately 28 minutes if the CO₂ scrubber fails totally. If the individual were working at 3 times the resting metabolic rate in manipulative tasks, then this level would be reached in less than 10 minutes. If a crewmember were working at a metabolic activity rate of 581 watts (500 kcal/hr), then this level would be reached in about 4 minutes without an active CO₂ removal system. The partial pressure of CO₂ is independent of suit pressure; however, the percentage of CO₂ varies inversely with suit pressure. In order to allow for 10 hours of work at an average of three times the resting metabolic rate, a total of $0.250 \times 3 \times 60 \times 10 = 450$ liters or 20.2 moles of CO₂ will be produced which must be effectively scrubbed to prevent the concentration from exceeding 2% or a partial pressure of 1.0 kPa (7.5 Torr or 0.145 psi) for a suit pressurized to 50 kPa (375 Torr or 7.3 psia). Even at this level, there will be significant CO₂ storage in the body, which will take an appreciable time to be eliminated when returning to the CO₂-free environment of lunar base. For example, a 10-hour exposure to a 0.93 kPa (7.0 Torr or 0.135 psi) CO₂ environment will cause an increase of approximately 3.3 liters in body CO₂ stores (Farhi, 1964). This is about a 50% increase in the normal CO₂ stores of the body.

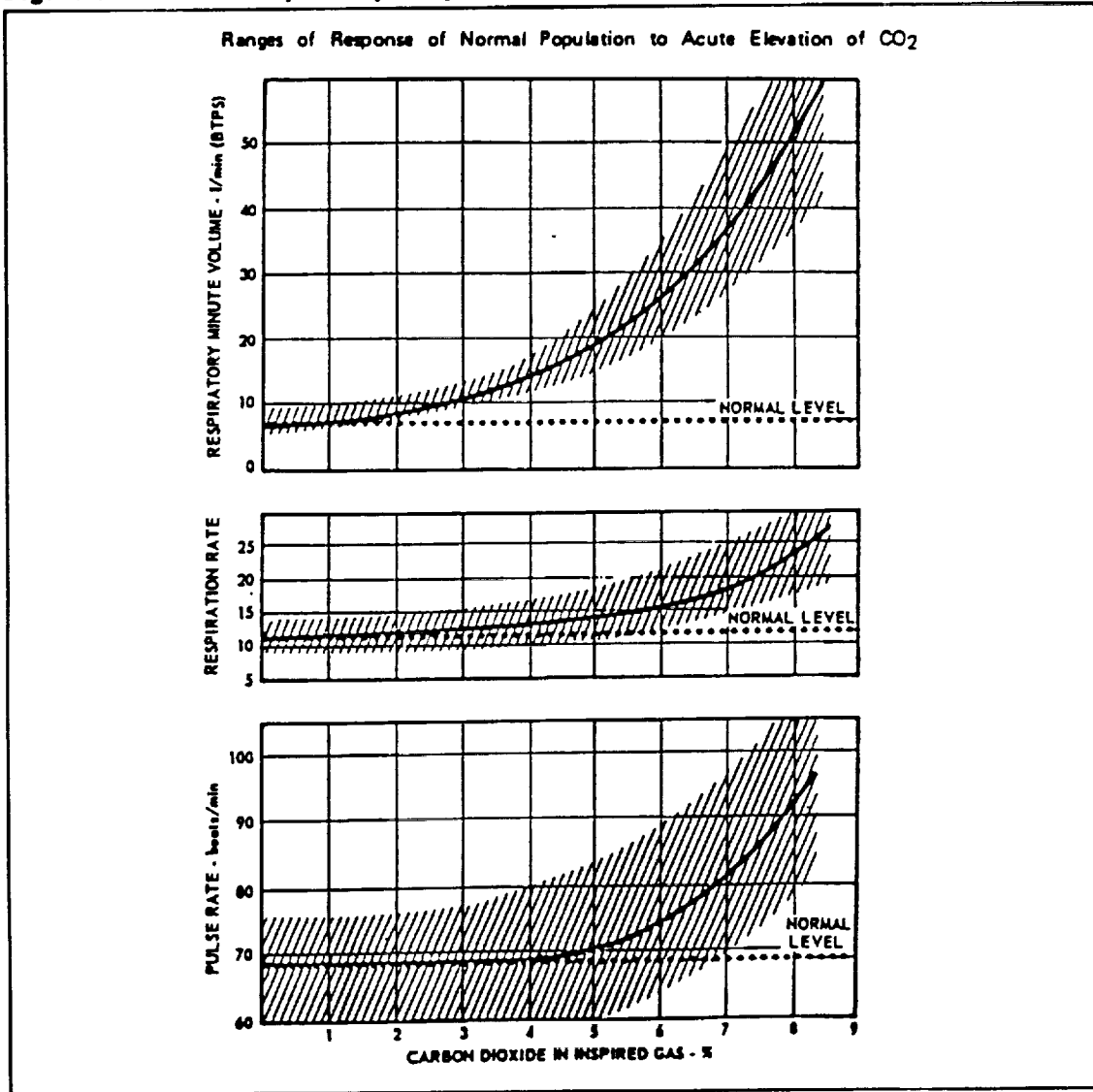
The use of disposable lithium hydroxide canisters should be reserved for emergency requirements. Due to the frequency and duration of EVA activities, recyclable methods for CO₂ removal will be essential. Several recyclable techniques might be applicable and should be traded off in the design of the suits. Such a scrubber should be capable of removing CO₂ at the minimum rate of 50 liters per hour and should provide advanced warning of depletion.

On occasion, a crewmember might be working in a pressurized facility with an elevated CO₂ level, such as an agricultural facility where atmospheric conditions are optimized for plant growth. Although most lunar base facilities will be pressurized up to a maximum of 101 kPa (760 Torr or 14.7 psia), some consideration should be given to the desirability of allowing a suited crewmember to enter a partially pressurized facility with an elevated CO₂ environment.

Recommended further study: How does long-term exposure to CO₂ affect calcium metabolism?

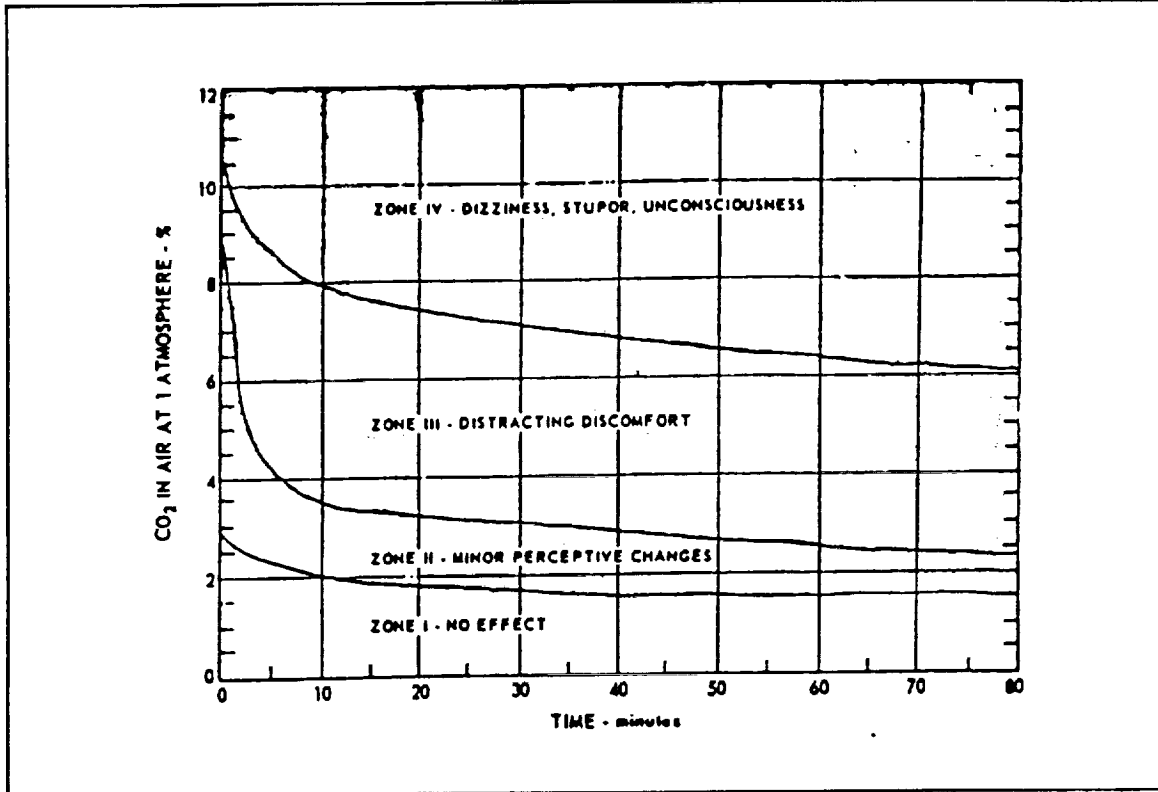
c-2

Figure 3-2. Cardiorespiratory Response to Carbon Dioxide



The immediate effects of increased CO₂ on pulse rate, respiration rate, and respiratory minute volume are shown for subjects at rest. The hatched areas represent one standard deviation on each side of the mean. To convert percentage of CO₂ to partial pressure, multiply fraction of CO₂ by 760 mm Hg. (Roth, 1968.)

Figure 3-3. Symptoms and Thresholds of Acute and Chronic Carbon Dioxide Toxicity



This chart presents the general symptoms common to most subjects when exposed for the times indicated to mixtures of carbon dioxide in air at a total pressure of 1 atmosphere. In Zone I, no psychophysiological performance degradation, or any other consistent effect, is noted. In Zone II, small threshold hearing losses have been found and there is perceptible doubling in depth of respiration. In Zone III, the zone of distracting discomfort, the symptoms are mental depression, headache, dizziness, nausea, "air hunger," and decrease in visual discrimination. Zone IV represents marked deterioration leading to dizziness and stupor, with inability to take steps for self preservation. The final state is unconsciousness. (Roth, 1968.)

3.2.5 Thermal Storage of Body Heat

The limits to crew performance may be defined in terms of the maximum allowable internal temperature, which is given as 39 °C for a resting or lightly working person (and 40 °C during exertion), or in terms of the maximum allowable heat storage, which is given as 6280 Joules/kg (1.5 kcal/kg) of body weight (or 3.14×10^6 Joules/m² or 75 kcal/m² of body surface) (Grumman, 1985) and as 4.2×10^6 Joules or 100 kcal (Blockley, et al., 1954). NASA STD-3000 allows up to 11,302 Joules/kg (2.7 kcal/kg or 4.9 Btu/lb) of body weight or 565,110 Joules/m² (135 kcal/m² or 49.9 Btu/ft²) of body area. The Grumman report (1985) and Marton et al. (1971) both agree on the use of 0.83 as the average specific heat of human tissue but differ in the description of heat storage. Marton (1971) offers formulae for terms in a heat balance rate equation, and so the heat storage term is made proportional to the time rate of change of temperature. Waligora (1979) and Marton (1971) consider the overall quantity of what one

might call "excess" thermal energy stored in a human body. It is to this overall quantity that the numbers given above as maximum allowable pertain. With regard to the prediction of thermal limitation due to storage, Waligora points out that the approach is accurate when the limitation to heat transfer is the removal of heat. When the storage is due to failure of the thermoregulatory system, individual variations will make predictions less accurate. The implication of this observation is that in the situation of a person working hard in a hot, dry and "windy" environment, thermal storage of body heat may not be predictable on the basis of heat transfer theory alone. Thus, if a high ambient temperature is allowed to occur in an EVA suit, development of specific countermeasures on an individualized basis may be necessary. Some dietary countermeasures to heat tolerance, such as various electrolytes and vitamin C, might be of use.

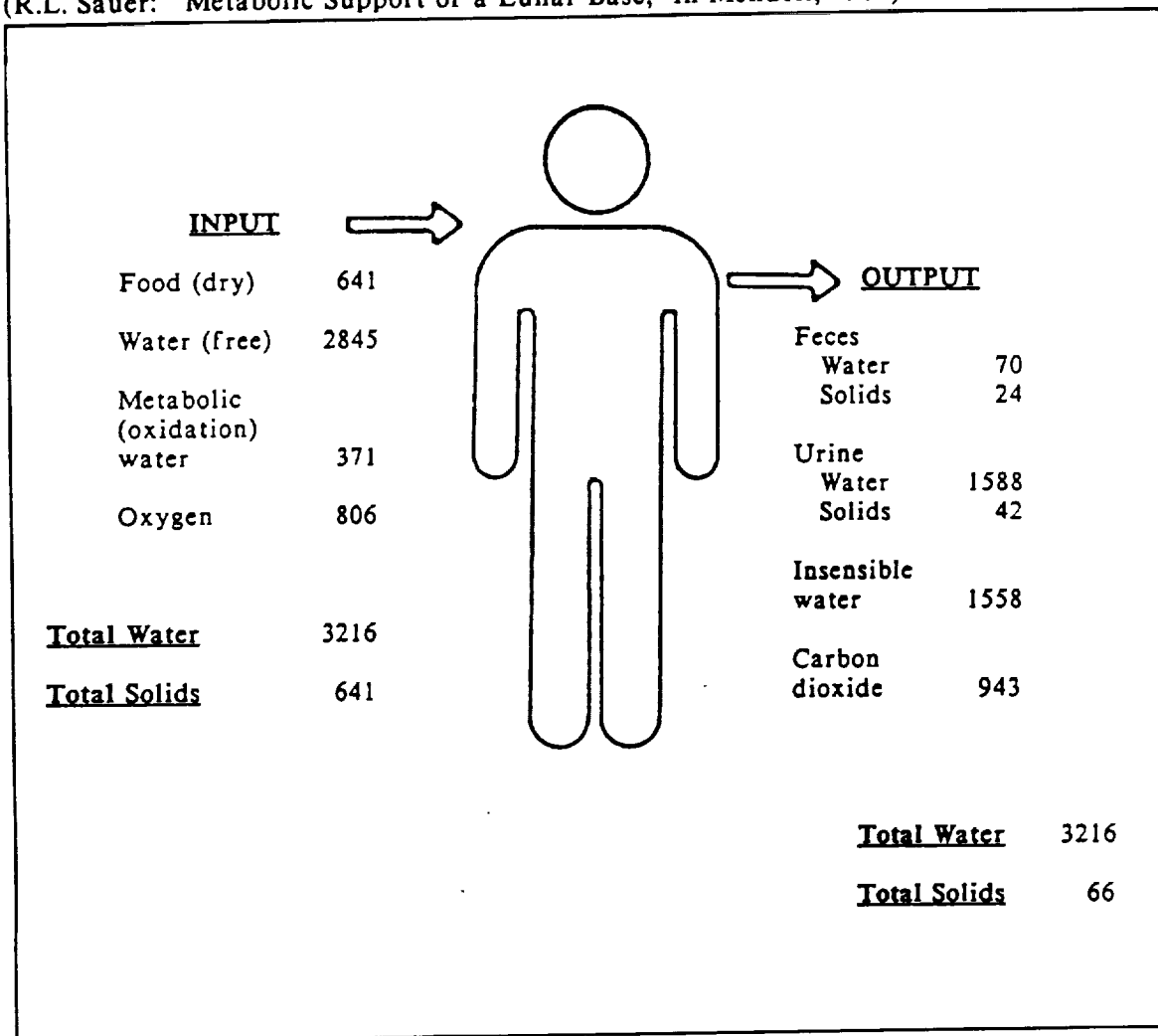
The liquid cooling garment (LCG) was found to work extremely well during the Apollo EVAs by allowing "work rates as high as 581 watts (500 kcal/hr) without thermal stress" (Nicogossian and Parker, 1982, pg. 110). This is particularly important for minimizing fatigue and maximizing comfort during long EVAs on the lunar surface. Air cooling, in addition to its generally inefficient heat transfer, produces a greater background noise level that could be a nuisance to the EVA crewmember engaged in daily EVAs. The overwhelming preference of a limited sample of astronauts who have evaluated both types of cooling and used the LCG in operations is for the recommendation of an LCG-type cooling system for advanced EVA.

One of the purposes of suit environmental control is to achieve a continuous balance between heat production and heat loss. Obviously, the exterior surfaces of the suit on the lunar surface are exposed to a wide range of temperatures as the exposure to incident radiant energy changes. Historically, the suit has provided isolation between these temperature extremes and the crewmember inside the suit while removing body heat with a LCG cooled by controlled sublimation of a water supply. For repetitive operation on the lunar surface, it will be important that the water supply be conserved. Thus, it may be a requirement that the LCG be cooled (1) by a change of state (such as from solid to liquid) without loss of consumables or (2) by a "heat pipe" type design that radiates the heat to the cold (lunar shade) environment. The total body heat to be dissipated is roughly 12×10^6 Joules/day (3000 kcal/day) per person. When the amount of energy involved is calculated on a long-term basis, it becomes obvious that efficient methods of transferring heat must be used for lunar surface EVAs.

Figure 3-4 lists the average daily input requirements and output estimates for humans in space. It is obvious that resource reclamation processes are an important technology gap that must be closed to make an operational lunar base possible.

A topic requiring further study is the degree of effect that exposure to ionizing and non-ionizing radiation has on the body's ability to thermoregulate.

Figure 3-4. Daily Support Requirements in Grams/Person/Day
 (R.L. Sauer: "Metabolic Support of a Lunar Base," in Mendell, 1985)



3.2.6 Personal Hygiene

All Crewmember personal hygiene activities in preparation for EVA that have been established for EVA in LEO are also applicable to advanced EVA at lunar base. However, there is a clear requirement for full shower facilities in the lunar base. The use of sponges and skin wipes is appropriate only as a supplement to a shower. Attention should be given to deodorization as well as to the provision for a supply of pleasant aromas.

All suits, as well as the LCG, must be designed for ease of cleaning and drying. Efforts must be made to minimize the entrapment of dirt, cleaning solutions, biocides, and body fluids within crevices. All materials used in the suits should be selected such that they do not serve as major growth media for bacteria or fungi. Methods of verifying the removal of bacteria and fungi should be developed and incorporated in the cleaning process. Any lubricants required to be used on the interior of the suits should be designed to be applied under reduced gravity conditions and should meet all toxicity requirements.

Cleaning and disinfecting procedures for all materials in contact with a crewmember should be thorough, effective, and simple to conduct. The use of large swabs saturated with cleaners and bactericides is appropriate. Drying may be best effected by the use of forced air. Techniques should be developed for automated cleaning and drying of the suits so that each enclosure can be cleaned and dried within the time allowed between EVA episodes.

The relatively short times between the extended EVA of each crewmember may make the use of salves or ointments important for crewmember comfort when abrasions have occurred. The types of activities in the scenarios and the relatively loose-fitting suit could cause a crewmember to abrade his skin in unpredictable places. The use of a salve or ointment may be an important palliative (and lubricant) to relieve ongoing skin irritation at pressure points. However, such materials must be carefully selected to avoid contaminating or damaging the suit.

3.2.7 Waste Management/Containment System

EVA activities will require that human waste products (urine, feces, menses, and vomitus) be containerized. Cumbersome devices for waste management and containment should be avoided. The devices currently used have proven adequate for zero-g EVAs, but slight modifications may be necessary to optimize their use in 1/6 g, where the weight of the waste is once again a consideration. Of course, dietary intakes of low-residue food should be considered during periods of planned EVA, but reasonable limits should be established to assure proper nutrition and hydration.

Treatment of the collected wastes within the confines of the suit should be considered. If a suit has "hands-in" capability, it might be possible to treat these wastes chemically in order to render them non-noxious, physiologically safe, and deodorized.

The quantities of human wastes to be contained (listed below) have been derived on the basis of historical guidelines as reconciled to the most recently accepted standards (NASA STD-3000):

- ▶ Urine Containment Devices must accommodate male/female usage and have an internal storage capacity for 1000 cc.
- ▶ Fecal Containment Devices must have an internal storage capacity for 500 cc.
- ▶ Vomitus Containment Devices must have an internal storage capacity for 750 cc.
- ▶ Menses Containment Devices might utilize conventional absorbent/collection devices (tampon or sanitary napkin) with a capacity of approximately 100 cc.

All devices must be designed for hygienic collection, containment, storage, and disposal in the 1/6-g environment. They also must be designed to operate as a system in the suit for the maximum duration of an EVA. Cross-contamination from containment subsystems to other suit subsystems (such as drinking water, food, circulating air supply, and helmet/visor) must be prevented. Consideration should be given to cleaning and reusing certain collection devices. Routine EVAs in a lunar base would use a significant volume of disposable containment devices which would be costly to supply for one-time use. Provisions must be made to dispose of the contents within the human waste disposal system of the lunar base. A combination of disposal and reuse techniques to reduce cleaning time might be desirable.

3.2.8 Food/Water

Provisions for adequate food and water will be necessary within the confines of the suits. Weight and volume limitations in the suit will make it necessary to provide small quantities of high-energy-producing foodstuff that will be matched calorically to the physiological load anticipated during EVA. Prior studies have shown that up to 1700 cc (56 ounces) of water and

3.14 X10⁶ Joules (750 kcal) of food might be required during each major EVA event in this scenario. Based upon the anticipated energy expenditure and the duration of each EVA, and recognizing the satisfying nature of "recreational" snacks, it is recommended that up to 6.3 x 10⁶ Joules (1500 kcal) of food be provided in the suit, especially for those missions involving strenuous activities.

The daily diet should supply the basic nutritional requirements of the National Research Council as established by their Recommended Dietary Allowances (RDA). The content of protein, carbohydrates, fats, vitamins, and minerals in the food supply should be monitored and controlled. A high caloric and low residue diet should be used to the extent possible during EVA activities.

To carry the required amount of water, the drinking bag may have to be distributed in the suit and compartmentalized to avoid "sloshing" disturbances with motion. It should be constructed of FDA-approved materials that can be cleaned and disinfected easily. Positive-activation valving is an essential part of the design to minimize spills within the suit. Supplementation of dietary electrolytes, such as potassium, will be essential and might be accomplished within the food or water supply. Considerable care should be exercised to maintain adequate electrolyte levels but to avoid overdosage that could lead to diarrhea. Oral administration of timed release supplements should be considered. Some method of indirectly monitoring serum electrolytes would be highly desirable.

The predominately vegetarian diet may be one of the unique characteristics of the food in a self-sustaining lunar base. Thus, plant proteins will, to a large degree, replace animal proteins in the diet, and additional effort and planning will be required to maintain nutritional balance. This high residue/high fiber diet might present problems in waste containment and disposal. It may become more practical to develop and raise fish or other animal products that produce less residual bulk in the feces.

3.2.9 Biomedical Data Monitoring

The biomedical data monitoring requirements on an operational basis at a site remote from the lunar base during lunar surface operations will be derived to measure and monitor only those data that are essential to assess the real-time physiological well-being of each of the EVA crewmembers.

The following indirect (noncontact) measurements are required for each EVA crewmember:

- Radiation exposure (dosimetry of both ionizing and non-ionizing radiation)
- Oxygen partial pressure (and consumption)
- Carbon dioxide partial pressure
- Suit pressure.

The following measurements might be made with direct contact transducers/sensors (perhaps built into the LCG):

- Lead II (or M-V5) electrocardiogram (processed for heart rate and arrhythmia detection)
- Respiration (monitored for respiration rate)
- Skin temperature.

Since these measurements will be made routinely on an operational basis, all transducers and/or sensors should be applied automatically when the LCG is donned. It is envisioned

that two (perhaps three) sensors can be configured to sense the electrocardiogram, respiration, and skin temperature.

The monitoring of these data must take place both at the EVA site and at lunar base. All data should be presented to the suit data system for alarm detection and selected display. The data also should be telemetered to lunar base where they should be monitored automatically for preset and adaptive limits. A complete arrhythmia detector should be used for analysis of the ECG data. Alarm conditions shall alert both lunar base personnel and EVA crewmembers.

Consideration should be given to the use of biological dosimetry techniques. These techniques might supplement electronic instruments and be sensitive to a wider range of radiation. However, it is not envisioned that such sampled techniques will completely replace real-time processing of radiation data in the time period of interest.

Pulse oximetry, with its expanding capability and shrinking size, might be a valuable addition to the biomedical monitoring instrumentation, especially if techniques can be developed for easy and automatic application of the sensor.

3.2.10 Medical Care/Facilities

EVAs at a site remote from lunar base provide an obvious planning problem for the provision of adequate emergency and routine medical care. It is assumed that the lunar base will contain a complete, well-equipped medical facility for both testing and treating all anticipated medical conditions. One of the rovers might be equipped with an ambulance module which will allow it to function as a remote urgent care vehicle, similar in many respects to a terrestrial mobile coronary care unit or an advanced life support vehicle but containing more specialized and diversified capability. Some of the provisions currently under consideration for the Crew Emergency Return Vehicle (CERV) might be considered also for installation in the ambulance module. The medical facilities and equipment in the ambulance module must have the capability to stabilize an ill or injured crewmember for transport back to the lunar base for more definitive care.

Medical care at the remote site might utilize the equipment and facilities of an ambulance module on a rover. Lunar EVA crewmembers should be provided with training in advanced life support techniques and procedures that are equivalent, at a minimum, to the level of "paramedic." Radio communications with lunar base are vital for detailed medical instructions and data transfer. Consideration should be given to the use of the LEMU as an emergency hyperbaric chamber, if pressurization to 2.8 ATA (41.1 psia or 284 kPa) can be safely accomplished.

Emergency rescue at lunar base may be better effected by bringing rescue supplies, equipment, and personnel to the base rather than by evacuating the critically ill or injured crewmember back to Earth or to Space Station. It is expected that a telemedicine system will be an essential part of the lunar base with interconnections to Earth and possibly Space Station.

Some of the major medical issues for a lunar base are the following: (Logan, April, 1988)

- ▶ Extent of general surgery capability
- ▶ Closed-loop control of general anesthesia
- ▶ Shelf life of medical supplies, consumables, and pharmaceuticals
- ▶ Reusability (vs current "disposability" medical concepts)
- ▶ Sterilization

- ▶ Blood products (handling, storage, and resupply)
- ▶ Appropriate imaging techniques
- ▶ Extent to which medical laboratory capability is required
- ▶ Use of artificial intelligence in medical diagnosis and medical management
- ▶ Provisions for dental procedures.

Consideration also must be given to the medical training of the crew. Because of the size and permanent nature of the lunar base, it is assumed that at least one of its inhabitants will be a physician. Continuing medical education must form a part of the activities of the physician(s) in order to maintain proficiency.

Other considerations include the extent of provisions for multiple patients and the extent that "paperless" record keeping can be realized. Provisions for health assessment and routine physical examinations also should be provided.

One of the major physiological/medical problems expected to develop during long-term missions on the lunar surface is the demineralization of bones and resultant loss of bone strength. While this might not be important to the well-being of the crewmember while on the lunar surface, it is vitally important to his or her health upon return to Earth. Since it has not been proven that bone loss under reduced gravity conditions is regained upon return to Earth, effective countermeasures must be developed in the form of bone-stressing exercises, dietary supplements, osteogenic-inducing agents, etc. Bone strength losses in lunar gravity are estimated to be 0.7% per week without the use of countermeasures (Keller and Strauss, 1988). This would limit the crewmembers to a cumulative stay of about 1.5 years on the moon. Individual variations in the rate of loss in bone strength make it desirable to have periodic measurements of each crewmember. Instrumentation to measure bone loss should be available at lunar base.

An exercise program is an essential part of lunar activity. EVA-specific exercises of the arm, forearm, and hands should be considered. Exercise countermeasures should be designed to provide some level of maintenance of 1-g conditioning against loss of strength and muscle mass, loss of bone minerals, and cardiovascular deconditioning.

Some anticipation of and provisions for "occupational hazards" of EVA at lunar base must be included in the planning for medical care. Consideration of the occupational ergonomics of EVA in the various suits should assess the possibility of repetitive activities leading to problems such as carpal tunnel syndrome. Possible allergic reactions to lunar dust also must be considered.

The pressurization of the suits with an air mixture rather than a highly oxygen-enriched atmosphere precludes the likelihood of oxygen toxicity, except under contingency emergency situations where high partial pressures of oxygen might be breathed for prolonged periods of time. Anecdotal reports of recent research results indicate that the conditions leading to oxygen toxicity may be even more unlikely than previously assumed. Also, the use of high pressure suits coordinated with the lunar base pressurization level eliminates the prebreathe requirement for nitrogen washout. Any small difference in pressure between the lunar base and the suits reduces the probability of evolved gas embolism to a minimum under routine operations. However, the possibility of a rapid decompression of either a suit or other pressurized facility exists. Therefore, the probability of bends should be considered in the event of a major system failure or disruption of the skin integrity of any pressurized enclosure.

It is assumed that a slow leak of the pressurized suit would be brought to the early attention of the crewmember by an appropriate caution-and-warning system. Under this condition, the

crewmember will have adequate time to implement contingency procedures and stop the leak. The suit failure emergency scenario of this study has mentioned the need for EVA crewmembers to share pressurization by hooking together with a "buddy system." It also has suggested that an emergency pressurized enclosure should be a part of each rover, either as a special section or as a trailer. Emergency oxygen systems with pressure demand regulators will be necessary to provide 100% oxygen under pressure. In this scenario, one or both crewmembers may be exposed to near vacuum for a significant time. Without pressure protection, dysbarism and subsequent gas embolization become a major possible risk. A hyperbaric capability could help minimize central nervous system (CNS) damage in the probable event of embolization. The LEMU might serve as such a facility if it were provided with adequate pressurization capability.

The tradeoffs for the requirement of a mobile hyperbaric facility with a pressurization capability greater than 2.8 ATA should take the contingency scenarios into consideration as the worst cases. The capability must be provided to treat barotrauma and dysbarism and also to help prevent serious CNS problems in the cases cited.

The toxic hazard risks for these mission scenarios are not identified as substantial. Protocols for dealing with inhalation exposures as a result of possible life support system contamination and surface exposure decontamination should be delineated clearly for each of the anticipated hazards. These will be very similar to the protocol procedures for the Space Station inhabitants, and no new technical data are anticipated.

Mechanical trauma within the suits should be considered as a possible occurrence. The severity of the trauma could range from minor cuts and abrasions to broken limbs and puncture wounds. Emergency supplies such as splints, sutures, and antiseptic ointments, as well as instructions for a crewmember trained in their use, must be available in the ambulance module and at lunar base.

Electric shock also should be considered as a remotely possible risk. Injury could occur from burns, cardiac dysrhythmias (including ventricular fibrillation), and mechanical injury due to recoil. However, such incidents are much more likely to occur at lunar base than during EVA. This contingency warrants the presence of a cardiac monitor/ defibrillator in the ambulance module. Defibrillation would have to be instituted as soon as the dysrhythmia is recognized. It would be unacceptable medical practice to rely on mechanical external cardiac compression alone for transport back to lunar base.

Although the crewmembers' immune systems may be compromised from a sustained stay in weightless or reduced gravity environment, infections of crewmembers in this scenario will probably be limited, for the first few weeks, to those which were already incubating while aboard the Space Station or prior to leaving Earth. It is assumed that infectious disease will be well controlled on Space Station and within the lunar base and that resident organisms will have been identified. The additional stress of EVA at lunar base may, however, cause subclinical diseases to become manifest. Antibiotic therapy must be available, by both oral and intramuscular routes, for the most common clinical infections.

With the absence of the protective shield of the Van Allen Belts in LEO, the lunar base operation presents greater risk of radiation sickness and/or life-threatening radiation overdose. Redundant and precise monitoring of the crewmember in EVA is necessary. This should be accomplished with personally worn monitors. Each crewmember's dose can then be added to his/her career dose by ground personnel. In the event of a highly radioactive solar flare, portable shelters and safe havens should be used for protection. Further consideration should be given to using some of the new experimental drugs being developed to provide some protection for cells against damage by ionizing radiation. The most promise in this area seems to be the development of drugs that promote the regeneration of bone marrow after destruction by high doses of radiation. Such developments, generally in the field of oncology, should be studied for possible utilization in this environment.

Blood volume shifts and changes in plasma electrolyte concentration have been demonstrated to be adaptive mechanisms to the microgravity environment of space. The added work load and metabolic load of EVAs on successive days may cause temporarily imbalanced electrolyte values. A non-invasive method of monitoring electrolytes and imbalances probably will be required. Dietary supplementation of possibly critical electrolyte losses may also need to be a part of the EVA protocol.

Other medical conditions, mostly of the variety treated by elementary first aid (e.g., minor burns or abrasions), are likely to occur and must be treated appropriately. Any medical problem not deemed to be definitively treatable in the rover ambulance module should be assessed for its severity and for the possible termination of the remote activities and immediate return to base. Under these circumstances, the crewmember's condition should be stabilized, if possible, and the vehicle returned to lunar base. The prevention of shock should be a major goal in stabilization. Therefore, analgesics, fluid and electrolyte replacement, and maintenance of circulation and ventilation are the paramount considerations and should be reflected in the equipment and supplies stowed in the ambulance module.

Based on the previous discussions, the facilities, equipment, and supplies required for the ambulance module should include the following:

- ▶ Portable radiation shelter
- ▶ Hyperbaric treatment capability up to 2.8 ATA
- ▶ Pressurized safe haven
- ▶ Mechanical external cardiac massage unit
- ▶ Pulmonary ventilator/respirator
- ▶ 100% oxygen supply with oral/nasal mask
- ▶ Cardiac monitor/defibrillator and external pacemaker
- ▶ IV fluid administration system.

Various examination and treatment kits, similar in content to the "High Technology Physicians' Black Bag" and medical kits already developed by NASA and used in the past, also will be required. These instruments will be needed to make and confirm diagnoses and monitor the progress of a disabled crewmember.

A "hands-in" capability of the LEMU would allow the crewmember to administer his/her own oral drugs, skin patches, or injectables as required (for example, antiemetics and radiation countermeasures). These could be provided in emergency-kit form within the LEMU. The use of such procedures and drugs should be under the supervision of lunar-based or ground-based medical personnel.

In the absence of a "hands-in" capability, which would facilitate medical care by the in-suit, self administration of oral or injectable pharmaceuticals to each of the EVA crewmembers, a injection patch in the thigh area or integral automatic injection system might be necessary. A patch on the thigh (as in Apollo) should prove adequate, but an automated system with adequate safeguards against accidental triggering might be more satisfactory. The use of an injection patch will be constrained to a unique administration device or use in pressurized facilities. No critical need for this patch is identified at this time with the planned rescue capability. Another possibility is an automated medical aid system using automated hypodermics, electrostimulation devices, and devices to clear the respiratory tracts, as reported by the Soviets (Bogomolov, 1986). Rapid injections of antiemetics or radioprotective pharmaceuticals during a solar flare might be desirable.

Health assessment of the crew should combine routine diagnostic physical examinations and monitoring during both exercise and EVA missions with pre- and post-mission health assessments. This assessment might also include the psychosocial and group dynamics aspects of the crew. The frequency of monitoring and testing should be based upon the findings and should be increased or decreased based upon deviations from normal and expected values. Standards should be set which define the limits of the monitored parameters and procedures to be followed in the event that a parameter approaches or exceeds its limits.

It is assumed that smoking and drinking alcoholic beverages at lunar base will be prohibited. A strict policy should be established and firmly enforced to control such activities or the impact on the medical care system might be significant.

3.2.11 Perception Acuity for Visual Displays and Warnings

Primary EVA-related visual displays and warnings can be displayed in the helmet/visor area of the suits. The technology for a see-through, heads-up display is well defined. All images should appear in focus when the crewmember is looking at a distant object. Generally, this means that the virtual image must be located at a viewing distance greater than eighteen inches away from the eyes of the crewmember. The brightness and/or contrast of the display should be adjustable by the crewmember over a limited range of control established by visibility studies.

The display should accommodate a combination of seven-segment alphanumeric data as well as scanned video. Discrete warning lamps should also be used where appropriate. The transmittance and reflectance of the see-through display should be optimized.

All crewmembers should be corrected to 20/20 vision with individually-fitted eyeglasses designed for adequate retention during use in 1/6-g conditions. Also, the lunar base should be equipped for vision testing and correction of any refraction errors that might occur during the crewmembers' stay on the lunar surface.

3.2.12 Audio Level, Quality, Range and Warnings

The following requirements are quite specific since they are based on document No. EE-2-87-005 (U) Rev. A (Space Station Audio System Derived Requirements). If Space Station requirements are revised, then these requirements should be changed accordingly.

The characteristics of the EVA suit audio system for use at a lunar base should include the following items:

▶ Acoustic Transducers

Microphones: Transducers should be redundant and non-noise-canceling. A noise-canceling type should not be needed since external acoustic input to the suit is eliminated by the lunar surface vacuum. Further, acoustic pressure conditions within the suit/helmet alter the relation of far-field and near-field signals such that very little benefit can be achieved from canceling type transducers. Used in this environment, canceling transducers must be very accurately located near the mouth or voice cancellation will result. Mounting the transducers on the helmet and not the head precludes the required positioning accuracy.

Headphones/speaker: The internal EVA noise level should be kept low enough that small loudspeakers may be used instead of headphones. (See also section 3.1.7, Helmet Utilities.)

▶ **Audio Level**

Speaker: The receiver AGC should be followed by a crew-accessible level control providing a maximum level of 75 dB(A) for operations. C&W tones should be at least 20 dB above voice communications but should not exceed 100 dB(A). Class I C&W tones may not be reduced below TBD dB(A) but should be controllable to permit hearing voice communications.

Microphone: This should be leveled to a nominal 0 dBm input by an AGC circuit with TBD ms attack and TBD ms release times (-12 dBm threshold referenced to nominal 0 dBm input). When noise-canceling microphones are used, a 10 dB SNR improvement should be attempted.

▶ **Audio Feedback**

Effective active and passive measures should be incorporated to allow open microphone and loudspeaker operation on the full-duplex signal that transmits and receives continually.

▶ **Hardware Interface**

Hardware compatibility should be provided for use during checkout, in the airlock, and when operating certain vehicles.

▶ **Redundancy/Reliability/Maintainability**

The design should provide levels of redundancy required for mission criticality 1R and very high reliability within each redundant system "string." It also should provide good checkout interfaces, accessibility, and repairability. (See also section 3.1.7, Reliability.)

▶ **Speech Syntheses**

The design should provide flexible synthesis capability to service multiple applications.

▶ **Speech Recognition**

The design should provide speech recognition for noncritical command functions such as the control of lighting, TV functions, HUD data display, and tool selection, inventory, or location. Manual or voice activated inhibit of outgoing voice transmissions should be provided for use during voice commanding to reduce non-communication chatter on the network.

▶ **Caution and Warning**

Processing/Distribution: All classes of C&W tones should be distributed by the suit audio system and should not be switchable. C&W for the suit should not depend on processing in the central control station for actuation of tones within the suit. An appropriate suit system reset should be provided on the suit. C&W tone and synthesized speech formats should be common with those of the Space Station for efficiency in crew cross-training and use.

► **End-End Quality**

Processing/Distribution: The digital processing and audio distribution system within the EVA suit should provide "very good" voice quality (A. I. NTL 0.7) using the same bandwidth and voice channel rate as the surface station and relay links to Earth. Very long duration exposure to distorted speech (typical of that used to minimize bandwidth) may reduce crew performance and cause other undesirable effects as have been demonstrated for continuous exposure to high noise environments. Research in this area appears to be appropriate.

Noise/Distortion: The processing should maintain a 50 dB SNR, with no more than 5 % distortion.

Time Delay: Local audio delay should be kept to a minimum to support an overall voice annotation synchronized to the video within 50 ms to ensure good "lip sync" and assist in achieving natural interactive conversations.

Bandwidth: Bandwidth is not expected to be a constraint. A voice channel rate of 64 kbs is considered the probable baseline for Space Station and the next generation of EVA hardware.

Verification Test: The standard modified rhyme test (or an equivalently accurate test) should be used to verify the articulation index achieved for end-to-end.

► **Voice Privacy**

Crew-switchable two-way voice privacy should be provided for all transmissions to and from the EVA. Processors should not degrade the link quality. Compatibility with all system elements should be maintained.

► **International Compatibility**

It is expected that 64 kbps (50-7000 Hz) wideband voice encoding associated with CCITT G.722 standard (SB-ADPCM encoding) will be in use during the mission and should be considered for a standard.

3.2.13 Perception of Surrounding Environment

Current suit technology provisions for vision (visors) and sensory feedback to touch (gloves) should be adequate for this mission. However, in the event of an emergency rescue, it may be necessary to provide some location aids. Some design consideration has been given to incorporating automatic ranging into a "smart" TV camera. It will be necessary to provide some equipment to assist the crewmembers in determining the location and range of large objects or other crewmembers. If the proposed communication system using direct EVA to L1 link is used, then discrete address of each EVA allows its position to be measured by the central station together with range and bearing from other EVAs.

The optical quality of the space helmets and visors currently being designed should be adequate for use on the lunar surface. However, the lunar environment places several other requirements on this equipment. The visors and faceplates should be hardened against scratches to the maximum extent. Lunar soil is extremely abrasive and will surely scratch most visors and helmets. These scratches were a problem during the Apollo missions. (See Apollo technical crew debriefing reports.) With the reuse requirements of these lunar EVA scenarios, scratches will accumulate over time and possibly impair vision. A disposable (replaceable or resurfaceable) shield also should be considered.

The extreme range of lighting conditions on the lunar surface might require the use of an automatic visor. Such a visor would change density (or possibly aperture) as a function of lighting. However, any automatic operation of this type should contain provisions for each crewmember to override the automatic setting under selected circumstances. This will allow him/her to optimize the transmission characteristics of the visor in the event that automatic control does not provide the visibility required under the circumstances.

For some detailed work under shaded conditions or during the lunar night, supplemental lighting will be required. Thus, supplemental light sources should be supplied to illuminate selected areas to a minimum level of 200 foot-candles, controllable by the crew.

The tendency to underestimate distances on the lunar surface can be solved partially by training, but optical or electronic aids for ranging might be required to compensate for the lack of textural gradient normally caused by atmospheric attenuation.

3.2.14 Toxicity

Toxicity is an inherent characteristic of a chemical--the ability to interact with and cause damage to a living organism, organ, tissue, or cell. Hazard is the likelihood or probability, under a given set of circumstances, that the toxicity of a chemical will be manifest. However, it must be remembered that a chemical must enter the body for most toxic responses to occur and, in so doing, it usually must pass through a membrane. The site of entry can be in the upper or lower airway, the naso-pharynx, or the gastrointestinal tract. Since they are an integral part of normal bodily functions, such as respiration, eating, etc., these sites are the usual ones for the entry of exogenous chemicals. Chemicals can also exert their effects at the surface of the membrane, causing irritation. Chemicals that enter the body usually must be transported to a site of action, such as the liver, kidneys, or lungs.

The data available from experimental toxicity studies and evaluations are usually the result of a carefully designed experiment where most variables except the chemical itself are eliminated. However, when making judgments on maximum allowable limits for EVA on the lunar surface, there are many complicating factors to consider. Exposures will most likely not be to only one chemical at a time, but to mixed materials. Committees of the National Research Council (in 1980 and 1987) have addressed some of the complexities associated with mixed exposures. For many years, the skin was considered to be a relatively impenetrable barrier, but recent studies have shown that dermal absorption can significantly add to the body burden (McDougal et al., 1985). Exercise (Horvath, 1981) and adaptation to hostile environments can significantly affect physiological functions such as blood circulation and, therefore, delivery of doses of absorbed chemicals to sites of action. All of these variables must be considered when determining maximum allowable concentrations.

Materials used in the construction of the suits, as well as in the construction of pressurized lunar habitats, should be selected from those acceptable as "non-toxic" on lists and specifications such as NASA STD NHB 60601B.

The extensive degree of regeneration and recycling required to take place at the lunar base will complicate the prevention of toxicant build-up. At least 97% of the water and atmosphere must be recycled in order to sustain the base. This presents potentially major problems of toxicity that must be solved in the design of each subsystem and in the derivation of the overall system operating plan.

3.2.15 Radiation Tolerance

EVA crewmembers will be exposed to both ionizing and non-ionizing radiation. Both types of radiation have natural as well as manmade sources. Ionizing radiation comprises charged (and uncharged) particles and high-energy electromagnetic waves. Natural radiation hazards include galactic cosmic radiation (GCR) as well as solar flares and storms. Manmade sources include reactors and possibly terrestrial high-altitude nuclear detonations. Non-ionizing

radiation possesses an energy level that is too low to ionize molecules. A broad definition might include pressure waves (infrasound, sound, and ultrasound) as well as magnetostatic and electrostatic fields.

Ionizing Radiation

Health effects due to long-term exposure, even to low levels of ionizing radiation, must be considered in planning lunar base operations. It has been proposed that the crewmembers be considered "radiation workers" when applying terrestrial exposure limits to the space environment (Angelo et al., 1988). However, the effect of chronic, low-level radiation on the health of the crewmembers, especially on the immune system and the development of auto-immune disease, is unknown.

The effects of low-level heavy ion exposures also are not well known. Behavioral modifications, such as a measurable "performance decrement," may occur at heavy-ion dose rates experienced in space (Hunt et al., 1988.) Studies of *Carausius morosus* ("stick insects") in space demonstrate the synergistic effect of microgravity conditions and heavy-ion exposure (Bücker et al., 1988). Further studies of heavy-ion effects are needed to fully characterize and quantify the risks of galactic cosmic ray exposure on humans.

Ionizing radiation exposure limits (Table 3-2) for Space Station and short missions to geosynchronous orbit have been defined for NASA by a subcommittee of the National Committee on Radiation Protection (NCRP) (Fry, 1986). Radiation exposure limits have not been established for a lunar base. Our understanding of the deliberations of the NCRP is that career dose limits are based on a maximum increase of 3% in cancer mortality over the projected lifetime of a crewmember, and monthly and annual limits are based on avoiding any acute radiation effects, such as skin burning, "radiation sickness," and hematological depression. While monthly and annual limits are likely to apply to a lunar base, career limits may be different.

Table 3-2. Space Station Radiation Exposure Limits (Fry, 1986)

Period	Dose Limit (Sv)		
	Bone Marrow	Eye	Skin
30 days	0.25	1	1.5
1 year	0.50	2	3
Career	1-4 ^a	4	6
^a Females:	$2 + 0.075 \times (\text{Age} - 38)$		
Males:	$2 + 0.075 \times (\text{Age} - 30)$		

Table 3-3 shows effective doses for 10%, 50%, and 90% of an exposed population to suffer various acute radiation effects (Langham, 1967). These effects occur at high dose rates such as might be experienced during a large solar energetic particle event. Except for skin effects, the dose refers to "bone-marrow" or "whole-body" exposure. Note that a space mission can be threatened by exposures as low as 0.5 Gy and that exposures of 4 Gy or more are considered

to be lethal. Astronaut radiation exposure to artificial sources of radiation must be limited to 0.05 Sv yr^{-1} according to international convention and federally mandated regulations.

Some recent advances have been made in developing pharmaceutical countermeasures to increase the tolerance of humans to ionizing radiation (Kumar and Ponnampereuma, April, 1988). Although the primary protection for the crewmembers should be provided by shielding, the adjunctive use of radioprotectors should also be considered. Such pharmaceuticals, in order to be effective, must be given before irradiation occurs. The current radioprotectors are not effective after symptoms of radiation sickness have developed.

Table 3-3. Effective Doses for Acute Radiation Effects (Langham, 1967)

Effect	Dose (Gy)		
	10%	50%	90%
Skin:			
Erythema	4	5.75	7.5
Prodromal Sequelae:			
Anorexia	0.4	1.0	2.4
Nausea	0.5	1.7	3.2
Vomiting	0.6	2.15	3.8
Diarrhea	0.9	2.4	3.9
Hematological Depression:			
Platelets	0.5	1.2	2.5
Lymphocytes	0.6	1.5	3.0
Neutrophils	0.8	1.9	3.9
Early Lethality:	2.2	2.85	3.5

Simple dietary supplements have been found to provide a minor radioprotective effect. Among these are:

- Vitamin A
- Vitamin C
- Vitamin E
- Zinc
- Selenium.

Also, manipulations of antioxidant enzyme activity may be important for radiation protection in EVA. Dramatic results have been reported on experiments with mice (Kumar and Ponnampereuma, 1988) which might lead to non-toxic compounds as suitable regimens for radioprotection in the time setting of these scenarios.

Solar Energetic Particles

Large solar particle events occur at intervals of 7 to 10 years. For a one-year mission on the lunar surface, the probability of such an event is 10% to 20% (Burrell, 1971). The proton fluences for large events are about 10^{10} cm⁻² or greater (Heckman et al., 1988). Whole-body doses exceeding the threshold for lethality can occur in "worst-case" models if crewmembers are inadequately shielded.

Intermediate-size solar energetic particle events occur with a frequency of 4 to 6 per year. Exposure to both large and intermediate events may result in radiation doses that contribute significantly to the crewmember radiation budget. Proposed dose limits for Space Station may be exceeded in one hour by a large flare if crewmembers are inadequately shielded.

Solar energetic particle events, once initiated, build up to peak flux intensity within 30 minutes to a few hours. Predictions based on X-ray precursors may provide 30 minutes to one hour additional warning. High particle intensities may be maintained for several days. It is not uncommon for two or more events to occur within a week.

Galactic Cosmic Radiation

Galactic cosmic radiation (GCR) doses on the lunar surface do not threaten acute radiation effects and do not exceed dose limits proposed for the Space Station. Models of the GCR environment and heavy-ion transport agree within a factor of two or three with dosimeter measurements on the Apollo lunar missions (Letaw and Adams, 1986). The GCR dose will make a significant baseline contribution to the crewmember radiation budget which is difficult to reduce. Uncertainties about the effects of low-level exposure to heavy ions exist and must be resolved before credible estimates of the risk of GCR can be made.

Non-Ionizing Radiation

The non-ionizing radiation spectrum is shown graphically in Figure 3-5. Non-ionizing radiation exposure has received considerable attention over the past few years due to the potential health hazards involved. Widely different limits have been set by various groups, and there is no international agreement on what these limits should be. Tables 3-4 and 3-5 contain the most recent U.S. terrestrial limits, set by the American National Standards Institute (ANSI). Figure 3-6 is a graph of the NCRP ultraviolet exposure limits and Tables 3-6 and 3-7 contain the available data for visible light.

Figure 3-5. Non-Ionizing Electromagnetic Radiation Spectrum (Schulze, 1988)

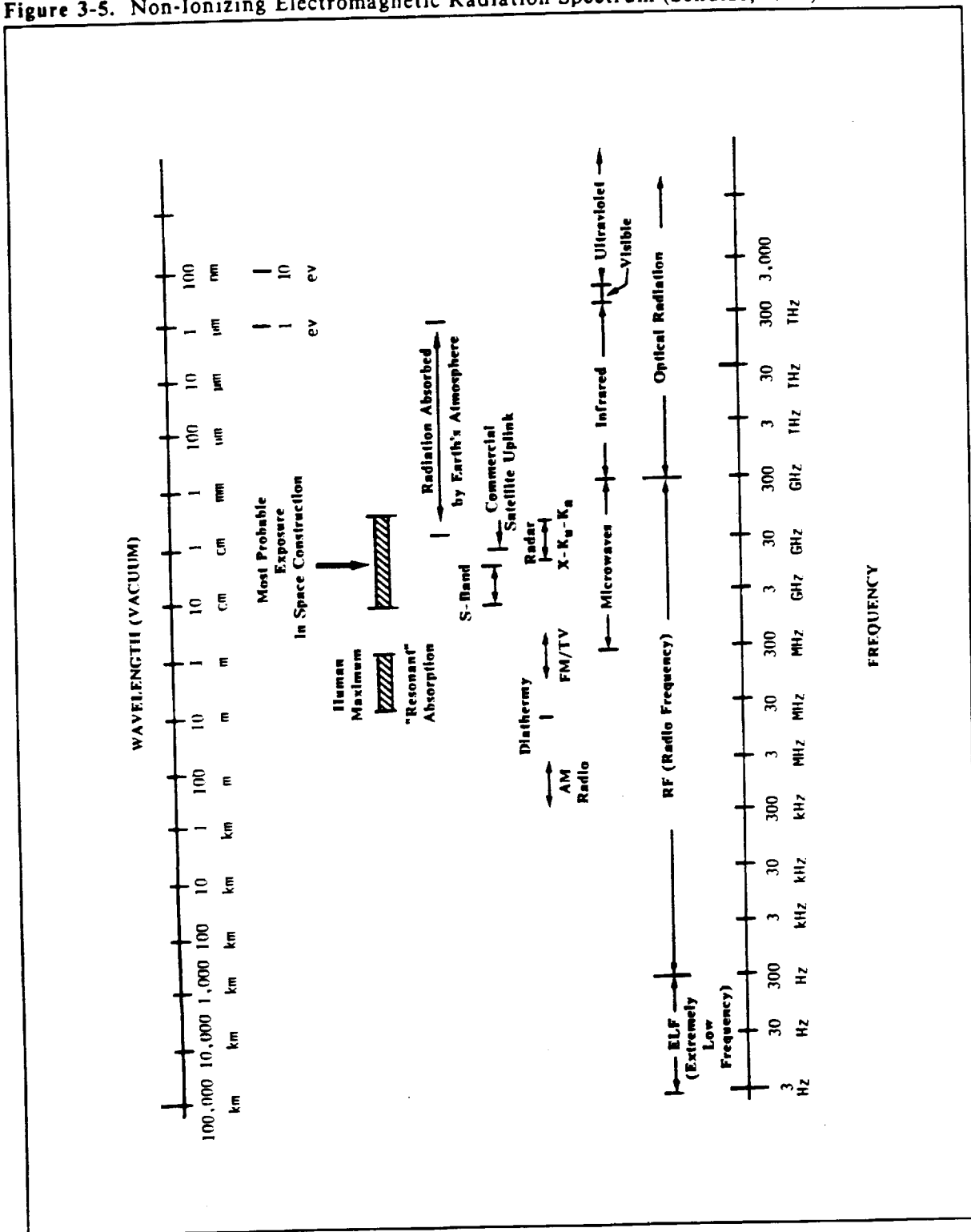


Table 3-4. Radio Frequency Protection Guide (RFPG) from American National Standards Institute (ANSI) Standard C95. 1-1982 (1982)

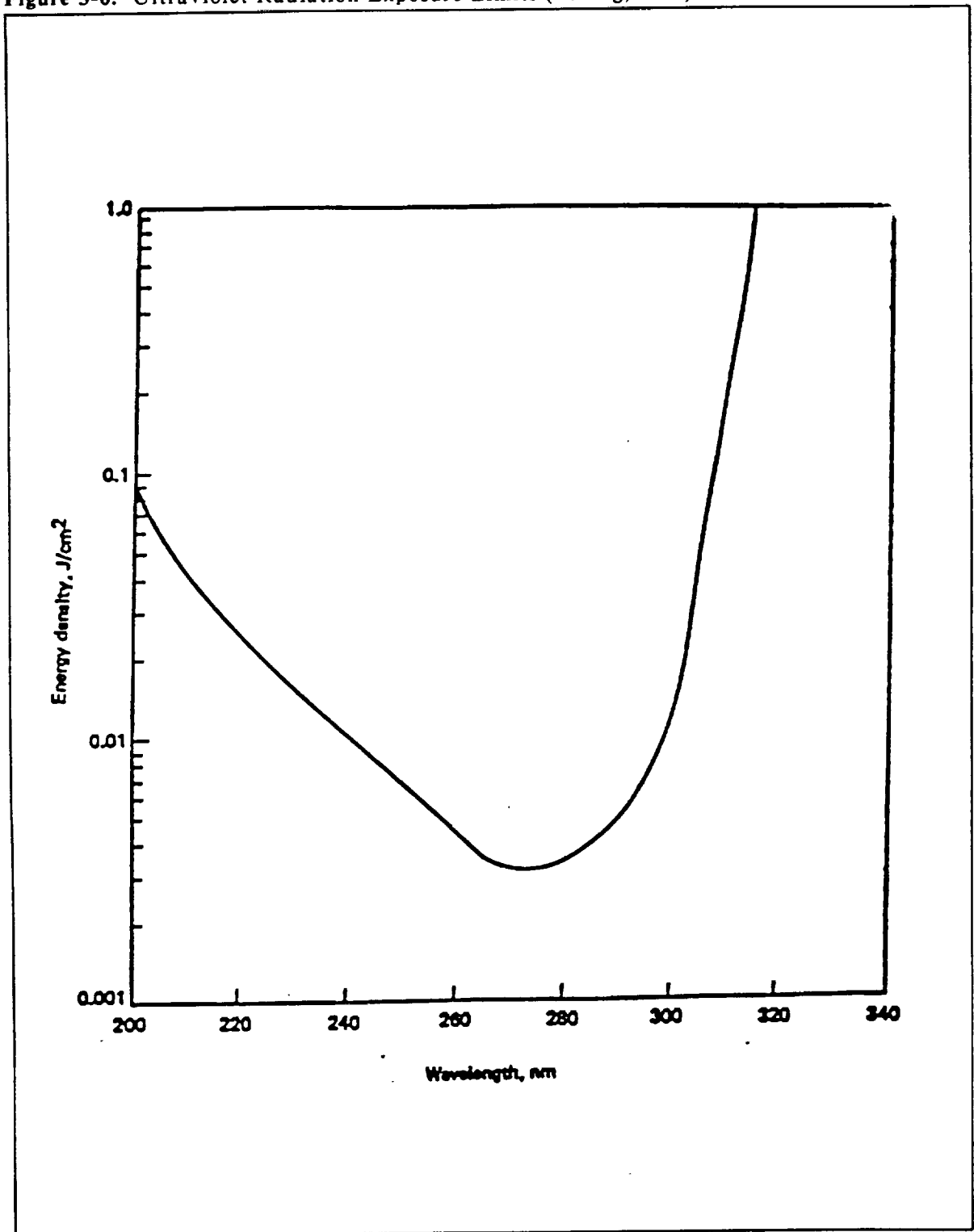
Frequency Range (MHz)	E^2 (V^2/m^2)	H^2 (A^2/m^2)	Power Density (mW/cm^2)
0.3-3	400,000	2.5	100
3-30	4,000 ($900/f^2$)	0.025($900/f^2$)	$900/f^2$
30-300	4,000	0.025	1.0
300-1,500	4,000 ($f/300$)	0.025 ($f/300$)	$f/300$
1,500-100,000	20,000	0.125	5.0

NOTE: f is the frequency in megahertz (MHz)

Table 3-5. Intermittent Exposure Limits from ANSI Standard (1982)

Exposure Level (mW/cm^2)	Exposure Time Allowed	Time Out of Field
1.0	6 min.	---
1.5	4 min.	2 min.
2.0	3 min.	3 min.
3.0	2 min.	4 min.
5.0	1 min., 12 sec.	4 min., 48 sec
10.0	36 sec.	5 min., 24 sec.

Figure 3-6. Ultraviolet Radiation Exposure Limits (Boeing, 1986)



**Table 3-6. Maximum Permissible Exposure Limits for Visible Light (Point Source)
(Grumman, 1985)**

Wavelength (nm)	MPE (MJ/cm ²)
400-450	3.
451-500	6.
501-550	12.
551-600	35.
601-650	100.
651-700	500.

Note: For $t \leq 10$ sec, multiply the above MPE by $.18 (t)^{-.75}$

Maximum Permissible Exposure Values for Point Source Radiation Between
400-700 Nanometers (with 7 mm limiting aperture $t = 10^1$ to 10^4 sec)

Table 3-7. Maximum Permissible Exposure Limits for Visible Light (Extended Source) (Grumman, 1985)

Wavelength (nm)	MPE (Joules/cm ² -sr)
400-450	6
451-500	12
501-550	24
551-600	70
601-650	200
651-700	1,000

Note: For $t \leq 10$ sec, multiply the above MPE values by $.18(t)^{.75}$. Source solid angle, in steradians (sr), = $\text{Area}_{\text{source}} / (\text{Distance to source from eye})^2$

Maximum Permissible Exposure Values for Extended Source Radiation Between 400-700 Nanometers (with 1 mm limiting aperture at cornea and time, $t = 10^4$ sec).

The approach to limiting exposure to radio frequencies (RF) during EVA, up to the present time, has been to turn off the transmitters or to avoid an imaginary zone around them. In the operation of lunar base facilities, this approach to exposure limitation may not be feasible. Terrestrial RF installations are usually elevated above normal work paths such that the probability of inadvertent exposure is minimal. Lunar installations might not be elevated.

The following actions should be taken to reduce health risks associated with exposure to non-ionizing radiation:

- ▶ Define the maximum dose limit (frequency, duration, field strength) based upon predicted biological effects.
- ▶ Measure the biologically weighted, non-ionizing field strength on a continuous, real-time basis during EVA such that the worker can detect the presence of the field and minimize his exposure to it.
- ▶ Construct all antennas and radiating devices such that zones of concentrated and focused energy are not encountered in the most probable work paths.
- ▶ Use established design practices of radio-frequency interference (RFI) and electromagnetic interference (EMI) isolation techniques in the design of critical EVA systems, such as life support equipment, which are likely to encounter non-ionizing radiation fields.

3.2.16 Meteoroid/Impact Requirements

The absence of a protective atmosphere on the moon means that micrometeoroids and meteoroids are of concern. The impact velocities of micrometeoroids impacting the lunar surface have been measured at 2.4 to 72 km per second. These micrometeoroids are generally of three different classes: cometary debris, interstellar grains, and lunar ejecta. Measurements have predicted that the established impact rate is 1.1 to 50 craters per square centimeter per million years for particles greater than 500 micrometers in diameter.

Meteoroid flux in the vicinity of the moon is comparable to that in LEO, so the design requirements for LEO will support the design requirements for lunar EVA as well. The NASA SP-8013, Meteoroid Environment Model - 1969, Near Earth to Lunar Surface, Chapter 3, Criteria gives a detailed description of the lunar surface and meteoroid interactions. Additional information on which to base requirements is gained from NASA-TM-82478, Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development (1983).

3.2.17 Sand, Dust, and Surface Terrain

NASA-TM-82478 provides a description of the distribution of lunar soil by particle size. Ranging from a medium sand to a medium silt, the regolith generally consists of particles less than 1 mm in diameter down to those of about 0.01 mm in diameter. More than 50% of the soil particles are less than 100 microns in diameter. The size distribution of particles less than 1 mm is approximately log normal.

The soil is a significant design driver; Table 3-8 lists some of the mechanical properties of the lunar surface.

The major requirement concerning soil and the lunar environment is that all equipment be operable in or protected from the silt-like abrasive soil and sand. This is an overriding consideration, like taking water into account in the design requirements for a submarine.

An excellent description (and a large bibliography) of the lunar surface is contained in "Rocks and Minerals on the Moon: Materials for a Lunar Base" by Lawrence A. Taylor.

Table 3-8. Mechanical Properties of Lunar Surface (from NASA-TM-82478)

Lunar Soil Parameter	Value	Reference or Comment
Density	near 1.0 g cm^{-3} 1.5 to 2.0	surface 10 to 20 cm depth
Angle of internal friction	30 to 50 deg.	higher for lower porosities
Mean porosity	$4.3 \pm 2.8\%$	All Apollo sites for upper 15 cm
Cohesion	0.03 to 0.3 Ncm^{-2}	Increase in cohesion for density from 0.99 to 1.87 gm^{-3}
Bearing strength	0.02 to 0.04 Ncm^{-2} 30 to 100 Ncm^{-2}	density: 1.15 g cm^{-3} density: 1.9 g cm^{-3}

4.0 EVA Hardware and Hardware Interface Requirements

During remote lunar extravehicular activity, humans rely almost entirely on hardware components and systems for life support, environmental protection, transportation, and shelter. This section discusses the lunar EVA hardware, how the crewmembers interface with it, and what requirements the hardware systems must meet in order to function together.

4.1 DESIGN LOADS, OPERATING LIFE, AND SAFETY FACTORS

The lunar surface presents many of the same environmental conditions that are generally present in space and that affect the operating life of equipment and hardware. The hard vacuum and the thermal extremes will quickly degrade conventional lubricants, the unfiltered solar radiation will degrade plastics and fabrics unless they are specially treated, and the thermal gradients will affect equipment and materials much as these conditions affect materials in Earth orbit. The two notable differences with respect to hardware requirements for the moon are the gravitational acceleration and regolith.

The one-sixth gravity force will influence design load requirements. The experience gained in Earth orbit cannot be considered valid due to the gravity differences, and the brief Apollo missions cannot be used to develop design criteria for very long duration missions. The current STS launch load requirements dictate that equipment withstand launch and recovery loads of ± 7.0 g in X and Z, and ± 3.0 g in Y; it may be appropriate to use these launch load factors for large assembled articles. For small packaged equipment, where the launch requirements are met by containers around the equipment, specific load factors would have to be developed.

The vacuum conditions on the lunar surface and the thermal extremes can be duplicated in test chambers on Earth, and the extreme values should represent the minimum design criteria with an additional safety factor. Current safety factors for space-based equipment range from 1.4 for components that can be mechanically and structurally tested to their limits to 4.0 for high pressure vessels.

The lunar soil characteristics offer a particularly difficult operating factor to consider in design loads, operating life, and safety factors. The abrasive nature of the soil is well understood, but the effects on material and equipment of large amounts over long periods of time are not documented. While current operating requirements call for thousands of operating cycles for the EMU joints, these cycles are in the void of space and not subject to contamination by lunar soil.

Ultimately, it is the combined environmental and task effects that will determine the requirements for operating life. When the Long Duration Exposure Facility is returned from orbit, we will be able to gather data on material degradation as a function of orbital exposure. Combined with testing that uses actual or synthetic lunar soil under appropriate thermal and vacuum extremes, investigations should reveal appropriate requirements for operating life on the lunar environment before refurbishment or replacement is required.

The current philosophy for major components and subsystems being developed for the Space Station is to have an operational life of 30 years with periodic maintenance and replacement of ORUs. It is not unreasonable to expect that major components for lunar EVA can be designed with the same goal in mind, especially given the capability to perform servicing and refurbishment at the main lunar base. Major components suitable for a 30-year design life, with replacement and refurbishment, include rovers, miners, science stations, communications stations and outposts, tools, lighting systems and shelters. Although the state of technology will be changing over any 30-year period and new models and new technologies will be brought to the lunar base to support EVA, for planning purposes the Space Station operating life cycle requirements appear to be achievable for lunar EVA equipment as well.

The operating life of primary and secondary life support equipment and LEMUs should be expressed in terms of hours of operation as a function of the types of operations performed. It should also be expressed in terms of the individual components that make up the primary and secondary man-systems EVA hardware. For example, gloves should have a specified design life for mining operations, a specified design life if used in assembly and servicing, and a specified design life for surveying and exploration. The more manual the tasks and operations and the more exposure a glove has to the blocks and regolith, the shorter its effective operating life will be and the sooner replacement of the glove will be required as a function of routine scheduled maintenance. This same approach would be followed for other components of the LEMU and the life support systems: operating life is defined as a function of design goal and operational exposure.

4.2 EVA TOOLS

The design of lunar tools and tool systems must accommodate their effective use in the one-sixth gravity environment. As noted in the Apollo films, considerable effort was required to use hand tools and adapt them to overcome some design shortcomings. In particular, hammers were used on their sides to permit the EVA crewmember to knock in probes. It was evident that the face of the hammer did not have enough surface area to be used as intended (see Figure 4-1). There was also noticeable verbal concern about the hammer flying free from the grip of the crewmember during operations. Swinging movements of the hammer appeared particularly difficult to perform with accuracy. The crew appeared to exert considerable energy to pound probes into the surface. Slide hammers or power hammers may be acceptable alternatives.

From these observations two requirements can be derived. First, the operating interface of the tool should be sized to accommodate the amplitude of the movement necessary to operate the tool. In the case of the hammer where a large swinging arc is required, the face of the hammer should be sized larger to reduce the terminal accuracy required. In the case of a socket wrench, the amplitude required to bolt and unbolt is much smaller at the tool and bolt interface; therefore, the terminal placement accuracy required can be increased to ensure a close fit between the bolt and tool. Second, the mass of the tool should be adequate to the task. In the case of the hammer, the mass should be greater; therefore, the amount of energy expended by the crew in driving a stake or probe will be less.

The integrated tool handles used on the Apollo missions were designed to accommodate the range of potential users. Experience reports and debriefings indicate that the handles were too small for some and too large for others and resulted in slipping and cramping. A requirement derived from these findings is to provide a custom-fitted tool handle for each EVA crewmember and to affix snap and lock-on tool heads to these handles. The handles would be designed to the individual and outfitted with a restraint system to preclude dropping the tool handle and tool or having the tool fly out of the crewmember's hand during operations. Hammer heads, drivers, scoops, wrenches, and like tools would snap in and out of the handles. These tool effectors would serve general and special purposes.

Tools used during EVA should be appropriately allocated to humans and machines. Drilling, for example, would be best done by a power driller mounted on the rover to relieve the crew from aligning and holding the drill during operations. Pile- and post-drivers might be similarly automated. Automated mules could haul bags of ore or samples about the surface more efficiently than the crew. The rover should be considered as a tool support and operations bed as well as a transport vehicle in order to reduce the EVA crew workload.

Figure 4-1. Apollo Hand Tool (NASA AS16-108-17697)



Power tools should have a manual operation and contingency override capability. Voice control of power tools might be considered.

For large tool systems such as a lunar miner, a greater degree of automation should be employed to permit the EVA crew to monitor the mining operation from a safe distance.

Table 4-1 lists some appropriate tools and equipment derived from the lunar reference mission scenarios.

Table 4-1. Tools and Equipment for Lunar EVA

<ul style="list-style-type: none">▶ Generic fabrication kit for EVA use▶ Extendible/erectable devices, telescoping poles/booms, reach extenders▶ Transporters/haulers for personnel and cargo, including a fold-up cart similar to METS (Apollo 14)▶ Power tools (materials cutters, loppers, joiners)▶ Conveyor belts for soil▶ Automated soil baggers, balers, stackers▶ "Dry dock" rigs for servicing, maintenance, repair disassembly▶ Erectable/deployable aids/fixtures (ladders, stairs/platforms, bridges)▶ Hoists, lifts, jacks▶ Cherry picker/hole plucker▶ Soil piler (to bank regolith against shelter)▶ Contingency manual soil movers (shovels, hoes, rakes)▶ Dust removal equipment (for use before entering airlock)
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4.3 RESTRAINTS/WORKSTATIONS

Lunar gravity provides the EVA crew with a sense of up and down as well as some stability while working on the lunar surface. Consequently, there is no evident need for foot restraints and workstations that provide a universal hold-down capability like those used in microgravity. It is evident from the Apollo experience that some means of crew stabilization is required to help them maintain balance during excursions and operations. Figure 4-2 shows an Apollo crewmember using a soil sample scoop; his stance suggests that he is also using the tool for balance. Support for the crew should be provided at workstations where stability is important or required. This might take the form of a chair, stool, or upper torso support to enable fine manual tasks to be performed without attending to body balance.

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Workstations for the remote expeditions will vary as a function of the mission requirements. Some workstations might be provided at the rover for maintenance functions, calibration of scientific equipment, analysis of samples, and similar operations. The workstation for the lunar miner might be a computer console and automated test station. The workstation must provide artificial lighting, protection from environmental contamination, access to tools and equipment, access to databases and diagnostic information, space to store tools temporarily, and space to work on LURUs or similar equipment. At the remote sites, the workstations should provide flexibility to accommodate a wide range of activities. Specialized work can be accomplished at the main base.

Restraints for the EVA crew should be provided while they are in transit on the rover.

Figure 4-2. Crewmember Stability and Balance at the Worksite (NASA AS16-106-17340)



4.3.1 Crewmember Translation/Equipment Translation

The assumption in this study is that crewmember translation occurs by ambulation or in a surface vehicle. The primary means of crew translation should be by vehicle, and the distance of this translation should be determined by the walk-back or drive-back time required to reach the base or other shelter. The primary means of equipment transport should also be by vehicle, reducing the EVA crew workload of moving equipment to and about the site.

The vehicles used to transport the crew and equipment across the lunar surface will be required to negotiate those features of the lunar surface where EVA sorties are conducted or where specific geological features and areas of the moon must be avoided. Vehicles such as the rover will be capable of extracting themselves from anomalous features of the surface, such as small craters or ridges, small blocks, or trenches, with a minimum of setup or preparation by the EVA crew.

Ambulatory crew translation should permit stabilized movement about the lunar surface, including the negotiation of ridges, craters, trenches, small blocks, and the loose regolith. Ambulation should be restricted to the vicinity of the rover, worksite, or shelters. While walking, the crew should be provided with a means to keep their balance and to avoid kicking up or falling down in the regolith. A "ski pole" approach to translation aids should be considered as a way to provide the crewmember with increased stability during movement on foot.

4.3.2 Worksite Interface Requirements

The lunar worksite interface requirements associated with remote operations will be concerned principally with tools, local and task lighting, motion and station aids, and special equipment brought to the site such as science stations, workbenches, and major equipment. The particulars of each of these are described in the scenarios and requirements survey in section 2.0.

Tools should be divided into tool handles, which are designed to accommodate the grip of the individual, and tool heads, which are designed to accomplish the task. Tool heads should be exchangeable and effectively retained during operations. It should be possible to locate tools through an active inquiry system in the event that a crewmember drops or misplaces a tool. Major tool subsystems, such as core drills, should be mounted on and operated from a platform (e.g., the rover) to reduce crew workload.

Lighting should be provided for both day and night operations. As shown in Figure 4-3, Apollo crewmembers often used reflected sunlight from their suits and the lunar surface for local illumination. Task lighting should be provided at workbenches and workstations and should be adjustable by the crew up to 200 footcandles. Scene lighting should be provided where wide area operations involve going in and out of shadows and intense light normal for the lunar surface, or when an area of interest is in the shadow of obstacles. Lighting for film and video recording should be provided. Both shades and reflectors may be necessary.

Station aids should be provided to the crew for working at one location for an extended period. On the moon, it is possible to use seats as station aids in front of workbenches in much the same way that we do on Earth, and this approach should be considered.

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Figure 4-3. Local Illumination by Sunlight Reflected from Suit (NASA AS14-64-9089)



4.3.3 External Configuration

The external configuration of the LEMU should present a minimum opportunity for the collection and retention of lunar soil and dust. Creases, cracks, folds, exposed joints, and open-weave fabric should be kept to an absolute minimum, if not avoided altogether. The external configuration of the LEMU should afford ease of cleaning.

The external configuration of support equipment for lunar EVA must be free of sharp edges and corners, as specified in NASA-STD-3000. Equipment also must preclude snagging or pinching the crew while they are working with the equipment.

External configuration of the rover should minimize the collection of soil, especially on sensitive components such as radiators and solar panels. The configuration also should preclude entrapment of the EVA crew during normal and contingency operations.

For remote lunar EVA, the external configuration of all systems, subsystems, and components that require or accommodate any connection or disconnection should be such that soil and dust contamination at the fittings is prevented.

4.3.4 Sharp Corner/Impact Requirements

All sharp corners on equipment likely to contact the EVA suit shall be rounded in accordance with established radii standards. The rovers especially should be analyzed in detail for sharp corners, as should all tools and major replaceable components of the life support system. For tools which must be sharp or pointed, appropriate storage and operational guards are required.

The requirement to protect the EVA crew from damage to their suits and equipment is well documented in NASA-STD-3000 for system and component design features. The lunar environment, however, presents the EVA crew with environmental hazards that are beyond the control of equipment designers. The regolith is covered with small blocks of rock, and many of the larger blocks have corners, edges, and points that do not meet the requirements of NASA-STD-3000. Equipment and personnel will have to be protected from the environmental hazards posed by these lunar landscape features.

4.4 EVA RESCUE EQUIPMENT REQUIREMENTS

A major component of the EVA rescue equipment will be the ambulance module installed on a rover (see sections 2.5.2, Rovers, and 3.2.10, Medical Care Facilities). This module will contain all emergency medical equipment normally required for rescue of an EVA crewmember. A preferred mode of rescue for sick or injured crewmembers at lunar base will involve moving equipment and medical personnel from Space Station or Earth to the lunar base, rather than returning the sick or injured to Earth. Only in extreme circumstances should return to Earth be considered because the stress of re-entry may contribute to morbidity.

4.5 RADIATION SHIELDING

The principal radiation threat during lunar EVA activities is the intense proton flux following an energetic particle event on the sun. Letaw et al. (1987) have recommended that "all manned spacecraft intended to spend a period of a week or more outside the [Earth's] magnetosphere should be equipped with a [solar-flare] storm shelter providing 9 cm aluminum (or equivalent) shielding in all directions." This shielding thickness will limit the radiation dose of crewmembers to a manageable level. Radiation protection strategies that provide for partial shielding of the face, hands, and torso while EVA crewmembers return to a fully-shielded base or a safe haven may be useful.

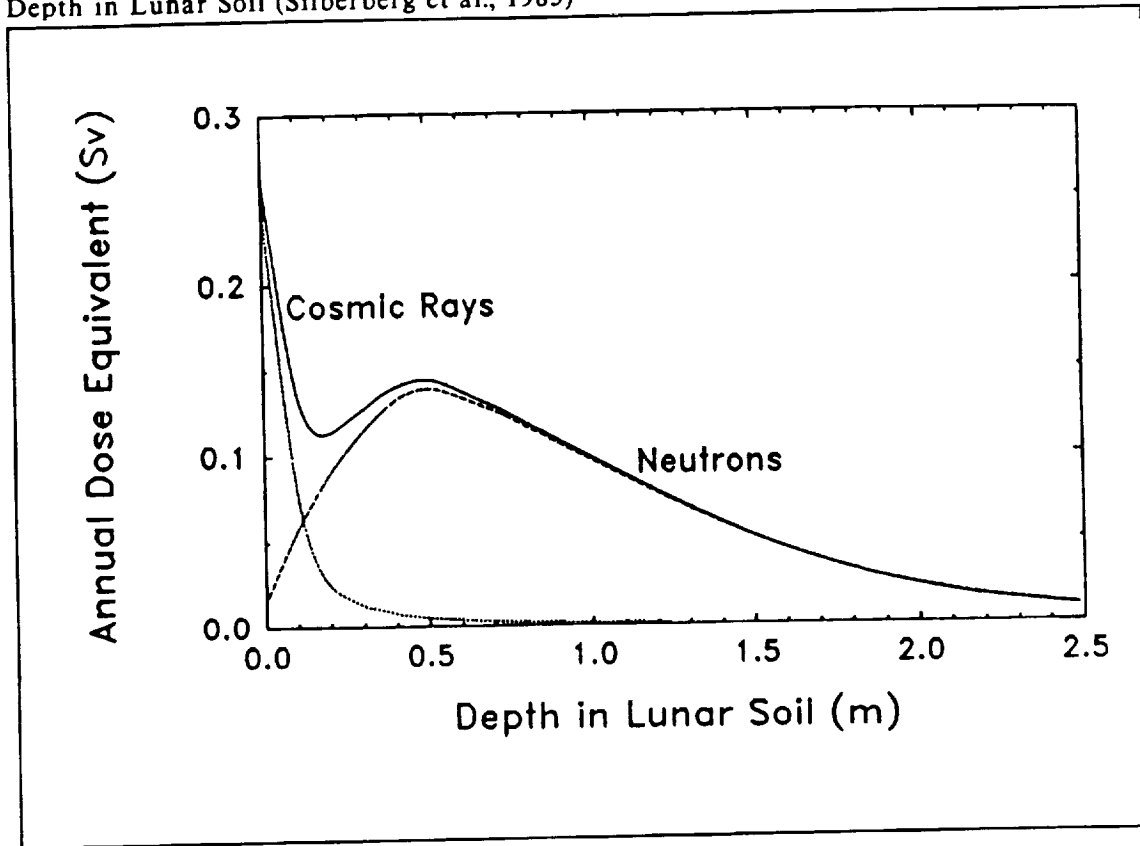
Galactic cosmic radiation (GCR) continuously contributes to crewmember doses. It is difficult and possibly impractical to shield crewmembers from GCR during an EVA. Over 1.5 meters of lunar soil would be required as shielding to reduce the dosage to the allowed level for radiation workers (Figure 4-4). Within the lunar base, the dose may be reduced to terrestrial levels with 5 m to 10 m of lunar soil.

High-altitude nuclear detonations, such as weapons testing, may be a possible contributor to radiation dosages on the lunar surface. Advanced detection and warning systems should provide the lunar base crewmembers with sufficient time to enter a safe haven or shelter.

The following additional research into radiation protection and radiation shielding for lunar surface EVAs is recommended:

1. Identify redundant and fool-proof techniques for anticipating a large solar particle event. These techniques would allow time for EVA crewmembers to head for shelter prior to an event that could make them ill.
2. Evaluate the effectiveness of radiation shielding materials of various thicknesses and compositions for protection of EVA crewmembers from solar proton events. Provide this information to those who will design spacecraft and equipment so that radiation protection may be optimized at an early stage of project development.
3. Continue research into characterization of heavy-ion effects on biological systems. Such research can eventually give us confidence that there will be no "surprises" on long-duration missions outside the magnetosphere.

Figure 4-4. Dose Equivalent to Bone Marrow (5 cm Tissue Depth) as a Function of Depth in Lunar Soil (Silberberg et al., 1985)



4.6 THERMAL PROTECTION

The thermal protection requirements for EVA are well-established in NASA-STD-3000. The performance of in-suit thermal protective systems being planned for LEO EVA on Space Station are adequate and satisfactory. The sharp thermal gradients that will be encountered on the moon should be accommodated by the current thermal systems.

The requirements of the thermal environment protection system are as follows:

- ▶ **Temperature**
 - Maintain crewmember's skin temperature between 33 °C and 34 °C (91.5 °F and 93.5 °F)
 - Maintain all surfaces in contact with crewmember between 10 °C and 45 °C (50 °F and 110 °F)
- ▶ **Cooling/Heating**
 - Automatic control to a manual setpoint that is operable by crewmember
 - Range of control sufficient to maintain thermal comfort at metabolic rates up to 500 watts (1700 Btu/hr or 430 kcal/hr) and as low as 100 watts (340 Btu/hr or 86 cal/hr)
- ▶ **Relative Humidity**
 - Maintain non-condensing atmosphere that will not fog visor
 - Control relative humidity between 40% and 70%.

It is recommended that feasibility studies be conducted on the design and development of small endothermic packages for emergency cooling and small desiccant packages for emergency removal of excess humidity.

4.7 LUNAR EVA SAFE HAVEN AND PORTABLE SHELTER

Solar energetic particles are a threat to the completion of any space mission outside the magnetosphere. Protection from this radiation is an essential engineering requirement and is unrelated to regulatory constraints. This fact should be well understood by all planners of lunar base activities.

The required shielding from solar flares is the subject of some debate. The quantity of shielding depends on the allowable risk, statistical models of the environment, energetic particle spectra and composition, transport models and calculations, and procedures for radiation risk assessment. Much additional study is required.

For purposes of this report, it is assumed that 5 cm of aluminum equivalent in lunar regolith or other material is required to protect astronauts in the event of a flare. This is less than the 6.7 cm shielding requirement at GEO and the 9 cm requirement referenced in paragraph 4.5 because of the additional protection offered by the moon. The 5 cm aluminum equivalent shielding has a mass of 135 kg/m² of surface being shielded.

Because there are many uncertainties in characterizing the lunar radiation environment, any solutions to the problem of crew protection against exposure are, at this point, suggestive and subject to modification as conditions become better understood. The broad requirement is to ensure a high probability of crew safety for the hazardous conditions that are currently recognized.

Several emergency plans are possible and should be considered with this shielding mass in mind (see Table 2-11). Flare protection strategies should be redundant, and trenching should be one of the plans. A trenching plan is a direct solution to providing shielding material on short notice (for a Martian analog, see Blacie et al., 1985). The complexities of safely handling explosives and/or trenching equipment may be difficult to execute under emergency conditions. A satisfactory shelter for a stay of 36 to 96 hours, produced on short notice, must use the life support resources of a rover. Another plan should be the placement of safe havens within 1 hour of all worksites. Pressurized safe havens could be of great importance in many emergency situations. Walls and roof could easily be structured to hold regolith for solar flare shielding. With safe havens in place, rovers could carry the few centimeters of shielding needed to protect crewmembers during the first few hours of the flare. It is not inconceivable that the rovers could carry all shielding necessary for solar flare protection, especially if supplemental shielding is available for the head, neck, and hands of the EVA crewmembers.

The solar storm protection requirements may best be stated as follows:

"Sufficient shielding shall be provided on EVA missions to reduce the risk of mission-threatening radiation exposure to allowable levels and to constrain astronaut radiation dose to within legislated limits. This shielding should be provided in suit design, vehicles, and safe havens. It should also be provided using locally-available geological structures or materials. Shielding requirements must be defined in concert with an appropriate solar-flare emergency plan." (Letaw, 1988)

In the event of medical, system, or solar flare emergencies, the range of movement from the main lunar base will be restricted operationally by the placement and capacity of distributed shelters and safe havens. Suggested requirements for safe haven and shelter are as follows:

- ▶ Safe haven should be a distributed network of facilities, each offering life support, medical and environmental protection, and resources for a full EVA remote expedition.
- ▶ Distribution and location of safe havens should be determined by EVA requirements, since concentrated EVAs (in one place and time) will require a safe haven. For EVA that is not concentrated, portable shelters should be used to ensure the safety of the EVA crew.
- ▶ Safe havens should be brought into position, buried in the regolith while activity takes place in the vicinity, and be removed and relocated as requirements on the lunar surface change.
- ▶ Portable safe havens should be part of the general configuration of the rover and should provide a pressurized environment where crewmembers can seek protection during system and medical emergencies.
- ▶ Shelters and safe havens should have the capacity to support a full expedition of EVA crewmembers for a period of 36 hours, plus time to effect rescue and removal, and a contingency safety margin. This requirement is based on a solar flare event that could keep the main base confined, preventing a rescue party from being sent.
- ▶ Portable shelters can be used in the emergency trenching scenario to augment protection of the crew during a solar flare emergency; however, portable shelters must be covered with regolith to provide protection from solar particle events.

4.8 PROPULSION SYSTEM ASSESSMENT

The principal propulsion system for remote lunar EVAs will be the surface rovers. Based on past experience and demonstrated performance, it is likely that battery power will be employed to propel the rovers across the lunar surface. The components of the battery system (chemicals, connections, heat, and pressure) that could be a hazard to the crew should be isolated or guarded.

Recharging and replacement of the rover batteries will take place at the servicing bay of the main base. Recharging of the batteries is possible at a remote location if solar panels and a charging system are built into the rover subsystems. Remote recharging can take place while the crew is involved in scientific or exploratory activity that does not require propulsion power.

Solar panels and radiators that are part of the propulsion system must be kept free of lunar dust for proper operation.

4.9 COMMUNICATIONS INTERFACE REQUIREMENTS

4.9.1 Internal Interfaces

This section identifies those requirements for the communication, instrumentation, and position-measuring hardware and software contained within the EVA system. All of these subsystems are closely related operationally and technically. Signals and data flow extensively among the elements, which should be closely integrated both electrically and mechanically.

A number of the elements also may be used in other systems and are well-suited for modular configuration. A standardized data base should interconnect the elements. An "intelligent system" should, at appropriate intervals, feed nondisruptive test signals through the subsystems

and analyze the elements' performance as a response to these stimuli. Status information should be presented aurally or visually along with recommended corrective action.

Outlined below are the subsystems and their functional elements which are required to provide the mission objectives of the EVA system.

Electric Power:

- ▶ The energy source may be common with that of the life support system but should be well-regulated and filtered to preclude EMI being introduced into the complex digital systems. This is particularly important when a relatively high-power pump or blower malfunctions and introduces large periodic loads on the system.
- ▶ Backup or emergency power should be designed into the system.
- ▶ Batteries should be easily changed, even while the suit is operating, to extend operating time and shorten down time for recharge.

Voice Communication:

- ▶ Service requests should be able to be made verbally or through an input keypad-type device located on the suit's exterior. Code generating circuits should link this device with the command subsystem. Groups of codes should be available for transmission as "macros" which activate preselected combinations of services.
- ▶ Redundant non-noise-cancelling microphones should be mounted within the helmet at locations allowing free head movement with minimum loss of speech.
- ▶ Redundant small speakers should be mounted within the helmet to provide near-uniform sound distribution.
- ▶ Specialized electronic equipment and acoustic treatment should be incorporated to prevent interaction of the incoming and outgoing full duplex signals. This will eliminate feedback and crosstalk.
- ▶ Aural signals from the suit caution and warning system and safety related C&W signals from the incoming radio signal should be connected to the speakers within the helmet in such a way that they may not be turned below a clearly audible sound level.

Outgoing Data:

- ▶ Subsystems contained within the overall EVA suit system should provide several types of outgoing data. These include telemetry from the suit, life support systems, and biomedical sensors; coded messages requesting communication services; data from task-specific tools or exterior systems; and outgoing commands of data retrieval, display inputs, and remotely controlled and teleoperator/robotic devices.

Incoming data:

- ▶ Incoming commands should be able to activate suit systems, such as emergency oxygen, from a remote location or assist the EVA by remotely controlling operational devices, such as the suit-mounted TV camera. Incoming data may be graphic or alphanumeric display inputs (typically procedures, position, or C&W information) or initializing parameters for task-specific tools.

TV Interface:

- ▶ Video output signals and control inputs associated with television and various smart sensors shall be interfaced into the suit signal complex for interaction through the RF link.

In-Helmet Display:

- ▶ This subsystem should allow a crewmember to display information around or on the inside of the faceplate so as to appear to be at visual infinity. Appropriate control of brightness, contrast, and other variables should be accessible to the crewmember within. Control of the light attenuation of the faceplate should also be accessible. This subsystem must interface extensively with the other suit subsystems.

Voice Privacy:

- ▶ The crewmember should be able to switch this decryption/encryption function. Compatibility shall be maintained with other network users.

Signal Processing and RF Transmission:

- ▶ These functions shall be transparent to the EVA user. They shall be controlled by automation and by the central station of the network in response to communication service requests. Redundant processing or channeling should be automatically activated.

4.9.2 External Interfaces

This section identifies the requirements that govern the communication and position measurement systems with which the EVA equipment must interface.

Scope of Surface Operations:

It is assumed that the systems must support the establishment and operation of a principal lunar base having a central facility, several outlying facilities, manned mobile equipment, surface vehicles, robotic or teleoperated equipment, and outside work/exploration areas. It also is assumed that EVA functions will be required at all sites. Most sites are clustered in one general area on the Earth side of the moon; however, operations must be fully supported anywhere on that hemisphere. By the addition of similar equipment, operations should be expandable to the far side of the moon. User equipment for the Earth and far sides should be identical and the transition from side to side should not be evident in operation. System configuration should allow suited EVA operation behind intervening terrain and structural features and within RF-shielded enclosures.

Communication Routing:

The ideal system should be very transparent, requiring a minimum of user insight into its mechanization. Several redundant signal paths should be inherently available for safety critical transmissions such as voice, life support telemetry/commands, and location information. Sortie or mission success communications should have some redundancy while enhanced capability functions may be single string. Design should minimize the opportunity for users to misconfigure their equipment, causing loss of communication, degraded data, or feedback through unintended paths.

Expected improvements in coding, bandwidth compression, beam switching antennas, microwave integrated circuits, RF component efficiency, etc., may allow transmission, at reasonable power levels, of the specified signals through a multiple access-discrete address system containing a central station plus a number of functionally similar user remote units.

User units would normally communicate with each other through the central station, not directly, except in an emergency backup mode where a direct EVA to EVA link is activated.

The preferred RF transmission path between a remote and the central station should be a direct line of sight. If satisfactory performance is not achievable through direct transmission, then the system should automatically relay the signal through a satellite orbiting overhead at libration point L1. This concept is depicted in Figure 4-5. Surface position measurement would be made in conjunction with satellites at L1, and later L2, and should be integrated with communication, using common carriers to the maximum extent possible.

If the achieved improvements are insufficient to support this configuration, then alternate signal paths should be used to provide adequate signal margins at reasonably low power. For this configuration, shown in Figure 4-6, an additional node is added at the rover or a portable relay unit. In this scenario, the EVA communicates directly through the reasonably high antenna of the base station if nearby or through the rover/portable relay if further out. If possible, the rover/relay will communicate directly with the base station. If this link is blocked by intervening terrain, then the signal will be relayed through a satellite orbiting overhead at L1 and back down to the base station. The EVAs can communicate directly with each other in a backup mode.

This configuration still allows discrete addressing and enables the EVA to operate at the lowest power level but may add complexity to the relay nodes and base station to maintain full flexibility of access, routing, combining, data distribution, etc. In this case, position measurements now identify the location of the mobile/portable node and not the EVA.

Relays:

Above the Earth side of the moon, the most likely location for an overhead satellite is at the libration point L1. Located on the 384,400 km line between Earth and the moon, L1 offers a stable point 58,000 km above the lunar surface. Very little stationkeeping and attitude control energy is required to maintain a relay at L1. Two small satellites on opposite sides of a halo orbit, in a plane perpendicular to the Earth-moon line and at the L1 point, provide maximum communication coverage of the lunar hemisphere and provide essential platforms for elements of a lunar surface position measuring system. This scheme is depicted in Figure 4-7.

Figure 4-5. Ideal Lunar Communication Links

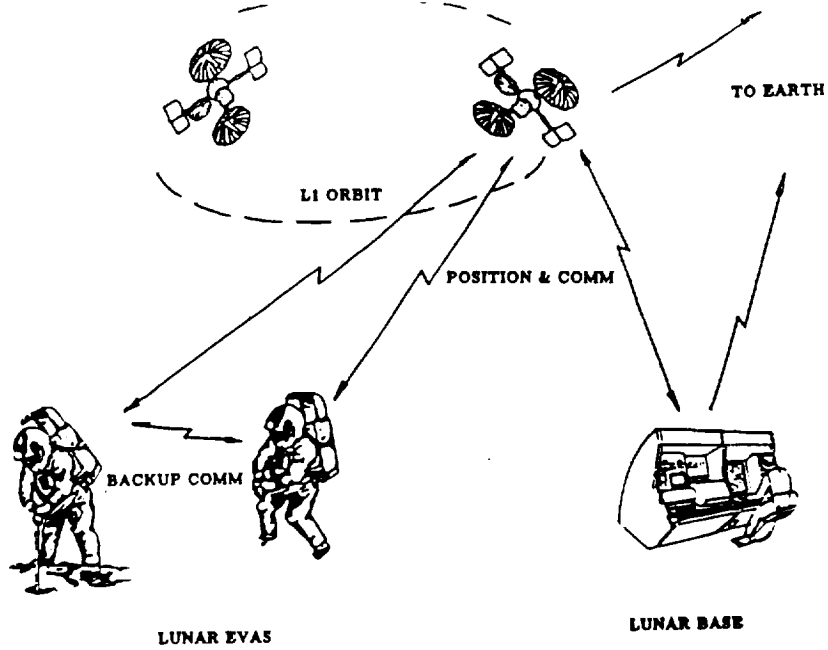
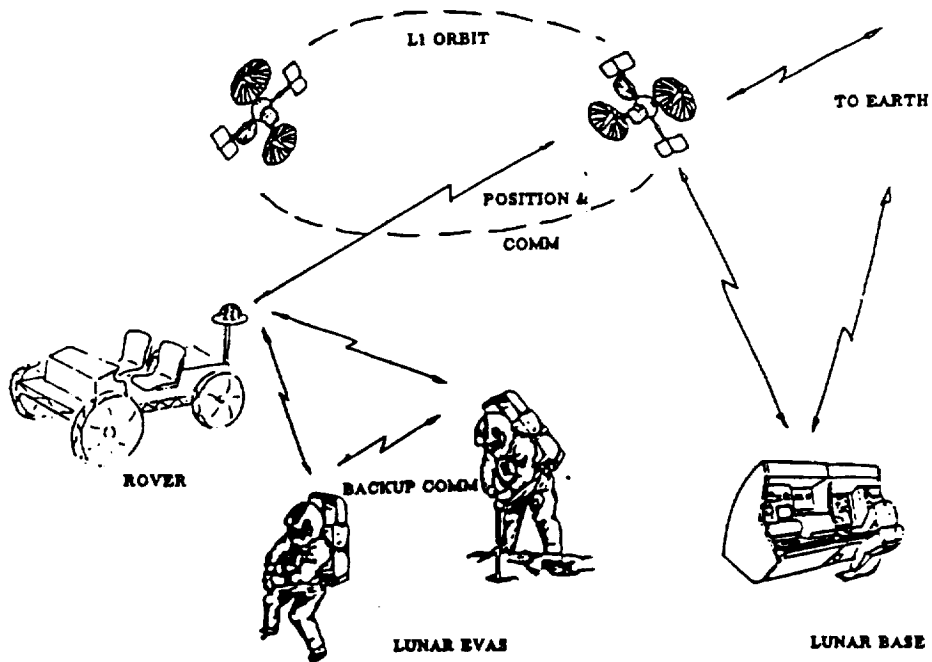
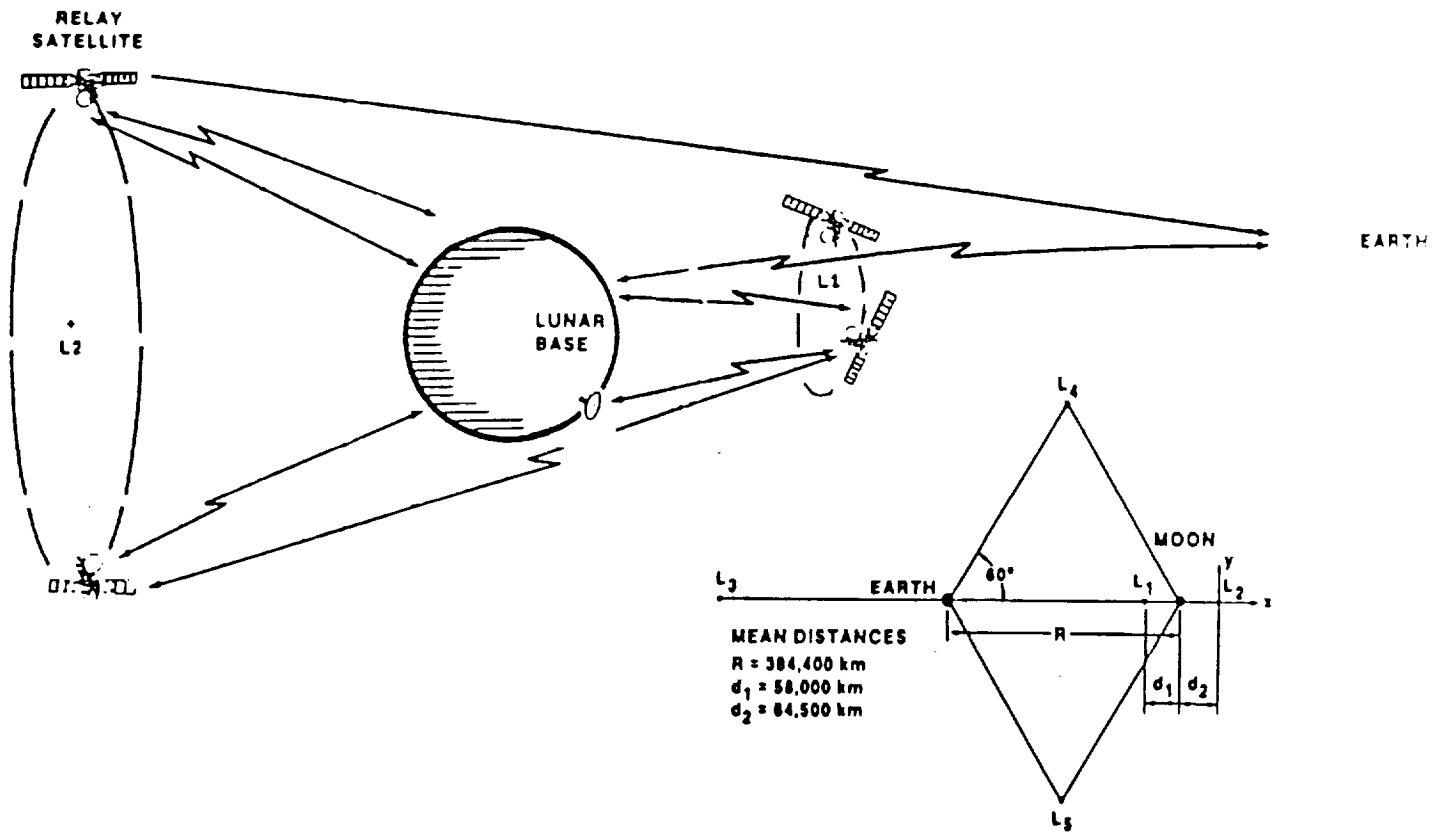


Figure 4-6. Alternate Lunar Communication with Rover Node



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Figure 4-7. Relay Satellite Locations



Earth Links:

Transmissions to and from Earth should be routed through either the orbiting relay point or the lunar base central station, both of which are in continuous sight of Earth. Future hardware capabilities and system engineering analysis will establish the optimum choice.

Future resources and technology will influence the choice between several sites for the Earth end of the moon-Earth transmissions. Presently known candidates include:

- ▶ a network of stations on Earth
- ▶ the Space Station
- ▶ the TDRSS network
- ▶ a geosynchronous space communications center (platform)
- ▶ the Advanced Communications Technology Satellite (ACTS).

Each of these, as well as those yet unannounced, offers identifiable advantages and limitations. Some of the factors to be considered when a selection is made include:

- ▶ frequency and duration of interruptions to the line of sight transmission path
- ▶ intervening signal losses, such as Earth's atmosphere for millimeter wavelength and laser transmissions
- ▶ in-place capability, such as NASA's network to TDRSS and access of multiple small users to the ACTS network
- ▶ international considerations to accommodate foreign participants
- ▶ bandwidth and traffic volume requirements
- ▶ available technology base
- ▶ cost
- ▶ ownership
- ▶ security needs - commercial, functional, national.

Access:

Users should access the system by making a service request by voice or by using a keypad. Requests may be entered during or prior to a sortie. They may be designated to commence and end at specific times, keyed to events or activated and terminated upon request. The elements of a request may be standardized and addressed as a "macro" or may be specified individually. Alteration may be requested during a sortie. Such requests specify required destination(s), types of services (voice, TV, telemetry, data, or other), and special features (multiple users, video recording, or teleoperator interface).

Unless deliberately inhibited, access should be available to any other system elements. Elements typically included should be:

- ▶ EVAs
- ▶ surface vehicles
- ▶ base consoles/individuals
- ▶ teleoperated equipment
- ▶ surface vehicles
- ▶ remote stations
- ▶ en route space vehicles
- ▶ Earth stations
- ▶ Earth-orbiting networks
- ▶ users/support on Earth.

The number of system users or elements has not been specified for two reasons. First, the features and capability of this system are provided in support of mission objectives that will change and be refined over the years to come, necessitating support requirement changes. Second, major changes in technology will drastically reduce the degree of difficulty in implementing progressively larger numbers of units. In any case, the system design must allow progressive expansion without restructuring/replacement.

Frequencies:

Emerging technology and its hardware capability implications are expected to have a profound impact on the selection of frequencies. There are, however, some invariable considerations that provide guidelines for proper choices:

- ▶ It is known that terrestrial VHF and UHF transmissions are readily received on the moon and are a potential threat to reliable network operation.
- ▶ Astronomical observations made from the moon open important portions of the spectrum in the microwave, HF, and LF (30 MHz down) bands. Earth's atmosphere and ionosphere prevent essential observations at each extreme. Lunar-based EMI in these bands is unacceptable.
- ▶ The same atmospheric losses inhibit reliable, efficient Earth-space communication at millimeter and optical wavelengths.
- ▶ The lack of atmosphere on the moon allows pathloss-free microwave and optical transmissions, as does the moon to low-Earth-orbit path.
- ▶ Operation in the optical spectrum and in progressively higher microwave bands reduces limitations on modulation bandwidths.
- ▶ Lunar dust presents a serious threat to optical transmission equipment.
- ▶ As operating frequencies increase, the size of components and hardware assemblies decreases.

- ▶ Operation with switched narrow beam microwave antennas greatly reduces transmitted power requirements.
- ▶ Progress in microwave, electronically steerable, array antennas indicates that beam forming and hemispheric scanning will be a reality in the lunar base time frame.
- ▶ Use of microwave, electronically steerable, array antennas on a relay satellite greatly reduces the attitude stability requirements and improves fuel economy.

Modulation/Multiplexing:

The use of Ku, Ka, W, and higher bands offers significant increases in available bandwidth and enables precise timing. Nevertheless, bandwidth compression algorithms will remain essential as data rates increase dramatically. Many modulation schemes should be evaluated as coding algorithms, multiplex techniques, and hardware capability continue to change and improve. Several new choices probably will be added to present selections of basic multiplexing schemes, which now include Frequency, Time, Code, and Space Division. Schemes like Quadrature Phase Shift Keying (QPSK) are revised to add Staggered QPSK. Nonlinear techniques offer different prospects.

Time Division Multiple Access (TDMA) schemes are of particular interest since they might be integrated with the position measuring function to utilize the minimum hardware for the maximum number of tasks.

Position Measurement:

An accurate, user friendly position measurement system should provide location data throughout the lunar hemisphere without concern for terrain features that block the line of sight and make most systems useless. Three or more levels of resolution should be readily available, providing appropriate accuracy and complexity for varied tasks.

Long wave systems are not usable because of high galactic noise and use of that spectrum by radio astronomy. Microwaves, however, are acceptable because the two orbiting satellites described at LI are high over head and offer equipment sites for a number of suitable position measuring systems. Operating in conjunction with the base central station and transponders at truth sites, excellent accuracy should be achievable with only moderate complexity and great utility. The lowest level of resolution suitable for routine position indication of nominal accuracy should be made using only a portion of the system capability. Shorter codes or other techniques will simplify the hardware and provide rapid data output. Full satellite system capability will provide the second level of resolution. The third level will be used on those limited occasions when very high resolution and accuracy are required. For this application, an independent system utilizing an adaptation of laser surveying equipment should be used.

A standardized position-data system element should be incorporated into the EVA suit communication equipment, or mobile first node, with data displayed in coordinate and graphic form by the HUD. A similar modular element should form the nucleus of the surface vehicle navigation system. This system should provide position, velocity, direction, control, range, and energy requirements related to defined or pre-established waypoints as well as topography information. Graphics from mass storage, controlled by position data, should be provided to the vehicle or EVA HUD.

Future Expansion Capabilities:

Systems based on the outlined requirements offer services to an inherently large number of users. Several methods are available to further expand the capabilities for more ambitious missions. A likely direction of expansion is toward operations on the side of the moon turned constantly away from Earth. Fortunately, this expansion fits perfectly into the concept already evolved.

Addition of two more halo orbit satellites, like those at L1, into a similar but larger diameter orbit at L2 provides the same service over the back side of the moon with coverage at the limb and relay capability between the front and back sides through L1 and L2 (see Figure 4-7). L2 is located 64,500 km above the lunar surface, directly away from Earth. The relay time through L1-L2 for Earth side to far side is about one second, while relay time for Earth side to far side through Earth and L2 is about five seconds. Teleoperations and remote control of activities on the far side are much more feasible when controlled through L1 from the Earth side of the moon rather than from Earth or through an Earth relay.

4.10 CREWMEMBER AUTONOMY

The issue of crew autonomy for remote lunar EVA is necessarily restricted to local operational autonomy. The crew are dependent upon lunar base or possibly Earth base for significant support, but the local area operations should be well understood and rehearsed so that both lunar base personnel and EVA personnel know what to expect during nominal operations.

The extent of autonomy will be highly dependent upon the types of support - communication, safe havens, caution and warning - that are in place during the EVA missions. To the extent that other requirements found in this study are met, such as a distributed safe haven network or local real-time warning of solar flares, the lunar EVA crew should be able to function with a high degree of autonomy and flexibility during the conduct of science, mining, and sampling operations. With appropriate training and experience, lunar EVA operations can be carried out by the EVA crew without the same level of watchfulness required during the Apollo missions.

The appropriate level of autonomy for the EVA crew will be dependent upon the maturity of the base operations, the levels of experience we will gain from successive lunar EVA operations, and the increasing maturity of major support systems such as crew rescue vehicles, lunar satellite systems, local area science stations, and portable habitats.

Remote EVA expeditions should be able to conduct a complete mission exercise under nominal conditions with the resources that they take to the remote site. Primary decision making concerning nominal operations should take place at the EVA site, with the capability to request additional information from lunar base or Earth base in support of nominal operations. Normal operations should be carried out under local executive authority, with the capability to request lunar base assistance as required.

The extent of crew autonomy during contingencies and emergencies is less well defined. The following requirements pertaining to crew autonomy are suggested:

- ▶ The EVA crew should be capable of being precisely located by the lunar base and a redundant locator system without any action on the part of the EVA crew.
- ▶ The EVA crew and the lunar base should be able to engage in two-way communication at any time during an EVA mission.
- ▶ The EVA crew should have the responsibility for pacing tasks at the remote sites and reporting back any significant deviation from the timelines established during training.
- ▶ The EVA crew should be able to announce targets of opportunity and execute a plan to take advantage of them.
- ▶ The lunar base must have solar flare detection instrumentation and a warning system that can be used to alert the EVA crew without help from Earth.

4.11 DEDICATED EVA HARDWARE SERVICING AREA

From an operational standpoint, hardware servicing should be conducted at the main lunar base. The requirement to support remote, local hardware servicing should be restricted to contingency mode operations.

Provisions at the remote site to service hardware at the LURU level should be made in a dedicated space on the rover. Requirements include a work surface that is free of soil and other contamination. The workstation should provide lighting, tools and tool storage, visual and manipulative aids such as magnifiers and holding aids, access to procedures for servicing, and diagnostic and verification equipment.

On lunar expeditions, it may be required to dedicate a hardware servicing area removed from the hardware assembly areas where bits and drill rods assembled for soil sampling are handled. It may be necessary to make a distinction between normal assembly and handling and hardware servicing.

For extensive servicing missions to a number of remote sites it may be desirable to have a dedicated portable workbench that provides isolation and protection for the equipment being serviced. Such a concept for a portable workbench and glove box appears in Figure 2-4. This type of equipment would not be carried on every mission, but on missions that are dedicated to servicing and repair or replacement it would reduce the down time and the inconvenience of having to return the equipment to the rover and then to the main base for servicing. (See also section 3.1.4, Hardware Servicing.)

4.12 AIRLOCK INTERFACES

The airlocks used to support remote lunar operations will function to pass people and material from a clean or pressurized environment to the lunar surface and to return material and personnel from the lunar surface to a pressurized, clean, or protective environment. The overriding consideration in the design of any airlock will be the contamination posed by the abrasive lunar soil. Airlocks should be designed to prevent any lunar soil from becoming trapped in the airlock mechanisms and limiting their effectiveness. This applies to both equipment and personnel airlocks.

4.12.1 Crew Airlocks

Crew airlocks at locations remote from the main base will be the exception rather than the rule during the initial stages of lunar exploration. At most of the outposts, the crew will remain in their LEMUs during operations. The solar storm shelters do not provide a pressurized environment but rely on the LEMU for life support and protection.

As the technology and requirements mature, there may be cases where remote operations occur in a pressurized environment and consequently there will be airlocks. The airlocks will have to provide a means for controlling lunar dust, such as positive pressure, filters, and scrubbers. They will have to be sized to accommodate at least two crewmembers for purposes of rescue on the buddy system. They should accommodate the temporary storage of equipment and outer garments in much the same way as the dustlock/airlock shown in Figure 2-16 does.

Crew airlocks attached to rovers might be the first use of remote airlocks. Several concepts for enclosed touring cabs, ambulance modules, and portable hyperbaric chambers have been considered in this study, and each would require a crew airlock capable of isolating the crew from the lunar environment while providing life support. The requirements for such portable airlocks in these concepts would still reflect the soil contamination problems and a means for controlling the entry of abrasive lunar soil or filtering it from the airlock should it be introduced.

4.12.2 Equipment Airlocks

Passing equipment at a remote EVA site through an airlock is not deemed a likely event unless there is also a crew airlock or a pressurized work area in which crew work in a shirtsleeve environment. Equipment airlocks would have to meet the same contaminant control criteria as the crew airlock so as not to introduce soil into the pressurized, habitable environment. Equipment airlocks should be sized to accommodate the largest LURU that will be serviced at a remote site. This may mean that the crew airlock serves both for equipment and crew pass-through.

5.0 Recommended Further Studies to Support EVA at Lunar Base

In our consideration of these lunar EVA scenarios and the systems required to support them, a number of candidate areas for further research and technology development have been identified. Open issues for further study are listed below by topics.

5.1 EXTENDED EVA

- ▶ 8-hour work period, not to include "overhead" and travel
- ▶ Umbilical connection to rover consumables
- ▶ Life support system recharge at rover or shelter
- ▶ Quick don/doff suit
- ▶ Suit maintenance technicians and EVA support technicians for pre-/post-EVA servicing

5.2 SUITS

- ▶ Greatly improved gloves with better hand motion and finger dexterity than Apollo gloves (taking into account Shuttle-era glove improvements) under pressure conditions in a "no prebreathe" suit (6 to 8.3 psia)
- ▶ Use of umbilicals to extend EVA time on-site or during rover excursions
- ▶ Seals for protection of rotating joints against long-term abrasive effects of lunar dust
- ▶ Effective lubricants for moving and rotating parts
- ▶ Cleaning and drying station for suits
- ▶ Impregnated "fabric" patches for colorimetric determination of exposure to toxic contaminants (e.g., propellants at a launch site)
- ▶ Helmet-mounted Heads Up Display for text, graphics, and video with sufficient range of brightness and/or contrast for operation under wide range of EVA lighting conditions (currently under development)
- ▶ Voice activation/control of displays and suit parameters
- ▶ Endothermic packages for localized emergency cooling and hygroscopic or desiccant packages for emergency removal of excess humidity
- ▶ Emergency packages of a supplemental scrubber material (e.g., activated charcoal) that might be used for rapid removal of inhalation toxicants within the suit
- ▶ Analysis of the utility and feasibility of an injection patch on the suit or the application of dermal patches during EVA
- ▶ Real-time internal fit adjustment for comfort and support

- ▶ Improved in-suit food/drink dispensing
- ▶ Suit "hardpoint" for lifting/hoisting in 1/6 g
- ▶ Contamination resistance (toxic chemicals, lunar dust)
- ▶ Abrasion/wear resistance (reinforced areas of outer suit, replaceable patches)
- ▶ Unassisted rapid donning/doffing
- ▶ Lightweight IVA suit with integral life support - rapid unassisted donning (30 seconds), rechargeable O₂ supply (1 hour purge flow)

5.3 ROVERS

- ▶ A basic power train and chassis to support a wide range of missions, payloads, and configurations
- ▶ System design concept in rover development; use of functional, modular subsystems to customize for different missions
- ▶ Broadband RF detector for detection and display of real-time electromagnetic field intensity as crewmembers move around various communications antennas
- ▶ Portable locating, pinpointing, and ranging devices for exploration efficiency, scientific data, and emergency rescue
- ▶ Design of rover as a source of power and consumables for EVA resupply
- ▶ Depots for rover recharge of power and consumables

5.4 SHELTERS

- ▶ Active and passive radiation shields
- ▶ Solar flare detection and warning system with sufficient advanced warning and a low false alarm rate
- ▶ Dust removal system (electrostatic precipitators, recyclable water shower, etc.)
- ▶ Systems analysis of statistical and practical value of safe haven concepts to develop an optimal mix of protective shelters

5.5 BIOMEDICAL CONCERNS AND TECHNOLOGIES

- ▶ Self-applying, unobtrusive medical sensors
- ▶ Non-invasive technique for monitoring blood electrolyte levels

- ▶ Expected exposure to ionizing radiation on lunar surface: new calculations based on most recent information and models
- ▶ Pharmaceutical countermeasures for radiation sickness
- ▶ Possible aggravation of health problems during EVA by presence of high-level radiation background
- ▶ Radiation protection, detection, monitoring, and exposure record
- ▶ Effects of ionizing and non-ionizing radiation levels on the body's ability to thermoregulate
- ▶ Physiological monitoring equipment containing algorithms for semi-automated alarm decisions
- ▶ Critical access requirements, if any, for 6 ATA, two-person hyperbaric chamber
- ▶ Effects of long-term exposure to elevated CO₂ levels on calcium metabolism
- ▶ Long-term consequences of breathing lunar dust and chronic exposure to it (e.g., pneumoconioses)
- ▶ Pulse oximeter as a monitoring device during EVA
- ▶ Suit sizing accommodations for crewmembers entering lunar base from Earth or from Space Station
- ▶ Possible use of "electronically tuned" (e.g., Piezo electric) eyeglasses which can be adjusted by the crewmember to accommodate changes in vision due to extended stays in space
- ▶ Dietary factors and considerations of lunar-grown food and any dietary supplements required for balance
- ▶ Plans for rotation of inventory of supplies to maintain shelf-life control on critical medical supplies, consumables, and pharmaceuticals; disposability versus reusability (and sterilization) of medical supplies and equipment; handling, storage, and resupply of blood products
- ▶ Degree of continuing education required in order to maintain proficiency in medical procedures, equipment repair procedures, emergency and contingency procedures, etc.
- ▶ Regenerable/recycling systems for life support consumables (e.g., O₂ and H₂O reclamation)
- ▶ Physiology profiles for response/adaptation to lunar gravity and lunar day-night cycle (circadian impacts)
- ▶ Physical conditioning protocols, facilities, equipment (time penalty, artificial gravity (1-g), special equipment for 1/6 g)
- ▶ Condition assessment for EVA work capacity (daily kcal capability), EVA work management (real-time budgeting/monitoring), and non-invasive biomedical parameter sensors

- ▶ EVA suited requirements for metabolic heat removal and food/drink
- ▶ Extent of reuse applicable to various human and/or process waste containment devices

5.6 TOOLS AND EQUIPMENT

- ▶ Voice control for suited and unsuited control of facilities, equipment, tools
- ▶ Emergency "come home" systems requiring minimal supplies and possibly self-powered by the crewmember to allow return to lunar base (e.g., ski poles or other simple accessories to speed EVA translation on the lunar surface and compete with rover speeds)
- ▶ Lightweight portable pressurized enclosure with and without airlock
- ▶ Lightweight gas pressure pumps with long life and high reliability
- ▶ Rechargeable batteries immune to limits/problems experienced with current products - accurate knowledge of state of charge and power delivering capability; automated reconditioning (deep discharge/rejuvenation); increased number of recharge cycles; insensitive to discharge depth points (% of discharge between recharges)
- ▶ "Smart" power tools and aids controllable by voice commands
- ▶ Post drivers (manual or power)
- ▶ Large-wheel cart for manual equipment transport at main base and remote worksites (similar to Modular Equipment Transporter System (METS) used on Apollo 14)

5.7 COMMUNICATIONS

- ▶ Appropriate application of speech synthesis and speech recognition techniques
- ▶ Predicted extent of communications disturbances during solar storms
- ▶ International Signaling and Symbol System (ISSS) - similar to maritime, aeronautical, and road traffic devices (signs, light signals, color standards, and graphic patterns) lunar surface location (latitude/longitude) convention, position locator, EVA personnel beacons, and communication configuration display
- ▶ Continuous voice/data capability, immunity to solar activity for effective voice communication from safe haven shelters during solar storms
- ▶ Elimination of suit airflow noise
- ▶ Duplex implementation
- ▶ Redundancy (RF-RF; RF-laser)
- ▶ Suited access to data systems (Earth and lunar)

- ▶ Laser, voice, and data communications (point-to-point lunar and Earth-lunar)
- ▶ Effect of noisy and distorted voice communication on crew attention and performance
- ▶ Display features that present communication configuration to preclude undesirable/unintended comm set-ups and to confirm selection of desired configuration

5.8 CONTAMINATION CONTROL

- ▶ Dust removal system (e.g., electrostatic precipitators, recyclable water shower)
- ▶ Electromagnetic/electrostatic techniques for moving lunar soil and removing dust contamination from suits and equipment
- ▶ Verification of contamination control (dust, toxic chemical, trace contaminant detectors and indicators)
- ▶ Gas purge decontamination (use of gas to destroy, neutralize, or remove biological and chemical contaminants)
- ▶ Absorbent patches

5.9 WORKSITE OPERATIONS

- ▶ Automated power up/power down
- ▶ Equipment guards to protect crewmembers from operating envelopes of moving parts of equipment
- ▶ Contamination guards/shields to protect suited crewmembers from debris and ejecta
- ▶ Automated emergency/contingency operations deactivation (emergency "kill switch") to permit rapid (immediate) termination of operations during crew emergency, solar storm alert, or safety contingency
- ▶ Task planning/sequencing aids for task priority/sequencing/monitoring and management, power optimization (power profile management), and real-time status/progress/task modification assessment
- ▶ Automated inventory management and control (e.g., RF responsive tags)

5.10 ENVIRONMENTAL PARAMETERS

- ▶ Updated radiation environment and exposure models for lunar EVA
- ▶ Classification of lunar soil mechanics/properties; definition of slope limits for vehicles, equipment, and suited crewmembers, definition of adhesion/contamination

5.11 LUNAR SURFACE EVA PLANNING DOCUMENT

- ▶ Similar to flight planning documents prepared for specific missions on previous programs

This generic document would serve as a comprehensive reference of standards and requirements for a wide variety of lunar surface EVA planning issues. A representative sample of topics from a lunar EVA planning document would include:

- Cartographic standards, requirements, and considerations
- Topographic classification of the lunar surface operations areas for assessment of slope, roughness, soil mechanics, regolith depth, etc. - a specialized lunar atlas
- Operational protocols and standards; for example,
 - Night operations support system - system of light poles on routes (strobes and floods), remote operation (area flood), features (telescoping height, spacing, installation/erection/removal, signaling applications)
 - Soil moving/stacking protocols (where to dump soil) - lighting/shadow considerations, distance/position/geometry of dumps/piles, sampling protocols applicable to soil mining operations where science is not the primary objective

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