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T INITIAL CONCEPT OF LUNAR EXPLORATION SYSTEMS FOR APOLLO,

Volume I: SUMMARY +2 [Final Report]

Prepared ~~under~~ (NASA Contract ~~No.~~ NASw-792) by
THE BOEING COMPANY
Seattle, Washington
for

Corp. auth.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, WASHINGTON, D. C. • MARCH 1964

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INITIAL CONCEPT OF LUNAR EXPLORATION SYSTEMS FOR APOLLO

Volume I - SUMMARY

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THE BOEING COMPANY
Aero-Space Division
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ACKNOWLEDGMENTS

The assistance of the following associates in this study is gratefully acknowledged.

Consultants	Areas of Interest
Admiral George J. Dufek	Operations and Logistic Support
Prof. Z. K. Kopal	Lunar Topography and Environment
Prof. W. R. Webber	Lunar Environment

Contractors	
General Engineering Division, American Machine and Foundry	Lunar Roving Vehicle
Allison Division, General Motors	Power and Fuel
Atomics International, North American Aviation	Power
AiResearch Mfg. Co., Garrett Corp.	Life Support
Bendix Radio Division, Bendix Corp.	Communications
Holmes and Narver, Inc.	Base Construction
General Motors Defense Research Laboratories	Lunar Roving Vehicle

Voluntary contributions received from other sources have been acknowledged within the respective sections of the document.

1.0 INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

This is the final report in a 4-month engineering study to provide a conceptual design of a modular lunar base system for lunar exploration as a part of Project Apollo. The study was performed by The Boeing Company with a team of industry associates for the NASA Office of Manned Space Flight under Contract NASw-792.

The system and subsystem functional analyses and conceptual design accomplished in this study are summarized in Volume I, and reported in detail in Volumes II and III of the final study report, Boeing Document D2-100057. Significant data abstracted from Volumes II and III are compiled in a data book, Volume IV of D2-100057.

1.1.1 Background

Lunar exploration may move into reality with the initiation of the landing of two men on the lunar surface in this decade. While the emphasis during this period will be on the first manned landing, it seems not too early to take a closer look at what might possibly follow this initial landing and how the major elements of Project Apollo may best be used. A program of scientific and exploratory work on the Moon is the rational sequel to and is virtually implicit in the present national commitment to manned lunar landing. The exact course of lunar surface exploration and exploitation cannot be predicted at present. Uncertainties exist in many areas, including detailed data on the lunar surface characteristics and environment, the level of funding of lunar operations, and the relative importance of many possible lunar missions. However, many probable lunar missions will require support by facilities on the lunar surface. Although the size, lifetime, and purpose of these facilities will vary with the specific mission, all must perform the fundamental functions of providing shelter, life support, power, communications, and surface mobility.

An acceptable lunar exploration support system concept must capitalize on the similarities that are certain to exist in any lunar facility, and yet must retain sufficient flexibility to accommodate the many uncertainties. Retention of flexibility appears to be a reasonable objective if some departure from optimum design is acceptable.

1.1.2 Objectives and Scope of Study

The basic objective of the study was to provide a conceptual design of a modular lunar base system within the criteria set forth by NASA in RFP 10-1132 (Reference 1) and summarized in Section 1.1.3.

To meet this objective in the 4-month study, Boeing accomplished the following:

1) Each major subsystem was defined and analyzed parametrically, from the minimum function for the specified 90-day-stay, two-man operation with limited transportation, to the 2-year system with an 18-man population.
2) Subsystem requirements were then applied to an analysis of modules designed to meet the requirements. Logical modules were derived to fulfill the needs of varying base sizes and deployment up to 18-man base complexes. The function of each was defined and the limits of desired functional capabilities were established.
3) A conceptual design of each module has been prepared. Dimensions, configuration and weight estimates, and operating characteristics and limits are provided.
4) The interfaces between modules and subsystems have been defined. The effect of these interfaces on base design weight, operating manhours, and performance were investigated to determine the impact on selected base complexes. Estimates of the flow of communications, materials, energy, and personnel have been prepared.
5) Concepts for installation, operation, and maintenance of several base systems of various degrees of complexity and lifetime have been delineated.
6) An analysis was made to determine quantities of materials required for installation, operation, and maintenance. The analysis considered base size, lifetime, degree of logistics independence, and activity level. The resulting data is summarized in the form of logistics plans for typical base systems.

Throughout the study, an attempt was made to identify areas where intensive added study and experimental tests are required. The nature and extent of such added effort are summarized.

1.1.3 Study Ground Rules

The general guidelines under which the 4-month study was conducted are contained in the work statement enclosed with NASA RFP 10-1132. These criteria, as modified by supplemental instructions, are summarized below.

1.1.3.1 NASA Outline Concept of Lunar Exploration System —

A. General

The system will consist of a family of prefabricated modules that can be assembled on or below the lunar surface in a variety of arrays to support a range of missions. The design will facilitate expansion of installations both to increase capacity and to decrease dependence on resupply from Earth.

B. Criteria

1. As a fundamental criterion, the system must be compatible with its primary mission of providing basic facility support to a variety of scientific missions.
2. All modules of the system must be transportable on lunar logistic carriers foreseen for the period 1970 to 1975. (Payload restraints imposed by Saturn V, which is the limiting carrier, are outlined in Section 1.1.3.2.)
3. The system must be adaptable to installations in the specified range of lunar environments.
4. Modules must be designed for 1 year of unattended storage on the lunar surface prior to use.
5. The system must be adaptable to small outposts manned by as few as 2 men and to large installations occupied by as many as 18 men.
6. The system must be adaptable to both temporary and permanent installations. Elements must be suitable for outposts with useful lives as short as 90 days and for more permanent installations with life expectancies of several years. In addition, the design must facilitate evolution of the former into the latter.
7. System must be feasible for development by 1970 to 1974.
8. The design of the system must consider the high cost of: (1) effective manhours of working time on the lunar surface, and (2) transportation of materials and equipment from Earth to Moon.
9. For missions of long duration, the design should permit individuals to remain on the lunar surface for up to 6 months before rotation back to Earth.
10. The design should make maximum use of natural lunar materials when: (1) there is a high probability that this is feasible, and (2) detailed analysis indicates that use of these materials will yield substantial advantages.
11. The base system must be useful during periods when the capability to transport men and materials to the Moon is severely limited. For the purpose of early planning, it should be assumed that, under the most austere conditions, one successful Apollo or Saturn V lunar logistic system shot will be available for lunar base operations each eight weeks. In less austere conditions, monthly launches may be assumed.

C. Subsystem Concepts

The following tentative descriptions of the major subsystems of the lunar base were provided by NASA as an initial guide to the study.

1. Personnel Shelter — The basic module of the lunar base system will be a shelter designed to house several men. It will have integral life support, power, and communication equipment, and could function virtually alone as the principal element of a small temporary outpost. In larger installations, separate subsystems will provide additional capabilities for life support, power, and communications and the equipment installed in the shelters may be retained primarily as standby for emergency use.

2. Life Support — This subsystem will consist of several modules; the number will depend on the population of the base and the desired degree of logistic independence. In larger, more permanent installations, the basic life support modules will be supplemented by additional regenerative equipment to reduce the need for resupply of consumable materials. The ultimate base complex may include modules to generate life support materials from lunar resources.

3. Power — For other than the smallest installations, nuclear power plants will serve as the basic source of energy. A single plant may be used for short missions and during the early phases of base development, but multiple plants of standard design will be the usual source of power.

4. Fuel — In the smallest installations, the fuel system will consist of modules that store and dispense fuel shipped from Earth. To reduce the logistic burden to a minimum, larger installations will be equipped with additional modules that regenerate fuel from engine combustion products using energy drawn from the nuclear plants. In the ultimate base, additional modules may make up fuel system losses by generating fuel materials from lunar resources.

5. Communications and Control — The basic module of this subsystem will provide local and Moon to Earth communications. In addition, it will serve as a navigation aid to spacecraft.

6. Vehicles and Mobile Equipment — Construction and operation of a lunar base will require vehicles for material handling, surface modification, transportation, and reconnaissance. In design, the practicability of multipurpose vehicles will be explored.

7. Maintenance — Maintenance modules will provide installations of various sizes with the capability to maintain vehicles and installed equipment.

8. Mission Support Equipment — Specialized equipment to support specific scientific missions will be developed separately and will not be considered part of the lunar base system.

1.1.3.2 Earth to Moon Transportation Payload Restraints — Preliminary Saturn V lunar logistic vehicle payload restraints are summarized below:

Maximum diameter: 260 inches;

Minimum height above lunar surface: 70 to 260 inches;

Maximum launch acceleration: 8 g's;

Maximum landing acceleration: 15 g's;

Maximum payload weight: 25,000 Earth pounds;

Maximum horizontal distance of center of gravity from Bus axis: 14 inches;

Payload center of gravity as low as possible;

Payload supported on periphery;

Overall height unrestricted, within reasonable limits.

Further adjustments in these restraints will obviously occur as the transport vehicle and payload designs evolve.

Crew transportation capability is presently limited to the two-man lunar excursion module. NASA Project Management has indicated that an advanced Apollo may logically be expected to carry three men to the lunar surface in 1970 to 1975. This latter capability was assumed in the phasing of base installation and manning.

1.2 PROBLEM AREAS

Problem areas defined in this study have suggested a number of technical investigations that appear to warrant further detailed study and experimentation. Knowledge gained thereby may be valuable or essential to appropriate planning for the Apollo mission, the lunar base, and even for extended manned exploration of space. These problems are described here to enlarge the picture of initial concepts (which includes definition of recognized frontiers), to delineate present understanding, and as a recommendation for urgent attention. Problems recognized in the areas of Environment, Materials, Man, Mobility, and Mission are the subjects of the suggested future investigations.

1.2.1 Environment

1.2.1.1 Radiation — The particulate-radiation studies begun at Boeing, in consultation with Dr. W. R. Webber, should be extended to determine the incidence and effects of "heavy" particles, which appear to compose a substantial portion of the radiation at the Moon. Studies should include experimental measurements and analyses of data to estimate the probabilities of biological effects as related to shielding.

1.2.1.2 Meteoroids and Meteoroid Shielding — Wide discrepancies still exist, from parallel sources of data, in estimates of the lunar meteoroid flux. In addition, the effects of hypervelocity particles on materials need examination. Existing test data are limited to velocities below 30,000 fps with most below 20,000 fps. Testing of proposed systems or material is required above 60,000 fps to determine the spacing and material properties of barrier elements needed for shielding against meteoroids. Self-sealing configurations or techniques to repair impact-damaged structures should be developed.

1.2.1.3 Thermal Control — Unique solutions are required for the temperature-control problems on the Moon. Although the suggested approaches to these problems are feasible, additional thermal analyses are required that consider not only the analytical problem but also the manifold requirements of the thermal-control system and the interrelationships between the thermal-control system and the rest of the shelter system.

1.2.1.4 Low-Frequency Lunar Communications System — Improved definition is required of the antenna and propagation problems associated with a voice-communications system for lunar operations. The system must be capable of providing a link between the base and points beyond line of sight on the Moon. The study should include a theoretical analysis of ground wave propagation over curved ground having conductivities on the order of 10^{-4} to 10^{-3} mhos per meter and surface roughness similar to the mountainous terrain of the Moon.

An experimental program should be conducted in conjunction with the theoretical studies. Propagation studies could be performed at microwave frequencies on a one-millionth scale model of the Moon. Since antennas cannot be modeled to this scale, actual antenna configurations must be tested in low-conductivity areas such as San Diego, California.

1.2.1.5 Power-Generation System Startup — The techniques and problems of remote terrestrial, automatic lunar, and manual lunar modes of control for startup of fuel cell and nuclear systems should be investigated and compared in detail.

1.2.1.6 Electrical Equipment and Transmission Line Cooling — Cooling configurations and rating for various types of lunar-base electrical equipment are required to support future development effort. A detailed study should be made to obtain ratings for a family of wires and cables suitable for lunar power transmission, including analysis of applicable cooling configurations.

1.2.2 Materials

1.2.2.1 Thermal Cycle Effects — The lunar environment would appear to aggravate some of the difficulties arising from thermal history in materials. For the alloys and compounds of principal interest, generalized investigations would help to increase design and mission assurance.

1.2.2.2 Cold Welding — Effects of ultrahigh vacuum on properties of materials are still only slightly known. Systematic studies can establish narrower boundaries on properties of idealized materials. In addition, for practical design, the need remains for invention and ingenuity so that materials, structures, coatings, and seals will function on the Moon in complicated systems with the flexibility or freedom of choice taken for granted on Earth.

1.2.2.3 Evaluation and Development of Lightweight and High-Modulus Alloys — Improved material properties will permit the attainment of lighter weight through more efficient structure, and also will provide improved meteoroid and radiation shielding. Experimental investigations should include:

1) Further fabrication and joining research on beryllium, beryllium alloys, and magnesium alloys, including adhesive bonding;
2) High-velocity impact testing above 60,000 fps on the lightweight alloys;
3) Investigation of toxicity hazards caused by sputtering or spalling of beryllium or its alloys;
4) Development of design data on fracture toughness of the light alloys;
5) Biaxial load testing of subscale tanks incorporating simulated flaws.

1.2.2.4 Development of Plastics and Elastomers — Principal development effort is required in the areas of seals, sealants, and structural applications. Operationally suitable hatch seals must be developed and tested for prolonged periods of time under irradiation and high-vacuum conditions. Subsystem components such as cryogenic and lubrication seals must be developed. More development in nonfoaming sealants and adhesives is required.

High-hydrogen-content plastics should be investigated for their radiation-shielding properties. Foaming and nonfoaming resins should be investigated as binders for lunar soil.

1.2.2.5 Thermal Coatings — Development of thermal control coatings is still in the laboratory stage and has not progressed to a usable system. The coatings are quite brittle and require sintering to achieve water insolubility. Testing has not progressed to wavelengths shorter than 2000 Å. Wavelengths shorter than 4400 Å have largely been neglected; this is the range that causes the greatest darkening of zinc oxide.

Binders should be investigated that are more practical in application and will give adequate corrosion protection before launch. The siloxane-type binders, using a magnesium-oxide filler, show promise. Vibration, salt spray, and thermal cycling should be conducted on large panels. Testing at short wavelengths should not be neglected.

1.2.2.6 Lunar Surface and Subsurface Analysis — The detailed composition and engineering behavior of the lunar surface and subsurface must be known to permit the rational design of lunar support facilities. Four major categories of research are required:

1) Mapping of the Moon's surface;
2) Study of lunar soil formation and general nature of surface and subsurface materials;
3) Terrestrial simulation of lunar soils;
4) Theoretical and experimental determination of lunar soil properties and mobility problems, construction problems, and soil stabilization problems.

1.2.2.7 Vacuum Cratering — Knowledge of the effect of reduced atmospheric pressure on the size of craters formed in a granular medium by a known quantity of chemical explosives at various scaled burst depths is required to evaluate the feasibility of blasting techniques on the Moon. A pilot test series should be planned initially to determine facility requirements and to delineate problems arising from the detonation of explosives in a vacuum environment.

1.2.3 Man

1.2.3.1 Effect of Prolonged Reduced Pressure on Man — Human response to various pressures and compositions of atmospheres has vital importance to lunar base design, especially at the lower pressures. Assured establishment of human tolerance to very low pressures over a reasonable tour of duty would add greatly to the assurance of a design based on such low-pressure criteria.

1.2.3.2 Multiple Environmental Stress — Data are needed that define the effects of multiple environmental stress on man in support of transit and surface operations, and to recommend acceptable tolerance levels. The scope of investigation should be to determine, by simulation of mission profiles, the effects of space environments on the individual. Such tests should determine the modes of stress interaction and accumulation, and acceptable tolerance levels for man.

1.2.3.3 Psychological and Physiological Problems — Physiological investigations should include problems of decompression sickness, optimum carbon-dioxide concentration at low pressure, the effects of nonstandard gas proportions, long-term toxicity to trace contaminants, mutation of harmless microbiological species to pathogenic forms, and the effects of reduced gravity on the circulatory system, nervous system, and skeletal strength.

Psychological investigations should include isolation, danger, and various difficulties that cause irrational action and serious errors by crew members.

1.2.3.4 Space Suit Limitations — A durable, highly mobile pressure suit is needed for operations on the lunar surface. The degree to which such a suit is feasible will strongly influence the design and operational plan of the base. A feasibility and preliminary design study should determine at an early date what limitations will be imposed by pressure-suit considerations.

1.2.4 Mobility

Definition is required of a vehicle family for the support of lunar surface operations with emphasis on providing an optimum relation of support capability to mission requirements. Surface vehicle classifications, such as multipurpose versus single-purpose, modular versus single unit, and interchangeable body versus tractor/trailer, should be considered. In addition, flight modes should be evaluated for special lunar surface operations, including obstacle crossing and long-distance travel.

1.2.5 Mission

1.2.5.1 Lunar Exploration Definition — Rational specifications are needed to define the scope of, and techniques for accomplishment of, lunar exploration. Improved knowledge in this area is necessary to permit a more exact derivation of lunar support facilities requirements. An important element in analysis of lunar support facility requirements is, therefore, a more exact knowledge of probable mission activities, based on the analysis of mission goals and their relative value and mission technique effectiveness.

1.2.5.2 Lunar Exploration Cost Effectiveness — The cost effectiveness of a program of lunar exploration is related to the cost of support facilities delivered to the Moon and the value of the research accomplished. Although an absolute evaluation of these factors (especially of the value of research) is not practical at this time, a parametric approach may be employed to relate cost effectiveness trends to a range of mission value assumptions.

1.3 CONCLUSIONS AND RECOMMENDATIONS

The initial lunar exploration system concept developed in this study has been successful in defining a family of subsystem modules suited to a wide range of base sizes and durations and to mission support requirements. This current definition of the initial concept should be further refined through more detailed subsystem studies, accompanied by a continuing system integration effort in preparation for hardware development and testing well in advance of Apollo flight dates.

An orderly extension of the Apollo program will not permit delay. Therefore, not all information on the lunar environment will be positively known before lunar exploration support system plans are finalized and actual construction and test of equipment is begun.

When a reasonable amount of environmental knowledge of the Moon is acquired, designs should be completed and hardware manufactured and tested. A reasonable time for completing preliminary studies and starting the R&D phase would be 4 years before the anticipated accomplishment of the current Apollo program. Subsystems would be provided in a timely program, and the base with all its associated equipment should then be assembled and tested in a simulated lunar environment. Plans and equipment should be modified as new lunar environmental data indicates the need for such adjustment. Thus, there would be no appreciable time lag between the completion of the currently planned Apollo launches and the initiation of the more comprehensive phase of the Apollo lunar-exploration program.

Conclusions reached in the technical studies are included throughout the final report document. The principal conclusions and recommendations are summarized in Section 10.0 of Volume II. Of these, the following are considered most significant for continuing studies.

1.3.1 System Requirements

Lunar-exploration support-system requirements will vary widely with the type and scope of scientific mission activity planned. This conclusion applies especially to the general parameters of crew size and system duration, and to the specific parameter of lunar-surface mobility capability. Realistic and definitive lunar-exploration mission goals and schedules should be formulated to guide an improved definition of support system requirements. Definitions of goals should include specification of their relative value.

1.3.2 Mission Operations

Lunar exploration may proceed on a gradually expanding evolutionary scale, from a small initial program to an eventual major base installation, without penalty on a gross cost-effectiveness basis. Development of a lunar-exploration support system should continue to emphasize the modular concept to ensure provision for system evolution potential.

The surface roving mode of lunar mobility is best suited to effective lunar surface reconnaissance. Flight modes are suitable for quick, long-range, point-to-point transportation and for obstacle crossing, but are much less competitive economically for stop-and-go travel and are not too attractive for one-stop reconnaissance use.

Surface roving vehicle development should be emphasized, including the study of means for obtaining vehicle range and crew duration capabilities extending up to a mobile base concept. Flight-mode applications should be analyzed further, and initial system concepts configured.

Quantitative projections of Apollo space-suit limitations should be factored into lunar-mission and support-system planning at an early date. Any resulting indications of incompatibility of these projections with desired mission accomplishments should signal accelerated investigation of automation substitutes.

1.3.3 Logistics Considerations

A goal of the exploration support-system development should be the reduction of crew transportation traffic through provision of large capacity vehicles and increased allowable crew stay-time. Development of the LH_2/LO_2 multiple mission module concept should be pursued, with possible applications as a lunar logistic vehicle, advanced Apollo service module, and advanced LEM descent stage. Detailed studies of large-capacity Apollo- and LEM-type spacecraft, consistent with advanced Saturn performance in direct flight, Earth-orbit refueling, and lunar-orbit rendezvous modes, should be pursued.

The feasibility of synthesizing fuel and life-support expendables from lunar raw materials is essentially unquestioned from the standpoint of the chemistry involved. However, because of the effectiveness of regeneration of these same materials from most using subsystems, it is not clear that a strong demand for synthesis exists. Further overall mission requirement and support-system analysis is required before development of synthesis equipment can be justified.

1.3.4 Base Installation

Surface emplacement of a base is feasible and is preferable to subsurface emplacement. Surface emplacement does not require unloading the basic shelter from the lunar logistic vehicle. Personnel shelters and other vulnerable elements should be designed to accommodate lunar soil coverage. The concept of an expandable caisson, built as part of the structure of the shelter to hold the soil cover, should be developed.

No single set of construction equipment now seems sufficiently flexible for soil excavation and placement at lunar sites that vary widely in surface and subsurface characteristics. It is premature to select any one type or family for preliminary design.

1.3.5 System Design

Shelter — Design of a basic, six-man, lunar shelter with integrated meteoroid and radiation shielding adequate for 1 year of storage and subsequent 3-month occupancy is feasible within the Saturn V/LLV payload limits. For longer operations, these shelters should be covered with lunar soil for added protection against the environment. A 2-foot-thick layer of soil covering the shelter will provide the necessary shielding for up to 2 years of operations, assuming personnel are rotated at 6-month intervals. Incorporating an expandable caisson in the shelter design to retain the soil cover is feasible.

Life Support — Life-support requirements can be met with the same techniques contemplated for advanced Earth-orbital systems, except for thermal control. New techniques will be required for thermal control. During the lunar day, reflective-radiation concepts may be used for heat rejection. Internally generated heat will be required to assist in temperature control during storage, possibly from an easily shielded radioisotope heat source.

Decompression sickness from pressure suit operation is a major factor in selecting the cabin atmosphere. An oxygen-nitrogen atmosphere of 6.0 psia is recommended for the personnel shelters.

Power — The study confirms that nuclear-reactor power is the superior generation concept for all but the smallest bases. It appears feasible to provide by 1971 any of the four base power subsystems considered in the study.

The SNAP 8 100-kilowatt, two-alternator system appears to be a very practical, reliable power module for application to large central nuclear powerplants on advanced bases. It is recommended that further studies be made to verify a practical module size and that development effort be initiated on the long-lead elements of such a system.

The small integral shelter power system should be developed for the 90-day base application. The fuel-cell/solar-cell system appears to be the most practical concept; however, intensive studies should be made to evaluate and compare radioisotope concepts in the 1.5- to 3.0-kilowatt range.

The use of lunar materials for shielding appears to be more practical and less expensive than the use of Earth-supplied materials.

Communications — Lunar-base communication requirements may be met with techniques that are well within the state of the art, except for point-to-point communications beyond the line of sight on the lunar surface. Existing and planned elements of the Apollo network may be used.

The use of LF (approximately 50 kc) surface-to-surface communication appears feasible and practical for the transmission of voice or telegraphy data beyond the line of sight between the lunar base to either a roving vehicle or a remote outpost. This concept also provides an aid to exploration and a means of navigation on the lunar surface with modest transmitter power and a simply erected horizontal dipole antenna. Further analysis and experimental tests are required.

Surface Mobility — The concept of a basic four-wheel mobile vehicle with extra pairs of powered wheels that may be attached for extending surface traversing capabilities, and fixtures that may be attached for material handling and construction tasks, should be adopted for the lunar-exploration support application. The vehicle and associated modules should be designed and tested in suitable test areas that most nearly simulate the lunar environment. The flexible chassis principle should be used for the mobility extension module and should be considered for use in the basic four-wheel module.

For exploration trips longer than those described in this study, the advantages that may come out of the development of vehicles scaled to comprise an entire LLV payload should be examined.

Long-range flight-mode propellant requirements are so large that the concept appears to be practical only in combination with the synthesis of propellants from lunar materials.

Fuel — Cryogenics (H_2, O_2, N_2) can be stored on the Moon for 1 year of unattended storage plus base operational periods. Regeneration of water into liquid hydrogen and liquid oxygen is both feasible and desirable for the larger bases. Modular concepts for fuel storage are not entirely practical because fuel requirements do not follow in logical increments from base to base.

Maintenance — The study has revealed both incentive and encouragement for minimizing rather than facilitating servicing and repair. Maximum reliability plus a modest fault-correction capability of the crew, rather than maximum maintainability, should become a major lunar-base design goal. The reduction of maintenance requirements should be pursued through design to eliminate all possible servicing needs during the projected base life, rather than through automated servicing or self-repair, which may degrade rather than improve reliability. The true impact of various maintenance needs on lunar-base operations will remain indeterminate until some conclusive evaluations of space-suit effectiveness in the lunar environment become available.

2.0 SYSTEM CONSIDERATIONS

2.1 INTRODUCTION

The basic modular concept, together with the stated ground rules and implied mission objectives, were the starting point for systems analyses aimed at guiding the subsystems investigations and contributing to the overall concept definition. Maximum use of Apollo system elements was considered. As the subsystem aspects of the base concept were developed, meaningful concepts for base installation, operation, maintenance, and logistics support were outlined.

Subsystem analysis effort started with technical investigations of ways to satisfy functional requirements, and proceeded to the selection of specific modular concepts logically matched to the base concept.

Design integration was accomplished by combining the subsystem module information with concepts for base installation, operation, maintenance, and logistic support to synthesize, on a total system basis, an improved definition of the initial base concept. This synthesis included considerations of base arrangements, packaging of base modules into lunar logistics vehicle (LLV) payloads, and resolution of the interface relationships between subsystems and modules of the base complex.

2.2 PHYSICAL ENVIRONMENT

The specification of the lunar surface environment was derived principally from NASA RFP 10-1132. The only significant supplement to this guidance was the further detailing of the definition of the radiation environment associated with solar flares. The lunar environment was considered in four major categories; (1) general environment, either not dependent on location or averaged over relatively large areas, (2) surface and subsurface characteristics of the lithosphere, (3) radiation, and (4) meteoroid flux.

2.2.1 General Environment

General environmental parameters were assumed as follows:

Atmospheric pressure: 14×10^{-13} psi

Maximum surface temperature: 390° ±20°K

Minimum surface temperature: 110° ±25°K

Thermal conductivity, surface material: 3×10^{-5} to 3×10^{-6} cal/cm-sec

Thermal conductivity, rock: 4×10^{-3} cal/cm-sec

Electrical conductivity: 3.4×10^{-4} mhos/meter

2.2.2 Surface and Subsurface Characteristics

The lithologic units assumed to be exposed at the lunar surface are as follows:

Very porous insulating layer, probably of silicate composition;

Finely divided material, or dust, principally of silicate composition;

"Rock froth" similar to volcanic ash associated with volcanism;

Shock breccia, composed principally of poorly sorted silicate fragments;

Crystalline silicate material similar to terrestrial rocks.

Using these five lithologic units, the stratigraphy of each of three sites was specified to provide a range of surface environment parameters for design purposes. The examples are representative of premare, mare, and postmare surfaces.

Physical characteristics of the surface material are summarized below.

SURFACE MATERIAL PARAMETERS

Unit	Specific Gravity	Acoustic Velocity (feet/sec)	Bearing Strength (psi)
Porous Insulating Material	-	-	0.01
Dust	1.0-1.5	1,000-2,000	10
Rock Froth	0.5-1.2	6,000-7,000	100
Breccia	1.5-2.6	1,500-5,000	100
Rock	2.7-3.0	18,000-21,000	>1000

2.2.3 Radiation Environment

The radiation environment of the lunar surface consists of radiation from sources external to the Moon and both primary and secondary radiation emanating from the lunar surface. The external radiation consists of primary galactic cosmic rays, which give a dose rate of about one rad per month, and the much larger contribution of particulate radiation (primarily protons) associated with solar flares. The flare events occur at random throughout the solar cycle, and the flux is essentially omnidirectional. The probability of encountering a specified integrated solar proton flux in free space at four exposure times is shown in Figure 2.2-1. The flux at the lunar surface will be half the amount shown in Figure 2.2-1.

2.2.4 Meteoroid Environment

The particle size threshold for impact damage is about 1 microgram at anticipated average meteoroid velocities. This size particle is near the upper boundary of satellite measurements of the meteoroid flux, and there are essentially no data other than meteor observations on the flux of particles larger than this. The lunar surface meteoroid environment was defined in Annex D of NASA RFP 10-1132. Interpretation of this description resulted in selection of the following meteoroid flux

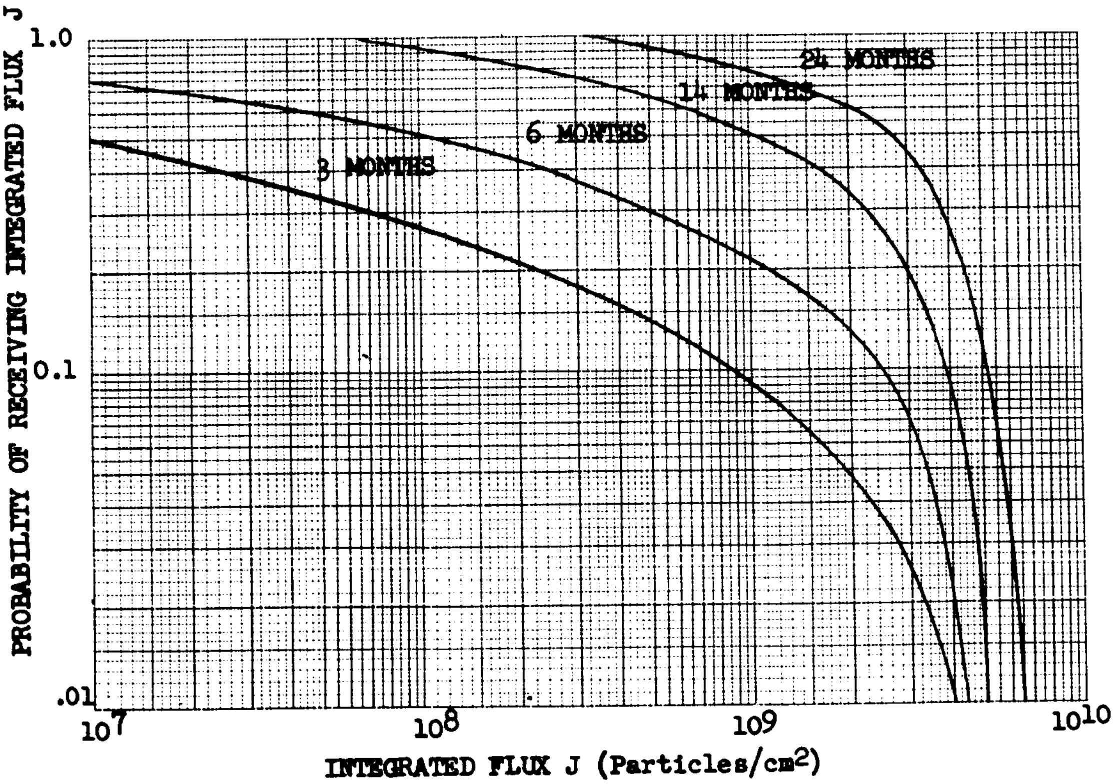
$$F = 10^{-12.955} m^{-1}$$

where F is the flux of particles of mass greater than m (in grams) per square meter per second.

Figure 2. 2-1

PROBABILITY VS INTEGRATED FLUX (E>30MEV)

FOUR EXPOSURE TIMES FOR A BODY IN FREE SPACE



2.3 LUNAR BASE SYSTEMS REQUIREMENTS

A convenient approach to determining lunar exploration support requirements, covering a range of base sizes (2 to 18 men) and durations (2 months to 2 years or longer), is to characterize these ranges by discrete examples or models of specific operations. Since the purpose of lunar support facilities is to make possible a variety of scientific missions, expected mission operational requirements were combined with considerations of crew delivery increments and crew stay time to select four base models. Functional requirements for each model were then summarized to guide the analysis and design of all base subsystems.

2.3.1 Lunar Exploration Mission Operations

The major emphasis in studies of possible mission activity has been on scientific investigation of the lunar surface and subsurface. Other programs considered include optical and radio astronomy, particulate radiation studies, and synthesis of fuel and life support expendables from lunar raw materials.

2.3.1.1 Lunar Surface Reconnaissance — When mission time is short and supporting facilities are limited, a reconnaissance type of field program designed to return a general knowledge of the largest possible lunar region is desirable. This type of operation is especially suited to determining engineering data that will be of value in planning follow-on systems. The principal requirement for such ventures is a surface roving vehicle capable of accommodating a two-man crew in meaningful missions. Estimates of mission scope and procedure are based on the following vehicle capabilities:

1) Trip range — 200 miles;
2) Trip duration — 120 hours (5 Earth days);
3) Average speed — 3 mph.

2.3.1.2 Geological and Geophysical Reconnaissance and Survey — Surface reconnaissance activities have a number of geological observations as their prime objective. With increased supporting facilities, including vehicle range and duration extension to 300 miles and 192 hours (8 days), even more detailed field observations and research are desirable. These missions will incorporate more extensive instrumentation for mapping, sampling, and surveying with magnetic, gravimetric, and seismic techniques.

2.3.1.3 Geophysical Research — In addition to the reconnaissance and survey operations planned to obtain data generally applicable to the study of the Moon, specific geophysical research objectives will undoubtedly serve to focus effort in particular areas. Some subjects of special research significance include research on mare formation, crater shape, and surface thermal anomalies.

2.3.1.4 Astrophysical Research — Scientific experiments done on the Moon can be divided into two classes: (1) those intended to study the Moon and its environment, and (2) those that take advantage of the Moon and its environment to study other things. Certain experiments that cannot be performed from Earth, because of atmospheric opacity or other reasons, can be done either on the Moon or in man-made Earth satellites. In general, the Moon base is advantageous when its large size is needed or when it is required to have a stable platform. The base will probably be advantageous when a low magnetic field is required. An estimate of the equipment needed, its weight and power, and the manpower (in hours of an astronaut-scientist's work time) required for a variety of astrophysical experiments are listed as indications of the order of magnitude of the effort required.

2.3.1.5 Technological Support Activity — Certain technological operations at a lunar exploration supporting facility may require the assistance of mission activities of an economic exploration character. To illustrate the scope of field geology that may be required, a projected program for evaluating the water potential assumed to be related to a small thermal anomaly is presented.

2.3.1.6 Pilot Plant Operation for Synthesis of Fuels from Lunar Resources — Geological exploration may include the discovery of valuable mineral deposits that will provide the raw material for the production of fuels and expendable materials on the Moon. For development of lunar chemical synthesis facilities, all of the research, development, and testing of components will be accomplished on Earth. The components and the completed pilot plant will be tested to the extent possible in environment-simulation facilities prior to shipment of the pilot plant to the lunar base. The operation of a pilot plant at the lunar base will be an important step in proving the reliability of its operation prior to commitment of the base and the logistic system to dependence on its products.

2.3.2 Base Model Selection

Size and duration specifications for the selected base models are listed in Table 2.3-A, together with general statements of mission objectives. Base model size and duration selections have been influenced both by the corresponding ranges of interest specified for this study and by guidance received from NASA with respect to crew stay time and crew delivery increments. In the former case, a maximum of 6 months was specified in RFP 10-1132. Apollo crew transfer capability in 1970 to 1975 was estimated to range from two to four men, with a value of three recommended for study purposes.

To assign a weight allowance for the scientific equipment required with each base model, equipment selections were made from Table 7.1-A (Volume II) and the data of Figures 7.3-1 and 7.3-2 (Volume II), and supplemented with communication equipment, structural support, and cabinet weight estimates. These equipment allowances have been divided into scientific payload modules for base design integration, as tabulated on page 22.

Table 2.3-A

LUNAR BASE MODELS

Condensed Specifications

Model	Crew Number	Base Duration (Months)	Mission Objectives
1	3	3	Lunar Surface Reconnaissance Lunar Environment Survey
2	6	6	Geological and Geophysical Reconnaissance Lunar Environment Research Geophysical Research Analysis
3	12	12+	Geological and Geophysical Surveys Astrophysical Research Geophysical Research Analysis
4	18	24+	Geological and Geophysical Surveys Astrophysical Observatory Geophysical Observatory Fuel Synthesis Pilot Plant (Possibility)

Module	Module Weight (pounds) 1	2	3	4
X-1	880	880	880	880
X-2		1650	1650	1650
X-3			1460	1460
X-4				2760
X-5				6900
Base Total	880	2530	3990	13,650

2.3.2.1 Base Locations — To supplement the definition of base models, three specific base locations have been defined. The purpose of this specification is to ensure consideration of the complete range of lunar surface conditions throughout the study, especially in connection with roving vehicle design and performance analysis and the development of base installation and construction concepts.

The sites were selected to represent the three major classifications of lunar terrain: mare, pre-mare, and post-mare, and to be representative of areas of scientific interest. The locations are specified as follows:

1) Site A (5.6°N, 26.6°W) — Site A is in the mare area 150 miles southwest of the crater Copernicus. This region is an Apollo landing site candidate and is typified by many small, isolated craters, dome formations, and ray material associated with Copernicus.

2) Site B (12.6°S, 2.9°W) — Site B is on the floor of the pre-mare crater Alphonsus. This region is crossed with many rilles or other lineaments and is of very great interest in connection with the observations of C^{++} emission reported there by Kozyrev in 1958.

3) Site C (40.9°S, 11.1°W) — Site C is on the north flank of the post-mare crater Tycho. This is the largest of the recent lunar craters and has an enormous ray system possibly extending completely around the Moon.

2.3.3 Base Model Functional Requirements

The base models have been further elaborated in terms of the functional requirements imposed on their constituent subsystems. These include requirements both for direct support of mission activities (as in the cases of surface mobility, fuel supply, and communications) and for crew accommodation in general (shelter, life support, power, and maintenance). These functional requirements reflect certain aspects of the study ground rules and the particular magnitude of exploration field trips assumed in each case. Translation of these functional requirements into quantitative subsystem performance requirements (as reported in the appropriate sections of Volume III) and thence into the system integration conclusions of Volume II preserves the effects of these assumptions.

2.4 BASE DESIGN INTEGRATION

The lunar base must provide shelter, life support, power, communications, surface mobility, and fuel to sustain a wide variety of manned scientific exploratory missions on the Moon.

Subsystem functional requirements were defined and divided into logical modular increments within each subsystem. Hardware modules were configured on the basis of multiple application. These modules were integrated into four tentative base models, shown in Figures 2.4-1A and 2.4-1B. Here, the shelter assumed peculiar importance because many of the other subsystem modules function within the shelter or are intimately associated with it. The investment of the various modules for each base is presented in Table 2.4-A.

Subsequently, the modules required for each base were organized into payloads consistent with the LLV payload limitation of 25,000 pounds and with the desired order of delivery and use. All modules and payload packages were designed for 1 year of storage on the Moon before installation and operation. These payloads and bases were then evaluated in terms of construction, operations, and logistics. The integrated base configurations reported here, and their several payload packages, are the result of five iterations following the sequence outlined above.

2.4.1 Base Model 1

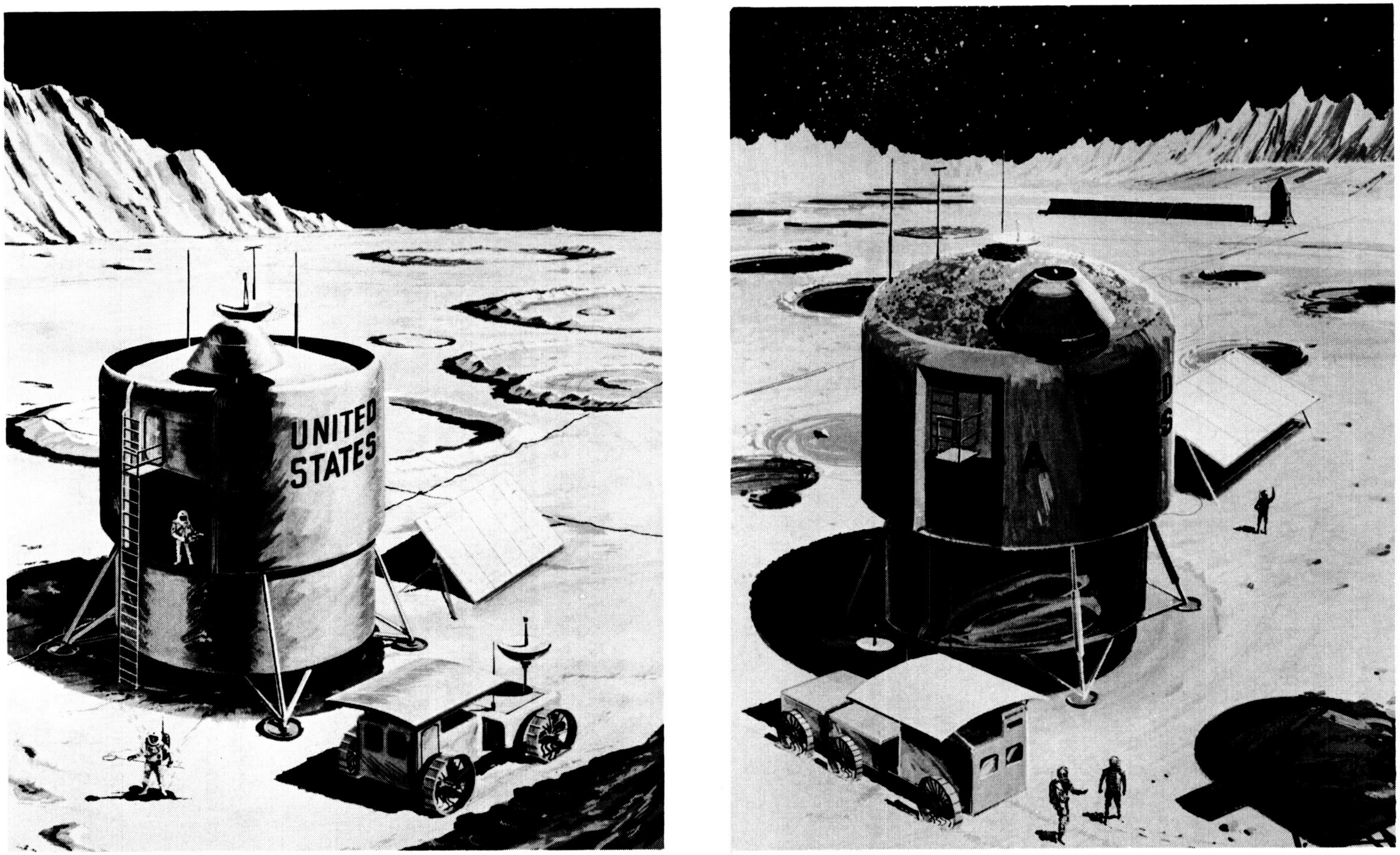
Base Model 1 is a single payload carried to the base site by the Saturn V LLV. The model is built up or integrated out of the subsystem modules that analyses have shown are required to meet its performance specifications (see Figure 2.4-2). This same pattern is followed in the design of Base Models 2, 3, and 4, wherein identical or multiple modules are employed to extend each module's utilization and to simplify evolution from one base model to another.

Lunar Roving Vehicle V-1 is carried under the shelter in a compartment that may be pressurized for use as a maintenance shelter. All fuel for the shelter and vehicle is carried in cryogenic storage tanks below the pressurized compartments. Water produced by fuel-cell operation is collected in a storage tank for crew use. The operational mission of this shelter may be extended by refueling after a periodic inspection confirms the shelter's structural integrity. It could thus grow directly to Base Model 2.

Planned maintenance is carried out from within the pressurized compartments of the shelter, except on the roving vehicle. Vehicle servicing and maintenance is accomplished on the lunar surface.

The payload has a maximum diameter of 260 inches, an overall height of 411 inches, and a gross weight of approximately 25,000 pounds. This gross weight includes Lunar Roving Vehicle V-1 and the shelter with integral, limited-stay

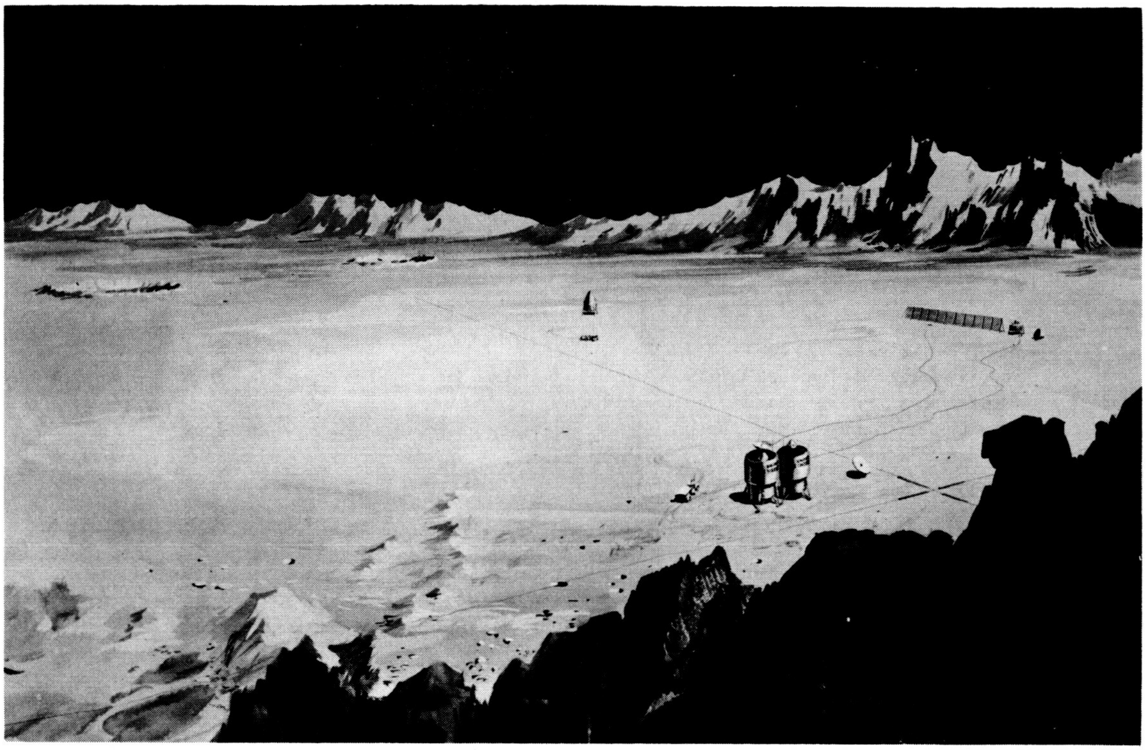
Figure 2.4-1A
BASE MODELS



BASE MODEL 1

BASE MODEL 2

Figure 2.4-1B
BASE MODEL 3



BASE MODEL 4

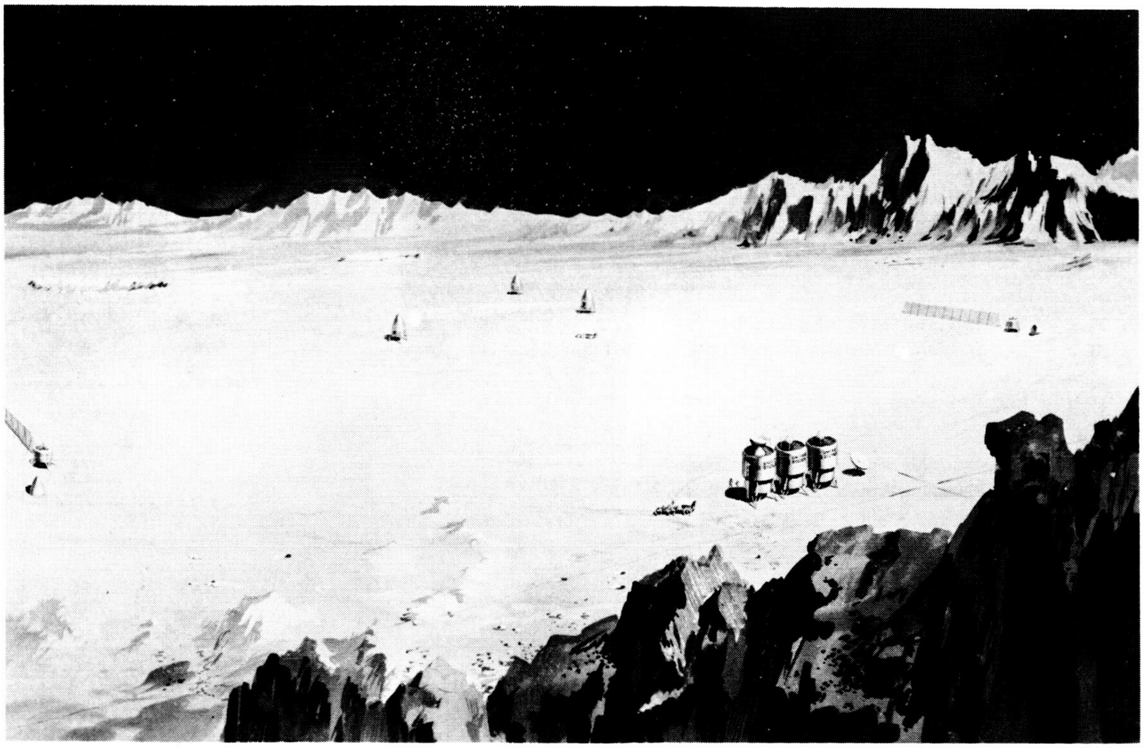
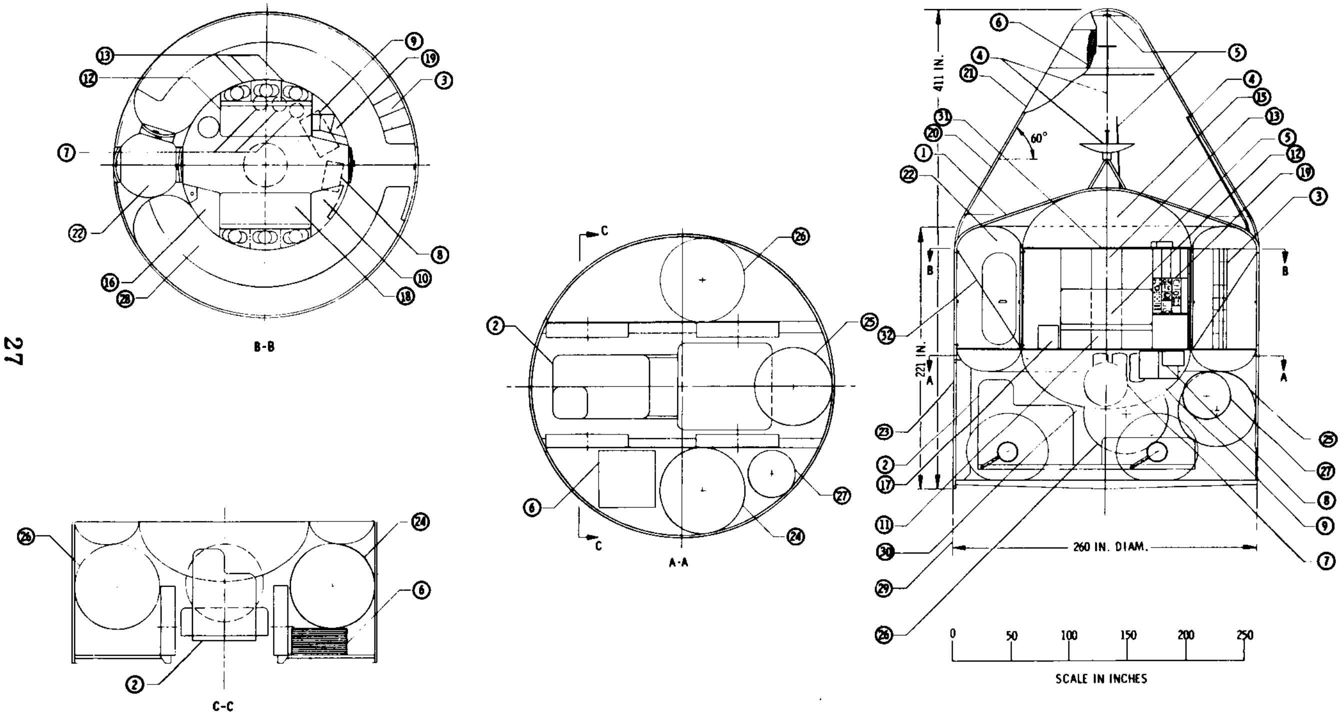


Table 2. 4-A

MODULE DEFINITION CHART

SUBSYSTEMS		BASE MODEL			
MODULE	NAME	1	2	3	4
S-1	Basic Shelter	★	★	★★	★★★
S-2	Radiation Shielding — Base 1	★			
S-3	Logistics Carrier		★	★★	★★★★
S-4	Resupply Carrier				★
L-1	Basic Life Support & ECS	★	★	★★	★★★
L-2	Supplemental Life Support & ECS		★	★★	★★★
L-3	Life Support Supply — Base 2		★		
L-4	Life Support Supply — Basè 3			★★	
L-5	Life Support Supply — Base 4				★★★
P-1	Basic Power Unit (FC + SC)	★	★	★★	★★★
P-2	Construction Power Unit (FC)		★	★	★
P-3	Nuclear Power Unit (10 kw)		★		
P-4	Nuclear Power Unit (100 kw)			★	★★
P-5	Base Substation Module			★	★
C-1	Basic Communication Equipment	★★	★★	★★★	★★★★
C-2	Antenna Set — Bases 1 & 2	★	★		
C-3	Antenna Set — LRV	★	★	★★	★★★
C-4	Emergency/Checkout Set	★	★	★★	★★★
C-5	Communication Equipment — Bases 3 & 4			★	★
C-6	Antenna Set — Bases 3 & 4			★	★
V-1	Basic Lunar Roving Vehicle	★	★	★★	★★★
V-2	Extended Mobility Module		★	★★	★★★
F-1	Basic Fuel Module	★	★	★★	★★★
F-2	Supplemental Fuel Module — Base 2		★		
F-3	Supplemental Fuel Module — Base 3			★	★
F-4	Supplemental Fuel Module — Base 4				★
F-5	Fuel Regeneration Unit			★	★
M-1	Basic Maintenance Equipment	★	★	★★	★★★
M-2	Supplemental Maintenance Equipment — Base 2		★	★	★
M-3	Supplemental Maintenance Equipment — Base 3			★	★
M-4	Supplemental Maintenance Equipment — Base 4				★
E-1	Engineering Equipment — Shielding		★	★	★
E-2	Engineering Equipment — Transportation			★	★
X-1	Mission Support Equipment — Base 1	★	★	★	★
X-2	Mission Support Equipment — Base 2		★	★	★
X-3	Mission Support Equipment — Base 3			★	★
X-4	Mission Support Equipment — Base 4				★
X-5	Fuel Synthesis Experiment				★

Figure 2.4-2
PAYLOAD CONFIGURATION
LUNAR BASE MODEL 1



1	S-1	SHELTER
2	V-1	LUNAR ROVING VEHICLE INCLUDES L-2 C-1 AND C-3
3	C-1	S-BAND, VHF AND LF EQUIP; TV MONITOR; DATA STORAGE ETC
4	C-2	COMMUNICATION ANTENNAS
5	C-4	EMERG/CHECKOUT COMMUNICATION EQUIP
6	P-1	SOLAR CELLS
7	P-1	FUEL CELLS
8	P-1	BATTERY
9	P-1	POWER DISTRIBUTION EQUIP
10	L-1	FOOD PREPARATION CABINET
11	L-1	PERSONAL STORAGE
12	L-1	BUNK SET
13	L-1	PRESSURE SUIT STORAGE
14	L-1	ATMOSPHERE CONTROL UNIT
15	L-1	FOOD STORAGE
16	L-1	PERSONAL HYGIENE FACILITY
17	L-1	TOILET AND WASTE TREATMENT EQUIP.
18		PROVISIONS FOR ADDITIONAL BUNKS (2) PRESSURE SUIT STORAGE (3) AND PERSONAL STORAGE (3)
19		COMM., POWER, AND LIFE SUPPORT CONTROL PANEL
20		AERODYNAMIC FAIRING
21		SOLAR CELL PROTECTIVE PANEL
22		AIR LOCK
23		LRV UNLOADING DOOR
24		LH_2 FOR POWER GENERATION; 222 POUNDS IN 72 INCH O.D. TANK
25		LH_2 FOR LRV; 167 POUNDS IN 65 INCH O.D. TANK
26		LO_2 FOR LIFE SUPPORT, POWER GENERATION, AND LRV; 4594 POUNDS IN 66 INCH O.D. TANK
27		LN_2 FOR LIFE SUPPORT; 300 POUNDS IN 34 INCH O.D. TANK
28		WORK AND EXPERIMENT STORAGE AREA
29		LUNAR LANDING VEHICLE
30		WATER 900 POUNDS IN 37 INCH O.D. TANK
31		S-2 ALUM RADIATION SHIELD ON BASE 1 ONLY
32		TEMPORARY STRUCTURE SUPPORTS

shielding plus supplies for three men for 3 months. Launch and landing loads are carried to the circumferential skin and shielding structure by a truss with removable diagonal tension rods.

A standard shelter (S-1) configuration should suffice for all shelter installations on the Moon, whether for the central base or for outposts. Since the shelter has integral radiation and meteoroid protection for a 3-month stay time, there is no requirement that it be covered by lunar soil. The present concept for all bases is to leave the shelter modules on the LLV. Base Model 1 installation requires only level adjustment and shelter activation, plus LRV unloading and checkout. Shelter activation will include a preactivation check followed by deployment of the outer skin caisson to expose the access door, then pressurization, power system startup, antenna deployment, etc. The caisson is used, when longer stay times are planned, to hold an annular ring of protective lunar soil emplaced around and over the shelter.

2.4.2 Base Model 2

Base Model 2 requires two Saturn V payloads to provide for six men for 6 months. One carries the same shelter module S-1 as used in Base Model 1, with integral subsystem modules and a roving vehicle (per Table 2.4-A) to the 25,000-pound payload limit. The other carries the nuclear power module with supplemental fuel and equipment, illustrated in Figure 2.4-3.

For stays beyond 3 months, the shelter of Base Model 2 must be protected with lunar soil in the caisson. The nuclear power plant will require remote placement and shielding with lunar materials.

Base Model 2 has one basic shelter module to accommodate six men. For the 6-month stay, the additional supplies, food, and fuel, a nuclear powerplant, the extended mobility module, and the construction equipment are delivered by another LLV as a separate payload. The first duty of the first crew of three men is to assemble and integrate these components for their 6-month stay. They must:

1) Activate and occupy the shelter;

2) Unload the multipurpose vehicle;

3) Assemble construction equipment;

4) Transport or position the shelter module as required:

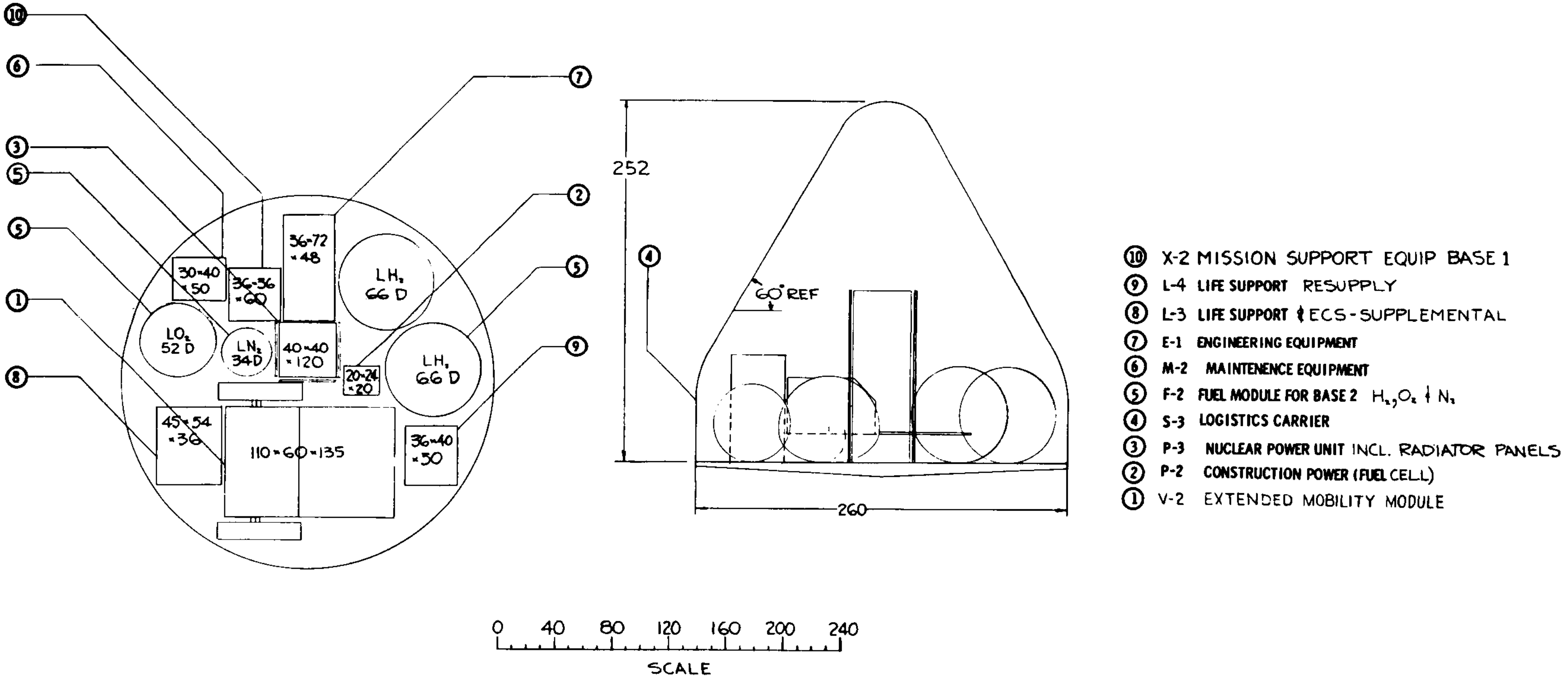
    a) Level the shelter module on its LLV,
    b) Cover most of the shelter with lunar soil,
    c) Emplace the nuclear powerplant (reactor buried or covered);

5) Deploy and connect the power transmission cables;

6) Organize the remaining additional supplies of fuel, food, and equipment for crew convenience.

Figure 2.4-3

PAYLOAD B
BASE MODEL 2



2.4.3 Base Model 3

Two shelter modules are joined back-to-back to make up Base Model 3 to accommodate 12 men. Two logistics carriers bring up supplemental supplies and equipment to maintain this crew for 12 months. The detailed design shows that, with the provision of fuel regeneration, resupply will not be required, since the four 25,000-pound payloads suffice.

Flexible bellows connect the work space between the shelters. This puts the airlocks on the north and south end of the joint base shelters for convenience or for access redundancy.

2.4.4 Base Model 4

Base Model 4 uses three shelter modules set in a north-south line. This arrangement also provides two airlocks for convenience or for access redundancy in case of emergency. In all respects, Base Model 4 simply extends the capability of this system to accommodate 18 men for 2 years or more.

2.4.5 Modular Interfaces

In the base integration, the principal design problem is the effective resolution of connections and interdependencies between the subsystem modules. Table 2.4-B identifies the relationship between modules. In some cases the interface involves action in both directions between two modules. In other cases several simultaneous relationships describe the interface.

Table 2. 4-B
MODULAR INTERFACES

SUBSYSTEMS MODULE	NAME	S-1	S-2	S-3	S-4	L-1	L-2	L-3	L-4	L-5	P-1	P-2	P-3	P-4	P-5	C-1	C-2	C-3	C-4	C-5	C-6	V-1	V-2	F-1	F-2	F-3	F-4	F-5	M-1	M-2	M-3	M-4	E-1	E-2	X-1	X-2	X-3
S-1	Basic Shelter																																				
S-2	Radiation Shielding — Base 1	AM																																			
S-3	Logistics Carrier																																				
S-4	Resupply Carrier																																				
L-1	Basic Life Support & ECS	MS																																			
L-2	Supplemental Life Support & ECS	MS				AP																															
L-3	Life Support Supply — Base 2	T		S		A																															
L-4	Life Support Supply — Base 3	T		S		A																															
L-5	Life Support Supply — Base 4	T		S*	S	A																															
P-1	Basic Power Unit (FC + SC)	M				C	C																														
P-2	Construction Power Unit (FC)			M																																	
P-3	Nuclear Power Unit (10 kw)	C		S							M	C																									
P-4	Nuclear Power Unit (100 kw)	C		S							M	C																									
P-5	Base Substation Module	C		S							C		C	C																							
C-1	Basic Communication Equipment	M									C																										
C-2	Antenna Set — Bases 1 & 2	M														C																					
C-3	Antenna Set — LRV															C	E																				
C-4	Emergency/Checkout Set	CM				C					C					C	E	E																			
C-5	Communication Equipment — Bases 3 & 4	M									C					AC																					
C-6	Antenna Set — Bases 3 & 4	M														C	E	E	C	C																	
V-1	Basic Lunar Roving Vehicle	S				S		S	S	S	C					M		M																			
V-2	Extended Mobility Module			S																		CM															
F-1	Basic Fuel Module	M				P	P				C								C			P	P														
F-2	Supplemental Fuel Module — Base 2			M							C											P	P	P													
F-3	Supplemental Fuel Module — Base 3			M											C							P	P	P													
F-4	Supplemental Fuel Module — Base 4				M										C							P	P	P													
F-5	Fuel Regeneration Unit			S		P									C							P	P	P													
M-1	Basic Maintenance Equipment	S																				S	T														
M-2	Supplemental Maintenance Equipment — Base 2	T		S																		T	S						A								
M-3	Supplemental Maintenance Equipment — Base 3	T		S																		T	S						A	A							
M-4	Supplemental Maintenance Equipment — Base 4	T		S																		T	S						A	A	A						
E-1	Engineering Equipment — Shielding			S									C		C							M															
E-2	Engineering Equipment — Transportation			S									C									M															
X-1	Mission Support Equipment — Base 1	S														C	E			C	E	T															
X-2	Mission Support Equipment — Base 2	T**		S**												C	E			C	E	T													A		
X-3	Mission Support Equipment — Base 3	S														C				C	E	T													A	A	
X-4	Mission Support Equipment — Base 4	T		S												C				C	E	T													A	A	A
X-5	Fuel Synthesis Experiment			S											C									P													

A — Augmented
C — Cable Connection (Electric-Antenna)
M — Mounted (Mechanical Connection)
P — Liquid Transfer
S — Stowed
T — Transferred for Storage:
originally delivered elsewhere
E — Electromagnetic linkage

*L-5 is divided and stowed in Payloads B-1 and D

**Module X-2 stowed in shelter payload for Base Model 4 only

2.5 LUNAR BASE CONSTRUCTION CONCEPTS

2.5.1 Construction Requirements and Recommended Construction Approach

Construction effort required to establish a modular concept lunar base involves assembly, alignment, and connection of modules. Additionally, when missions exceed some 3 months' duration, lunar soil is used profitably to shield shelter modules against solar radiation and meteoroids and to shield nuclear power plants. Recommendations for construction are derived from an integrated consideration of the basic shelter modules and other basic components of the base, the use of the simplest suitable construction equipment and techniques, and the minimum use of space-suit labor.

Construction requirements include base assembly (moving, positioning, and interconnecting payloads or payload components) and base emplacement (providing environmental protection with lunar soil). When adequate detailed data on the lunar surface and subsurface are available in the future, the final selection of construction equipment and techniques should be evaluated in terms of:

1) Productivity — equipment type and characteristics;
2) Operating cost — crew time, capital investment;
3) Flexibility — multipurpose potential;
4) Reliability;
5) Development cost.

The last two considerations were not studied to any extent in the initial concept. Preliminary data on the first three considerations resulted in the following conclusions:

1) The shelter module need not be unloaded from the LLV.
2) Multiple shelters are assembled by moving them (together with the LLV) into the desired position and alignment. Construction Module E-1 contains accessory jacks and powered wheels for this purpose. The LRV is used as a prime mover. Movement distances are small.
3) Surface emplacement of shelters is preferable to subsurface or semiburied emplacement in view of the current lack of knowledge of the lunar subsurface. The shelter is provided with an expandable caisson. Soil is collected to fill the caisson by shallow mechanical excavation. The type of equipment needed depends on the subsurface consistency. A thrower-type mechanism is recommended for placing the collected soil in the caisson and on the roof of the shelter.

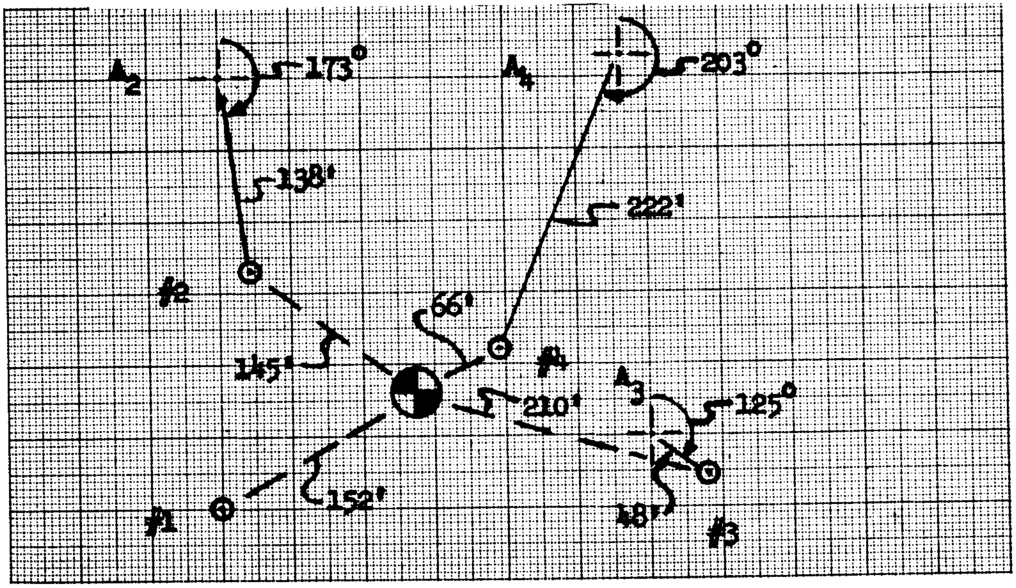
   The shelter emplacement equipment is also used to emplace the reactor and shield it with lunar soil. Explosives and a drilling attachment for the LRV are required in hard soil or rock.

2.5.2 Base Assembly

Engineering equipment will be required to move (as a unit) a shelter module and LLV over the lunar surface for Base Models 3 and 4. Factors of interest are:

2.5.2.1 Distance of Movement — Boeing studies indicate that adequate automatic landing guidance, based on beacons and computer controlled LLV final descents, can provide landings of individual payloads with a 3σ CEP of less than 300 feet. Limited studies indicate that blast and ejecta during landings will not be hazardous to previously landed payloads with such close landings of consecutive payloads. (Further and more detailed studies are required.) A probability study, based on a 300-foot CEP and using random digits in a 20-trial Monte Carlo system was made to determine the azimuth and distance error from the aiming point. This study produced the following predictions for the landing pattern in Table 2.5-A. One landing-pattern trial is shown in Figure 2.5-1.

Figure 2.5-1
LANDING PATTERN FOR FOUR LLV'S



2.5.2.2 Site Conditions — Three sites were postulated, having characteristics shown in Table 2.5-B.

Table 2.5-A

No. of LLV's	Average Distance to CG of Pattern (ft)
1	0
2	200
4	210
6	220
8	235
10	250

Table 2.5-B

POSTULATED SURFACE AND SUBSURFACE CONDITIONS

Characteristic	Site A	Site B	Site C
Mean Slope (a)	2.0° 3.5%	2.0° 3.5%	6.0° 10.5%
Maximum Slope (b)	4.0° 7.0%	4.0° 7.0%	45° 100%
Roughness (c)	1 cm	10 cm	1 meter
Stratigraphy (d)			
Dendritic	0.3 cm	0 to 10 cm	0 to 1 cm
Dust	---	10 cm to 1 meter	---
Breccia	0.3 cm to 1 meter	1 meter to 100 meters	1 cm to 100 meters
Lava	1 meter to 100 meters	---	---

NOTES:
(a) A selected route is assumed.
(b) A maximum slope on a direct route is assumed.
(c) "Roughness" is defined as the maximum gap under a straight edge 10 meters in length.
(d) Bearing values:

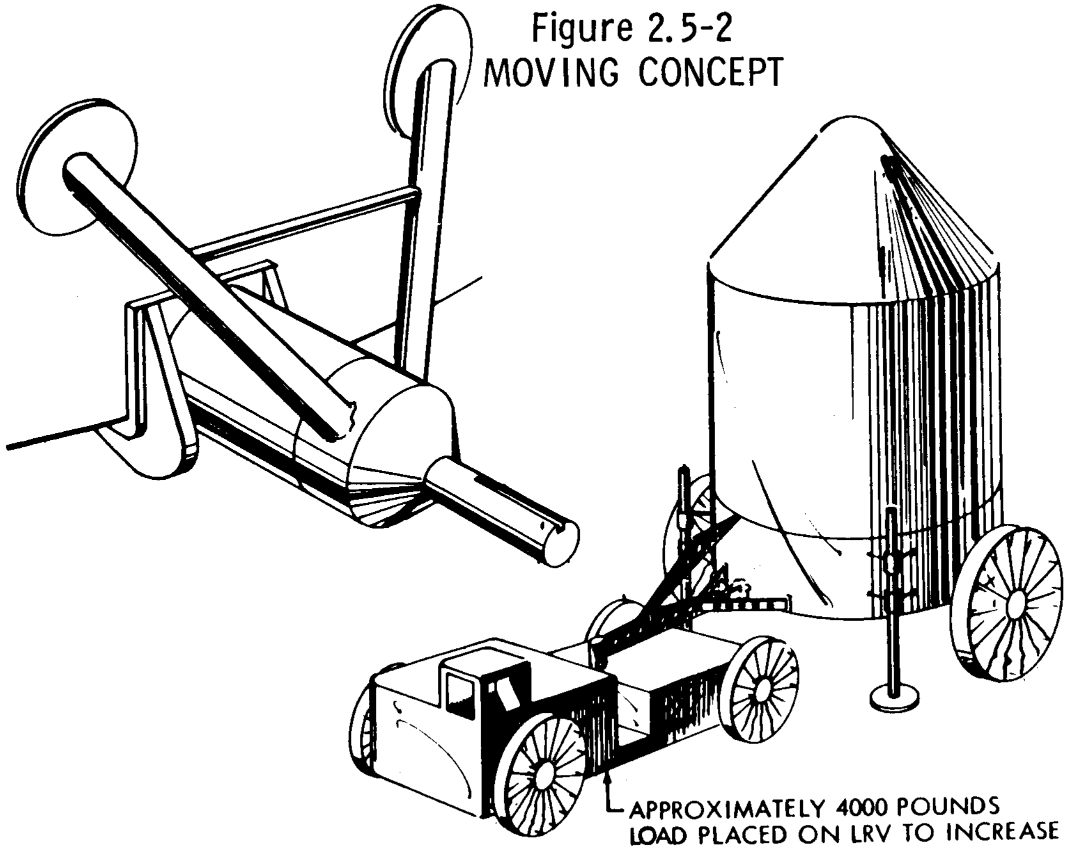
Dendritic	0.01 psi	Dust	10.0 psi
Breccia	100.0 psi	Lava	1000.0 psi

2.5.2.3 Movement of Shelter Modules — The construction equipment for moving the shelters includes three plug-in powered jacks, a gooseneck bracket, and two plug-in powered wheel axles with separate large wheels. The movement concept is shown in Figure 2.5-2. The LLV landing gear has been omitted for clarity, but removal is not required.

A study by General Motors Defense Research Laboratory indicated that a shelter and LLV weighing about 29,000 Earth pounds could be moved across the lunar surface by the lunar roving vehicle at each of the three sites. The study was based on the following assumptions:

1) Site conditions and soil bearing values were assumed as given in Table 2.5-B.
2) The gooseneck bracket transfers 4000 pounds of the load to the LRV. The LRV weighs about 4000 pounds before accepting this load.
3) The LRV develops 608 pounds of drawbar pull at low speeds (about 2 to 3 mph).

Figure 2.5-2
MOVING CONCEPT



APPROXIMATELY 4000 POUNDS LOAD PLACED ON LRV TO INCREASE TRACTIVE EFFORT

4) An additional pull of 4000 pounds is developed by the self-powered wheels.

5) Some route preparation will probably be required at Site C.

The following conclusions were reached:

1) Skids or sleds require much larger drawbar pull than wheels.

2) Tracks have larger resistance than wheels, as well as serious design problems due to the environment.

3) Wheels larger than 6 feet in diameter do not offer significant advantages.

4) The movement concept proposed is simple and feasible.

2.5.2.4 Shelter Connection — A corrugated, pressure-sealed, flexible-bellows type connector shown in Figure 2.5-3 is recommended. Relatively large orientation tolerances in the interface of adjacent shelters are permissible. Elevation and tilt are adjusted by use of the plug-in jacks or by adjustable LLV landing gear. Future detailed shelter design should provide automatic extension and coupling of the connector with minimum space-suit labor. Lunar soil shielding for the connector can be placed in a U-shaped flexible sling, surrounding the connector with the open end up.

2.5.2.5 Other Base Assembly Jobs — Deployment of solar panels, reactor radiators, reflectors, antennas and other assembly jobs were studied sufficiently to secure approximate job time requirements and determine the type of lunar ground support equipment needed. In all cases, it was assumed that maximum use would be made of the LRV (with suitable manipulator arms and attachments) so that space-suit labor would be minimized.

2.5.3 Base Emplacement

Construction equipment will be needed for Base Models 2, 3, and 4 for collection and placement of lunar soil shielding and for emplacement and shielding of nuclear power plant(s). The equipment should be light, flexible in use, low in power demand, and operable from a pressurized environment.

2.5.3.1 Construction Equipment — The self-contained, automatically expanding caisson proposed for the shelter is shown in Figure 2.5-4. This provides an annular space, 2 feet wide when opened. Two feet of soil surrounding the shelter and covering its roof, plus the structural density of the shelter, provides adequate radiation and meteoroid protection, assuming the crew is rotated each 6 months. Five different methods were studied to evaluate various concepts for collecting and placing lunar soil within the caisson. (Requirements for emplacing and shielding a nuclear reactor were also kept in mind and evaluated.) Table 2.5-C indicates the equipment studied and its suitability at the three sites postulated in Table 2.5-B.

Figure 2.5-3
LUNAR SHELTER CONNECTOR

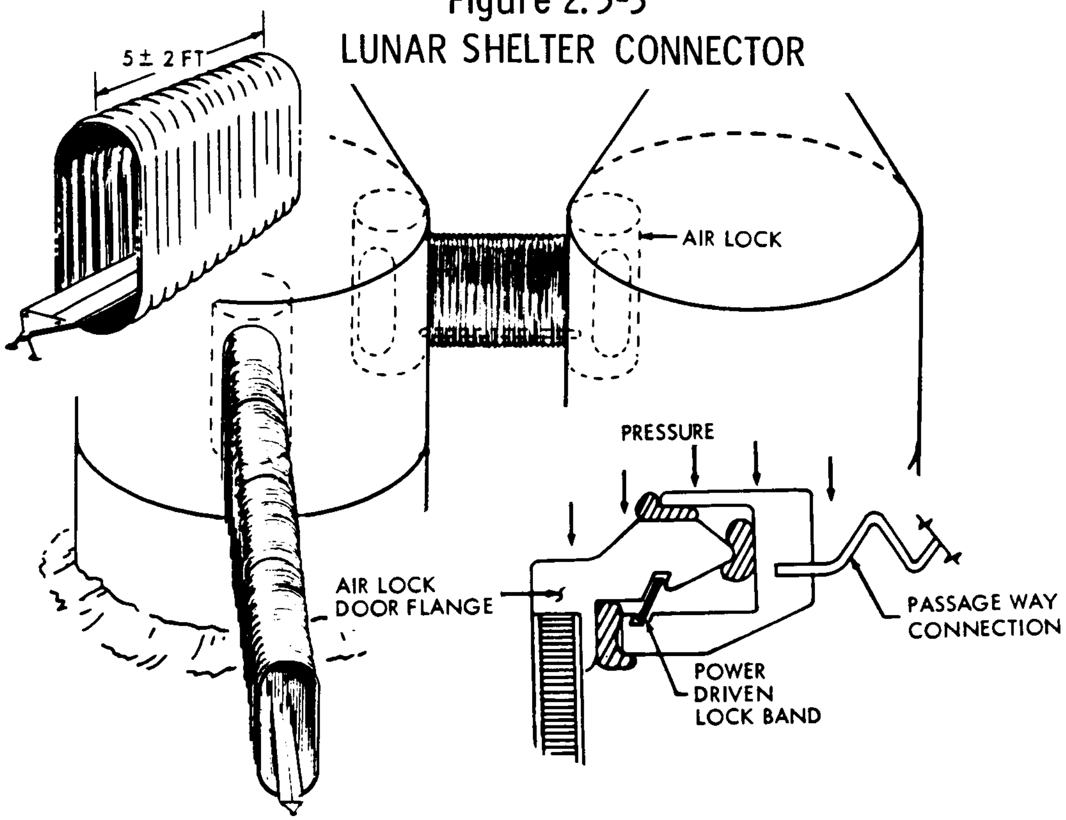


Figure 2.5-4
EMPLACEMENT

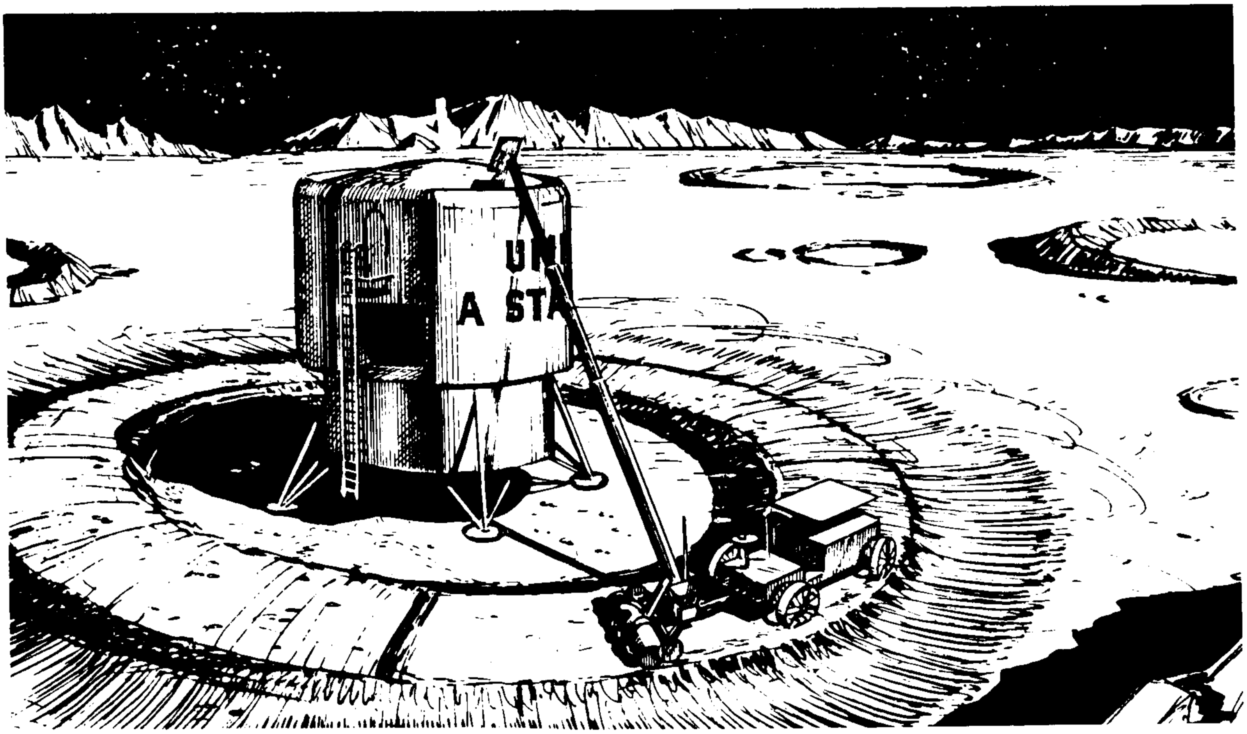


Table 2.5-C

CONSTRUCTION METHOD APPLICABILITY

Construction Method		Site A	Site B	Site C
1	Bucket scraper and belt conveyor	Suitable	Suitable	Suitable
2	Drum scraper and gravel thrower	Suitable	Suitable	Suitable (a)
3	Bucket scraper and gravel thrower	Suitable	Suitable	Suitable
4	Backhoe, crusher, and gravel thrower	Not evaluated (b)	Not evaluated (b)	Suitable (c)
5	Crane, crusher, and gravel thrower	Not evaluated (b)	Not evaluated (b)	Suitable (d)

NOTES: (a) Suitable only if material handled is less than 2 inches in size.
(b) Other methods are less costly and take less time at this site.
(c) Suitable only if original material is less than 12 inches in size and is reduced to 2-inch size by the crusher.
(d) Two crushers in series are required if original material is up to 36 inches in size.

Figure 2.5-4 shows the use of the construction equipment listed in the table above as Method No. 2. Conclusions on construction equipment for collecting and placing lunar soil are:

1) It is premature to select the equipment or initiate preliminary design.

2) No single set of equipment can presently be expected to have adequate flexibility with high productivity at all lunar sites.

3) Testing in a simulated lunar environment is required to ensure reliability and to determine the proper man/machine ratio. The extreme vacuum poses serious design problems.

4) Construction equipment designed as an attachment to the LRV, as shown in Figure 2.5-4, reduces space-suit labor to a minimum.

5) Explosives will be required at some sites.

2.5.3.2 Power for Construction Equipment — Activation of the nuclear power plant should be given high priority in the construction effort. Once it is emplaced, shielded with lunar soil, and operating, it provides the power for other construction requirements. The fuel cell used for the emplacement effort is then used as a backup to the nuclear plant. A trade study first estimated the construction times and costs of emplacing a reactor with power levels of 3, 6, and 15 kw. Construction time was costed at $100,000 per manhour. Use of the LRV was costed at $200,000 per day (rental rate). The production cost, weight (including fuel), and delivery cost of each fuel cell was also estimated. A delivery cost of $5000 per pound was used for both the construction equipment and the fuel cells. The total cost of construction and the fuel cell was then plotted against power level. This total cost decreases steadily from about $45 million to $30 million as the power level increases from 3 to 10 kw. There are only slight savings for higher power levels. Weight allocations in payload packaging solutions permitted a selection of 15 kw without serious penalty.

2.5.3.3 Advantage of Lunar Soil Shielding — Figure 2.5-5 indicates that about five to ten times as much soil is needed for shielding a shelter if the soil is placed in a conical fill rather than in a caisson around the shelter. (The exact amount depends on the height of the LLV). Using a figure of 195 cubic yards as the quantity of soil required with a shelter caisson (2 feet of thickness of soil on the roof and sides of the shelder), a study was made of the cost of self-shielding required for each base. This weight was costed at $5000 a pound for delivery. The construction cost for providing soil shielding in lieu of self shielding was also estimated for the shelters, the nuclear reactor(s) and the fuel synthesis module. These costs included manufacture of the construction equipment, delivery, manhours for the operators, and rental rate of the LRV, using the same costs as in Section 2.5.3.2 above. For Bases 2, 3, and 4, the delivery and use of construction equipment and the use of lunar soil for shielding is much more economical than self-shielding, although time is required for the effort. In addition, since an arbitrary 2-foot thickness of soil shielding was provided by the shelter design, the degree of radiation and meteoroid protection afforded to the crew was higher with lunar soil.

2.5.4 Additional Construction Studies

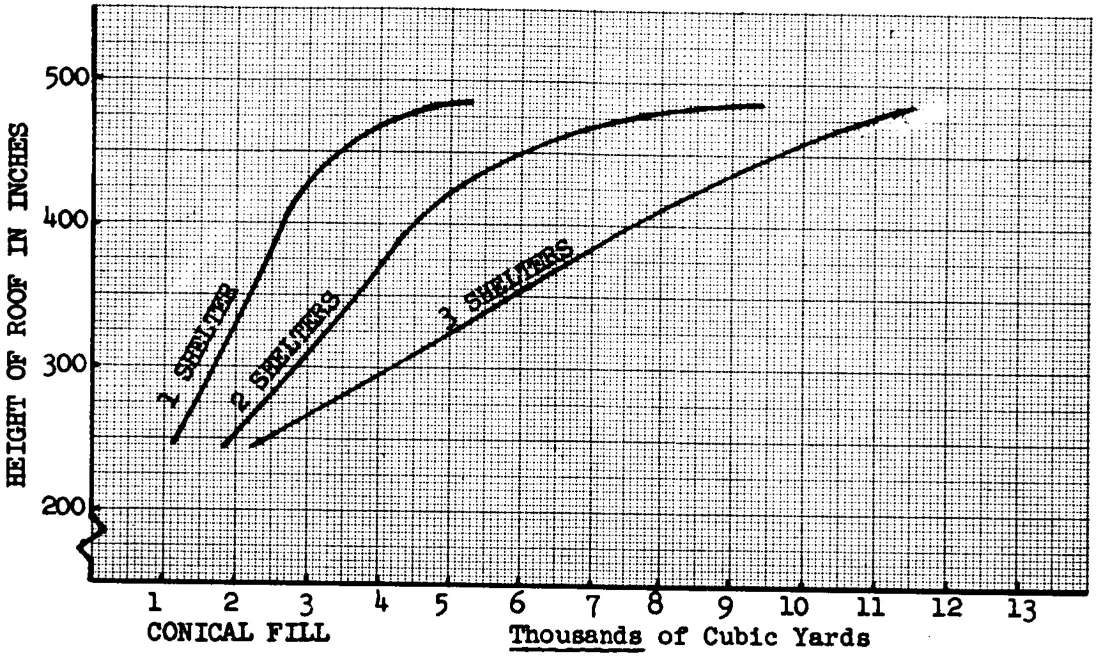
The following summary indicates the results of brief studies of other construction considerations.

1) Excavation in rock will be required in some cases. The use of shaped charges to fracture rock so that the ejection of rock fragments can be minimized should be investigated. The design of suitable drill attachments for the LRV will be difficult, and large amounts of power will be needed.

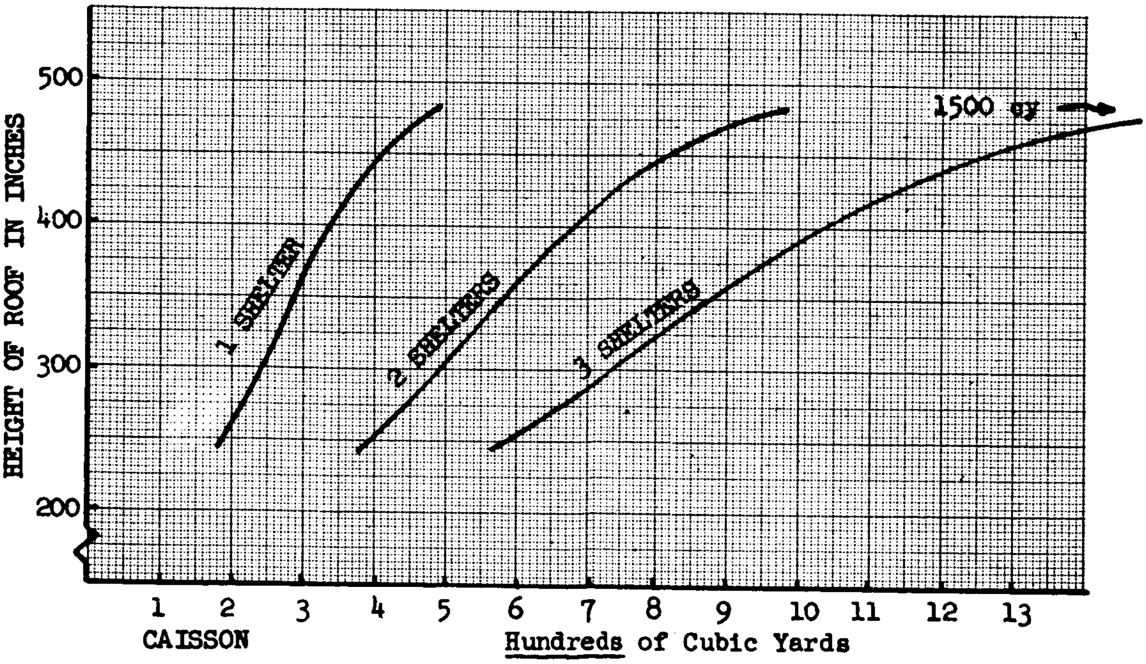
2) Quarrying will be required for fuel synthesis, or if crushed rock is needed for surface route modification. The use of explosives should be investigated. Testing in a simulated lunar environment is required.

3) Theoretical and small-scale tests indicate to date that the problem of ejecta and blast during an LLV landing will not be serious. Additional investigation is needed.

Figure 2.5-5
VOLUME OF FINE MATERIAL REQUIRED
24" THICK SHIELD IN 360° CAISSON



NOTE: For both graphs, volume of coarse material is slightly greater. Data is from Holmes and Narver



4) Concepts for a self-burying shelter were considered to be too complicated, expensive, and unreliable. The two concepts studied were not suitable if the subsurface were rock or dense cohesive soil.

5) Flexible materials appear to have numerous applications. For each case, their suitability in the lunar environment should be tested. Radiation and thermal cycles should be simulated.

2.6 LUNAR BASE OPERATIONS CONCEPTS

Operation of a lunar base in support of lunar exploration and research activities must provide for efficient use of total program resources, for effectiveness in accomplishing mission objectives, and for safety of the expedition crew. Selected aspects of lunar base operations which have special significance in relation to these criteria have been considered. These subjects do not encompass all details of base operation, but rather represent a first screening consistent with the overall scope of this study.

2.6.1 Subsystem Monitoring and Control

2.6.1.1 Payload Storage Periods — Monitoring and control during storage periods ahead of base occupation will verify capability of the delivered modules and equipment to support the mission before crew launch, and will provide data on which to base remote control actions. Control functions will be required for system checkout prior to occupation and possibly for command-mode operation of the storage thermal control system.

Communications Module C-4 is included in each shelter payload to provide the monitoring and control telemetry functions required. The same or equivalent telemetry equipment will be required in other types of payloads that may be stored at the lunar base site ahead of base occupation. The functional description of Module C-4 is contained in Section 6.0, Volume III.

2.6.1.2 Base Occupation Periods — Monitoring and control during base occupation will be both by remote operations from Earth and by direct actions involving the expedition crew. Monitoring functions during occupied periods will be those required to promote base security (hence, crew safety) and those inherent in routine subsystem operation. Control functions will be primarily those of subsystem performance regulation to meet the fluctuating demands of continued base occupation.

The prime communications Module C-1, contained in the principal shelter of each base and each roving vehicle, provides the expanded monitoring and telemetry functions required for operation in the remote modes. After base installation is complete, all base subsystems are tied into this module; hence, no additional telemetry equipment is required.

The lunar base crew may rely on the remote mode for the bulk of the systems monitoring task, with periodic summary reports from Earth providing detailed knowledge of system status. However, the requirements for more immediate reaction to emergency conditions will dictate the provision for constant crew monitoring of vital system functions.

2.6.2 Base Activation

2.6.2.1 Direct Buildup vs Base Evolution Trades — The four base models, selected to guide this study by typifying the range of base sizes, capabilities, and durations, may be considered as discrete and independent or as successive stages in an expanding program of lunar exploration. The application of the modular base concept in these two modes of base activation is compared with respect to the operational factors of launch schedule requirements, mission effectiveness, and module utilization.

2.6.2.1.1 Activation Schedule Analysis — To permit an analytical approach to these comparisons, the study ground rules are:

1) Earth-Moon cargo payloads of 25,000 pounds;
2) Round-trip Earth-Moon crew transportation in increments of three men;
3) Crew stay time of 6 months.

Those ground rules are combined with the following simplifying assumptions:

1) Cargo deliveries to establish or increase the size of a base are spread over a 1-year period, with a linearly increasing launch rate throughout the year.
2) Resupply cargo is delivered at the rate of 500 pounds per man-month.
3) The base crew complement or increment is delivered and rotated at a uniform rate over the 6-month stay period.

The launch rate requirements are compared in Figure 2.6-1. The evolutionary scheme shown provides for operation at the nominal capabilities of each of the four models, followed by 1-year of operation at the previous crew level while base increment cargos are delivered. For this scheme, the increase in launch rate is quite gradual, with one launching per month reached in 6-1/2 years.

The cost-effectiveness comparison shown in Figure 2.6-2 favors the evolutionary mode over any direct buildup for the first 50 launchings (7-1/2 years with evolution).

2.6.3 Mission Operations

2.6.3.1 Surface vs Flight Mode Mobility Trades — As presently conceived, crew mobility in the lunar environment is an essential requirement for mission accomplishment. Development of the most efficient means of ranging over the lunar terrain on both close-range detailed reconnaissance missions and on far-reaching scouting trips is a prime requirement for the exercise of the manned scientific disciplines.

Figure 2.6-1

COMPARISON OF LAUNCH RATE HISTORIES

DIRECT BUILDUP VS BASE EVOLUTION

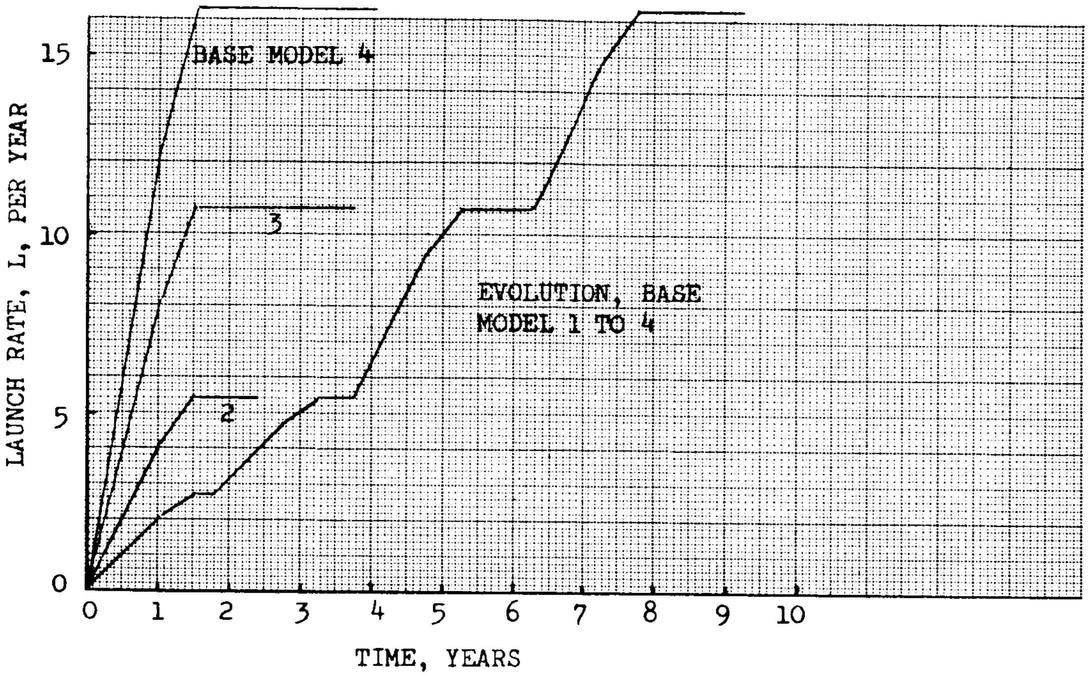
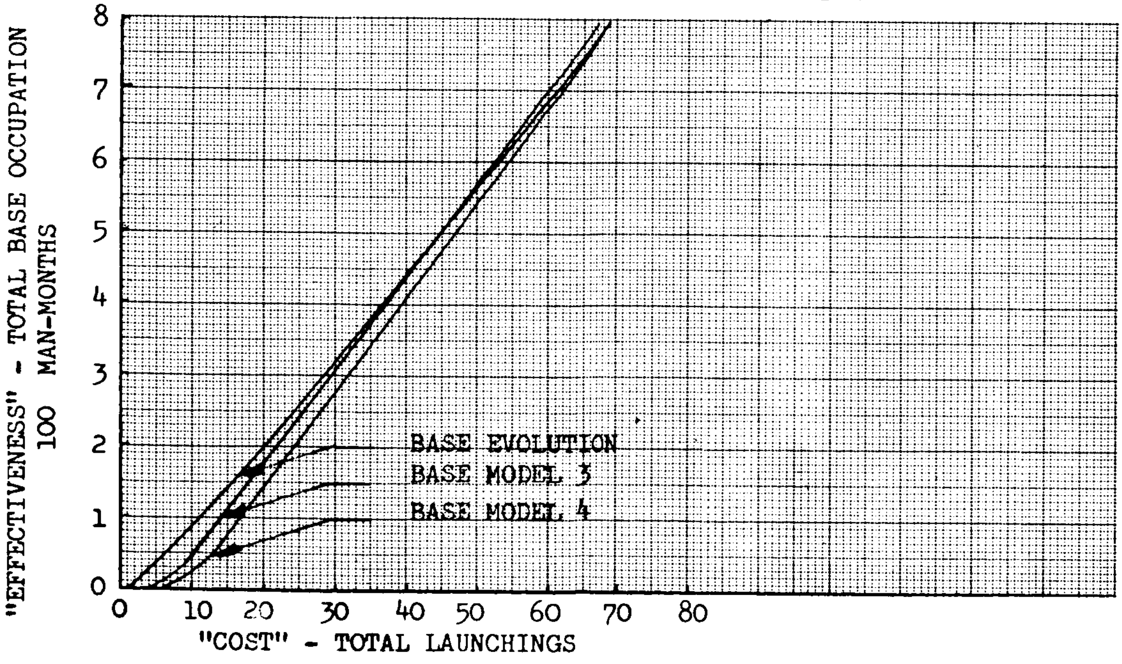


Figure 2.6-2

COST-EFFECTIVENESS COMPARISON

DIRECT BUILDUP VS BASE EVOLUTION



Performance data are presented for a spectrum of vehicles in terms of the requirements of several typical lunar exploratory missions. From these data, comparisons are made with respect to mission capability and relative propellant and mission time penalties. Based on this analysis, the conclusion is reached that only the surface mode offers the flexibility of being suited to a wide range of mission types.

2.6.3.1.1 Mission Characteristics — The mission categories, characteristics, and specific evaluation criteria tabulated below have been adopted for this study.

Mission Category	Characteristic Interval Between Occupied Sites	Mobility Evaluation Criteria
Scientific Reconnaissance	1 to 5 miles	Number of 3-mile trips per sortie Total distance travelled per sortie Propellant weight per mile Number of sites occupied per day
Scientific Survey	10 to 50 miles	Number of 25-mile trips per sortie Total distance traveled per sortie Propellant weight per mile Number of sites occupied per day
Remote Scouting	100 to 3400 miles	Maximum round-trip range Propellant weight per mile

2.6.3.1.2 Mobility Modes Parametric Performance Analysis

1) Surface Vehicles. Range performance of surface vehicles is essentially only time-limited, with the crew tolerance to their on-board environment being the prime determining factor. For fixed mission durations, surface vehicle range is directly proportional to average speed regardless of the distance increments in which the mission proceeds. Current estimates of surface trafficability suggest that 40 miles per day (13 hours travel time per 24) be adopted for mission planning. The corresponding fuel and expendables loading requirement is 1.6 pounds per mile. Additionally, the surface vehicle can readily preserve its products of combustion for later regeneration with the use of "cheap" nuclear power.

2) Flight Vehicles. Range performance of flight modes may be categorized as time-independent with propellant consumption the range-controlling parameter. Additionally, there is no possibility of propellant regeneration; hence, vehicle range is directly convertible to lunar materials supply costs.

   The basic requirements for ballistic flight are severe, with a 500-mile flight (takeoff and landing), requiring a velocity expenditure (7900 fps) equal to lunar escape velocity. Lunar orbital velocity (5600 fps) is equivalent to only a 200-mile surface-to-surface ballistic flight.

Parametric performance data for three conceptual flight mode vehicles have been developed. These data relate the multiple flight capability (number of sequential flights of specified distance) to the initial propellant weight and vehicle gross weight. The largest, "LEM-type" vehicle is described in Section 7.2, Vol. III. The "lightweight" flight concept embodies the assumptions of a one-man capsule providing minimum shirt-sleeve environmental facilities, navigation and communication subsystem within a 750-pound payload (including the crew). The "flying belt" concept has been synthesized by extrapolations to higher propellant weights of preliminary data provided by Bell Aerosystems, Inc.

2.6.3.1.3 Mobility Mode Comparison — One measure of mission capability is the total distance covered in one sortie consisting of the maximum number of trips of specified distance each. This parameter is related to the area that can be covered with specified resolutions, or distance between sites, since a vehicle can work no further from a supply base than one-half its total distance capability. The bar charts of Figure 2.6-3 compare this measure of performance of "design point" flight vehicle concepts.

The undoubted great advantage of flight modes over surface travel with respect to travel time is seen to largely disappear when viewed from a total mission basis, as in Figure 2.6-4. Thus, with reasonable ground rules for time spent at each site visited, and for vehicle preparation time before each sortie, the flight modes show only a 2 to 3 advantage in exploratory sites visited per day.

2.6.3.2 Crew Performance Potential — In the conduct of manned lunar exploration, human performance of a variety of tasks is a major consideration. The tasks range from those for base installation and functional operation to those involved with mission activity. Outstanding in this regard are operations external to the lunar shelters. Both direct manual and automated modes of task performance may be envisaged for such activities.

Aside from the question of crew safety, the choice of operating modes depends upon the relative cost (in equipment and time) and performance capability of a space-suited man versus an automated procedure. The scope of this problem is too large, and the quantitative data too meager, to attempt a definitive resolution in this study. Some qualitative considerations are presented regarding the conduct of mission operations in the field. These suggest a severe penalty to mission value if human performance capability is limited. The same conclusion may also apply in other tasks where close coordination of mechanical actions and visual cues are required.

Figure 2.6-3

COMPARISON OF MULTIPLE-TRIP MISSION CAPABILITY

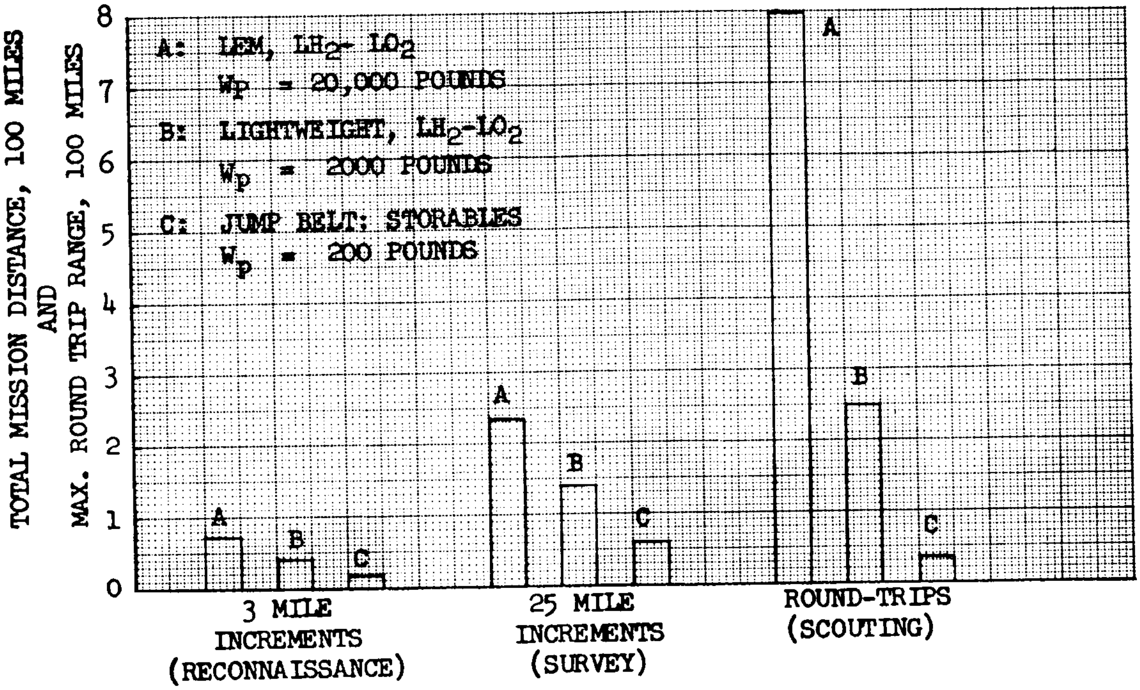
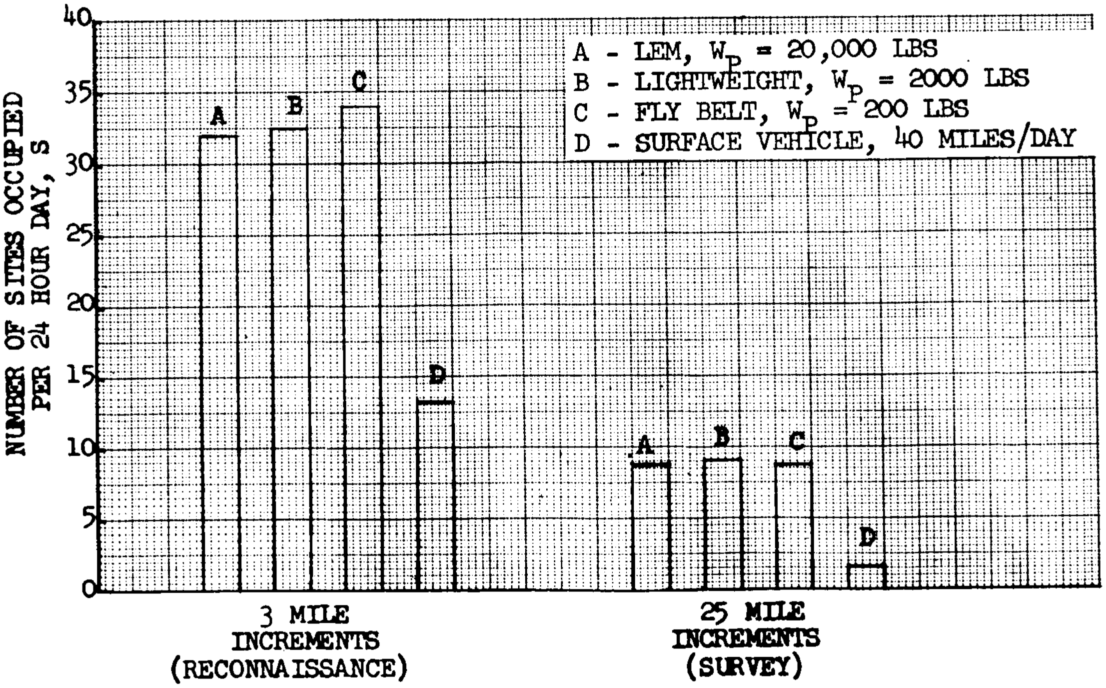


Figure 2.6-4

COMPARISON OF MULTIPLE TRIPS

MISSION TIME REQUIREMENTS



2.6.4 Emergency Operations

Emergencies at a lunar base may range from those permitting complete recovery by the unassisted base contingent, through those requiring various degrees of assistance from Earth, to those from which recovery is impossible. Because the subsystems of the base will be designed and protected against the worst disasters, the probability of a particular emergency is inversely related to its seriousness.

Provision for maintaining Earth-return crew vehicles in a ready status at the base greatly enhances crew safety by providing a mission abort capability. In less stringent circumstances, assistance from Earth may be adequate and will avoid the otherwise necessary abandonment of the base.

2.7 LOGISTIC SUPPORT CONCEPTS

Logistic support encompasses the operations of supplying bases with the men and materials to permit the bases to function for planned or extended time periods. In this analysis, the material and manning requirements are summarized in terms of the parameters of base duration (shelter-months), base occupation (man-months), and base support capability as defined by the subsystem performance characteristics of the four base models. The operational aspects of logistic support are considered in terms of Earth-to-Moon transportation system trade studies, material handling and storage at the lunar base, and the potential for attaining logistic independence through synthesis of fuel and life support expendables from lunar raw materials.

2.7.1 Logistics Support Requirements

2.7.1.1 Expendables Resupply Requirements — Examination of the requirements for major expendables (life support and power generation materials) indicates their dependence on both base occupation and base duration, hence on crew number per shelter. Thus, the fuel equivalent of the power consumed for thermal control of a shelter is essentially independent of crew size, whereas such items as food and metabolic oxygen are directly related to total base population regardless of the number of shelters.

The performance characteristics of the life support and power generation subsystems considered for use in various stages of base development have a direct effect on resupply requirements. Constituents of the total requirements dependent on shelter duration and base occupation are identified for four combinations of subsystem performance capability. Shelter-duration dependent quantities dominate the resupply requirements, and are most affected by subsystem performance. The major change in oxygen and hydrogen requirements with the provision for roving vehicle fuel regeneration is especially noteworthy.

2.7.1.2 Scientific Mission Support Equipment — Scientific mission support equipment was not required to be treated as a lunar base subsystem in this study, in recognition of the necessity to assimilate the data from projected Ranger, Surveyor, LOS, and early Apollo flights before a definitive scientific mission plan for lunar exploration can be formulated.

At the same time, some broad format of mission endeavor is desirable to provide a basis for subsystem sizing in such areas as power, fuel, and communications. The programs of geophysical exploration outlined in Section 2.3 were therefore nominated as a basis for developing system requirements, and have proved an adequate device in this respect. As an adjunct to that effort, a catalog of possible mission equipment items has been assembled. Equipment selections were made from this catalog as a basis for mission equipment weight estimates required for payload integration.

2.7.1.3 Base Manning Requirements — Manned spacecraft launchings are required for both crew delivery to the base and crew return to Earth. In the steady-state maintenance of base manning level at a value N, crewmen in numbers N must be delivered and returned in the time interval, S, equal to the desired individual stay time. The relationship between these parameters is shown in Figure 2.7-1. It is seen that the launching requirement for manning Base Model 4 is one per month with the study ground rules of a 6-month staytime and a three-man spacecraft.

Increasing crew stay time is an attractive means for reducing launch rate, since no major additional system costs or performance penalties are known to be incurred as a consequence.

The technical requirements for ferry capacities in excess of three are beyond current Apollo-Saturn system performance, and will involve improvements in launch vehicles, spacecraft, and space propulsion systems.

2.7.1.4 Base Manning Performance Trends — The effects of Saturn V escape weight growth on allowable LEM weight are shown in Figure 2.7-2 for Apollo service module configurations representative of both the current storable-propellant design and an advanced LO_2/LH_2 design. In both cases, Apollo fixed weights are 9500 pounds for the command module and 4500 pounds for service module equipment. These weights are considered usable for Apollo crew sizes from three to six, with the assumption of future system design refinements permitting the growth in crew size without weight penalty.

Performance of a current and an advanced LEM in the lunar orbit rendezvous mode are shown as functions of LEM gross weight in Figure 2.7-3. In the round-trip mode, appreciable cargo delivery capability in addition to the crew is indicated for various combinations of launch vehicle and space propulsion improvements.

Performance potential in the direct flight mode is shown in Figure 2.7-4 for both one-way and round-trip flights. Saturn growth to 135,000 pounds escape weight, refueling in Earth orbit, or refueling on the Moon, are approaches to obtaining direct flight round-trip capability. One-way trip performance may be of interest even at 100,000-pound escape weights since with provision for 14,000-pound command and service module equipment weights an additional cargo capacity of the order of 20,000 pounds is indicated. This value is very near that required for major modular building blocks of the lunar base. With this capability, initial one-way crew launchings could also deliver the large base elements such as shelters; subsequent advanced LEM round-trip crew flights could deliver small logistics packages, and most, if not all, purely cargo logistics flights would be eliminated.

Figure 2.7-1
CREW TRANSFER LAUNCH-RATE REQUIREMENTS

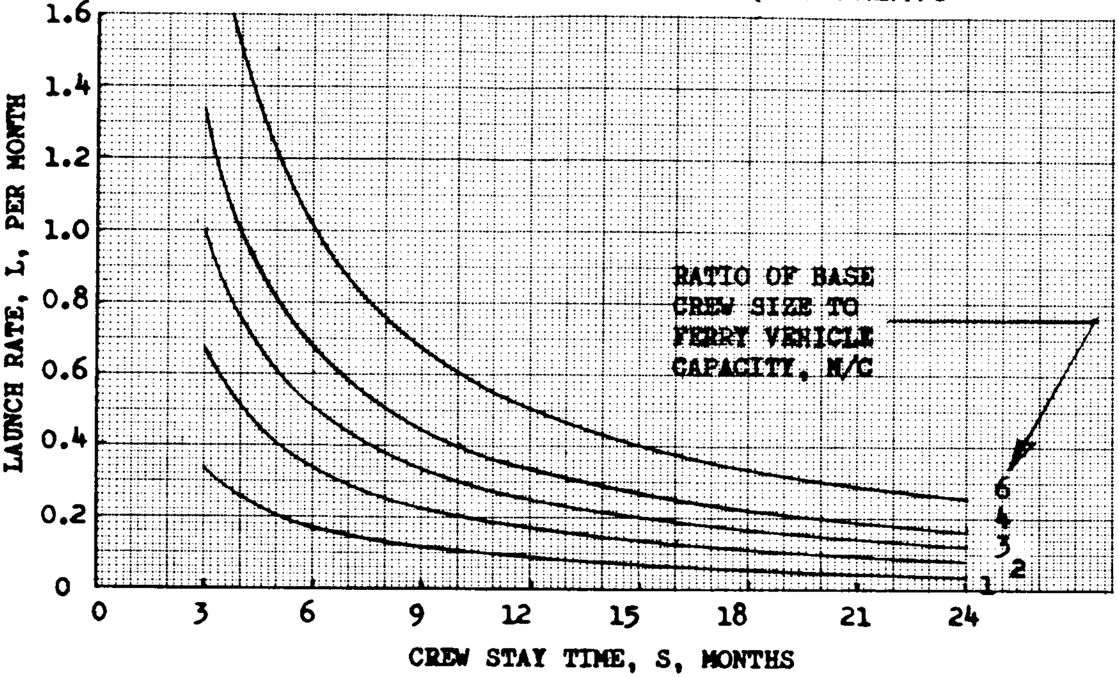


Figure 2.7-2
EFFECT OF SATURN V GROWTH ON LEM GROSS WEIGHT

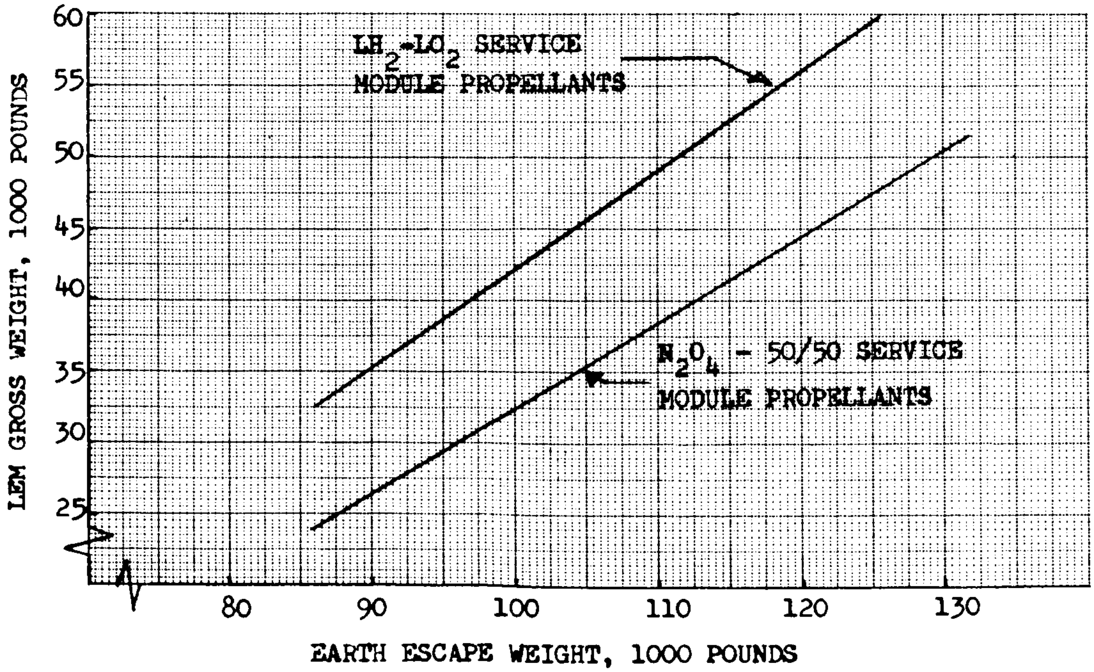


Figure 2.7-3

LEM ROUND-TRIP PERFORMANCE POTENTIAL

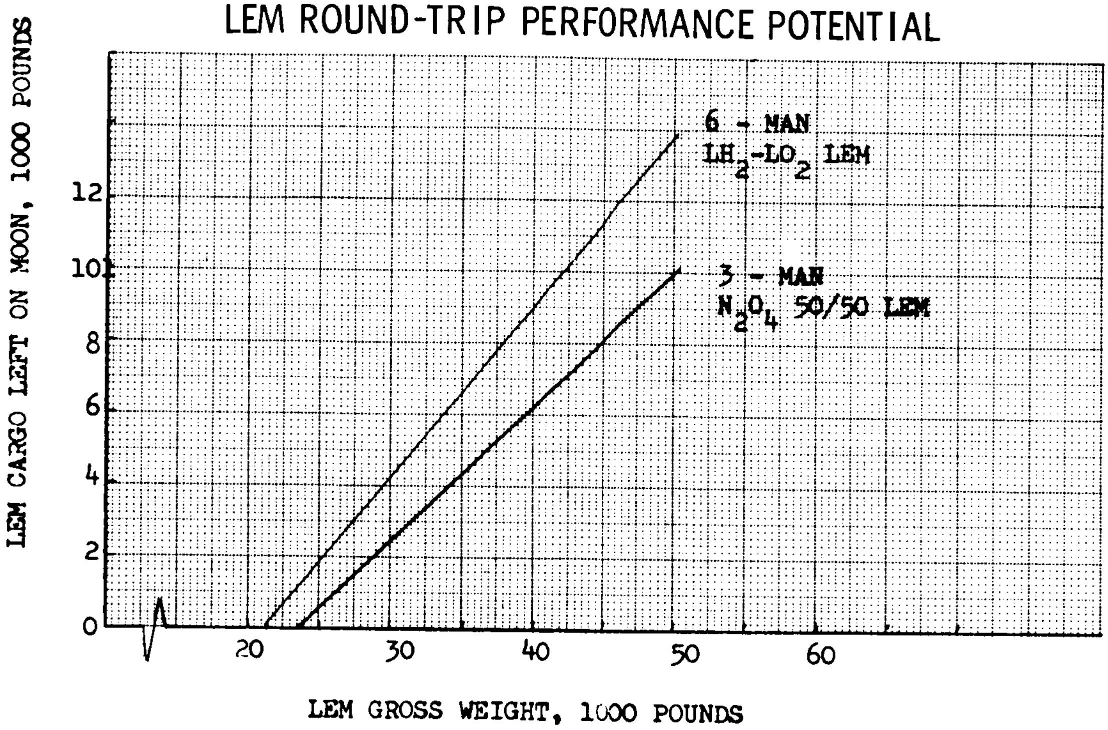
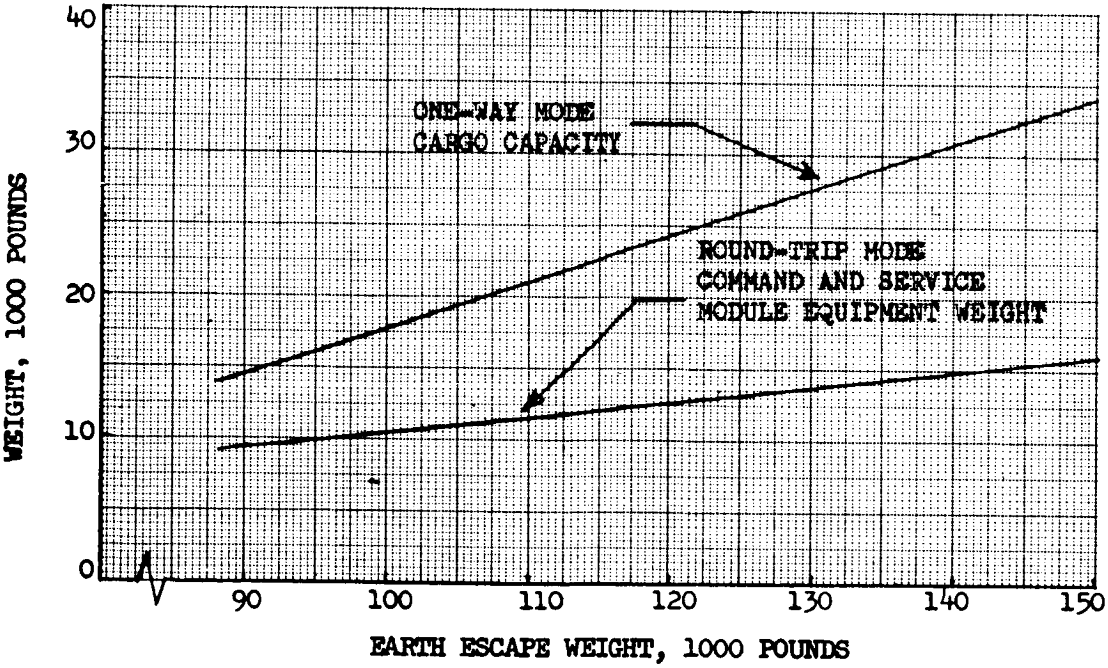


Figure 2.7-4

APOLLO/SATURN DIRECT-FLIGHT CAPABILITY

LH_2-LO_2 PROPELLANTS



2.7.2 Logistics Operations Considerations

2.7.2.1 Earth-Moon Transportation System Trades — Evaluations of total lunar logistics transportations systems (crew and cargo) involves not only vehicle performance, but also consideration of traffic requirements. In the base build-up phase, or for small, short-duration bases, logistics system optimization may be of not too great importance, since the requirements is for a relatively few "special deliveries." Of principal concern is the period of base manning and maintenance which follows initial equipment delivery. Here, as base duration is increased, relatively large numbers of routine launchings are required, and attention to transportation system efficiency can have an appreciable effect on total system cost.

Steady-state transportation system performance in a separate crew and cargo vehicle mode is shown in Figure 2.7-5 for crew vehicle capacities of 2, 3, 4, 5, and 6 and a nominal cargo vehicle capacity of 25,000 pounds. It is apparent that the relative advantage of increasing crew vehicle capacity decreases with increasing cargo-to-crew ratio.

Cargo vehicle performance capabilities of 25,000 and 30,000 pounds are compared in Figure 2.7-6 when matched to several crew-only and a combined cargo/crew element to form complete transportation systems. At low values of Ca/Cr, the effect of crew vehicle cargo capacity dominates the cargo vehicle improvement contribution, and any cost for cargo vehicle payload increase is warranted only for a system with little or no crew vehicle cargo capacity. For large Ca/Cr values, the benefit of cargo vehicle improvement is nearly independent of crew vehicle cargo capability.

2.7.2.2 Materials Handling and Storage Trades — Delivered payload items must be integrated into the scheme of base operations, such as crew feeding, shelter atmosphere control, and mobile or stationary power equipment refueling. Accomplishment of this integration is an important base operation, and particular procedures for payload handling and storage may be preferred on such bases as reliability, equipment requirements, and crew time demands. The analysis presented constitutes an outline of possible operational procedures, a qualitative discussion of evaluation criteria considered pertinent, and a judgment evaluation of the alternate modes with respect to the applicable criteria.

The operational mode for logistic supply handling amounts to the technique employed for transfer of the materials to the using subsystems. Three general techniques can be identified:

1) Direct usage — Transfer from the logistics payload containers to the using subsystems on a demand basis;

2) Refilling — Transfer from the logistics payload containers to base prime or auxiliary storage facilities on a one-shot basis;

Figure 2.7-5

SEPARATE CARGO-CREW TRANSPORTATION SYSTEM PERFORMANCE

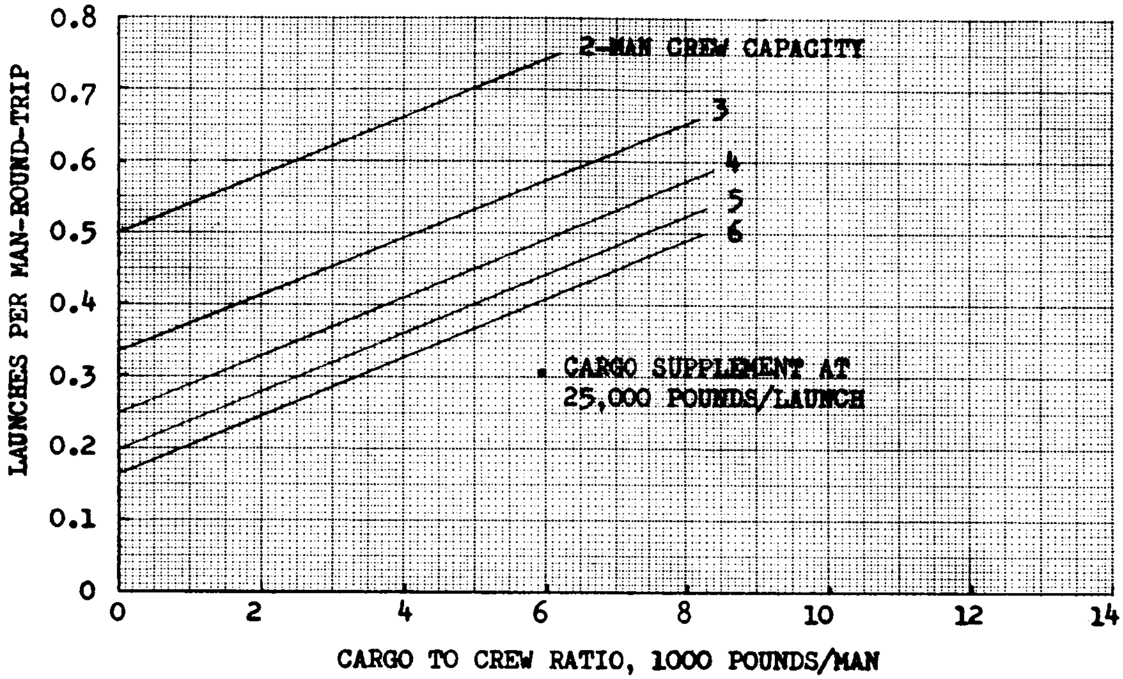
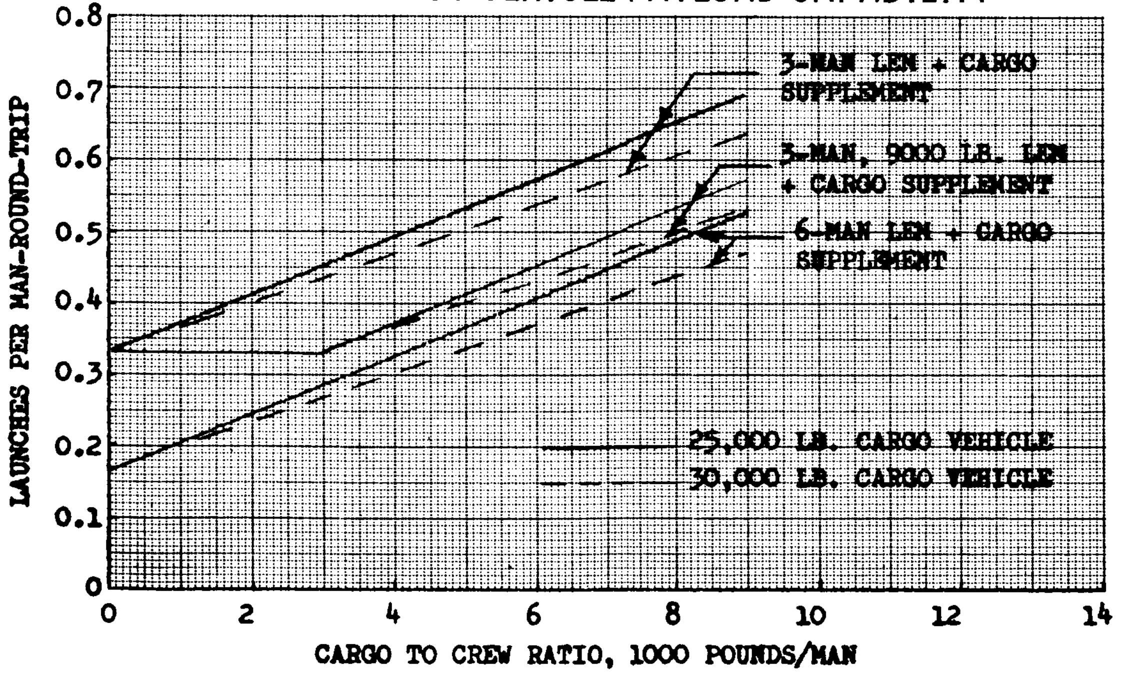


Figure 2.7-6

EFFECT OF CARGO VEHICLE PAYLOAD CAPABILITY



3) Tank replacement — substitution of logistics payload containers for expended tanks of the prime storage or an auxiliary storage system.

Evaluation criteria considered pertinent to the operations described are: weight penalty, time penalty, mechanical feasibility, flexibility, reliability, and safety.

The qualitative evaluation of the three proposed operational modes is summarized below.

MATERIAL HANDLING CONCEPT COMPARISON*

Operational Mode	EVALUATION CRITERIA Weight Penalty	Time Penalty	Mechanical Feasibility	Flexibility	Reliability and Safety
Direct Usage	2	1	3	3	3
Refilling	1	2	2	2	1
Tank Replacement	3	3	1	1	2

*Ranking: 1 = Best, 2 = Intermediate, 3 = Poorest

2.7.2.3 Logistics Independence — Among the raw materials on the Moon for which a critical need exists, water or a material from which water may be obtained, is outstanding. A supply of water can furnish life support systems with oxygen and also hydrogen and oxygen for fuel cells. In view of the probabilities of recovery of waste and regeneration of fuel from these systems, the important need for large quantities of hydrogen and oxygen may be for uses where the waste cannot be collected. Hydrogen and oxygen as rocket fuel or water used in evaporative cooling are two examples of such uses. Propellant for return of vehicles to the Earth will require an amount of fuel approximately 2.25 times the inert gross weight of the vehicle. Thus, for a vehicle weighing 10,000 pounds, 22,500 pounds of fuel are required. A chemical plant on the Moon producing oxygen at a rate of 10 pounds per hour and hydrogen at the equivalent rate of 1.25 pounds per hour will produce fuel for a return vehicle trip roughly every 90 days.

2.7.2.3.1 Lunar Resources — The availability of water on the Moon depends on the original elemental composition of the material from which the Moon was agglomerated and upon the thermal history since its formation. The best evidence of the gross composition of the Moon is obtained by assuming that it is similar to that of the Earth's crust and to meteoritic material which has fallen on the Earth. Therefore, we may expect to find oxygen as the major constituent combined with the other common elements, silicon, aluminum, iron, magnesium, etc., as silicates similar to the crust of the Earth.

Carbon, either free or combined as carbides or hydrocarbons, is present in the Earth's crust in only minor elemental abundance. Yet it is the only element for which there is direct evidence of its existence on the Moon. It was observed spectroscopically by Kozyrev in 1958 in what he interprets as volcanic activity in the crater Alphonsus. It has been suggested by Urey in 1961 that the observed C_2 molecule might have been derived from a reaction between CaC_2 and water, which yields acetylene.

Sulfur is very frequently associated with volcanic activity on Earth and therefore can be expected to be found in regions of similar activity on the Moon.

2.7.2.3.2 Extraction Processes — Estimates of the payload trades associated with the provision for logistics independence of oxygen and hydrogen requirements have been made on the basis of production of hydrogen and oxygen from hydrated rock and production of oxygen from silicate rock containing no water. Product payout times in the order of 60 days are indicated.

The estimates made for weights of machinery and chemical apparatus are based on existing technology and process equipment. Adjustments have been made for weight reduction where the design goal is lightweight. This is usually not the goal of the chemical process industry. Unquestionably significant advances will be made in chemical processes which will reduce the weight of components further.

2.8 TYPICAL LUNAR BASE OPERATIONS PLANS

Operations plans are summarized in terms of launching schedules and crew activity schedules. A more detailed discussion is organized in terms of the plans for four characteristic program phases:

1) Base Activation Plans — principally the operations for base installation.
2) Mission Operations Plans — the operations for direct conduct and base support of the scientific missions.
3) Logistics Support Plans — crew and material delivery and the handling and storage operations associated with such support.
4) Base Deactivation — the operations associated with final crew return.

2.8.1 Launching Schedule

Launch schedules for each of the four base models and a program of evolution from Model 1 to Model 4 were selected as follows:

1) The logistic buildup, which will continue until the arrival of the first crew increment, is set at the rate of one launch per month for all four discrete base models, as well as for the initial increment of the logistic buildup of the evolutionary base. This rate is chosen to illustrate the minimum logistics buildup time, recognizing that a lesser launch rate and an extension of the logistic buildup are feasible.
2) Starting with the first crew increment deliveries for discrete Base Models 1, 2, 3, and 4 (each considered as an independent choice), the maximum launch rate of one per month is chosen and pursued to its maximum need.
3) An arbitrary "evolution" of Base 1 to Base 4 is chosen on the basis of a reasonable (but less than maximum) initial launch rate, followed by a gradual increase.
4) For the evolutionary base, the delivery dates for logistic payloads of equipment (additional shelters, power modules, etc.) needed to expand one base to the next larger size must occur before the expiration of the smaller base's planned life and before the increase in crew size above the capacity of the smaller base.

2.8.2 Summary Operations Plans

The operations plans corresponding to direct buildup to Base Models 1, 2, 3, and 4 are summarized in the form of crew assignments by skills, time, and basic types of operation. In general, these plans provide for complete base installation and activation by the initial crew increments at the outset of each program. Mission operations are started and expanded as rapidly thereafter as the launching schedule permits. A crew delivery and return capability of three men per month is assumed.

As operations extend beyond the 6-month crew residence period, a repetitive pattern of crew assignments is developed. This pattern could be continued for program durations in excess of those used in the examples. Similarly, operational schedules for a program of base evolution may be synthesized by proper joining of the patterns derived for the individual base models.

2.8.3 Base Activation Plans

For direct base buildup, base activation encompasses the operations performed by the first crew increment to convert the previously delivered and stored payloads to full operational status as a lunar exploration support facility; for base evolution, similar operations are performed by incumbent base personnel whenever base expansion payloads are delivered.

For all the cases considered, the sequence of operations will be performed in accordance with the following general plan:

1) Final payload "go" status verification via the payload storage monitoring system;
2) Crew launching;
3) Crew arrival;
4) LEM checkout and preparation for emergency return;
5) Crew occupation of the principal shelter module;
6) Crew checkout and verification of all shelter systems not requiring lunar surface deployment;
7) Activation of the occupation-mode remote-monitoring system;
8) Permanent base installation and activation, including provisions for long-term crew transport vehicle storage.

Completion of all these activities but the last is expected to occupy the first 24 hours, including periods of rest. The major tasks involved in base installation are described and their time requirements estimated.

2.8.4 Mission Operations Plans

Once the base is activated and the scientific mission can be started, the crew activities must be directed toward accomplishment of the following tasks:

1) Installation of instrumentation at the base site;
2) Reconnaissance trips concurrent with base operations;
3) Feasibility studies.

A number of instruments will be installed near the base for extralunar hazard monitoring: point detectors where measurements are not directly related to a specific lunar location, and instruments too cumbersome to be transported on the mobile vehicle.

An important objective of the early reconnaissance trips will be to locate a suitable site for a permanent base — a site where a semipermanent base can evolve, if desired, to a permanent base. The field crew will be composed of two of the three crew members of the Base 1 complement. The third member must remain at the shelter alone to operate this base while the field crew is out.

During the stay on the lunar surface, feasibility studies or tests must be made and techniques developed for planned future work. Such feasibility studies are necessary in the lunar environment to determine possible different instrument design approaches, materials, and methods that must be used to complete specific tasks.

These phases of crew activity will be present whether the base is a temporary shelter module or a large, complicated, permanent base. As the base increases in size, the principal differences will be in the number and sophistication of the physical experiments, geological mapping, geophysical and geochemical explorations, biological experiments, and feasibility schedules that are performed.

2.8.5 Logistics and Resupply Plans

2.8.5.1 Initial Base Supply — For direct buildup of Base Models 1, 2, and 3, all hardware equipment and stocks of expendables required for the nominal base duration and level of mission activity will be delivered in the "A" and "B" payloads prior to arrival of the first crew increment. For Base Model 4, the initial supplies will be sufficient for the first year of operation. Combinations of "A" and "B" payloads similarly supply the requirement for base evolution until the later phases of such a program.

2.8.5.2 Base Resupply — The single resupply payload for Base Model 4 delivers 12,033 pounds of food and crew equipment and 10,274 pounds of cryogenic materials. This payload will not have meteoroid shielding; hence, it will be recovered and disposed of immediately on arrival. The "dry" cargo will be unloaded and transferred to the shelters by crews using the surface vehicles. In view of the one-shot nature of resupply required for the mission-activity level assumed in this example, direct transfer of the cryogenic tankage to the shelter areas and construction there of new tank farms will be employed. The resupply payloads for base evolution are similar to those for Base Model 4 and will be handled in the same manner.

2.8.5.3 Crew Delivery and Return — The requirement that crews be delivered and returned in three-man increments is consistent with a modest expansion of Apollo/LEM capabilities. To provide the greatest measure of crew safety, the abort capability represented by ready-status storage of Earth-return crew vehicles is desired; therefore, the first-in/first-out mode of base manning, where each crew increment arrives and returns in the same vehicle, is specified. Vehicle storage time is 3 months for Base Model 1 and 6 months for all the other cases.

2.8.6 Base Deactivation

The final operational actions at a base are concerned with the preparation for return to earth of the final crew increment and possibly with actions taken to "mothball" the base for future usefulness.

Until further details of the lunar program are refined, and particularly until the relative geographic positions of initial and subsequent bases are determined, it would be premature to assert that each base should be "mothballed" when its use is terminated. Certainly, consideration is warranted if an unmanned phase occurs in an evolutionary concept. A "mothballed" lunar base could very possibly serve as a temporary camp for a trip made from a nearby later base. The lunar environment, the amount of protection required, and the effort and amount of material would need to be determined, and the base's location would need to be recorded, both by coordinates and by a long-life beacon.

3.0 SUBSYSTEM ANALYSIS AND MODULE CONFIGURATION

3.1 INTRODUCTION

The following summaries outline the principal results of lunar base subsystem analyses and module design, including functional definitions and the results of parametric analyses of each major subsystem. Logical modules within each subsystem are defined and conceptual designs of the modules are described. A summary list of the subsystem modules derived in this study is contained in Table 2.4-A.

3.2 STRUCTURAL ANALYSIS

During structural analyses all significant environmental effects that could affect the integrity of structural and/or mechanical systems were considered. Parametric studies were performed with specified environmental factors and loads for radiation and meteoroid shielding, shelter structure thermal response, structural concepts, structural material evaluation, and stress analysis. These analyses define the S-1 shelter configuration.

3.2.1 Radiation Shielding

Potential radiation sources harmful to lunar base personnel include:

1) Solar Flares;
2) Galactic Cosmic Rays;
3) Lunar-surface Radiation;
4) Transit through Van Allen Belts;
5) Lunar Base Nuclear Powerplants.

Of these five sources, the solar-flare proton environment contributes the major radiation hazard, and consideration of maximum allowed radiation skin dosage was based on this environment. Nuclear powerplants will be provided with sufficient shielding so that the total integrated dose from all sources will not exceed the allowable. A parameter study of aluminim shielding weight versus exposure time for various allowed skin dosages, Figure 3.2-1, showed the effectiveness of radiation shielding to diminish allowed dosages below 200 rads.

Based on an optimization of shielding weight and a review of allowable radiation exposure for humans, an allowed skin dose of 200 rads was selected for the shelter study. Aluminum shielding weight per unit surface area versus exposure time was determined for various probabilities of not exceeding the assumed 200-rad allowed dose. The effectiveness of lunar material in providing radiation protection was assumed equivalent to an equal mass of aluminum. In conclusion, the maximum indicated thickness of lunar material is 2 inches, considering a 24-month exposure time and a 200-rad allowed skin dose.

3.2.2 Meteoroid Shielding

Meteoroid shielding requirements were determined, based on the environment proposed in Volume II, Section 3.0 and the methods presented in Appendix A for analyzing the meteoroid flux. Mission times of interest range from 1 to 3 years. An unattended stay time of 1 year establishes the minimum shielding to be included in the module shelter payload. Operation stay times up to 24 months beyond the 1-year unattended period were studied. A parametric study of total aluminum shielding thickness, for a double-wall concept with 2 inches of filler material, versus exposed surface area for various stay times and a probability of no penetration, P_0, equal to 0.99 is illustrated in Figure 3.2-2.

Figure 3.2-1
RADIATION SHIELDING

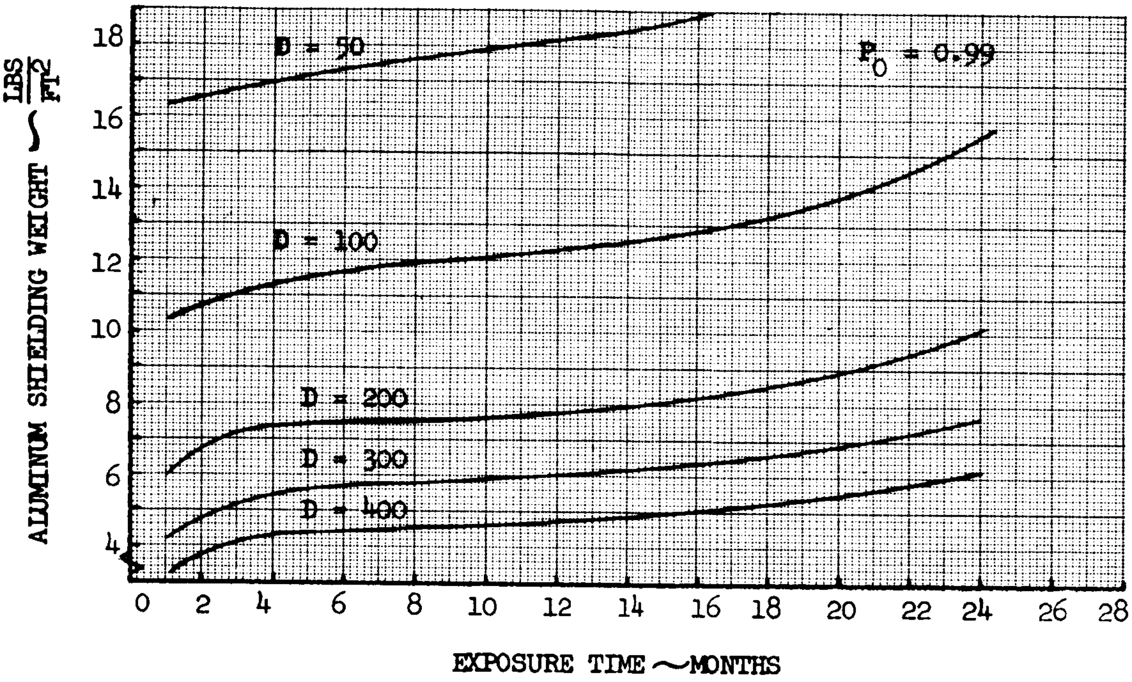
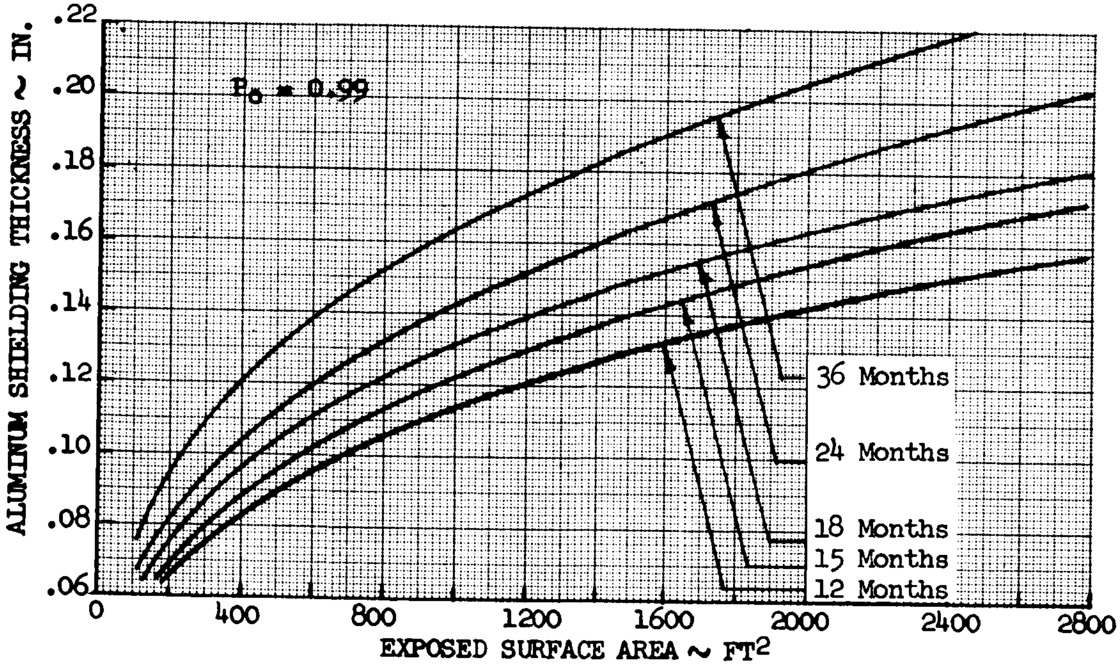


Figure 3.2-2
METEOROID SHIELDING



Present knowledge of penetration resistance for single- and multishield meteoroid bumpers indicates that a proper multishield design may be as effective with a total equivalent skin thickness equal to 0.16 times the thickness of a single shield. However, further research on meteoroid penetration criteria is required to establish a firm foundation for shielding design.

Lunar material may be used for meteoroid shielding. For this study, specified properties of the lunar material for stopping meteoroids results in a considerably reduced efficiency compared with those of aluminum sheet. Also, the use of lunar material as meteoroid shielding is not possible until the lunar base personnel arrive; therefore, metallic shielding is required during the unattended stay time. As a comparison of relative efficiency, a 3-month stay time (beyond 1 year) for $P_0 = 0.99$ requires 6.2 inches of lunar material as compared to an additional 0.01 inch of aluminum.

Required shielding thickness for combined radiation and meteoroid protection was determined. This trade study compared the ratio of radiation to meteoroid shielding thickness versus exposure time for exposed and completely covered shelter modules. A surface exposed module is critical for radiation shielding, and a covered module is critical for meteoroid shielding. Loads due to lunar material overburden, when the shelter module was completely covered, are negligible when compared with lunar landing loads.

Four structural configurations — monocoque, skin-stringer, honeycomb sandwich, and corrugated-core sandwich — were analyzed with respect to lunar landing loads. An optimum structural shell requires additional meteoroid shielding thickness when a 12-month unattended stay time at $P_0 = 0.99$ is considered. This additional material was determined for two criteria. Criterion A assumed 1.5 inches and Criterion B assumed 2.0 inches of foam filler between structure and the bumper shield. The monocoque configuration resulted in the lightest structure for Criterion A; the sandwich configurations were the lightest structures for Criterion B. Criterion B produced the lightest overall configuration, therefore a corrugated-core sandwich structure was chosen for the boost shroud and inner module walls.

3.2.3 Thermal Analysis

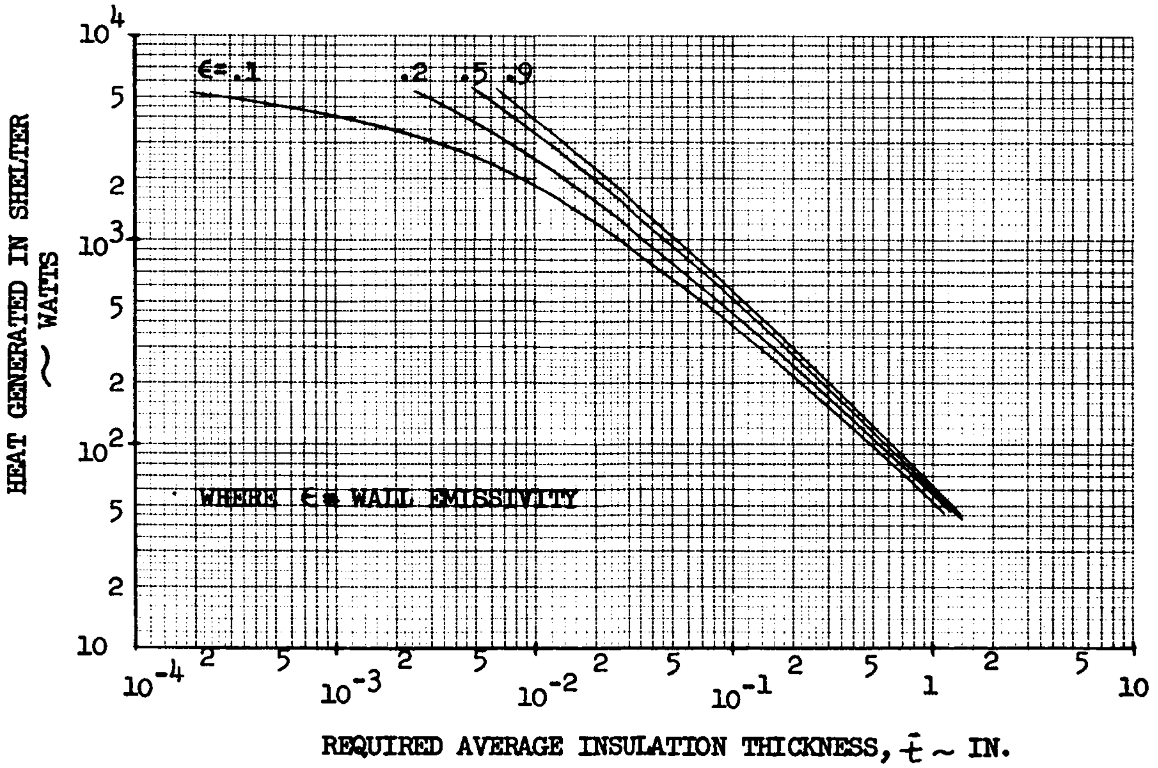
Thermal protection is required for personnel, structural seals, electronics, and life support equipment. The main thermal problems are prevention of heat leakage and extreme temperature fluctuations. A passive type thermal protection system composed of insulation and an outer surface with desirable radiative properties was chosen based on reliability and system simplicity.

Five basic shelter shapes were considered: (1) a vertical, flat-topped cylinder; (2) a cone; (3) a hemisphere; (4) a sphere; and (5) a quonset. During lunar midday, the hemisphere is best for ratios of $\frac{\alpha}{\epsilon}$ (solar absorptivity to emissivity) less than 0.5, while the cylinder is best for ratios greater than 0.5. During lunar night the sphere has the best thermal efficiency. The thermal insulation weight penalty for any of these shapes is not prohibitive.

It was found that the critical thermal design point occurs in the lunar night during the long term storage period. The amount of insulation required depends upon the amount of heat generated within the shelter in the storage condition. Figure 3.2-3 shows this relationship for the cylindrical shelter with a multi-layer of super-insulation (K = 0.0004 Btu-in./hr-ft^2-°F, ρ = 2.5 lb/ft^3).

The possibility of using lunar material as thermal insulation was considered. Three methods of accomplishing this were analyzed: (1) complete burial of the shelter; (2) covering the shelter; and (3) filling the void between the shelter and a surrounding caisson. It was concluded that one foot of lunar dust (K = 0.00726 Btu-ft/hr-ft^2-°F) would provide adequate thermal protection in all cases.

Figure 3.2-3
INSULATION REQUIREMENTS



3.2.4 Structural and Material Selection

The development of a lunar-base shelter structure was approached by evaluating proposed space and lunar structures disclosed in a literature survey. From this study three feasible lunar base concepts were considered; rigid preassembled, rigid expandable and inflatable. Twenty-three proposed configurations were evaluated with respect to structural weight per unit volume. The S-1 shelter module, with a pressurized volume three times greater than that of the other configurations, is approximately in the center of the structural weight to volume range.

Seven shelter configurations were selected for a meteoroid shielding study. The following ground rules were applied: (1) the structure was shielded for 1 year of unattended stay time at $P_0 = 0.99$, (2) inherent shielding of the normal load structure was considered, (3) expandable and inflatable structures were shielded in a contracted form, and (4) it was assumed that a double shield configuration with 2 inches of foam filler required a shield thickness 0.16 times the net thickness of a single shield. The inflatable concepts have no inherent shielding but do have expansion ratios on the order of 30. Therefore, the required shielding weight in their contracted form is small. Results of this study, based on structural and meteoroid shielding weight per unit volume, showed that the S-1 shelter was excelled only by the inflatable concept.

A shape study was performed to compare surface area above the lunar ground plane and internal volume. Results of this study show that the hemisphere is an ideal shape, followed by the quonset, cone, cylinder and sphere, respectively. The S-1 shelter does not correspond exactly to any of these shapes; however, it is midway between the hemisphere and quonset.

Comparison of lunar structure concepts was completed with an investigation of packaging and gross payload characteristics of four selected configurations: two rigid-preassembled, a rigid-expandable and an inflatable toroid. For this study, all four configurations would have an internal pressurized volume equal to the S-1 shelter module. A cylindrical shape was used for the rigid structures, and structural weight to volume relationships for two loading conditions were considered—internal pressurization and compressive buckling. The inflatable-toroidal structure was extrapolated to required volume from weight-volume data given in the literature.

In addition to the equal pressurized volumes, as noted above, the following ground rules were applied: (1) each shelter was packaged within a 260-inch-diameter envelope; (2) allowances were made for existing structure in computing additional meteoroid shielding and packaging structure; (3) radiation shielding was neglected on the assumption that all concepts, when operational, would be covered with lunar material and (4) identical nonstructural subsystems were included in the total payload weights for each configuration. From this study, two major conclusions may be drawn: (1) the net variation in gross payload weight between the inflatable-toroidal concept and the preassembled S-1 shelter concept is on the order of 4 percent, and (2) the preassembled concept best adapts to the lack of knowledge of man's capabilities and the performance of structural materials in a lunar environment.

Material comparisons of mag-lithium, Lockalloy and beryllium alloys in place of aluminum for structural and meteoroid shielding indicate the possibility of significant weight savings. However, fabrication difficulties and possible brittle-cracking effects of these materials tend to eliminate them as a material choice. In the near future it is anticipated these materials will have the needed reliability and new fabrication methods will be devised so that potential weight savings may be realized.

3.2.5 Stress Analysis

The basic shelter structure was analyzed to determine component sizes and structural weights, and to aid in evaluation of structural arrangement and manufacturing feasibility. The primary aim of all parametric studies was to optimize the structure with regard to minimum weight.

A requirement for the payload support structure is that the payload be supported at its periphery. Critical ultimate landing loads of 15 g vertical and 7.5 g horizontal cause an axial compression load of 965 pounds per inch of shell circumference in the outer cylinder.

A study was made of structural weight per unit volume for cylindrical structures of monocoque, skin-stringer, corrugated-core sandwich, and honeycomb core sandwich construction under axial compression loads. The horizontal cutoff of Figure 3.2-4 represents a minimum gage of 0.030 inches at a cylinder radius of 130 inches. The material chosen for this study is 2219-T62 aluminum alloy.

The shelter module is composed of two pressure shells; the outer cylinder is the boost shroud, and the inner cylinder defines the living quarters. Ellipsoidal pressure heads were selected as end closures for the inner cylinder. An analysis relating head thickness to the ratio of minor to major semi-axes indicates that the thickness is a minimum when the heads assume a hemispherical shape, ($b/a = 1$). However, this condition is restrictive to useful volume. If the ratio of b/a is less than 0.707, the head thickness increases sharply due to compressive stresses occurring at the juncture of the head and cylinder.

Therefore, elliptical heads were selected at the optimum ratio of $b/a = 0.707$. For the annular space between the two cylinders, the head can be either an elliptical dome (spanning both cylinders) or a toroidal head (spanning only the annular space). A weight optimization study concluded that the toroidal heads would produce a net weight savings of 240 pounds.

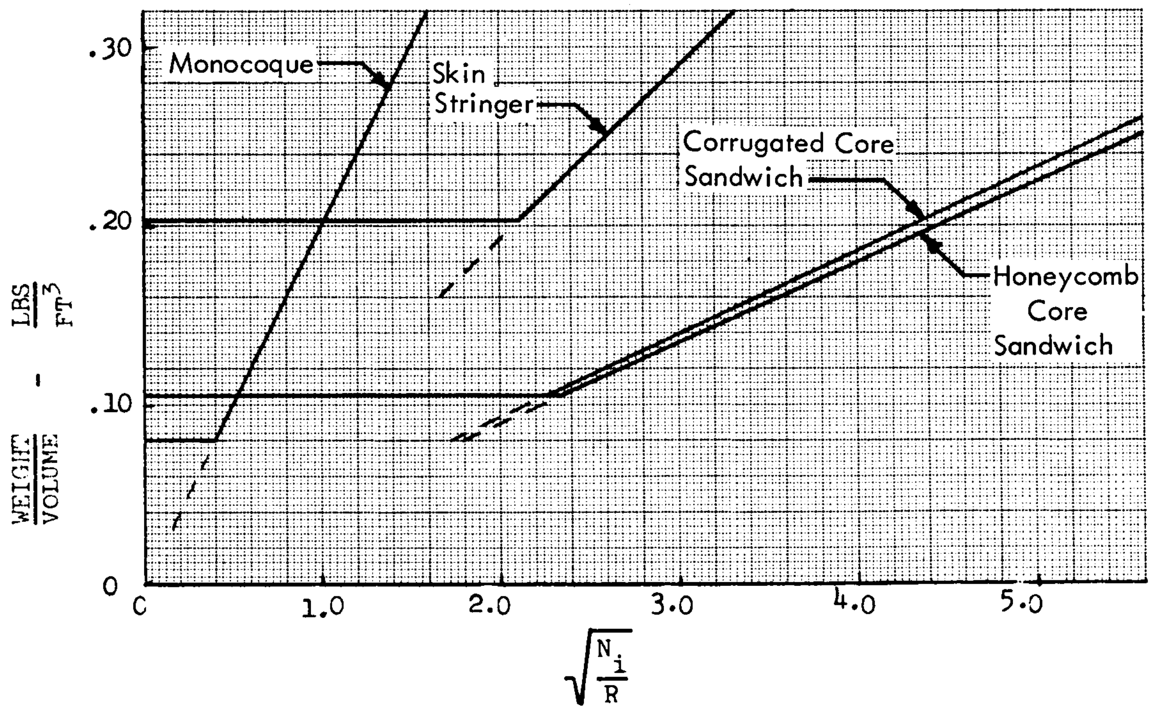
Stress analysis indicates that a multiradial truss system will best support the shelter and equipment loads across the 260-inch-diameter boost shroud.

Airlock analysis was performed considering two configurations: (1) monocoque structure with sausage ends, subjected to internal pressure only; (2) honeycomb sandwich structure without sausage ends, subjected to external buckling pressure. The results of this analysis indicate that the configurations are comparable in weight. A further parametric study was performed to show the variation in airlock weight versus door height.

Figure 3.2-4

STRUCTURAL WEIGHT TO VOLUME RATIO

CYLINDRICAL SHELL UNDER AXIAL COMPRESSION



3.3 PERSONNEL SHELTER

The personnel shelters for this extended lunar exploration system must protect the crew from the hostile lunar environment; provide adequate indoor comfort, security, and convenience; transport, store, and protect other essential equipment and supplies; and be adaptable to reasonable base construction and operation plans. Although the individual's space suit and the cab of the lunar roving vehicle are, in fact, personnel shelters also, this section discusses the personnel shelter subsystem (Figure 3.3-1) to house the entire crew, their logistics, and resupply.

3.3.1 Requirements

In addition to the general requirements mentioned in the definition, these shelters shall support a range of missions for extending the exploration of the Moon, employing three men for 3 months and up to 18 men for 2 years or more.

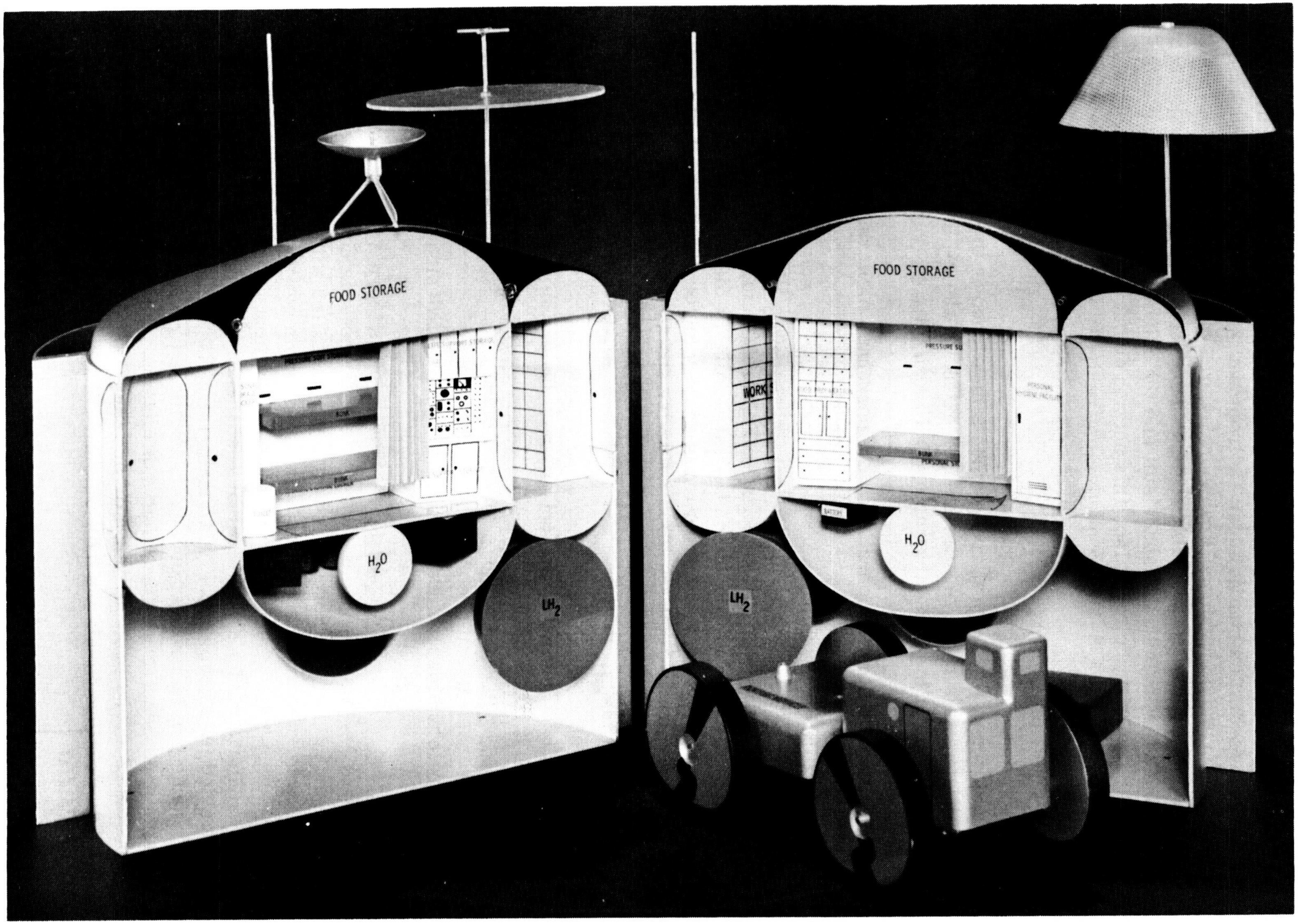
In addition to normal operations, the personnel shelters must accommodate emergencies to the extent that they shall provide for crew refuge and be conveniently and readily repairable.

3.3.1.1 Volume and Floor Area —The architectural design is predicated on the available transportation and on the extraordinary difficulties in construction on the Moon. This leads to the selection of preassembled structures. In general, sufficient volume is required for crew living space, support equipment and supplies, and mission equipment and supplies to ensure the safe and orderly accomplishment of mission tasks.

For six men, the 469 cubic feet per man inside the protection of the shelter allows each man a space of approximately 7.5 by 9 by 7 feet high. About half of this volume is occupied by stores and equipment; about half is free space. Since the six-man shelter can accommodate three men and carry all their mission supplies in a single payload, there is no need for further design refinement.

3.3.1.2 Meteoroid Protection —Studies of meteoroid activity on the lunar surface and shelter shielding required to protect against this hazard have resulted in the design of a four-ply aluminum wall structure filled with foam. The outer wall serves as caisson and bumper shield, and the inner wall serves as the structural pressure shell. This structure affords sufficient protection for 1-year storage on the lunar surface. After arrival of the crew, additional protection will be provided by a covering of lunar material. The basic shelter module would require 7 pounds per square foot of lunar covering to provide a probability of 0.99 of no meteoroid penetration for a 6-month mission, and 153 pounds per square foot to provide a 0.999 probability. For missions longer than 6 months, 24 inches of fill is provided inside the caisson and over the entire top for all shelters, at an estimated 125 psf.

Figure 3.3-1
PERSONNEL SHELTER



3.3.1.3 Radiation Protection — Results of radiation studies show that 7.5 pounds per square foot of aluminum, lunar soil, or a combination of these materials are required to provide a probability of 0.99 that the crew will not be subject to more than an acceptable dosage of 215 rads during the crew exposure for the 6-month rotation period. Increasing the shielding to 8 pounds per square foot will provide a probability of 0.999. This quantity of shielding is not required during the 1-year unmanned storage.

3.3.1.4 Safety and Reliability — The arrangement of the shelter is designed to provide redundancy in all mission safety components. The shelter volume is divided into three independent pressuretight chambers. The innermost "living space" houses the six spare space suits to provide a fourth pressure protection. Secondary access and escape routes are defined.

The outer shell is designed to withstand the meteoroid and radiation environment also, although the 2-foot-thick blanket of lunar fill is six times thicker than needed for protection. In addition, supplies and equipment are located where they will contribute most to protection. This same philosophy applies to accessibility for adjustment or maintenance to all subsystems housed in the shelter.

3.3.2 Functional Description

The basic shelter module illustrated in Figure 3.3-1 is a rigid structure, designed to provide living and work space for six men for 6 months. The shelter consists of two pressure vessels, concentric in planform, surrounded and covered by a meteoroid shield. Total enclosed volume is 2813 cubic feet, with 288 square feet of floor. The space below the pressure vessel is occupied by three spherical cryogenic tanks, 28 stowed solar cell panels, and the lunar roving vehicle.

A three-door airlock provides primary access from outside to the work and living compartments; area = 14.2 square feet; volume = 148 square feet. A vacuum pump reclaims 80 percent of the air during locking cycles and delivers it to the work compartment. Normal access to the work compartment is through a pressure door in the living compartment. A secondary access door is provided in the wall of the work compartment, 180 degrees from the airlock, for shelter access in case of airlock failure. This operation requires depressurization of the work compartment. This door, as well as the outside airlock door, mounts a clustering boss to facilitate connecting shelters together for lunar-base expansion.

3.4 LIFE SUPPORT AND ENVIRONMENTAL CONTROL

The life support and environmental control subsystem encompasses the following functional areas:

1) Thermal control;
2) Atmosphere control;
3) Water management;
4) Waste disposal;
5) Personal hygiene;
6) Feeding;
7) Crew systems and furnishings.

3.4.1 Subsystem Studies

3.4.1.1 Thermal Control — The major thermal control problems for the lunar base are:

1) Shelter temperature control during storage (little or no power);
2) Shelter temperature control during operation (normal and emergency);
3) Management of thermal energy within the shelter;
4) Temperature control of modules not within the shelter (solar panels, power modules, and maintenance and service modules);
5) Temperature control of electric cable and miscellaneous small articles placed on the lunar surface;
6) Temperature control of lunar surface vehicles;
7) Heat-sink problems if shelters are covered or buried.

3.4.1.1.1 Heat Sinks — Possible heat sinks for the lunar shelters are:

1) Space radiators;
2) Lunar substrate thermal mass;
3) Expendable mass (evaporants);
4) Transient heat storage in internal thermal mass.

The lunar substrate is not promising as a heat sink for a large heat loads because of its expected low thermal conductivity and diffusivity and high contact resistance.

However, temperature regulation may be good for buried shelter modules generating only a small amount of internal heat.

Use of expendable evaporants for shelter cooling will probably be limited to emergency conditions. Evaporative water cooling will be needed for pressure-suit cooling outside the shelter and may also be needed for supplementary cooling of the lunar surface vehicles.

Space radiators will provide the primary heat sink for the shelter modules.

3.4.1.1.2 Temperature Control Concepts — Analysis of simple geometric shapes normally expected on a large landing vehicle shows heat-sink temperatures to be either excessive or marginal.

A simple approach to achieving low effective heat-sink temperatures on the Moon is to alter the radiation characteristics of part of the lunar surface with a different material. In addition, if the radiator is oriented or shielded from the direct rays of the Sun, a minimum heat-sink temperature would be realized.

One means of obtaining a low heat-sink temperature for vertical radiators on the sides of the shelter module is to use a reflective ground cover around the base of the shelter. Figure 3.4-1 shows the effective sink temperature as a function of the solar angle and the angular position around the cylinder.

3.4.1.1.3 Shelter Heat Rejection Estimates — Table 3.4-A summarizes the heat rejection estimates for the lunar shelters. Radiator sizes determined are based on:

1) Radiators on cylindrical sides of the shelter, out of the view of the Sun;
2) Radiators facing specularly reflecting ground covers.

3.4.1.1.4 Temperature Control During Storage — Temperature control of the shelter during storage (prior to occupancy) is required to prevent degradation or failure of equipment. After the shelter has been vacated, temperature control to maintain equipment for reuse may also be desired, although this is presently considered a secondary requirement. Figure 3.4-2 shows the results of a typical analysis using thermal insulation, heat storage, and heat generation to maintain the desired control.

3.4.1.2 Atmosphere Control —

3.4.1.2.1 Atmosphere Selection — A study of the preferred compartment atmosphere for lunar base shelter modules has resulted in the following recommendations: (1) normal, manned operation: 6.0 psia, with an oxygen partial pressure of 3.5 psia; and (2) emergency manned operation: pure oxygen at 3.5 psia.

Figure 3.4-1
EFFECTIVE SINK TEMPERATURE
SPECULAR REFLECTING GROUND COVER

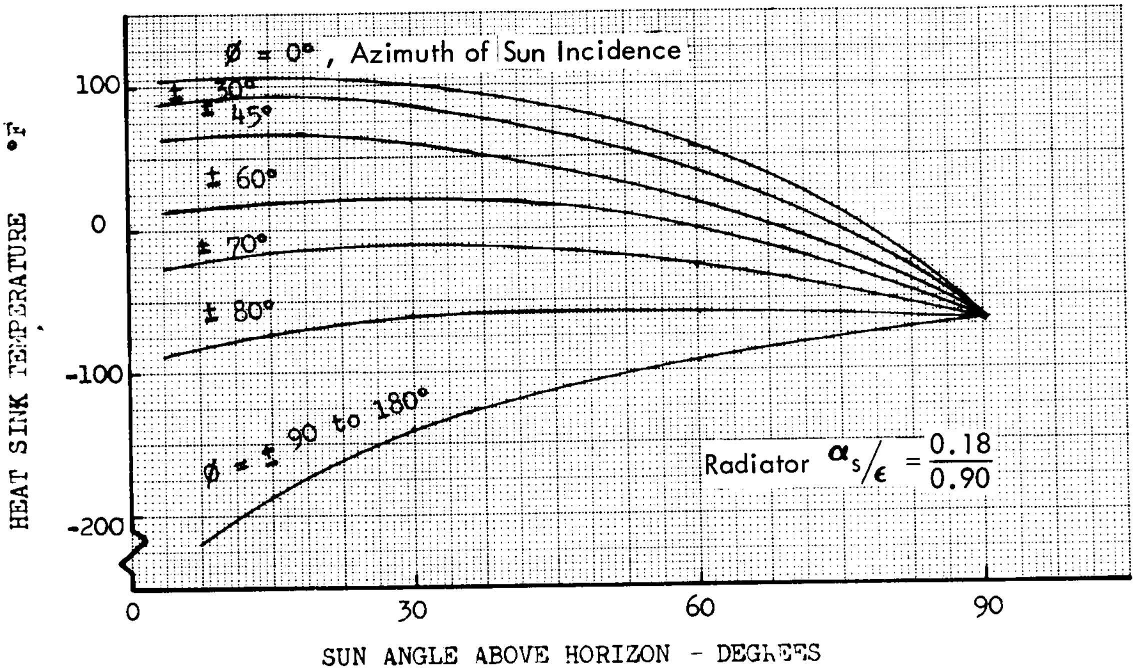


Figure 3.4-2
SHELTER TEMPERATURE CONTROL DURING STORAGE

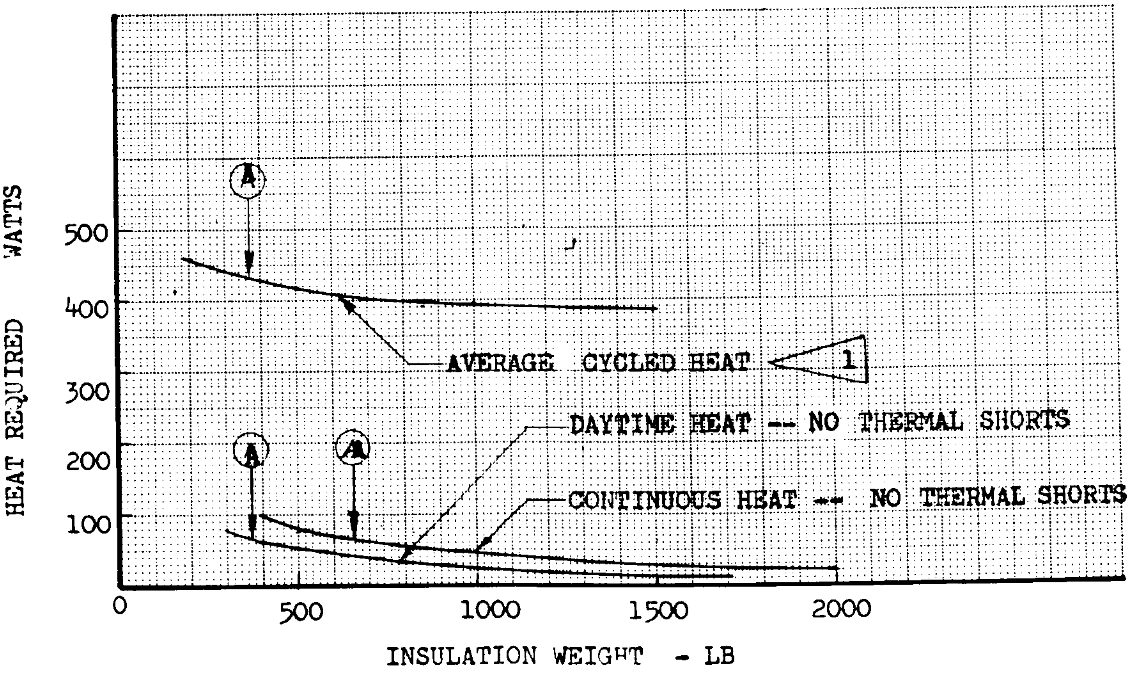


Table 3. 4-A

ESTIMATED HEAT REJECTION REQUIREMENTS FOR LUNAR SHELTERS

		Lunar Day — Watts (per shelter)				Lunar Night — Watts (per shelter)						
		Electrical Power Inside Shelter	Meta-bolic Load	Heat Leak (In)	Total	Electrical Power Inside Shelter	Fuel Cell Heat Load	Meta-bolic Load	Heat Leak (Out)	Total	Radiator Design Point	Radiator Size Required
BASE 1	Average	1195	275	255	1725	1400	1245	275	70	2850	4625* watts Lunar day	320 Ft^2
	Peak	1670	455	255	2380	1875	1720	455	70	3980		
BASE 2	Average	3060	620	80	3760	3330	2880	620	22	6808	4625 watts Lunar day	320 Ft^2
	Peak	3635	910	80	4625	3905	3320	910	22	8113		
BASE 3	Average	3060	682	80	3822	3330	2880**	682	22	6870	4625 watts Lunar day	320 Ft^2
	Peak	3635	910	80	4625	3905	3320**	910	22	8113		
BASE 4	Average	3060	682	80	3822	3330	2880**	682	22	6870	4625 watts Lunar day	320 Ft^2
	Peak	3635	910	80	4625	3905	3320**	910	22	8113		

* Designed for evolution to Base 2

** Base startup only

This conclusion is based upon the following findings and rationale.

1) There is some evidence (although not conclusive) that a pure-oxygen atmosphere is harmful for durations longer than 2 weeks.
2) A pure-oxygen atmosphere is recommended as an emergency mode of operation so that a failure in the nitrogen supply, control, and distribution subsystem will not result in total failure of the cabin atmosphere system.
3) Because a pure-oxygen atmosphere will be an emergency mode of operation, it will be necessary to control the fire hazard and the trace-contaminant problem by materials selection and not to rely on the nitrogen in the air. Analysis and experience with pure-oxygen systems show 3.5 psia nominal to be a good design point for emergency operation.
4) With an oxygen-nitrogen atmosphere, the maximum pressure in the cabin is limited by the consideration of decompression sickness. An analysis of existing test data shows that the safe upper limit is approximately 6.0 psia.
5) The minimum concentration of inert gas required is not known, although a minimum design point of 30-percent nitrogen has been recommended to meet physiological needs (Reference 33a).

Figure 3.4-3 shows a correlation of decompression tests while the crew members are exercising. These data suggest that decompression from 6.0 to 3.5 psia will be safe.

It is concluded that the cabin atmosphere should be between 5.0 and 6.0 psia. To favor a higher concentration of inert gas, which is the least known of the several requirements, 6.0 psia is recommended.

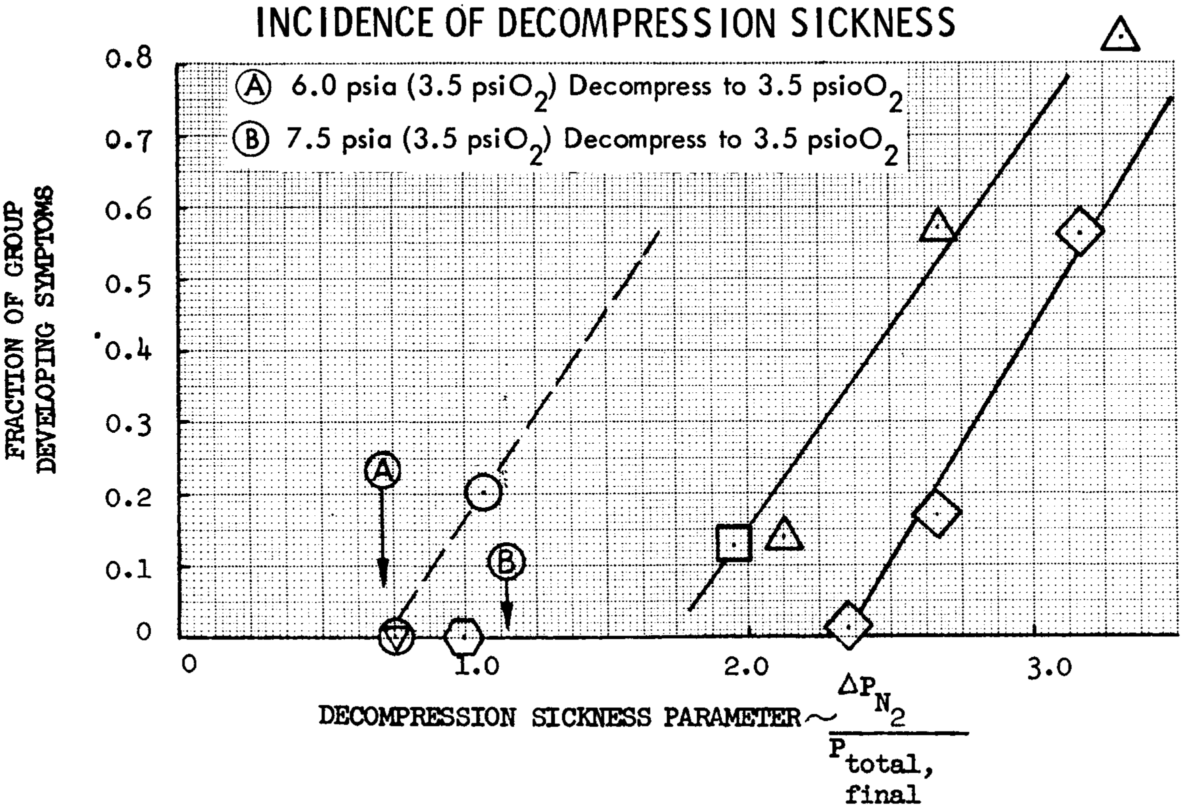
3.4.1.2.2 Airlock Operations — A study was made of airlock operation penalties comparing:

1) Air recovery with a pump;
2) Exhausting to space;
3) Decompression to a second airlock before exhausting to space, assuming that a second airlock is carried for reliability.

For Base Model 1, the equivalent weight penalty for the two-airlock system is only slightly greater than for the pump system. For Base Model 2, it is not clear whether the weight advantage of the pump system is great enough to offset possible problems with reliability and pump-air contamination.

Figure 3.4-3

INCIDENCE OF DECOMPRESSION SICKNESS



Assuming 2 lockages per day per shelter for Base Models 3 and 4, a pump airlock clearly will be worthwhile, even though on occasion the pump will not be used in order to save time. Assuming a base evolution from Base Model 1 to Base Model 4, all bases will use pumped airlocks.

3.4.1.2.3 Carbon Dioxide Removal and Processing — Regenerable carbon dioxide removal methods will be needed for the primary atmosphere control system on the lunar base. Among the more promising methods at the present time are:

1) Molten salt electrolysis system;
2) Electrodialysis cells;
3) Molecular sieves (desorption either by heating or venting to space);
4) Absorption by regenerable liquid;
5) Solid amines.

Because of the use of fuel cells in the power system, large amounts of surplus water are available. Based on the availability of this water, it is preferable to recover oxygen from CO_2 only for Base Models 3 and 4 and to obtain the remaining oxygen from the surplus water, assuming no base evolution; with base evolution, oxygen should also be recovered from the CO_2. Evaluation of applicable methods has led to a choice of the simple Sabatier system with molecular-sieve CO_2 adsorption for preliminary design purposes.

3.4.1.2.4 Trace Contaminant and Humidity Control — The trace contaminant and humidity control system removes particulate matter, undesirable gases, and excess water vapor. Major components and functions are:

1) Filters for dust;
2) Ultraviolet lamp for bacteria;
3) Activated carbon for vapors and odors;
4) Catalytic burner for low-molecular-weight gases;
5) Dehumidifier to remove excess water vapor;
6) Materials control to minimize toxic contaminants.

3.4.1.2.5 Oxygen and Nitrogen Expendables Required — The nitrogen and oxygen needs of the lunar shelters for each base are shown in Tables 3.4-B and 3.4-C, respectively, with the basis for the estimates indicated.

3.4.1.3 Water Management — Approximately 7 pounds of water per man per day are required in each of the four base concepts under study for the metabolic needs of the crew in the shelter module, and an additional 4 pounds are required for pressure-suit operation. Each man is allowed 4 pounds per day for washing.

Table 3.4-B
ESTIMATED NITROGEN NEEDS FOR LUNAR SHELTERS*

	Leakage During Operation (pounds)	Leakage During Storage (pounds)	Decompression Loss (pounds)	Airlock Loss (pounds)	Total Nitrogen Required (pounds)
BASIS	4.0 lb air/day per shelter 6.0 psia, 40% N_2	1 year at 0.1 psia	1 per month per shelter — 2800 ft^3	70 ft^3, 2 lockages/day per shelter, 90% pumpdown	Sum
BASE MODEL 1	144	10	110	9	273
BASE MODEL 2	288	10	220	18	536
BASE MODEL 3	1168	20	892	72	2152
BASE MODEL 4	3505	30	2676	216	6427

* Exclude reserve and boiloff

Table 3.4-C

ESTIMATED OXYGEN NEEDS FOR LUNAR SHELTERS

	Shelter Metabolic Needs						Leakage During Operation (lb)	Leakage During Storage (lb)	Decompression Loss (lb)	Airlock Loss	Total Oxygen Required (lb)
	Base Mandays	Backpack Mandays	Lunar Vehicle Mandays	Shelter Mandays	Shelter O_2 (lb)	Makeup Need (lb)					
BASIS		Table 4.2-S***	Table 4.2-U***	Table 4.1-A*** Less Backpack and Vehicle	2.0 lb per Man-day	Oxygen Reclamation Bases 2, 3 and 4 From CO_2 Only	4.0 lb air/day for shelter-6.0 psia, 60% O_2	1 year at 0.1 psia	1 per month per shelter 2800 ft^3	70 ft^3, 2 lockages/day per shelter** 90% pump-down	
BASE MODEL 1	270	8	74	188	376	376	216	15	152	12	771
BASE MODEL 2	1080	39	150	891	1782	520*	432	15	304	25	1296
BASE MODEL 3	4380	64	440	3876	7752	1710*	1750	30	1216	101	4807
BASE MODEL 4	13,130	107	880	12,193	24,286	4505*	5260	45	3648	302	13,760

* No reclamation first month during nuclear power setup

** Airlock usage may range between 1 and 4 lockages per day per shelter

*** Volume III table numbers

3.4.1.3.1 Mission Constraints — The lunar base concept imposes the following requirements on the water management system:

1) Water recovery must be conducted at maximum efficiency.

2) The waste residues must be rendered inoffensive and harmless.

3) Overall system weights must be minimized.

3.4.1.3.2 Water Reclamation — Various processes can be used to reclaim waste water, depending on the source and the use intended for the product water. One significant water reclamation problem area is the establishment of realistic quality standards for water potability. Currently used Public Health Standards are based on ground water supplies and do not include the possibility of a buildup of hormone and protein products that might occur with closed-system recycling of water.

Water management considers the reclamation of water from respiration, perspiration, urine, and wash water for potable water supply. Use of recovered fecal water will be limited to cooling and makeup oxygen requirements. The vapor compression/distillation, electrodialysis, air evaporation, and incineration (pyrolysis, vapor compression/distillation) water recovery systems were considered compatible with lunar base system requirements.

Comparisons of the four systems were made for all four lunar base concepts, as typified by Table 3.4-D. On the basis of overall system weight and assurance of high water quality, the incineration, vapor compression/distillation system is the first choice. The air evaporation system is fairly competitive and is the second choice. A simplified block diagram of the selected system is shown in Figure 3.4-4.

3.4.1.4 Waste Disposal — All waste material must be collected and the usable material reclaimed; the unusable residue must be disposed of. Culinary byproducts, packaging material, urine residue, and various wastes from water reclamation, feces, vomitus, and various body products from personal grooming constitute the range of wastes that must be accommodated by the disposal system.

Avoidance of contamination is the major requirement of the waste disposal system. Therefore, all waste material must be rendered inert or sealed to prevent escape from containers. Disposal methods considered acceptable include incineration and vacuum sublimation. The vacuum sublimation method includes collecting wastes in vapor-permeable, sealable bags, which are then exposed to lunar vacuum. When all volatiles are removed, the semipermeable bag is sealed in an impermeable bag and stored.

The incineration method uses high-temperature ashing of the waste materials anticipated during lunar base operation. On the basis of weight trades, the vacuum sublimation waste disposal system is selected for the lunar base.

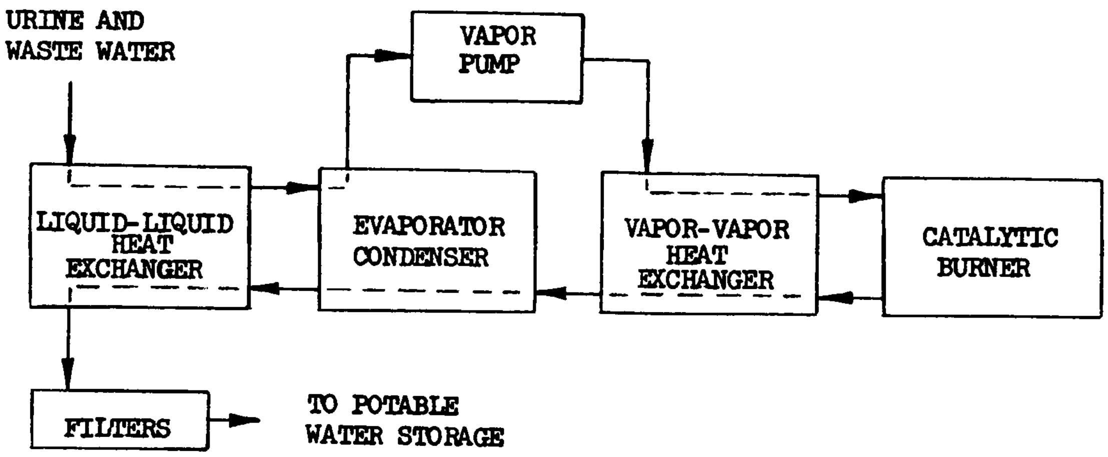
Table 3.4-D

COMPARISON OF WATER RECLAMATION SYSTEMS

Base Model 2: Six Men, 180-Day Mission

		Electrodialysis	Air Evaporation Waste Heat	Vapor Compression Distillation Batch	Incineration (Pyrolysis) Vapor Compression Distillation
WASH AND METABOLIC WATER BALANCE (lb/day)	System Efficiency	96.6%	97%	93%	97%
	H_2O Treated	69.0	69.0	69.0	69.0
	H_2O Recovered	66.65	66.93	64.2	66.93
	H_2O Required	66.6	66.6	66.6	66.6
	H_2O Balance	0.5 (surplus)	+0.33 (surplus)	-2.4	+0.33 (surplus)
FIXED SYSTEM WEIGHT (pounds per shelter)		53.5	82.0	93.5	84.2
TOTAL SYSTEM EXPENDABLES	Lb/Lb H_2O Treated	0.053	0.0192	0.0138	0.0109
	Expendables (Lb)	659	238	171	135
POWER	Watts	74.5	168.0	98.0	181
	Wt Equivalent, Pounds (1.85 lb/watt)	89.0	202.0	118.0	217
REPLACEMENT WATER (pounds)		0	0	432.0	0
TOTAL WEIGHT/MISSION (No Surplus H_2O Credit)		801.5	522.0	814.5	436.2
COMMENTS		$4,000,000 Development Cost. High expendable weight. Unknown membrane reliability. Low power concumption	Urine-soaked wicks require frequent changing	Low recovery rate	Low expendable weight. High power. High-purity water. Advanced state of development
SELECTION			SECOND		FIRST

Figure 3.4-4
INCINERATION, VAPOR COMPRESSION/ DISTILLATION WATER RECOVERY SYSTEM



3.4.1.5 Personal Hygiene Considerations — Dirt, microorganisms, and nonliving particles may constitute a hazard because of pathogenicity or toxicity. Cleansing requirements are:

1) Whole-body cleaning;
2) Hand and face cleaning;
3) Dental hygiene;
4) Clothing;
5) Cabin cleaning.

Identical compounds will be used for all cleaning applications, with the exception of dental hygiene and special conditions discussed below. Pure soaps appear to be the best cleaning agents from cleaning efficiency and low-toxicity considerations. Sodium or potassium oleate or palmitate is recommended.

1) Whole-Body Cleaning — Conventional shower baths with collapsible, stowable shower stalls that minimize space requirements may be used. The limited wash-water allowance per man-day will limit shower bathing to approximately once per week for each man. Sponge bathing between showers will serve to maintain a hygienic body cleanliness.

2) Hand and Face Cleaning — A small wash basin with adequate splash shielding will suffice for hand and face washing and sponge bathing. Chemically treated wash pads will be adequate for roving vehicle operation.

3) Dental Hygiene — An ingestible dentifrice is proposed to simplify collection and disposal of oral waste products. This method also lends itself readily to emergency water use conditions or roving vehicle operation.

4) Laundering — A trade between laundering and disposable clothing was made. In view of the weight penalty per manhour of labor on the lunar surface, disposable clothing was selected over washing and reuse of clothing. An additional advantage is the high reliability of disposable clothing (unaffected by water or power system emergencies).

5) Cabin Cleaning — Particulate matter may be swept up, sealed in plastic bags, and stored. Surface films and grime will be removed by wiping surfaces with a soap-impregnated sponge or spongecloth.

   A small vacuum cleaner will be used to remove lunar debris from the space suits on return from extravehicular operations. Removal of this dust during or immediately after completion of airlock operation will minimize contamination of the cabin interior.

3.4.1.6 Feeding — Precooked freeze-dehydrated foods minimize storage and preparation power requirements and stored weight; they also eliminate conventional cooking. The food is reconstituted in the storage packages. A reasonable variety of foods can be freeze-dehydrated and reconstituted into palatable meals. This form of food has therefore been chosen for the lunar base.

Food packages will serve as dishes to conserve weight and to eliminate dishwashing requirements. Conventional eating utensils will be used.

3.4.1.7 Crew Systems and Furnishings — Crew systems and furnishing include such items as pressure suits and backpacks, clothing, recreation equipment, personal items, first-aid and medical equipment, bunks, bedding, furniture and the necessary cabinets, storage facilities, and fixtures.

Pressure-suit operations will be required for excursions on the lunar surface, part of the time while in the shelter, and part while in lunar surface vehicles. Shelter use will be for scheduled operations such as deliberate depressurization or preparation for cabin exit, or for emergency situations such as cooling system failure or atmosphere control system failure. Lunar surface use will be for construction, maintenance and resupply, and scientific activities.

The expendables required for portable life support system operation on the lunar surface will be a significant weight item. Figures 3.4-5 and 3.4-6 show expendables needed for suit atmosphere control.

It is seen that the largest weight item is cooling water. To reduce this weight penalty, it is worthwhile to consider cooling by radiation during the lunar night

Figure 3.4-5
EXPENDABLES FOR PRESSURE SUIT ATMOSPHERE CONTROL

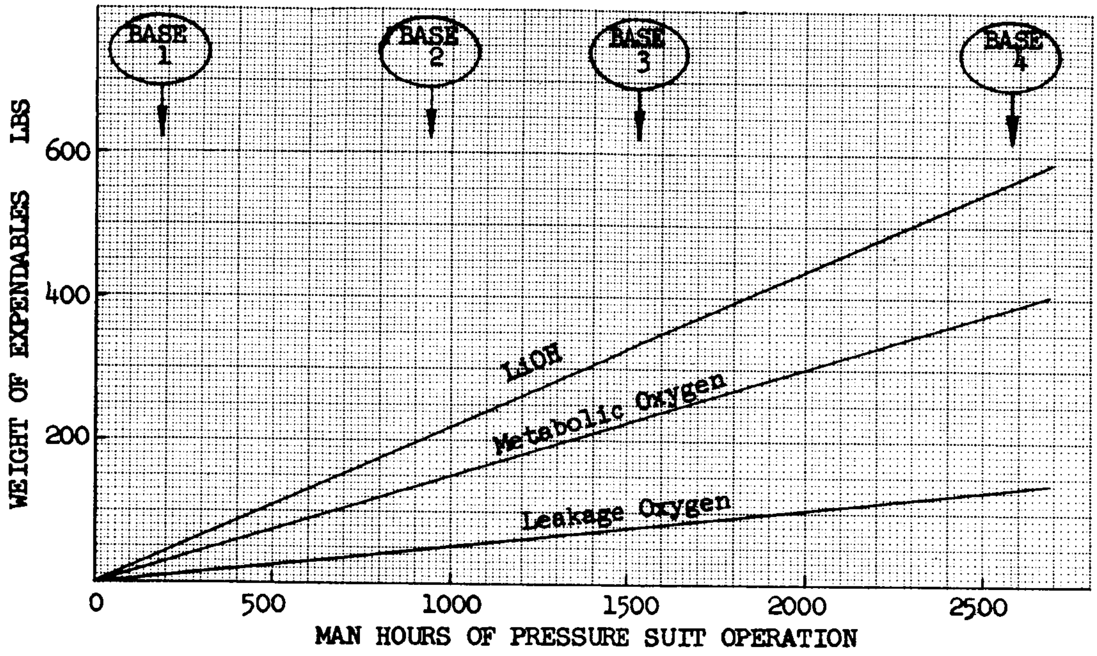
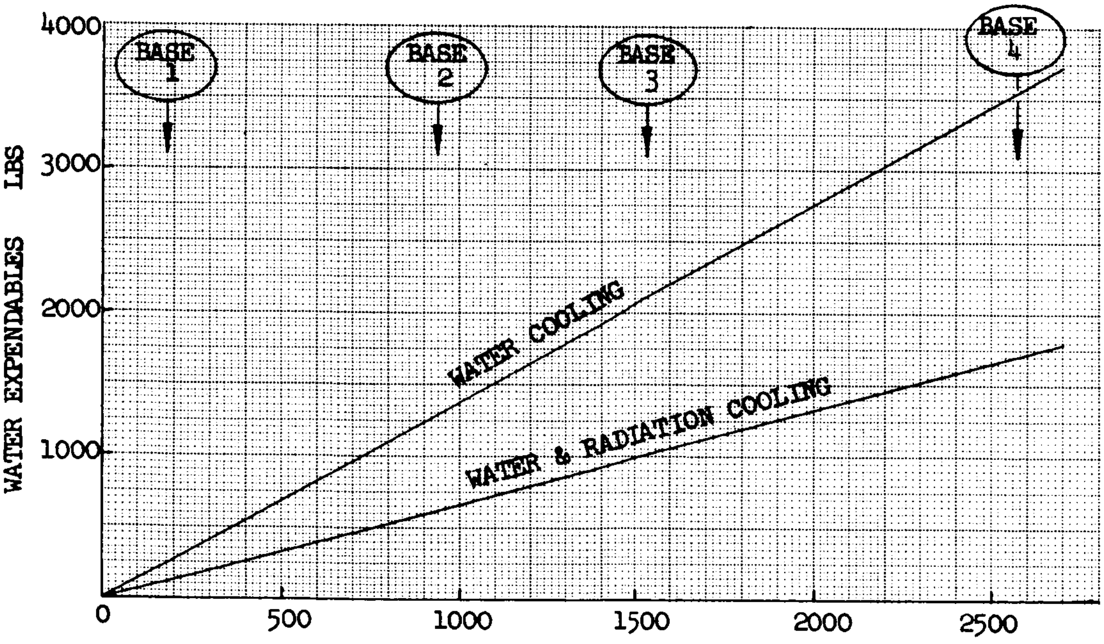


Figure 3.4-6
WATER EXPENDABLES FOR PRESSURE SUIT COOLING



and to use the expendable evaporant only during the lunar day or in event of failure of the radiative cooling mode.

3.4.1.8 Lunar Surface Vehicle Life Support —

3.4.1.8.1 Atmosphere Control — A pure oxygen atmosphere at 4.0 psia was assumed for all lunar surface vehicles in estimating expendables required.

Total oxygen needed for lunar surface vehicles represents 30 to 40 percent of the total life support oxygen requirement.

3.4.1.8.2 Temperature Control — An external radiator will provide the primary heat sink for lunar surface vehicles. Temperature control during the lunar day is one of the important problems of lunar vehicles. For preliminary design purposes, the following assumptions were made for cooling during the lunar day:

1) Most of the heat load is at high temperature and can be handled by the vehicle radiator.
2) The low-temperature cooling load consists of two men and 300 watts.
3) Power is provided by a 4.0-kilowatt fuel cell system.
4) The maximum endurance required is 5 Earth days.
5) An emergency cooling system is necessary.

Based on these assumptions, a system employing the melting of 500 pounds of ice is reasonable and has been selected pending a more thorough study of this problem. The ice would be frozen during the lunar night, and the melt water is retained. In emergencies this water can be evaporated after melting. Additionally, it may be possible to use this mass for solar flare shielding of the lunar vehicle.

3.4.2 Modular Division of Subsystems

Module L-1 is the basic life-support building block and is designed into the basic shelter to perform all the life support needs of Base Model 1, including expendables for the roving vehicle. For the advanced bases, each Module L-1 is supplemented by a module of additional equipment and a supply module of expendables. The additional equipment modules are identical, whereas the resupply modules are not. Thus, five life-support modules are identified:.

1) L-1 — the basic life support module designed into each shelter;
2) L-2 — the additional equipment module that elevates L-1 from a three-man to a six-man capability;

3) L-3 — the supply module that provides the extra expendables needed with Base Model 2;

4) L-4 — the supply module that provides one-half of the extra expendables needed in Base Model 3;

5) L-5 — the supply module that provides one-third of the extra expendables needed in Base Model 4.

The equipment within Module L-1 is also organized into component packages, and may be broken down into fixed equipment and movable equipment. Logistic Modules L-4 and L-5 are broken down into packages small enough to permit transfer of expendables to the roving vehicles, or to more than one shelter if necessary.

3.5 POWER

The objectives of this study are: (1) to define conceptual electric power-system modules suitable for selected lunar-base configurations and operations in the 1970-75 period, and (2) to present general considerations, parametric data, and optimization criteria useful for comparison and selection of electric power systems over a wide range (power level and mission duration) of base concepts. To accomplish these objectives, the following approach has been adopted:

Define Requirements

1) General Criteria
2) Power requirements
    a) power quantity
    b) power quality
    c) power blocks
    d) type of power
    e) load profiles

Perform Basic Studies

1) Define system parameters
2) Compare applicable generation concepts
3) Compare applicable transmission and distribution concepts
4) Compare basic control functions
5) Compare emergency power concepts
6) Develop optimization criteria

Selection of Optimum Concepts

1) Compare most applicable systems for range of base operations
2) Develop system configurations in form of power modules to cover range of operations

3.5.1 Requirements

Requirements in the form of general criteria and electric power demand are defined so that the evaluation and comparison of systems are determined for a specific range of lunar-base applications.

Specific load requirements have been defined for four proposed base configurations. These load requirements are presented in charts which show power level, duty cycle, lunar day and night division, essential and nonessential blocks, and type of power preference, such as a.c. or d.c. Table 3.5-A, which defines load requirements for Base 4, is an example of the load charts presented.

General considerations regarding load requirements are discussed in detail and include the following principal topics:

1) Optimization of the interface between power quantity requirements and the power system (this optimization includes consideration of load scheduling or load management and energy management);
2) Power quality;

Table 3.5-A
LOAD REQUIREMENTS — BASE MODEL 4

OPERATING PERIOD	LOAD	BASE POWER BLOCKS							
		ESSENTIAL D-C OR A-C		ESSENTIAL A-C		MAIN D-C OR A-C		MAIN A-C	
		Watts	Duty	Watts	Duty	Watts	Duty	Watts	Duty
OPERATIONAL Note: Storage and base activation loads are the same as for Base Model 2 on a per-shelter basis.	Atmosphere Control					4500 ① 4500 ①	c c	260 260	c c
	Thermal Control			90* 90*	c c			570 800	c c
	Water Purification					140 ① 140 ①	c c	400 400	c c
	Water Recovery							60 60	1h-6h 1h-6h
	Airlock Operation							600 600	8m3/d 8m3/d
	Suit Loop Operation			570 570	1h4/d 1h4/d				
	Suit Air Drying							450 450	1h4/d 1h4/d
	Suit Cleaning							1200 1200	5m4/d 5m4/d
	Portable Recharge					150 ① 150 ①	c c		
	Shelter Lighting	140* 140*	c c			600 1200	c c		
	Food Preparation					1200 900	15m5/d 15m5/d		
	Waste Treatment					80 80	c c		
	ECS Instrumentation	50 50	c c						
	Communications	75* 75*	c c			$\frac{250}{750}$ $\frac{250}{750}$	$\frac{c}{5m18/d}$ $\frac{c}{5m18/d}$		
	Flood Lights					0 1000	— c		
	Service and Installation							15,000 15,000	10h-24h 10h-24h
	Scientific Experiments					1800 1800	c c		
	Mission Activities					18,000 18,000	c c		
	Maintenance Garage					2000 2000	2h1/d 2h1/d	1000 1000	15m2/d 15m2/d
	Welding (200-amp)							13,500 13,500	2h1/d 2h1/d
	Fuel Regeneration (67 lb/day)					12,000 ① 12,000 ①	c c	3000 3000	c c
	Water Synthesis (67 lb/day)							7000 7000	c c

Key to symbols:
- m - minutes
- h - hours
- * - emergency only
- d - 24-hr. day
- ① - D-C preferred
- Watts shown are maximum demand
- c - continuous duty
- Intermittent duty indicated as follows:
  10m5/d - ten minutes on, five times per day
  5h-2h - five hours on - two hours off

Lunar day	Lunar night

3) General power quantity requirements for various types of loads (Figure 3.5-1 is an example of power quantity for synthesis and regeneration of water on the lunar base);

4) Power system optimization with respect to type (voltage level and d.c. or frequency of a.c. power) of power at the utilization level.

To define the total power quantity requirements for the specific lunar configurations, load profiles have been prepared for each base. Figure 3.5-2 is an example showing the load profile for Base 1.

3.5.2 Basic Considerations

To provide the tools and the foundational information from which the most applicable and optimum power system concepts may be determined, certain basic analyses must be made. These analyses present general information and data relative to the concepts that can provide the various functions required in a lunar-base electrical system.

3.5.2.1 System Parameters — Quality-type parameters are defined and applied in conjunction with selected optimization criteria as a systematic means of comparing various system concepts and of selecting the most applicable and optimum concepts. The quality-type parameters chosen for the comparison of lunar base power system candidates are:

1) Reliability;
2) Safety;
3) Installation labor;
4) Maintenance and replacement labor;
5) Weight;
6) Space factor (volume or area);
7) Development and hardware cost;
8) Growth potential;
9) Power quality;
10) Availability,
11) Active and storage lifetime;
12) By-product credit;
13) Operating labor (startup, normal, shutdown);
14) Efficiency.

Figure 3.5-1
POWER REQUIREMENTS
WATER SYNTHESIS AND REGENERATION

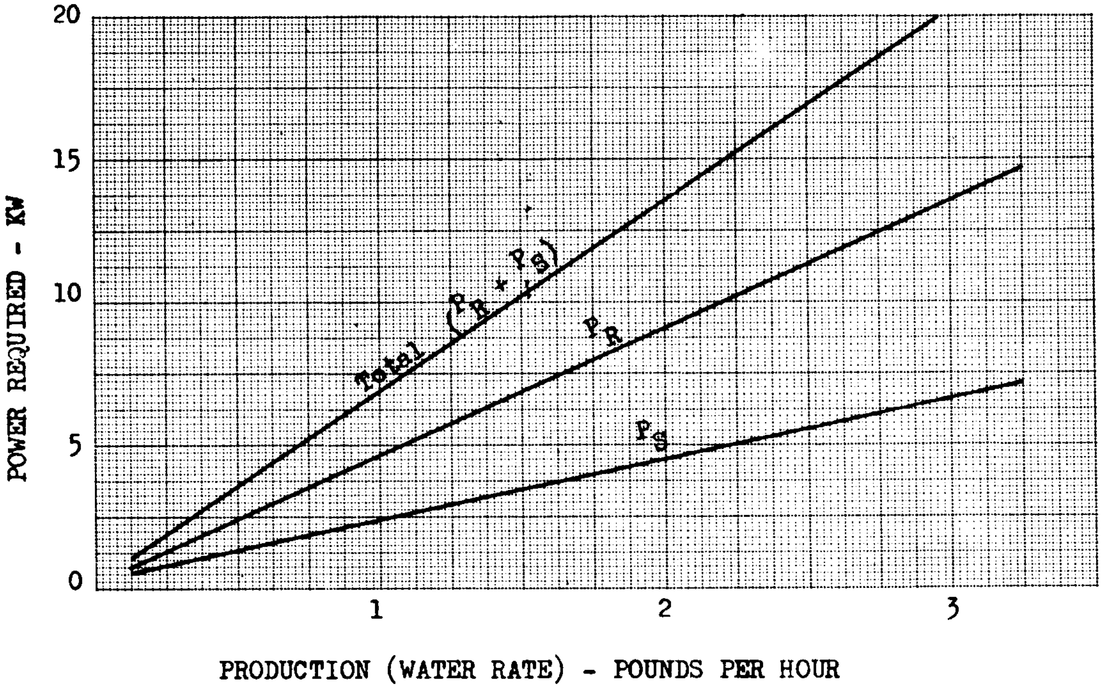
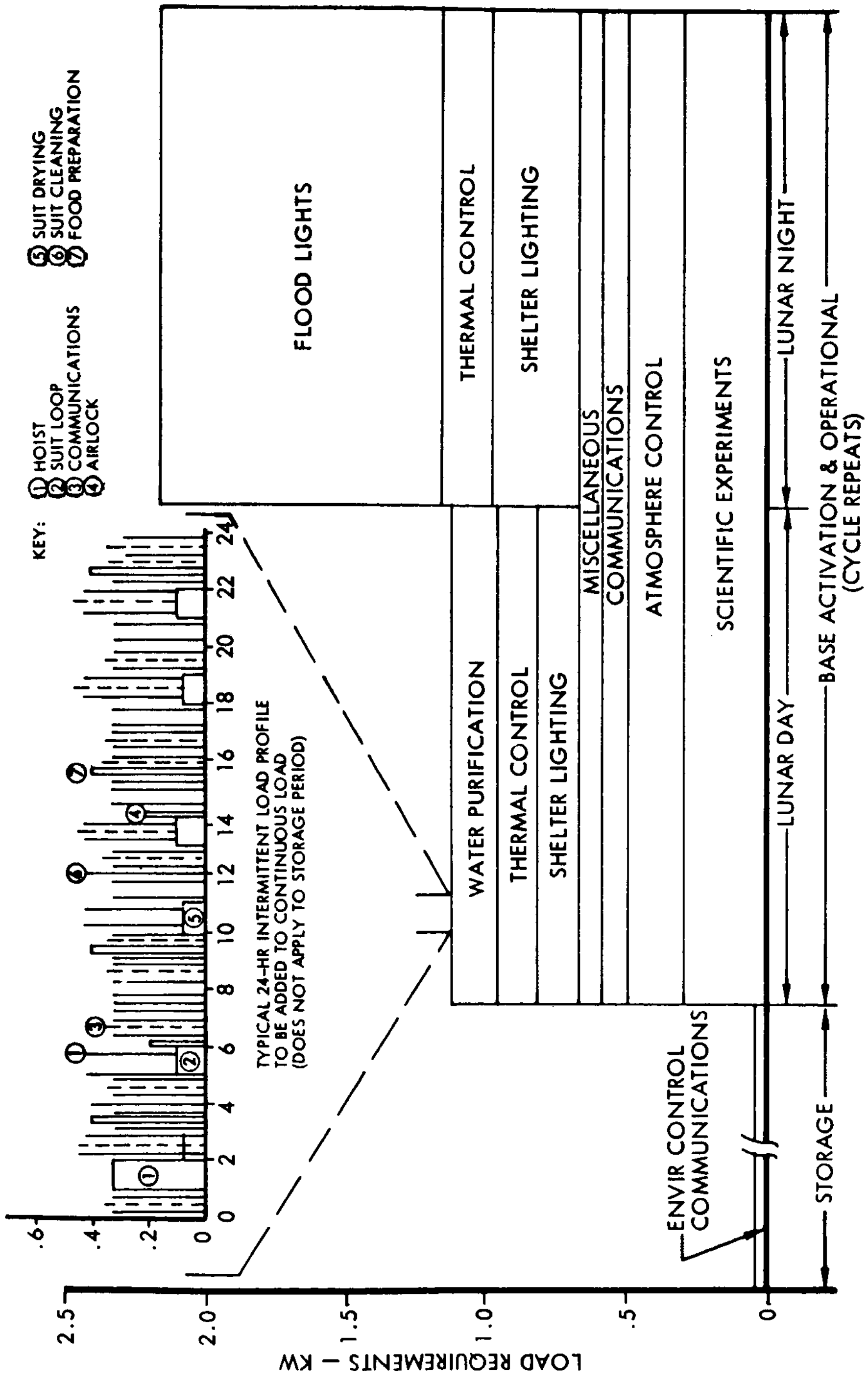


Figure 3.5-2
LOAD PROFILE—BASE MODEL 1



3.5.2.2 Generation Concepts — General conclusions are presented, based on a state-of-the-art survey, regarding the range (power level and mission duration) of applicability of various electric power generation concepts.

Applicable generation concepts are compared on the basis of the selected quality-type parameters. Figures 3.5-3 and 3.5-4 are comparisons of generation concepts on the basis of weight as a quality-type parameter. Comparison on the basis of other quality-type parameters is presented in tabular form with accompanying notes of explanation.

Comparisons are made of nuclear reactor generation system emplacement and shielding concepts. Several lunar shielding configurations are analyzed to determine radiation dose rate versus distance from the reactor. The weight of Earth-launched shield configurations for various power levels and radiation level patterns has also been determined. On the basis of cost estimates for nuclear reactor burial it is concluded that radiation shielding by burial on the lunar surface will be more economical and will have less restrictive exclusion patterns than Earth-launched shields.

3.5.2.3 Transmission and Distribution Concepts — The link between generation and utilization functions in the lunar base electrical system includes power conditioning, power transmission between a generation module and the base or shelter, and distribution of electric power on the base or within the shelter.

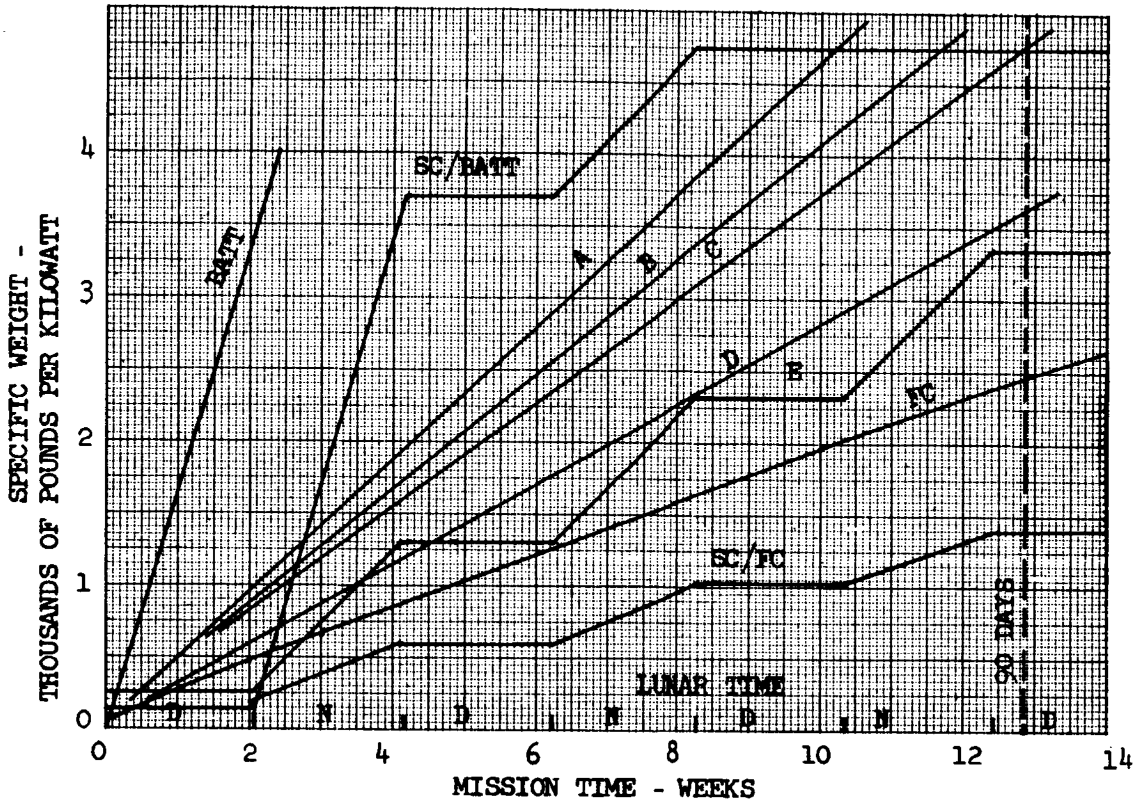
In a detailed power system study, design optimization should be performed on a system level to include generation, transmission and distribution, and utilization. In the present lunar-base study the transmission and distribution concepts illustrated in Figure 3.5-5 are compared together with the generation systems that appear most applicable. For example, in the low power level d.c. generation concepts in which the power system is integral with the base shelter, it is logical to consider utilization of the main block of power at the generation level. In larger bases of long mission duration, a central nuclear powerplant is practical. Network configurations, voltage level, and d.c. or frequency of a.c. must be compared in a system with transmission lines and central nuclear plants to determine optimum combinations. Figure 3.5-6 is a comparison of some types of electric power transmission on the basis of weight as a quality-type parameter.

3.5.2.4 Control — The control of a lunar-base power system is provided in the fulfillment of such basic functions as automatic regulation, fault detection and isolation, system start-up and shutdown, circuit and load switching, and monitoring.

The control functions govern performance (dynamic and steady state) of the system as a whole, warn of impending trouble, and protect the system from catastrophic failure. These functions play a significant role in ensuring electric service continuity, a factor that is of critical importance on the lunar base.

Figure 3.5-3

SOLAR AND CHEMICAL GENERATION CONCEPTS



LEGEND

SC	Solar Cell (N/P 14% at air mass 1 and standard conditions)
FC	Fuel Cell (G. E. Ion-Exchange Membrane. Estimated 1965-68 capability).
Batt	Battery (Silver-Zinc)
A	Cryhocycle (Sundstrand)
B	H_2 - O_2 Turbine (Sundstrand)
C	H_2 - O_2 Engine (Boeing Estimate)
D	H_2 - O_2 Turbine (Allison)
E	Solar Collector-Stirling (Day), H_2 - O_2 - Stirling (Night)

Figure 3.5-4

NUCLEAR REACTOR GENERATION CONCEPTS

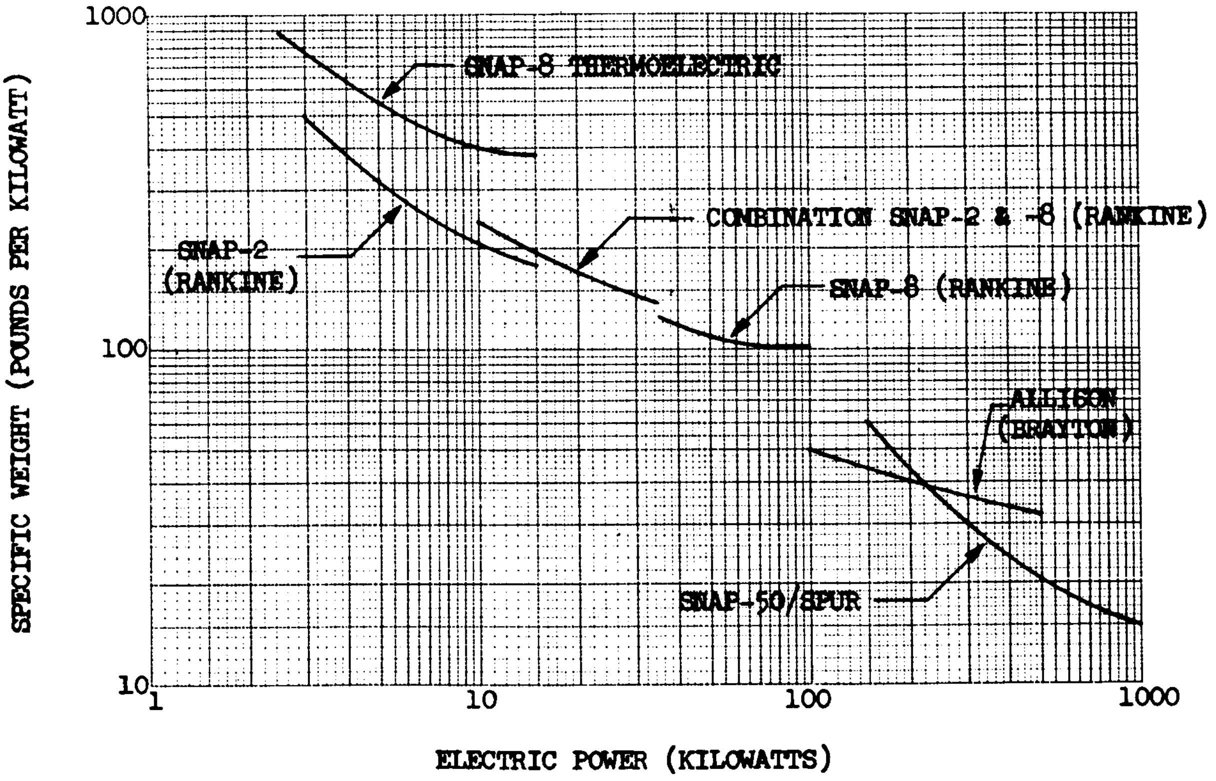
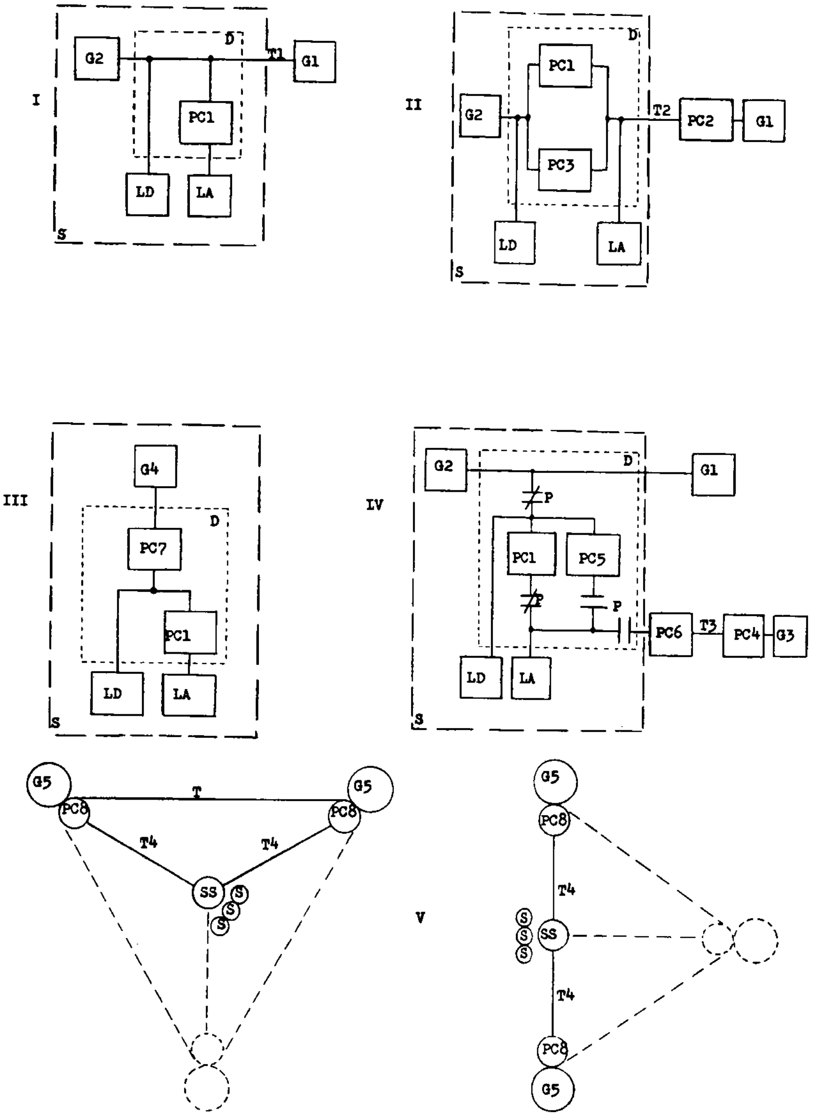


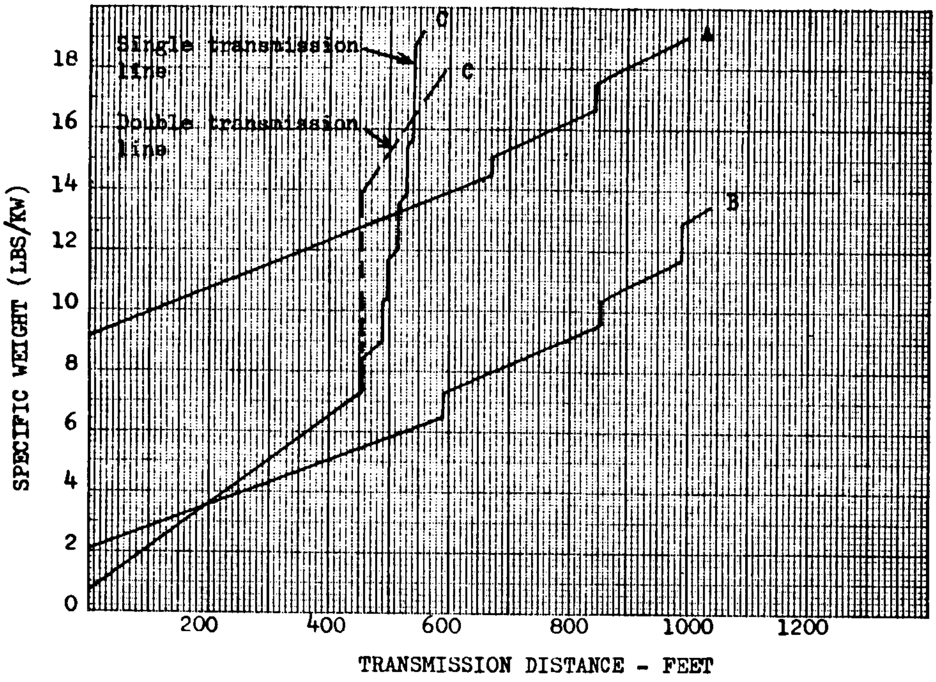
Figure 3.5-5
APPLICABLE TRANSMISSION AND DISTRIBUTION CONCEPTS



P - Power Transfer
D - Shelter distribution box
S - Shelter
SS - Base substation (PC9 included)
LD, LA - d-c and a-c loads respectively
PC - Power Conditioning
PC1, PC2, PC4 - inverters
PC3,PC5 - T-R units
PC6 - Transformer
PC7 - Rectifier
PC8,PC9 - (various concepts)
T- Transmission Line
T1 - 50', 28 v, d-c

T2 - 50', 200 v, 3 phase, a-c, 400 cps
T3 - 50' to 500', 200 to 400 v, 3 phase, a-c, 400 cps
T4 - 500' to 1 mile (various concepts)
G - Generation
G1 - solar cell
G2 - fuel cell
G3 - SNAP-8 - Thermoelectric plus fuel cell surge source
G4 - Radioisotope (High Frequency Alternator)
G5 - SNAP-8 (Rankine) or SNAP-50 (Rankine) or Allison Reactor (Brayton)

Figure 3.5-6
TRANSMISSION CONFIGURATION WEIGHTS



	Transmission				Rec. End Cond.	
Syst.	Voltage	Freq. & Phase	Power Conversion	Send. End Cond.	D.C. Load	A. C. Load
A	600	D-C	3200 cps Alternator	Rectifier	D.C. to D.C. Converter	**Inverter**
B	345/ 600	400 cps 3 phase	400 cps Alternator	None	T-R Unit	**Transformer**
C	115/ 200	400 cps 3 phase	400 cps Alternator	None	T-R Unit	None

A comparison of control functions is presented for the generation system concepts that appear most applicable over the range of proposed lunar-base configurations. The comparison is arranged into a reference table of control functions, system schematics, and notes of explanation for the control functions.

3.5.2.5 Emergency — Emergency is defined as the condition when all prime electrical power has failed. It is logical to provide a reliable emergency power source as a part of each shelter power system. The rating of the emergency source should provide the base essential power requirements for a period of time required to make repairs of a reasonable magnitude on the prime power system, or to make a systematic safe abort.

The secondary battery rates best as a reliable emergency power source for the lunar-base application, provided the emergency period is limited to a few hours. For long emergency periods, batteries are impractical from a weight standpoint, as illustrated in Figure 3.5-3. A comparison of batteries applicable for lunar-base emergency power indicates that the silver-zinc battery is best from a weight standpoint.

3.5.3 Power Modules

A power module is a complete electric power package that may have applications to one or more of the proposed base configurations. Logical power module concepts are developed for the four base models in accordance with criteria, specific load requirements, and rationale based on the information and data developed in the section on basic considerations.

Five power modules have been developed for the lunar-base configurations.

1) Power Module P_1 — An integral shelter fuel cell/solar cell power system provides the power requirements (1.5 kw to 2.0 kw) for Base 1. P_1 also provides shelter power during activation of Bases 2, 3, and 4, and standby power during the operational period of Bases 2, 3, and 4. Figure 3.5-7 is a schematic diagram of Module P_1.

2) Power Module P_2 — The primary objective of P_2 is to provide power (about 15 kw) for Base 2, 3, and 4 service and installation during base activation periods. P_2 is a fuel cell system and is shown schematically in Figure 3.5-7.

3) Power Module P_3 — P_3 is a SNAP-8 thermoelectric system that provides power (about 5 kw maximum demand) for Base 2 after installation.

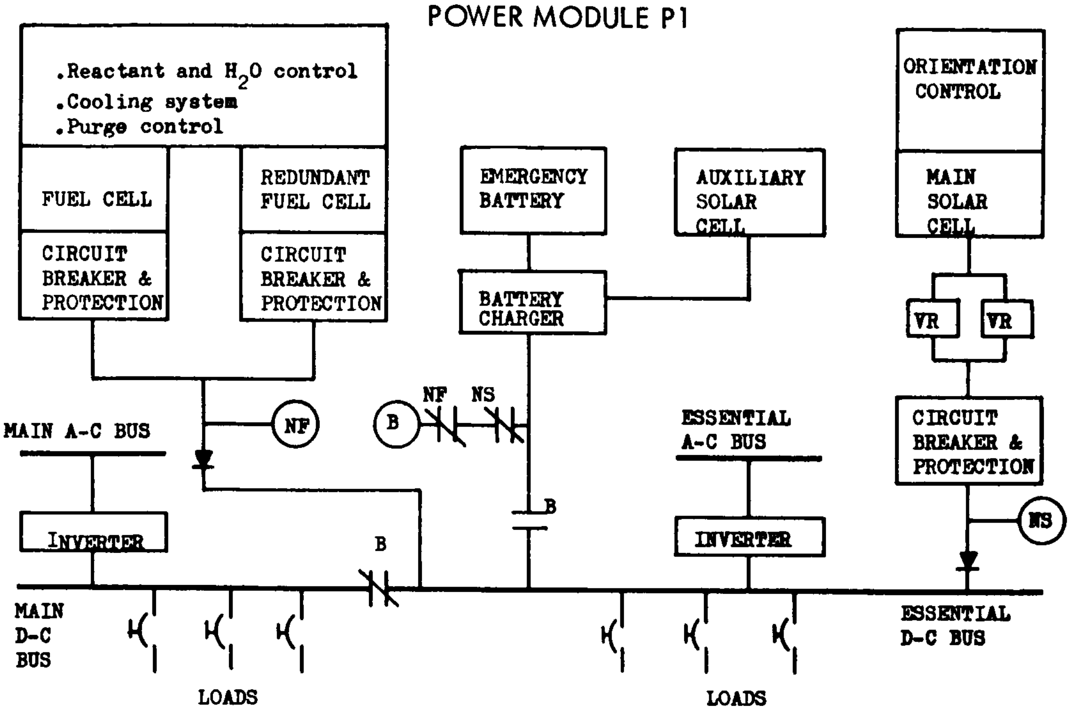
4) Power Module P_4 — The objective of P_4 is to provide central power for Bases 3 and 4. The minimum requirement for Base 3 is about 55 kw and for Base 4 about 75 kw. The nuclear-reactor, 100-kw, advanced SNAP-8, Rankine cycle, generation concept illustrated in Figure 3.5-8 is recommended for P_4.

5) Power Module P_5 — P_5 is a central substation for Bases 3 and 4 and contains switchgear, power conditioning equipment, and power buses for large central load blocks.

Figure 3.5-7

SCHEMATIC DIAGRAMS OF POWER MODULES P-1 AND P-2

POWER MODULE P1



POWER MODULE P2

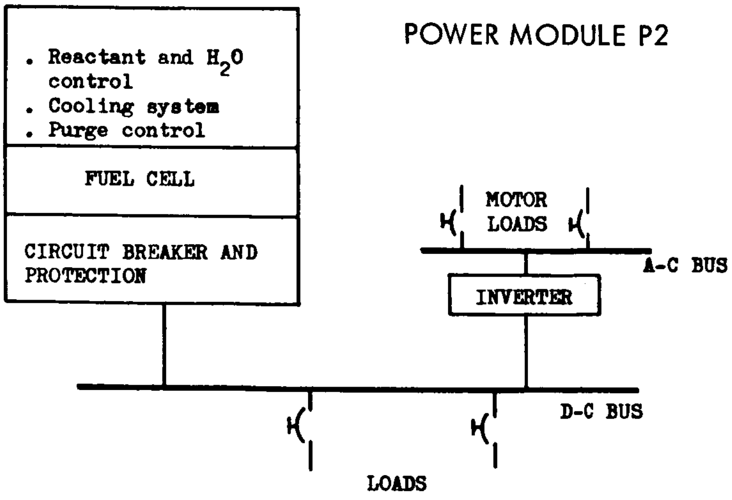
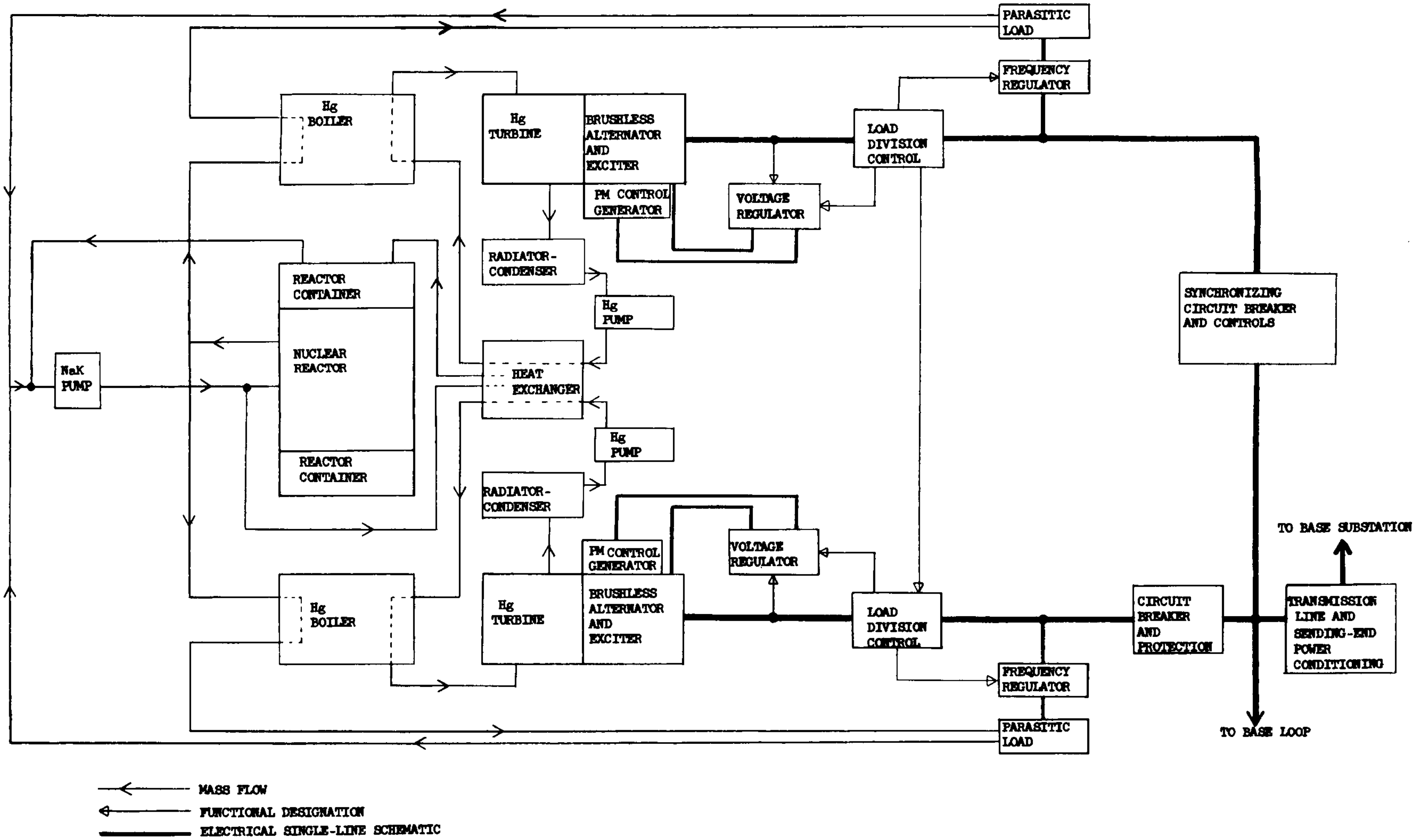


Figure 3.5-8
SCHEMATIC DIAGRAM OF
POWER MODULE P-4



3.6 COMMUNICATION SUBSYSTEM

3.6.1 Subsystem Analyses

3.6.1.1 Requirements — The communication requirements for the various lunar base models are defined for each of the following necessary links with the lunar base:

1) Earth;
2) Orbiting spacecraft (Apollo command module or lunar excursion module);
3) Man on the lunar surface (roving astronaut or roving vehicle);
4) Scientific instrumentation on the lunar surface (line-of-sight or beyond-line-of-sight).

Considering the four lunar base models assumed for this study, a nominal communication capability is defined for Base Models 1 and 2 and an expanded communications capability is planned for Base Models 3 and 4. This communication network is illustrated in Figure 3.6-1.

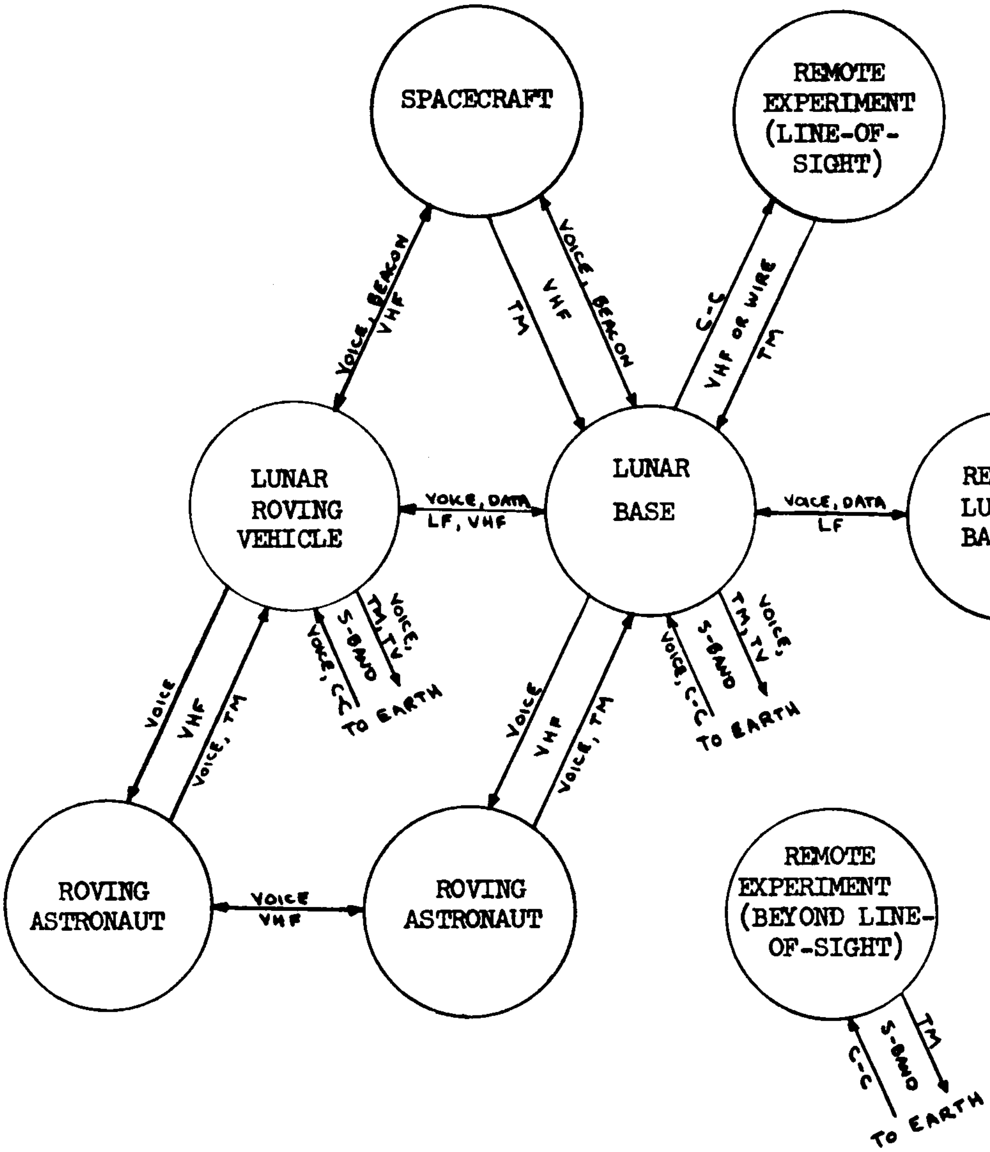
3.6.1.1.1 Base-to-Earth Links — The nominal data requirements for this vital two-way communication link involve the transmission of data consisting of voice, telemetry, television, and command over an average range of 215,000 nautical miles. In an emergency, the data requirements would diminish to command and voice or narrow-band telemetry (roughly 2000 bits per second).

The number of two-way voice channels should be at least two for operational and scientific purposes. The more complex bases (Base Models 3 and 4) may require four to six channels to satisfy operational and control functions brought about by multiple shelters and increased scientific instrumentation. The audio baseband is assumed to occupy a frequency spectrum of 250 to 2500 cps. An intelligible, medium-grade voice reception can be obtained with an output signal-to-noise ratio of 15 decibels.

The telemetry data consists of information derived from the checkout and monitoring of the various subsystems and scientific instrumentation. The data rates involved will depend on the real-time transmission requirements in conjunction with the storage requirements for delayed transmission to Earth. A time-division multiplex system such as PAM or PCM is the most appropriate for monitoring subsystem performance levels, which are basically slowly varying quantities. The number of channels, sampling rates, and number of encoding bits per sample cannot be firmly estimated at this time, but a voice/data modulation baseband of 100 to 200 kc/s is an appropriate estimate for the initial base configuration involving both scientific and operational data sources. The modulation baseband will grow to as high as 1 megacycle for the larger base complexes. An acceptable output signal-to-noise ratio for telemetry is in the range of 12 to 15 decibels.

Figure 3.6-1

LUNAR BASE COMMUNICATION NETWORK



In an emergency, or for subsystem checkout prior to crew habitation, a narrowband telemetry requirement exists whereby only critical subsystem performance levels are monitored using low sampling rates. A data rate of 2000 bits per second is adequate and is consistent with time-sharing a single voice channel.

For television transmission back to Earth, the minimum requirements, as established by previous studies are as follows:

1) Frame rate — 10 frames per second;
2) Resolution — 278 lines per frame;
3) Acceptable signal-to-noise ratio — 26 to 30 decibels;
4) Modulation — analog;
5) Video baseband — 400 kc.

The video baseband requirements will be expanded for the more complex bases to 2-4 mc to enable television to be transmitted at commercial standards of 525 lines and 30 frames per second. This video baseband could also be used for the transmission of high-resolution (greater than 1000 lines) pictures using film scanning techniques.

The command data requirements will consist primarily of discretes or "on-off" commands for remote control of the various lunar base subsystems before and during habitation. A digital system is assumed because of its ability to provide an address to identify the various subsystems and to ensure reliability, adequate capacity, and the ability to incorporate encoding for security and error-correcting functions. The modulation baseband for both voice and data is assumed to be less than 100 kc. An output signal-to-noise ratio of at least 15 decibels would ensure an acceptable low bit error rate (less than 10^{-6}).

3.6.1.1.2 Base to Orbiting Spacecraft — The data requirements for this link involve transmission of two-way voice, command, telemetry, and tracking data (beacon) over an initial slant range of 400 nautical miles. This range capability is adequate for orbiting and landing spacecraft altitudes of 100 nautical miles and is considered satisfactory for the initial base complexes. Ranges on the order of 1000 nautical miles should be considered for later base complexes to enable a large variation of orbital parameters to be used by the spacecraft.

A voice and data modulation bandwidth of approximately 10 kc appears satisfactory to handle the command, telemetry, and voice requirements dictated by local use. However, future capability should be considered for data bandwidths of 100 to 200 kc, so that a redundant spacecraft-Earth link can be provided via the lunar base.

3.6.1.1.3 Base to Man on the Lunar Surface — Two basic cases present requirements: (1) the roving astronaut within line-of-sight of a communication terminal (base or roving vehicle); and (2) the roving vehicle, operating both within and beyond line-of-sight of the lunar base.

For the roving astronaut, both two-way voice and telemetry data must be transmitted over a range of approximately 4 miles. The telemetry data will be used to monitor the spacesuit environment and physiological measurements on the astronaut. The data rate is estimated to be in the vicinity of 100 bits per second for telemetry in conjunction with a 2.5-kc voice baseband. The output signal-to-noise ratio should be at least 15 decibels for both types of data.

The roving vehicle communication requirements are similar to those of the lunar-base-to-Earth requirements, in that voice, telemetry, television, and command data are required for proper operation. To maintain contact with the lunar base beyond line-of-sight, a voice link is considered as a minimum capability out to ranges of at least 150 miles radius from the base. This voice link may take the form of normal voice bandwidths of 250 to 2500 cps or 60 words per minute teletype (150 cps bandwidth) operating at signal-to-noise ratios of 15 and 10 decibels, respectively. This capability should possess sufficient growth potential to enable 600-mile ranges to be achieved.

In addition to this narrow-band signaling from the roving vehicle, a wide-band data link capability should be provided from the vehicle to Earth for transmission of one voice channel, 10- to 20-kc telemetry baseband for subsystem monitoring and experimental data, and slow-scan television. The slow-scan television would occupy a video baseband of approximately 70 kc corresponding to a frame rate of 1 to 2 frames per second and a resolution of 278 lines per frame. The vehicle should be capable of receiving the same voice and command data format used for communicating with the lunar base.

3.6.1.2 Functional Performance Trade Studies —

3.6.1.2.1 Earth-Moon Links — The ground instrumentation facilities planned for the time period of the lunar base were examined for possible use as a ground support system. Use of a portion or all of these facilities would reduce the cost of establishing a lunar base, shorten the time required for ground instrumentation, and provide an Earth facility of proven capability.

The two facilities considered were the Apollo Ground Operational Support System (GOSS) and the Deep Space Instrumentation Facility (DSIF). Both can be considered to have proven capability and known characteristics. In addition, both consist of a world-wide network that can provide 24-hour-per-day coverage. The DSIF, however, is designed primarily for unmanned vehicles engaged in deep-space exploration. Furthermore, the DSIF can be expected to be fully engaged in communication with many such probes during the time of interest. The Apollo GOSS has the distinct advantage of being designed for manned lunar exploration and is not being programmed for conflicting missions. Hence, the Apollo GOSS will be given primary consideration as the Earth network for the lunar base, but its characteristics are not considered as a limitation.

The selection of optimum frequencies for the Earth-Moon links was based initially on such factors as cosmic noise temperature, oxygen and atmospheric absorption, and rainfall attenuation. It is found that S-band (1500 to 5000 mc) is a nearly optimum band for these considerations, with antenna temperatures in the vicinity of 30°K for antenna elevation angles greater than 5 degrees. In addition, factors such as component availability, compatibility with existing facilities, efficiency of rf power generation, and available frequency bands further indicate S-band as the optimum frequency band. For purposes of this study, specific frequencies have been chosen within S-band for later analysis. These frequencies are nominally 2300 mc for the Moon-Earth link and 2100 mc for the Earth-Moon link.

3.6.1.2.2 Lunar Surface-Surface Links — A major study effort has been made to evaluate the various means of providing surface-surface communications for the lunar base. The principal methods investigated were: (1) microwave relay, (2) surface-Earth-lunar base relay, and (3) ground-wave propagation. As a result of these studies, several conclusions were reached regarding the potential of each mode to provide adequate communications for lunar exploration (roving vehicle or remote outpost). A portion of the study on ground-wave propagation is included in the following paragraphs.

VLF/LF Ground-Wave Propagation — The lack of information concerning the lunar composition and environment complicates the determination of the requirements necessary for surface-to-surface communication systems on the Moon. Largely unknown factors that affect the communication systems are the values of conductivity, permeability, and permittivity of the lunar surface material; the possible presence of an ionosphere; the possibility of layering below the surface; and the intensities of lunar and extralunar noise sources. The lunar communication studies at the present time can give only a general indication of what may be expected in the way of propagation losses and antenna types.

In this study, ground-wave propagation is assumed over a smooth, homogeneous, spherical lunar model of radius $r_0 = 1738$ km in free space. The relative dielectric constant of the material is assumed to be $\epsilon_r = 1.5$, and the magnetic permeability μ is assumed to be that of free space. All the calculations are made for two values of conductivity $\sigma = 10^{-4}$ and 10^{-3} mhos/meter. These values of ϵ_r and σ are consistent with general agreement that the relative dielectric constant is close to unity, and that the conductivity of the lunar material is low.

External Noise — In this study, external noise is assumed due to galactic sources only as observed on Earth and extrapolated for frequencies less than the plasma frequency of about 20 mc/s. The empirical expression used, based on a reference temperature $t_0 = 288.4$°K, is:

$$f_e = 1.585 \times 10^5 \, (f_{mc})^{-2.3}$$

where f_{mc} is the frequency in megacycles.

Basic Transmission Loss — The basic transmission loss, L_b, for points beyond the radio horizon may be calculated following the numerical procedures developed by various authors. In this study, Norton's method developed in 1955 has been used to calculate the data shown in Figure 3.6-2 for a surface conductivity (σ) of 10^{-4} mhos/meter.

Vertical Monopole Versus Horizontal Dipole — Using the data derived in the study for both the horizontal dipole and vertical monopole antennas, a comparative analysis of their radiation efficiency and antenna lengths is shown in Figure 3.6-3. As indicated, a vertical monopole length in excess of 500 feet (160 meters) is required to compare favorably with the efficiencies of a horizontal dipole at operating frequencies greater than 65 kc. For the vertical monopole antenna to exhibit any advantage in radiation efficiency within the LF band (30 to 300 kc), a ground plane is required as indicated by the dotted portion of the curves, consisting of radial wires several hundred feet in length. Although the monopole data was calculated on the basis of a surface conductivity of 10^{-4} mhos/meter, any improvement in this factor would result primarily in reducing the size of the required radial ground-plane (dotted portion of curves).

Conclusions —

1) The fundamental limitations of electrically short monopoles as expressed by the equation, Q_{in}/Efficiency = a constant, cannot be altered.
2) The efficiency of the long, horizontal, insulated dipole is low at frequencies below 100 kc, but comparable efficiencies using a vertical monopole require an antenna height of approximately 500 feet (160 meters).
3) The horizontal dipole does not have the bandwidth limitation imposed by the use of the vertical monopole.
4) Using a horizontal dipole, an optimum frequency appears to exist in the vicinity of 50 kc based on the previously discussed parameters of range, required transmitter power, antenna length and weight, bandwidth, and feasibility of erection.
5) The use of low-frequency surface-to-surface communications appears feasible and practical for use on the lunar surface for the transmission of voice or telegraphy data beyond line-of-sight from the lunar base to either a roving vehicle or remote outpost. This concept also provides, as an aid to exploration, a means of navigation on the lunar surface with modest transmitter power, and antenna requirements.

3.6.1.3 Modular Division of Subsystems —

3.6.1.3.1 Rationale of Modular Division — The communication subsystem has been divided into six major modules in an attempt to satisfy the assumed requirements of Lunar Base Models 1 to 4 (see Figure 3.6-4). Section 3.6.2 of this document contains the modular description. The modular breakdown used consists

Figure 3.6-2

BASIC TRANSMISSION LOSS (L_b) FOR GROUND WAVES ON MOON

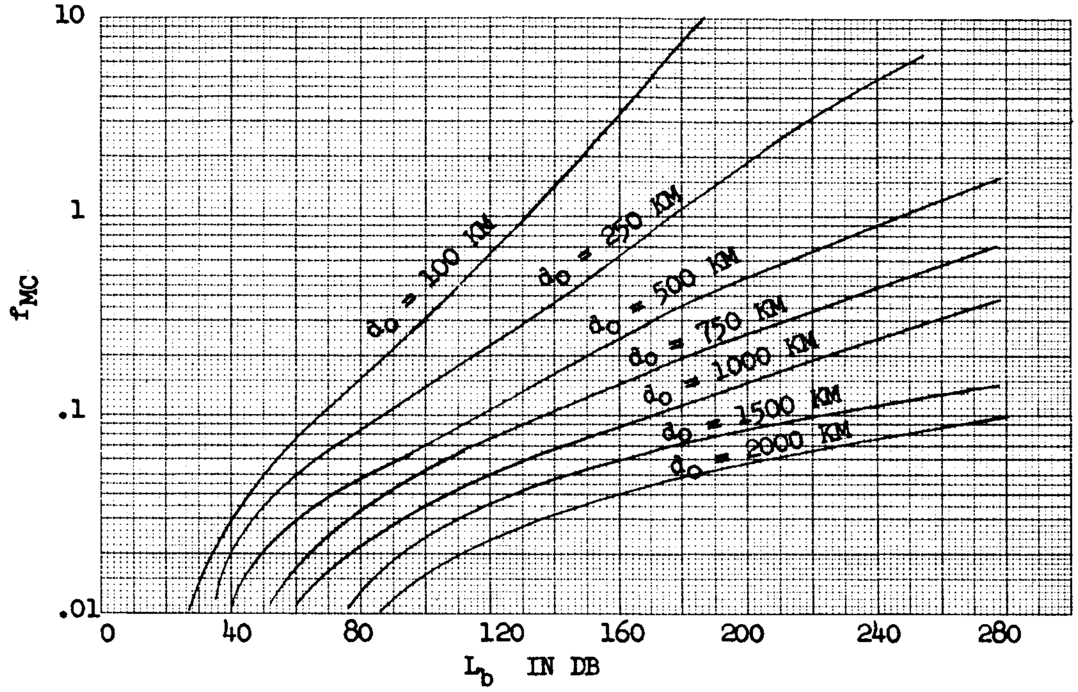


Figure 3.6-3

RADIATION EFFICIENCY

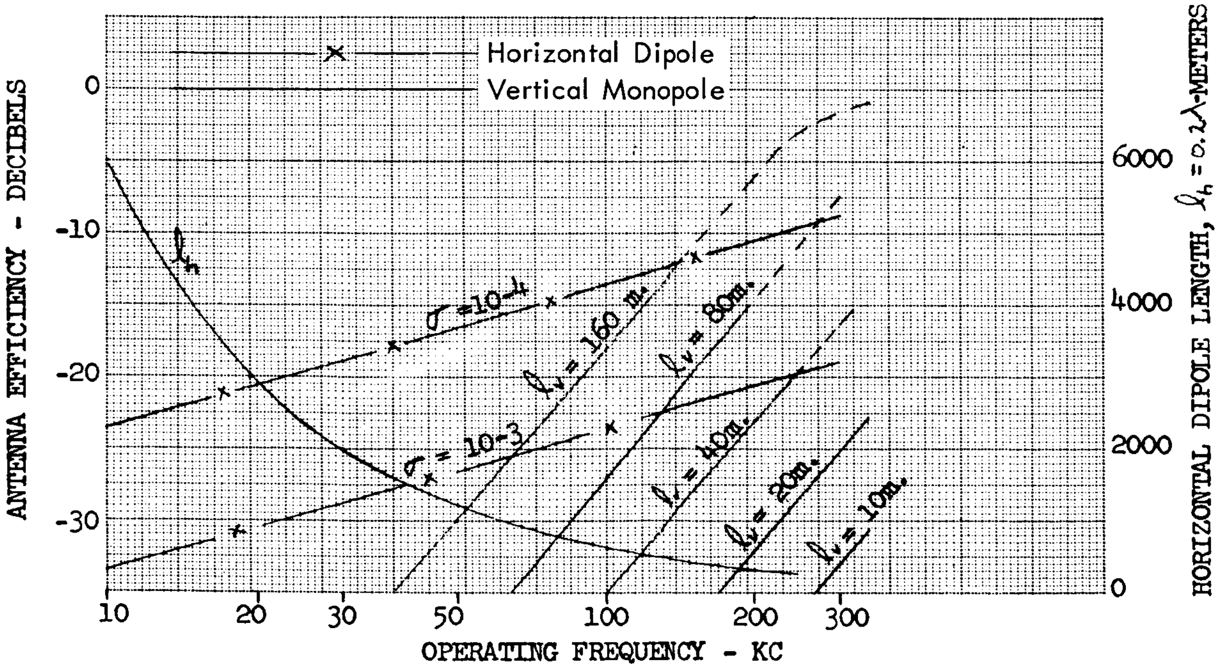
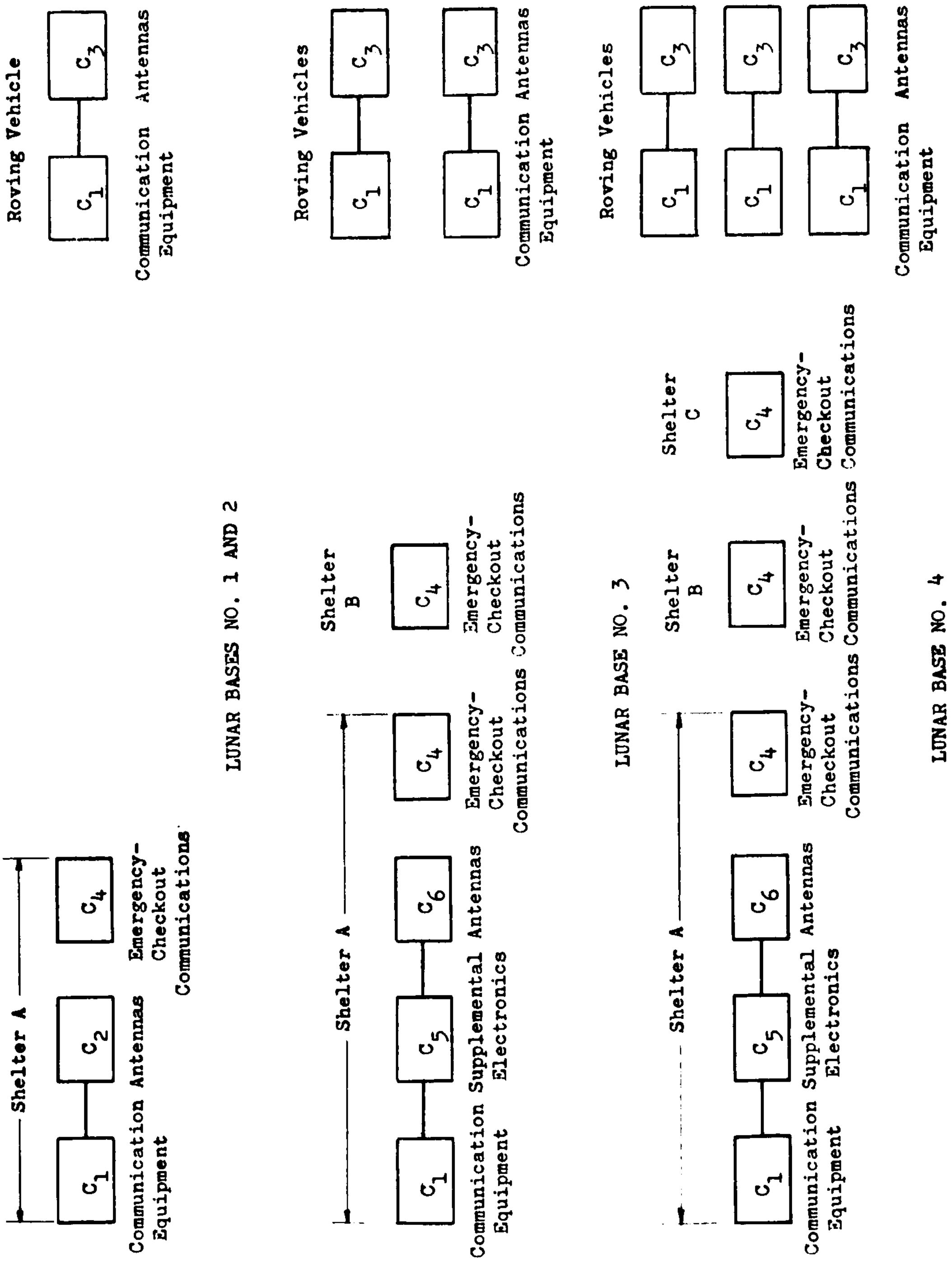


Figure 3.6-4
MODULAR DIVISION OF SUBSYSTEM



basically of grouping the active components (power consuming equipment) into one set of modules (C-1 and C-5) and the passive components (antennas) into another set of modules (C-2, C-3, and C-6). This modular division provides increased reliability by using selected spare modules of lower reliability components.

The exception to this rationale is Module C-4. In this case, the module contains all equipment, including antennas, to provide two-way emergency voice communications from each shelter (via S-band to Earth or VHF to a nearby roving astronaut or vehicle) independently of the other module. This module also serves to provide for the transmission of checkout telemetry data from each shelter prior to crew habitation.

3.6.1.3.2 Weight Statement — An overall weight statement is shown in Table 3.6-A for the communication subsystem for each of Lunar Base Models 1 to 4.

3.6.2 MODULE ANALYSIS AND DESIGN

3.6.2.1 Module C-1 —

3.6.2.1.1 Functional Description — This module provides the basic communication equipment (exclusive of antennas and transmission lines) necessary for the transmission and reception of voice, telemetry (experimental and subsystem monitoring), television, command, and tracking data between a shelter or roving vehicle and any one of the following communication terminals: auxiliary shelters, Earth, roving astronauts, orbiting spacecraft, and experimental instrumentation on the lunar surface. A functional block diagram of Module C-1 is shown accentuated on Figure 3.6-5, as it is related to the remainder of the communication subsystem.

3.6.2.1.2 Performance Specifications — S-Band Voice/Data Links — Referring to Figure 3.6-5, the S-band communication equipment provides for the transmission of voice, telemetry data (subsystem monitoring), scientific data, and television to Earth and for the reception of voice and command data from Earth. To establish the performance of these two Moon-Earth links, modulation bandwidths were formulated consistent with the requirements stated in Paragraph 3.6.1.1 for Base Models 1 and 2 as well as for the roving vehicle. The modulation basebands used in the analysis are illustrated below:

a) Voice/data transmission

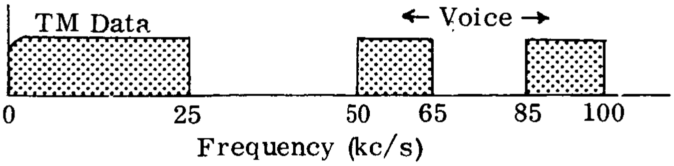


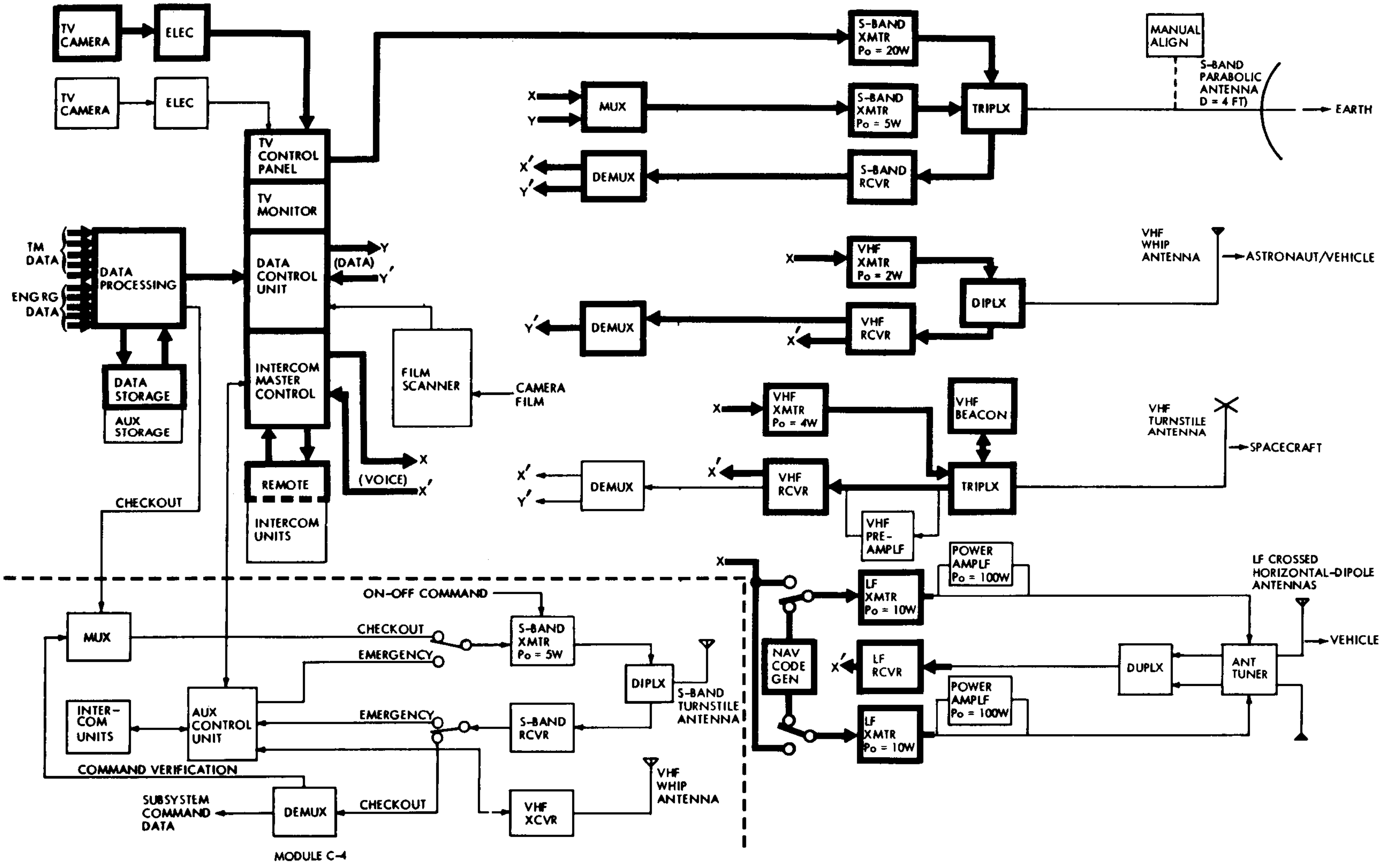
Table 3.6-A

OVERALL WEIGHT STATEMENT FOR COMMUNICATION SUBSYSTEM

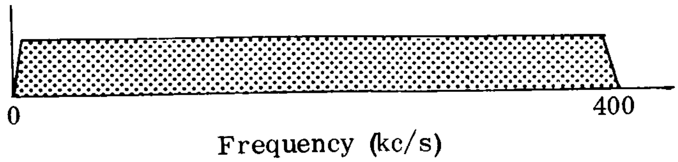
Modules	BASE MODEL 1			BASE MODEL 2			BASE MODEL 3			BASE MODEL 4		
	Qty	Wt (lb)	Average Power (watts)	Qty	Wt (lb)	Average Power (watts)	Qty	Wt (lb)	Average Power (watts)	Qty	Wt (lb)	Average Power (watts)
C-1	2	342	200	2	342	200	3	513	300	4	684	300
C-2	1	85		1	85							
C-3	1	120		1	120		2	240		3	360	
C-4	1	44	12	1	44	12	2	88	24	3	132	36
C-5							1	238	96	1	238	96
C-6							1	128		1	128	
Belt Pack	3	12	5	6	24	10	12	48	20	18	72	30
Expt. Inst.	6	60	18	6	60	18	12	120	36	12	120	36
Operational Subtotal		663	235		675	240		1375	456		1734	498
(Spares) C-1				1	171		1	171		1	171	
C-2												
C-3												
C-4	1	44		1	44		1	44		2	88	
C-5							1	238		1	238	
C-6												
Belt Pack	3	12		6	24		12	48		18	72	
Spares Subtotal		56			239			501			569	
Total		719	235		914	240		1876	456		2303	498

Figure 3.6-5

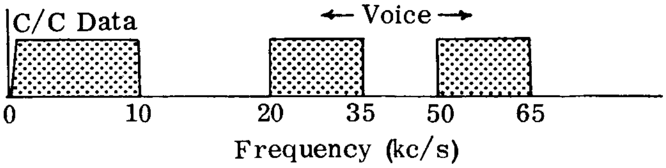
COMMUNICATION SUBSYSTEM – BLOCK DIAGRAM FOR BASE 1 AND 2-MODULE C-1, C-2 AND C-4



b) Television transmission



c) Voice/data reception



The television baseband illustrated above is predicated on the use of an analog signal consisting of 10 frames/second at a resolution of 278 lines/frame.

VHF Voice/Data Links — The VHF communication equipment shown in Figure 3.6-5 is primarily for two-way voice communication between the shelter and astronaut, vehicle, or spacecraft. Duplex frequency equipment is provided to permit simultaneous two-way communication within line-of-sight range of the shelter module.

In addition to voice communication, provisions are included in the module design to receive psychological data (upon request) from the astronaut via an Apollo-type beltpack transceiver. These data may be monitored locally in the shelter or relayed via S-band to Earth.

To aid in spacecraft navigation, a VHF beacon is provided in the module, whose characteristics are compatible with the spacecraft equipment. A peak transmitter power of 400 watts is required to provide a maximum range of 400 nautical miles. This range will enable a spacecraft at an orbital altitude of 100 nautical miles above the lunar surface to track the lunar base for all elevation angles above 3 degrees from the local horizon.

LF Voice/Data Links — Referring to Figure 3.6-5, two low-frequency transmitters are shown for the transmission of either voice or navigational data to the roving vehicle as it explores the lunar surface within a 200-mile radius of the lunar base. Normally, navigational signals will be transmitted continuously whenever the roving vehicle is beyond the line-of-sight of the lunar base. This is accomplished, for example, through the use of a code generator to produce a series of conjugate signals in Morse Code such as the letters "A" and "N" for separate transmission over the two horizontal dipole antennas. This technique, which is similar to the range beacons for aircraft, would enable the roving vehicle to establish its bearing relative to the base by comparing the relative strength of the two signals. A reception at the vehicle of a continuous-wave tone would indicate an equiangular bearing between the two dipoles.

Voice transmission would be initiated by the reception of voice signals from the vehicle. In this event, the inputs to both transmitters are switched over to the voice circuit as shown in Figure 3.6-5, so that omnidirectional coverage is provided by the crossed horizontal dipole antennas. At the termination of two-way voice communications, the equipment is switched back to the "normal" navigational mode. The performance of this link using 10-watt transmitters is shown in Figure 3.6-6.

3.6.2.2 Module C-2 —

3.6.2.2.1 Functional Description — This module is intended for use with Module C-1. Primarily, the module contains antennas and transmission lines for the S-band, VHF, and LF links, plus any accessory items such as duplexers or antenna tuners. A high-gain S-band antenna is included for use with the wide-band data link to Earth. Provisions must be included in the antenna design to enable periodical manual realignment of the antenna beam relative to Earth. A VHF antenna system composed of a turnstile and whip antennas is included to cover the VHF band and to provide proper operating characteristics for each of the VHF links. A low-frequency antenna package is also included and consists of a duplexer, tuner, and transmission line for two long-wire horizontal dipoles.

3.6.2.2.2 Performance Specifications — S-Band Voice/Data Links — Using the data requirements and corresponding modulation basebands described earlier for the transmission of voice, telemetry data, and television, and for the reception of voice and command control data, circuit quality charts were developed and analyzed for all of the major links. Two S-band charts are tabulated in Tables 3.6-B and 3.6-C for the Moon-Earth link.

3.6.2.3 Module C-3 —

3.6.2.3.1 Functional Description — This module is similar to Module C-2 in that it consists primarily of antenna components to be used with Module C-1 for roving vehicles. The antennas included in this module are:

1) High-gain S-band antenna (2-foot diameter) for Moon-Earth link;
2) VHF whip and turnstile antennas for roving astronaut, lunar base, and spacecraft links;
3) LF receiving and transmitting antennas for vehicle/lunar-base link.

Figure 3.6-6

LF SURFACE-TO-SURFACE COMMUNICATIONS

PERFORMANCE CAPABILITIES AS A FUNCTION OF RANGE

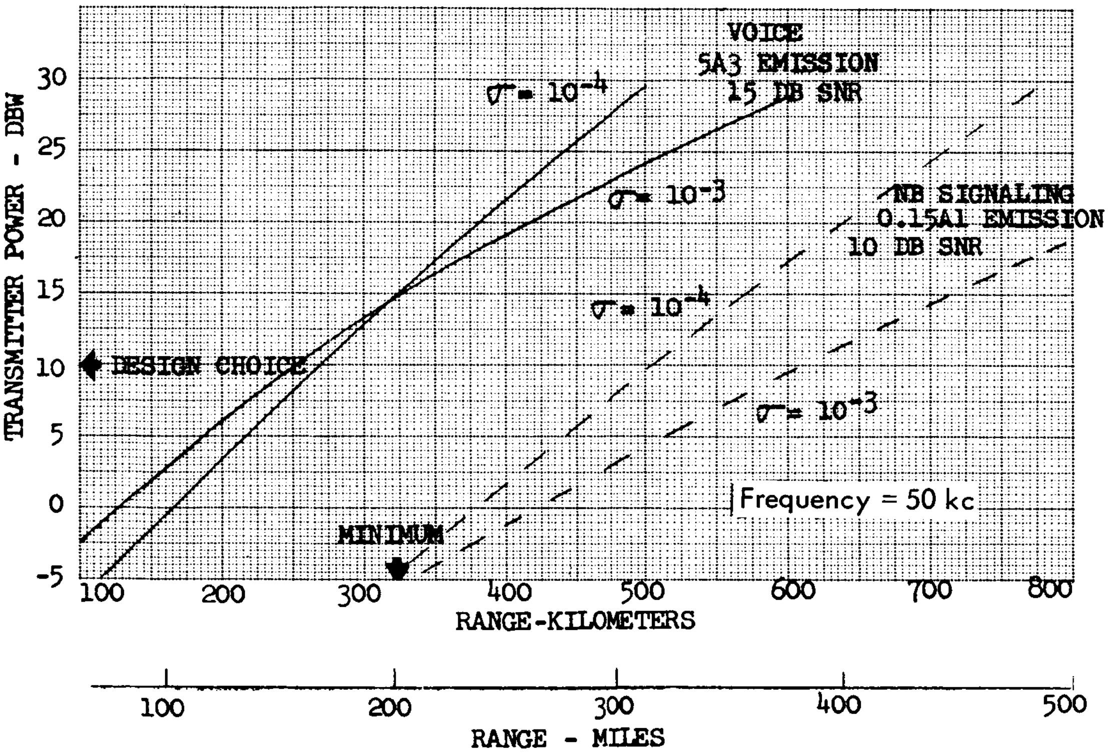


Table 3.6-B

CIRCUIT QUALITY CHART

LUNAR BASES 1 and 2 MODULES C-1 and C-2

CIRCUIT — MOON-EARTH FUNCTION — VOICE/DATA

PARAMETERS	ASSUMED VALUE	DECIBELS
Frequency (mc)	2300	
Modulation/Index	FM/1.0	
Transmitter Power (dbw)	5 watts	+7
Transmit Antenna Gain (db)	D = 4 feet	+26.5
Range (nautical miles)	215,000	
Free-Space Loss (db)		-212
Predicted Losses[1] (db)		-3
Receive Antenna Gain (db)	D = 85 feet	+53
Received Signal Power (dbw)		-128.5
Overall Receiver Noise Temperature (°K)	180	
Receiver Noise Power in 1 cps (dbw)		-206
Modulation Bandwidth, fm (kc)	100	+50
RF Bandwidth (mc)	0.4	
Required Input SNR[2] in fm (db)		+15
Output SNR (db)	> 15	
Receiver Threshold (dbw)		-141
Circuit Margin (db)		+12.5

NOTES: [1] This factor includes atmosphere, polarization, and hardware losses

[2] Input SNR = signal power/noise power (kTfm) for FM demodulator

Table 3.6-C

CIRCUIT QUALITY CHART

LUNAR BASES 1 and 2	MODULES C-1 and C-2
CIRCUIT — MOON-EARTH	FUNCTION — TELEVISION

PARAMETERS	ASSUMED VALUE	DECIBELS
Frequency (mc)	2310	
Modulation/Index	FM/2.5	
Transmitter Power (dbw)	20 watts	+13
Transmit Antenna Gain (db)	D = 4 feet	+26.5
Range (nautical miles)	215,000	
Free-Space Loss (db)		-212
Predicted Losses[1] (db)		-3
Receive Antenna Gain (db)	D = 85 feet	+53
Received Signal Power (dbw)		-122.5
Overall Receiver Noise Temperature (°K)	180	
Receiver Noise Power in 1 cps (dbw)		-206
Modulation Bandwidth, fm (kc)	400	+56
RF Bandwidth (mc)	2.8	
Required Input SNR[2] in fm (db)		+18
Output SNR (db)	> 26	
Receiver Threshold (dbw)		-132
Circuit Margin (db)		+9.5

NOTES: [1] This factor includes atmosphere, polarization, and hardware losses

[2] Input SNR = signal power/noise power (kTfm) for FM demodulator

3.6.2.4 Module C-4 —

Prior to habitation, Module C-4 provides a narrow band (approximately 2000 bits per second) telemetry link via S-band (2.3 kmc) to Earth for subsystem monitoring and checkout. This link will be activated and controlled by Earth with an S-band (2.1 kmc) command receiver. The telemetry transmitter and command receiver are diplexed to a common low-gain antenna that is an integral part of the shelter module.

During the lunar-base mission period, Module C-4 is switched over to provide for two-way emergency voice communications via S-band to Earth. In addition, a VHF transceiver (simplex) provides two-way voice communication for each shelter to either a roving astronaut or roving vehicle. Voice intercom units using hard-line provide for shelter-to-shelter communications. The functional block diagram of Module C-4 is shown in Figure 3.6-5.

3.6.2.5 Module C-5 —

3.6.2.5.1 Functional Description — This module contains those supplemental electronic components necessary to enable Module C-1 to provide an expanded communications capability for the larger lunar-base installations. As shown accentuated in Figure 3.6-7, Module C-5 enhances the Moon-Earth link to provide, in addition to the larger volume of telemetry and scientific data, the following:

1) Voice/data relay capability from another terminal such as an orbiting spacecraft;
2) Film scanning and readout for transmission of high-resolution pictures;
3) Transmission of commercial quality television;
4) Auxiliary data storage capability.

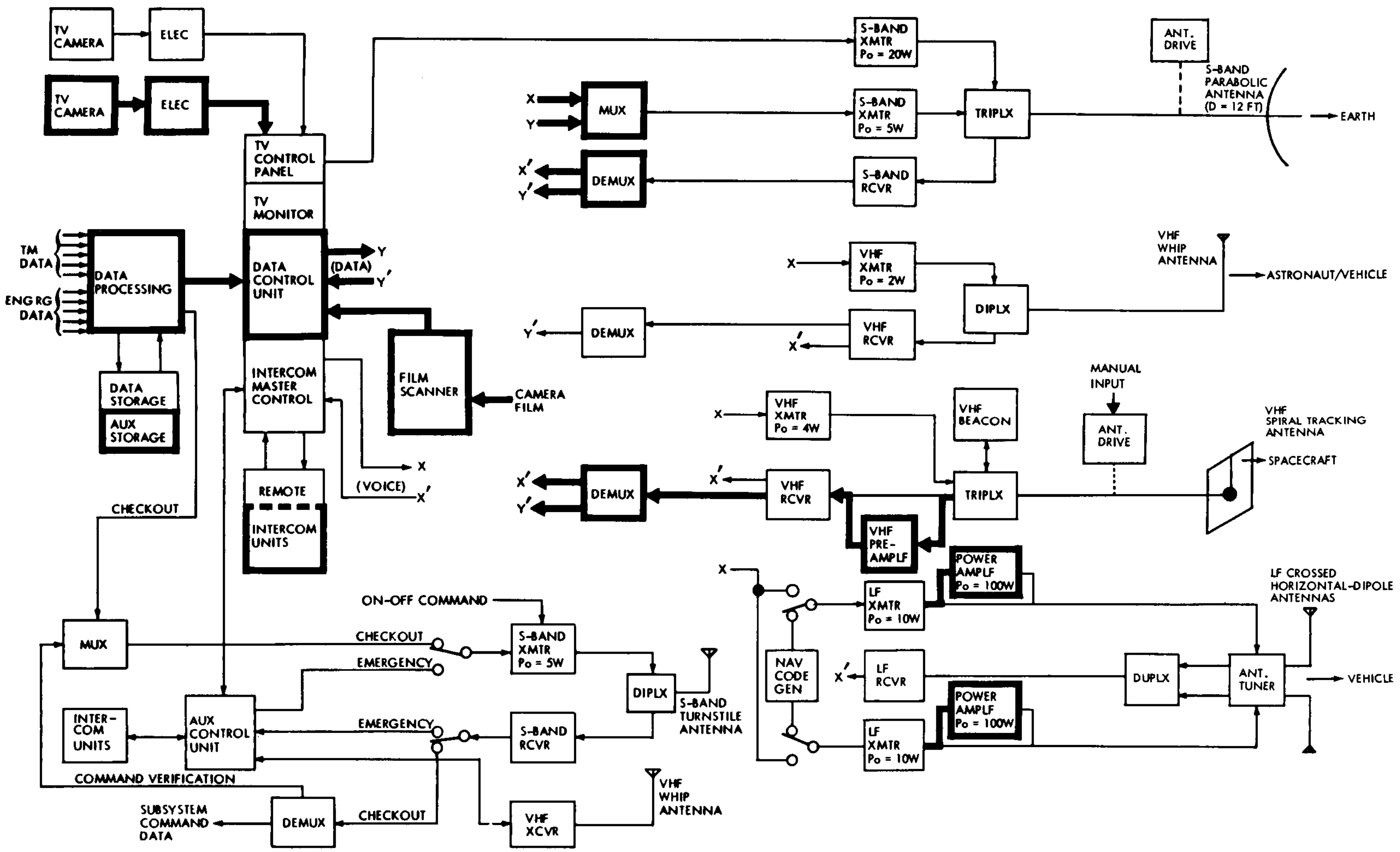
To assist in achieving Item 1) above, a VHF preamplifier has been inserted in the spacecraft/base link to improve the receiver sensitivity along with a voice/data demultiplexer.

The only other communication link that will be affected by Module C-5 is the LF surface-to-surface link for the roving vehicle or possible remote lunar base. As shown in Figure 3.6-7, power amplifiers have been added to provide increased range and/or modulation bandwidth.

3.6.2.5.2 Performance Specifications — S-Band Voice/Data Links — As shown in Figure 3.6-7, Module C-5 provides the supplemental electronics to Module C-1 for the transmission to Earth of four voice channels with expansion capability to six, commercial-quality television, and a telemetry data rate equivalent to 600 kbits per second (NRZ format). In addition, a utility channel is provided for the relay transmission of voice/data or film scanner data. The module also

Figure 3.6-7

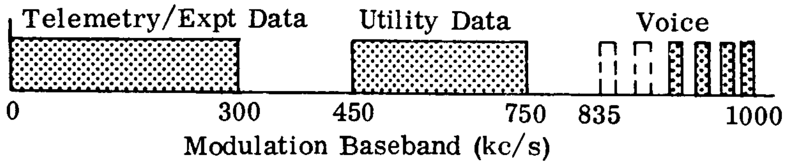
COMMUNICATION SUBSYSTEM – BLOCK DIAGRAM BASES 3 AND 4, MODULES C-5 AND C-6



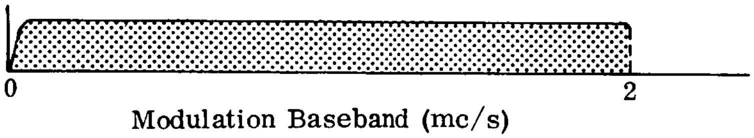
provides for the reception of 4 to 6 voice channels from Earth and thus for full duplex operation. Provision is also made for the reception of 5 to 10 kbits-per-second digital command data.

To establish the performance of these two-way Moon-Earth links, modulation bandwidths were formulated and are illustrated below.

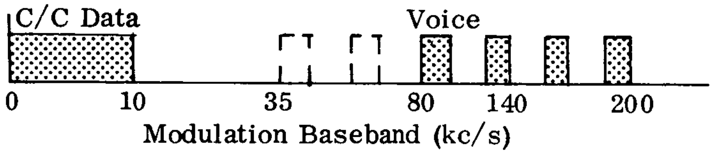
a) Voice/data transmission



b) Television transmission



c) Voice/data reception



The utility data channel shown above in illustration (a) has been inserted to provide a capability beyond the "normal" postulated requirements of a more complex lunar base (Base Models 3 and 4). Some of the anticipated uses of this channel are:

1) A redundant transmission of voice/data from an orbiting spacecraft (relay);

2) Transmission of stored experimental data in parallel to real-time transmission of telemetry data;

3) Transmission of high-resolution film.

3.6.2.6 Module C-6 —

3.6.2.6.1 Functional Description — This module is intended to be used with Modules C-1 and C-5. The module contains primarily antennas and transmission lines for the S-band, VHF, and LF links.

The functional block diagram (Figure 3.6-7) shows, for the S-band Moon-Earth link, a high-gain antenna using a 12-foot parabolic dish. As a result of antenna beamwidth considerations (approximately 2.5 degrees at 3 decibel points), a small boresight telescope to assist in initial alignment and a drive mechanism are attached to the antenna to ensure proper orientation of the beam relative to Earth and to compensate for lunar vibrations. A VHF whip antenna is provided for lunar point-to-point communications required by roving astronauts or vehicles within line-of-sight of the shelter module.

To enable tracking and reception of voice and data from an orbiting spacecraft, a VHF tracking antenna mounted on an appropriate swivel tripod with attached boresight telescope is included in this module. The antenna element consists of either a spiral-wound feed in a cavity, or an end-fed helix. For an antenna gain of 8 to 10 decibels, manual tracking by a simple open-loop antenna drive mechanism can be done.

An LF antenna package consisting of duplexer, tuner, and transmission line for two long-wire horizontal dipoles is included for the lunar surface-to-surface link.

3.7 SURFACE MOBILITY

The purpose of this subsystem is to provide transportation for moving people, equipment, and material from place to place on the Moon during establishment and operation of the lunar base system. Requirements for a roving type vehicle and a multipurpose vehicle were assumed.

3.7.1 Locomotion Concepts

Modes of locomotion over land surfaces may be grouped into categories of rolling, flying, jumping, and walking. Because of the excellent performance on Earth of rolling surface-contact modes, and anticipated limitations of other modes in lunar service, the rolling mode is considered the primary, most feasible candidate for accomplishing satisfactory locomotion performance over lunar surfaces.

3.7.1.1 Rolling Mode — Locomotion performance in the surface-contact modes is measured in terms of net traction, or drawbar pull. A "locomotion performance" indicator is expressed in terms of drawbar pull/vehicle weight. Comparison of rigid wheels, flexible wheels, and tracks in terms of this performance indicator shows that locomotion performance of flexible wheels and tracks is substantially superior to that of the rigid wheel for all proposed lunar sites. Since flexible wheels and tracks perform in a similar manner, only the flexible wheel analysis is developed. It is shown that for maximum soft soil performance of a vehicle using flexible wheels, the largest wheel diameter and wheel deflection possible is desirable. Conclusions concerning obstacle performance are as follows:

1) Obstacle capability is directly proportional to the friction available at the vehicle/obstacle interface;
2) Vehicle obstacle capability is directly proportional to wheel diameter;
3) Drive torque requirements are directly proportional to wheel diameter;
4) Drive torque requirements are directly proportional to obstacle size;
5) Maximum obstacle capability requires an optimum relationship of wheel radius to wheel base.

The effect of the number of wheels on soft-ground mobility performance is illustrated in Figure 3.7-1. The effect of wheel number is significant at low soil strength but is less marked when more than eight wheels are used. Obstacle climbing performance is influenced as shown in Figure 3.7-2.

3.7.1.2 Flight Mode — The concept of a rocket-powered, point-to-point, ballistic flight mode has been studied to establish performance requirements and to estimate the capability of vehicles that might be developed within the lunar excursion module technology. Anticipated propellant requirements for trips of useful distance are so large that this concept appears practical only in combination with the synthesis of propellants from lunar materials.

Figure 3.7-1

EFFECT OF WHEEL NUMBER ON MOBILITY PERFORMANCE

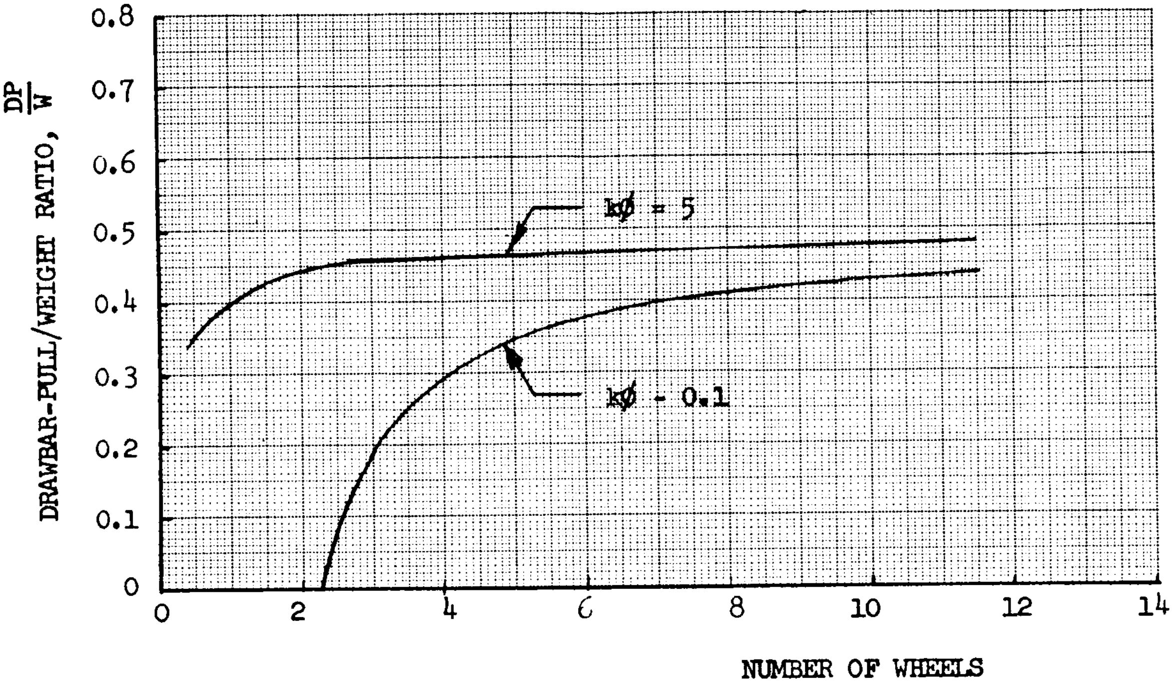
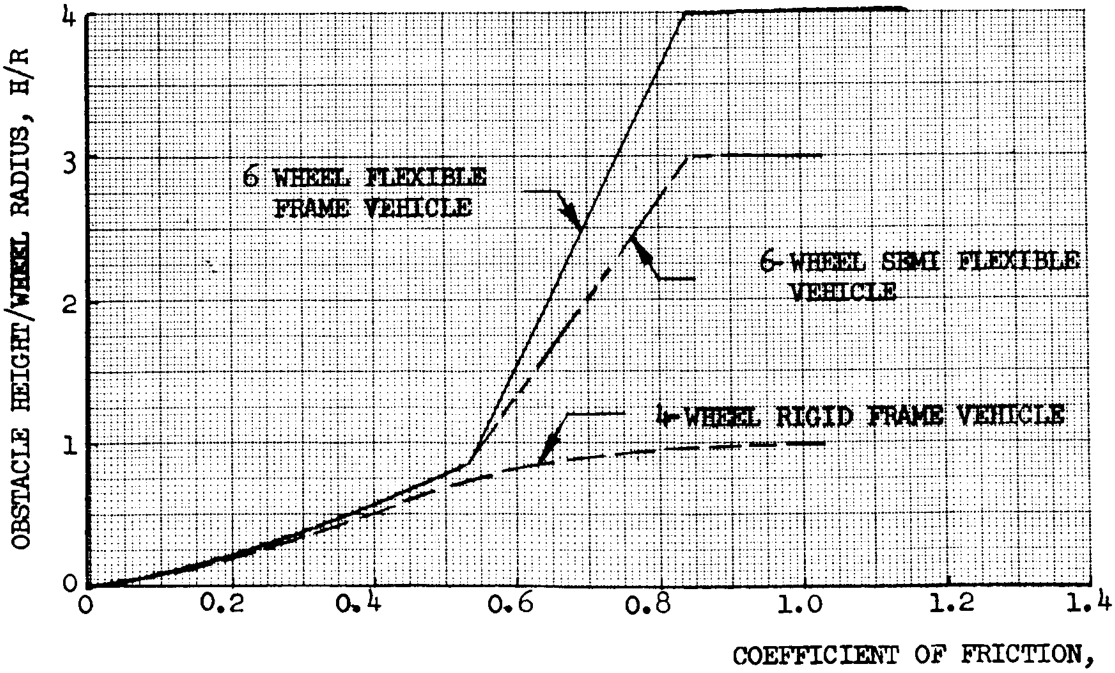


Figure 3.7-2

OBSTACLE PERFORMANCE OF LRV



3.7.1.3 Jumping Mode —Small jump belts appear to offer advantages as individual personnel transports for short distances and to areas of difficult access. Successful jumps have been accomplished on Earth and improved performance in the lunar environment is anticipated due to lower gravity, absence of atmospheric drag, and improved propulsion system performance in the vacuum environment.

3.7.1.4 Walking Mode — Walking machines are characterized by complexity and by sensing and guidance requirements that are difficult to satisfy. Also, they are immobilized by soils that will support rolling vehicles of similar scale. Consequently, the walking mode is of questionable value for further development.

3.7.2 Primary Power

The selected primary vehicular power system is the fuel cell with a silver-zinc battery backup. This system will meet the power requirements, be suitable for mobile operation, provide water as an exhaust product, operate at low power density and fuel consumption, have good reliability, and will be compatible with other power supplies within the lunar base system.

3.7.3 Vehicle Dynamics

The principal factors affecting the dynamic behavior of the lunar vehicle will be its environment (gravitation field, soil conditions, surface contours, surface details) and the vehicle requirements (tasks, weight limitations, limiting accelerations, frequency ranges, limiting velocities, and limiting motions).

In the analysis, disturbances have been described in terms of axle motion rather than surface contours. One- and two-degrees-of-freedom models have been studied. Figure 3.7-3 illustrates the one-degree-of-freedom model and the assumed versine trajectory of the axle. Figure 3.7-4A and 3.7-4B show the two-degrees-of-freedom model. It is suggested that advanced concepts should be subjected to a detailed investigation, including computer programming of a mathematical model and physical model testing.

The design of the vehicle should ensure that slipping precedes overturning during the negotiation of curves. Figure 3.7-5 illustrates the limiting conditions during this maneuver.

Low power requirements and the lunar environment point to the choice of an electrical drive. Other advantages include high traction forces at low speed, and high acceleration torques for frequent start-stop conditions.

A comparison of a.c. versus d.c. motors shows the following advantages for the d.c. motor:

1) Greater margin of torque;

Figure 3.7-3
SURFACE EFFECTS MODEL

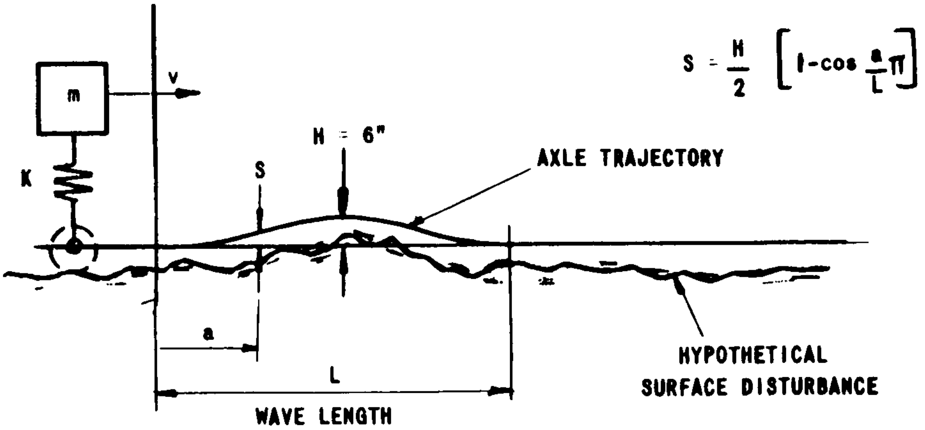


Figure 3.7-4
VEHICLE ACCELERATION VS VEHICLE VELOCITY
ONE MODEL AND DISTURBANCE

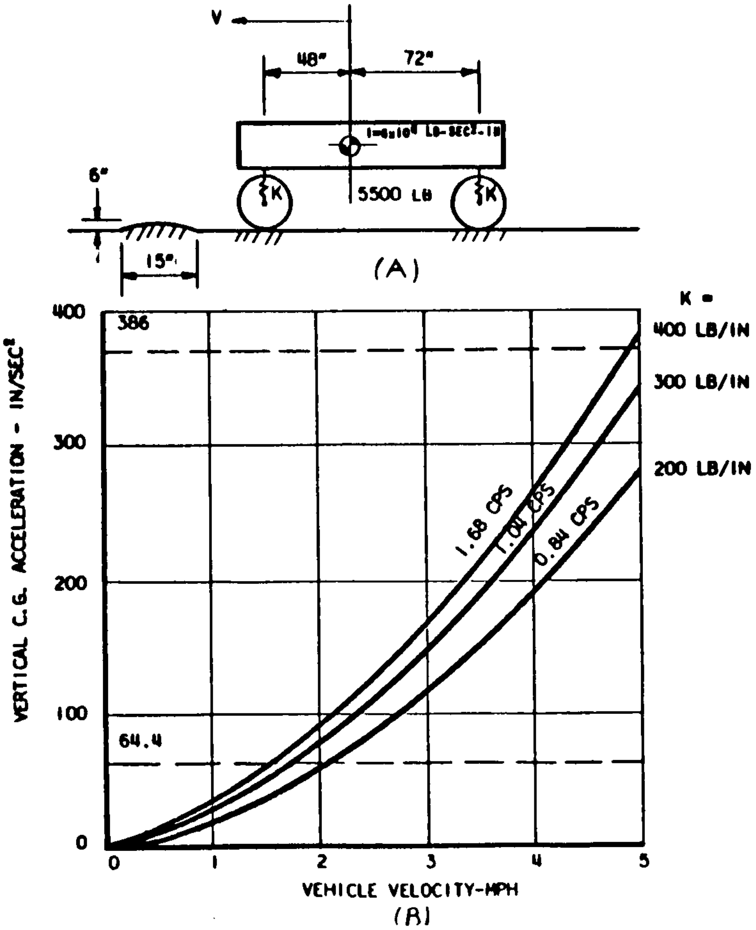
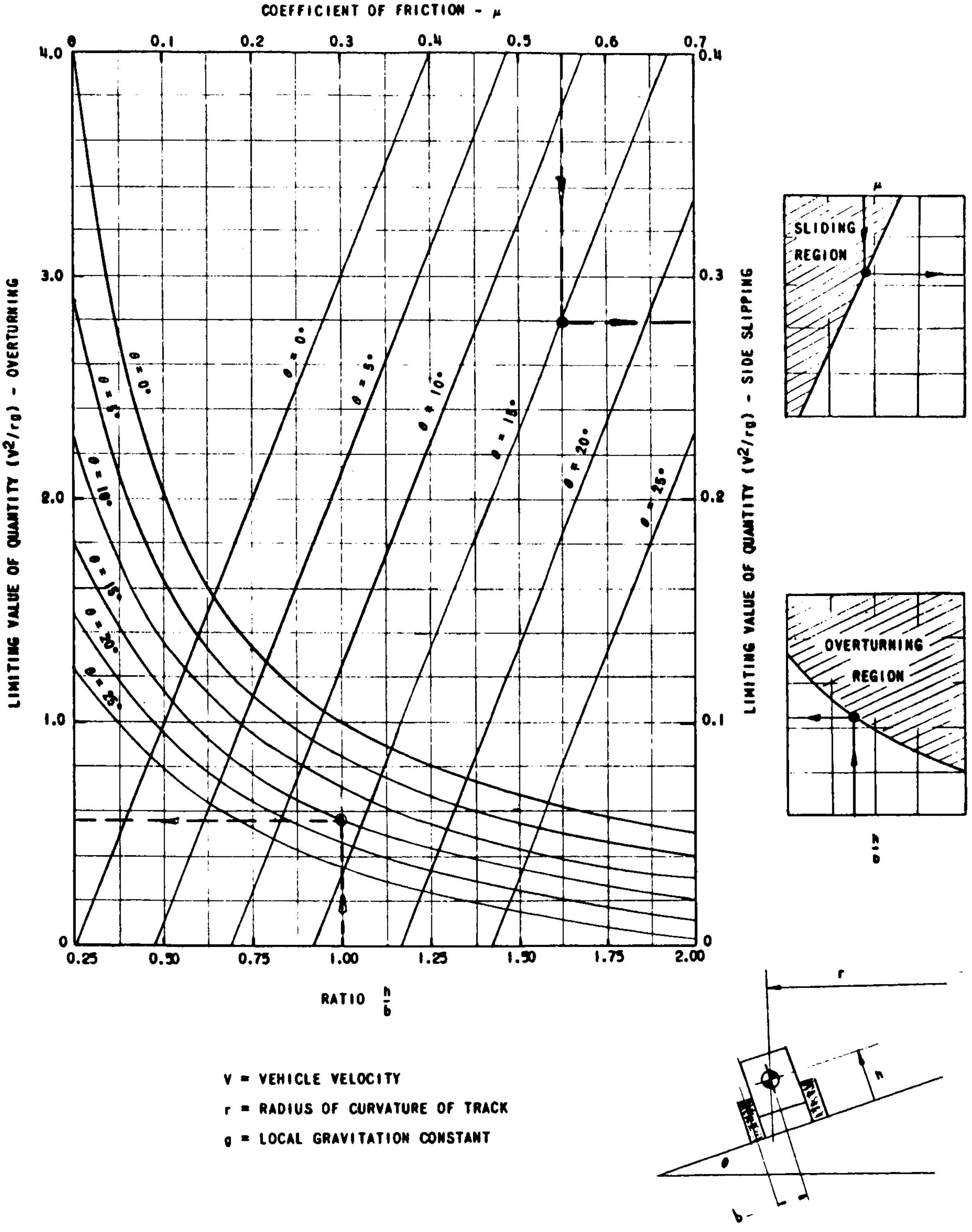


Figure 3.7-5

OVERTURNING AND SLIDING CHARACTERISTICS

VEHICLE TRAVELING ON INCORRECTLY BANKED CURVE



V = VEHICLE VELOCITY

r = RADIUS OF CURVATURE OF TRACK

g = LOCAL GRAVITATION CONSTANT

2) Probable compatibility with power supply;
3) Superior acceleration characteristics;
4) Fewer design restraints;
5) Simple speed control;
6) Greater horsepower per unit weight and volume;
7) Greater efficiency for wide load fluctuations.

The greatest advantage in d.c. vehicular control systems is achieved through the use of the controlled, gated-power input method because of its flexibility, versatility, and efficiency.

Figure 3.7-6 illustrates weight comparisons of a.c. and d.c. motors and controls.

Mechanical drive and steering investigations indicate that individual motors for each driven wheel are desirable with either Ackerman or skid steering control. Steering system choice, however, requires a more detailed quantitative analysis.

3.7.4 Structure

Estimates of LRV structural weights are based on the accelerations predicted for launching and landing, radiation protection requirements, meteorite protection, and internal pressures. An all-titanium capsule structure has been tentatively selected.

3.7.5 Life Support

A cabin atmosphere of pure oxygen at 4.0 psia was assumed. Oxygen requirements for surface vehicles will be 30 to 40 percent of the total life support oxygen requirement. Radiators will be the primary heat sinks. The cryogenic fuel supply, supplemented by evaporation of water or melting of ice, will supplement the radiators.

3.7.6 Construction Performance

Primary work functions of the LRV during the base construction period will be towing, powering light machinery, and some bulldozing operations.

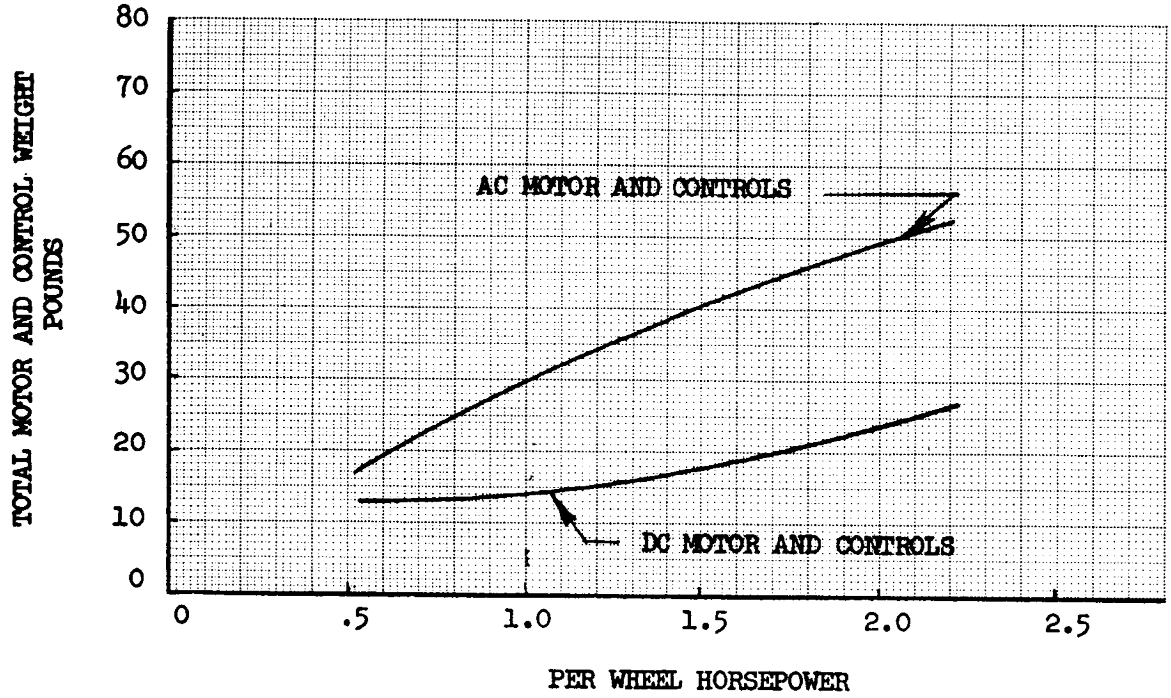
A parametric study of the requirements of a towing operation, as shown in Figure 3.7-7, shows that the application of power to all wheels provides superior performance. Bulldozing requirements were analyzed to provide design data.

3.7.7 Concepts for Future Consideration

Two large-scale surface contact vehicles are suggested for study. An increased

Figure 3.7-6

MOTOR AND CONTROL WEIGHT VS WHEEL HORSEPOWER

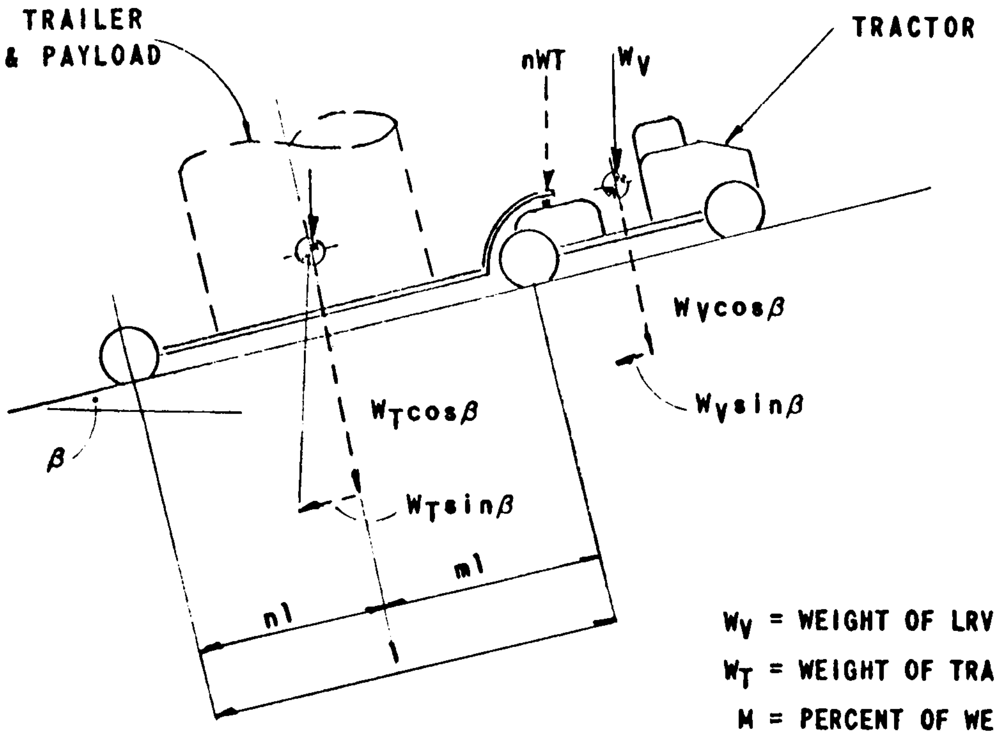


mobility, range, and crew capacity appears possible through these concepts. A combination surface-contact/flight system is also illustrated.

3.7.8 Mobility Modules

Mobility and work units are achieved by combining basic modules. A four-wheel vehicle is the basic module (V-1), as shown in Figure 3.7-8. Greater mobility can be achieved by adding the V-2 module (Figure 3.7-9). Construction tasks require attachment of module E-2, a construction tool kit.

Figure 3.7-7
LRV/SEMITRAILER GEOMETRY AND GENERAL EQUATIONS



W_V = WEIGHT OF LRV (OR TRACTOR)
W_T = WEIGHT OF TRAILER AND PAYLOAD
N = PERCENT OF WEIGHT ON TRACTOR
ϕ = SOIL FRICTION ANGLE

GENERAL EQUATIONS

- GRADE RESISTANCE: $R_G = (W_T + W_V) \sin \beta$
- ROLLING RESISTANCE: $R_R = 0.20(W_T + W_V) \cos \beta$
- GROSS TRACTIVE EFFORT: $H = \tan \phi (W_V + nW_T) \cos \beta$

$$H = R_G + R_R$$

- $n = \dfrac{(W_T + W_V)(\sin \beta + 0.20 \cos \beta)}{(\tan \phi \cos \beta) W_T} - \dfrac{W_V}{W_T}$

Figure 3.7-8
MULTIPURPOSE VEHICLE

V-1 (AMF)

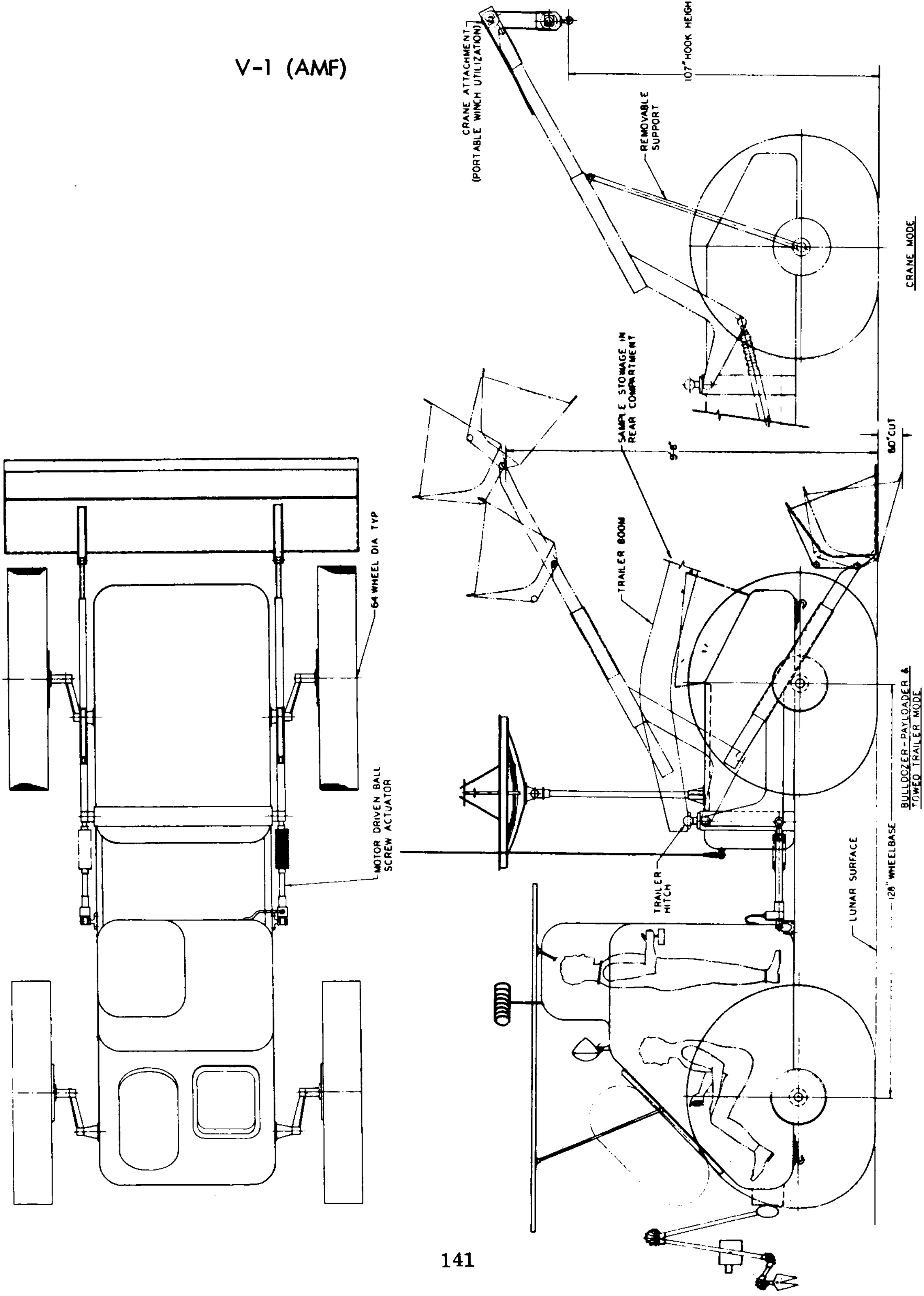
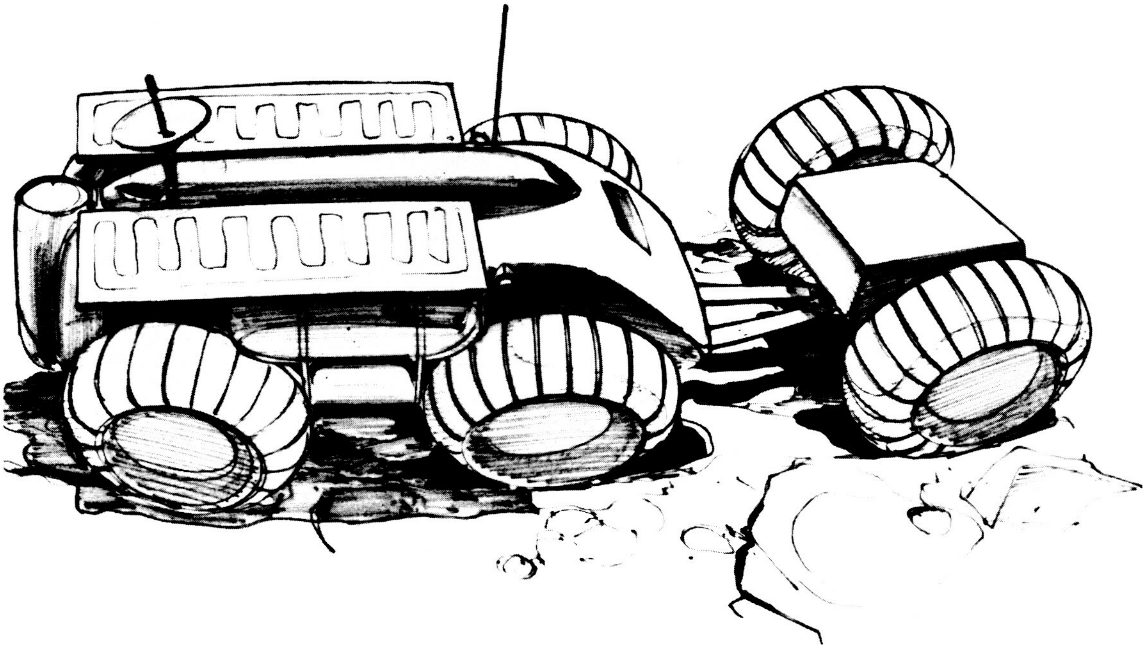


Figure 3.7-9
6x6 SEMIFLEXIBLE LUNAR SURFACE VEHICLE



FROM GMDRL DATA

3.8 FUEL SUBSYSTEM

3.8.1 Subsystem Analysis

Chemical fuels are required throughout the evolution of the lunar base as a source of energy for various power producers. Lunar Base 1, outposts of Base 4, shelter construction modules, as well as the lunar roving vehicles all use chemical fuels for their power producers. The chemical fuel selected is liquid hydrogen. Liquid oxygen serves as the oxidant.

In addition, the fuel subsystem includes oxygen and nitrogen used to provide base personnel life support. Water requirements will be included in this section since water is both the product of the hydrogen-oxygen reaction and the feed to the fuel regeneration plant.

3.8.1.1 Tradeoff Studies — The cryogenic tanks for Bases 1 and 2 are located in a compartment just below the working space of the lunar shelter. Consideration was given to insulating the walls, floor, and ceiling of the cryogenic tank compartment to reduce the amount of insulation necessary for the cryogenic tanks. Mass trade studies were made in which the insulation thicknesses on the cryogenic tanks and the floor, walls, and ceiling of the cryogenic tank compartment were varied. The results of this optimization study are given in Figure 3.8-1. A net savings in insulation mass of 16 percent is possible by insulating the walls, floor, and ceiling of the cryogenic tank compartment.

A mass trade study was made in which the inside tank diameter, tank insulation thickness, and amount of hydrogen boiloff were varied. The common consideration for each case was that there be a 220-pound mass of liquid hydrogen remaining in the tank after a 1-year unattended storage and minimum tank ullage equal to 10 percent. The condition of the liquid at the start of the unattended-storage year was assumed to be saturated liquid at 25°R. Because of the low vapor pressure of liquid hydrogen at 25°R the hydrogen tank was assumed to be pressurized to 1 atmosphere by means of a corrugated aluminum diaphragm installed between the liquid hydrogen and the ullage space, and helium gas introduced into the ullage space at the start of operations. For this study it was assumed that the transfer plumbing was disconnected, and that no heat-leak penalty would be incurred by the plumbing necessary for tank venting.

The results of the trade study are given in Figures 3.8-2, 3.8-3, 3.8-4, and 3.8-5. Figure 3.8-2 shows no net reduction in system mass if boiloff is allowed until the inside diameter of the tank reaches 62 inches.

Minimum system mass occurred at an inside tank diameter of 63 inches and a hydrogen boiloff of 15 percent of the original hydrogen content (see Figure 3.8-3). However, only 18 pounds is saved by allowing boiloff, and it is recommended that the hydrogen tank be unvented. Figure 3.8-4 shows the effect of insulation thickness on tank and insulation mass for nonvented hydrogen storage.

The effect of unattended storage time on the system mass of a 63-inch-inside-diameter, 220-pound hydrogen tank for various starting conditions is given in Figure 3.8-5. The transfer plumbing (when connected) was assumed to be thermally equivalent to three connections of 0.375- by 0.065-inch-wall aluminum tubing with 1-inch-thick Teflon washers inserted to reduce heat conduction. The curves in this figure show that, for nonvented storage of hydrogen, the hydrogen tank plumbing must be disconnected and the initial temperature of the hydrogen reduced to at least 31°R in order to store the hydrogen for a year without a severe weight penalty. Assuming no vent line plumbing heat-leak penalty, it is estimated that the use of vented tanks extends by only 1 month the permissible unattended storage time.

During 1-year unattended storage, the temperature and pressure of the cryogenic fluids will increase. Once the lunar base is occupied, the cryogenic tanks will be vented to either the fuel cells or life support system. The result of this venting will be to reduce appreciably the temperature and pressure of the cryogenic fluids. With proper fuel management, the pressure within the cryogenic tanks for the 3-month operational period should not exceed the pressure at the end of the year of unattended storage. The pressure and mass profiles for the hydrogen tank for the 3-month usage schedule expected for Lunar Base 1 are plotted in Figure 3.8-6. Estimated hydrogen use schedules for Lunar Bases 2, 3, and 4 are such that the tanks will be depleted in 3 months or less and that the tank pressure cycling will be less severe than that shown in Figure 3.8-6.

3.8.1.2 Results of Tradeoff Studies — The results of the optimization of fuel storage requirements are given in the following table:

SPHERICAL TANK REQUIREMENTS

Cryogenic Fluid	Tank Description			System Mass		
	Tank Diameter		Insulation	Tank Plus	Cryogenic	
	Inside (inches)	Outside (inches)	Thickness (inches)	Insulation (pounds)	Fluid (pounds)	Total (pounds)
Hydrogen	63.0	71.6	4.3	250	222	472
Hydrogen	57.8	66.0	4.1	215	167	382
Oxygen	63.8	65.2	0.7	67	4594	4661
Oxygen	60.8	62.2	0.7	64	4050	4114
Oxygen	49.2	51.4	1.1	51	2042	2093
Nitrogen	57.3	59.3	1.0	60	2367	2427
Nitrogen	30.1	33.5	1.7	51	300	351
Water		61.0	0	96	3664	3760
Water		53.3	0	64	2425	2489
Water		38.1	0	24	900	924

Figure 3.8-1

OPTIMIZATION OF TANK COMPARTMENT INSULATION

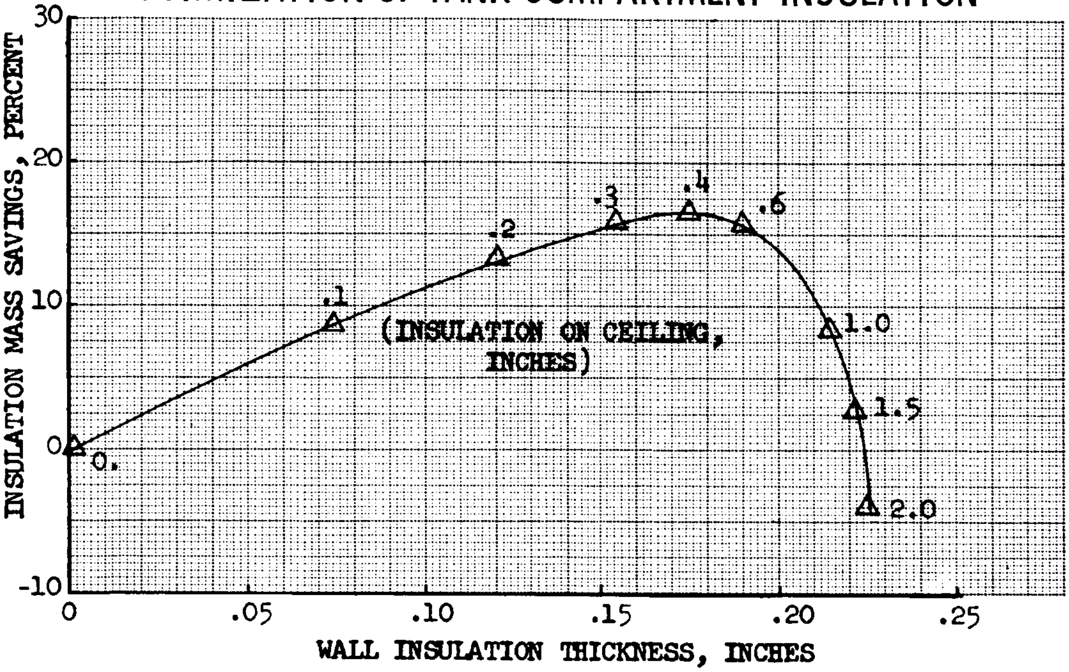


Figure 3.8-2

EFFECT OF VENTING HYDROGEN TANK STORAGE SYSTEM MASS

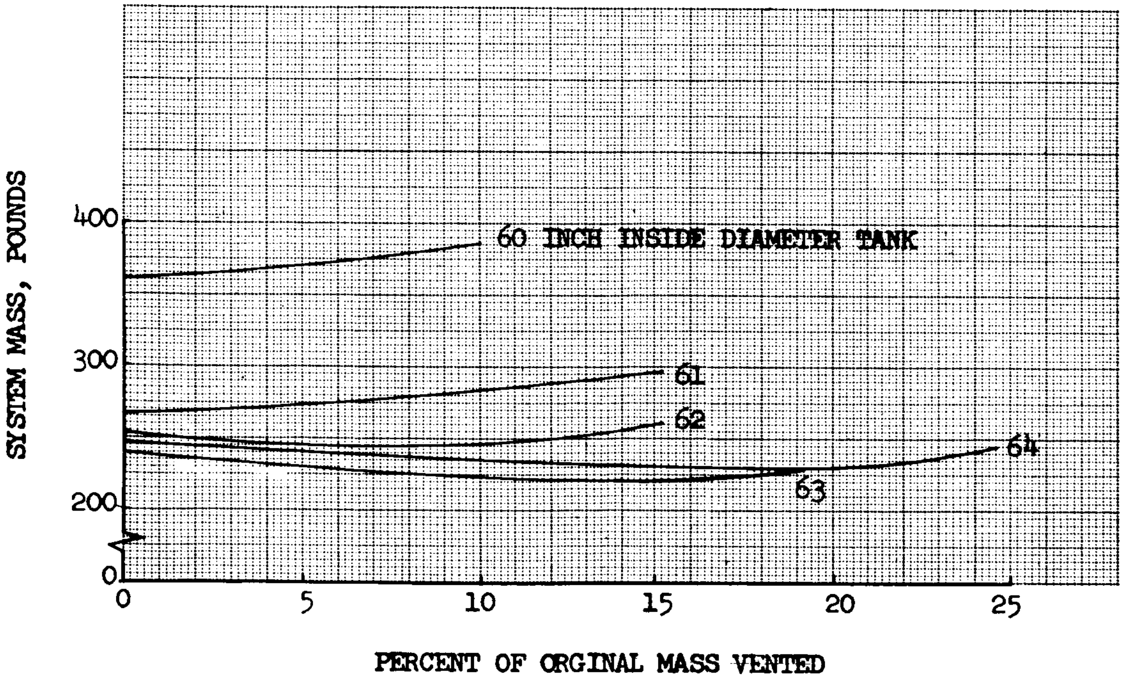


Figure 3.8-3

EFFECT OF TANK DIAMETER ON HYDROGEN TANK SYSTEM MASS

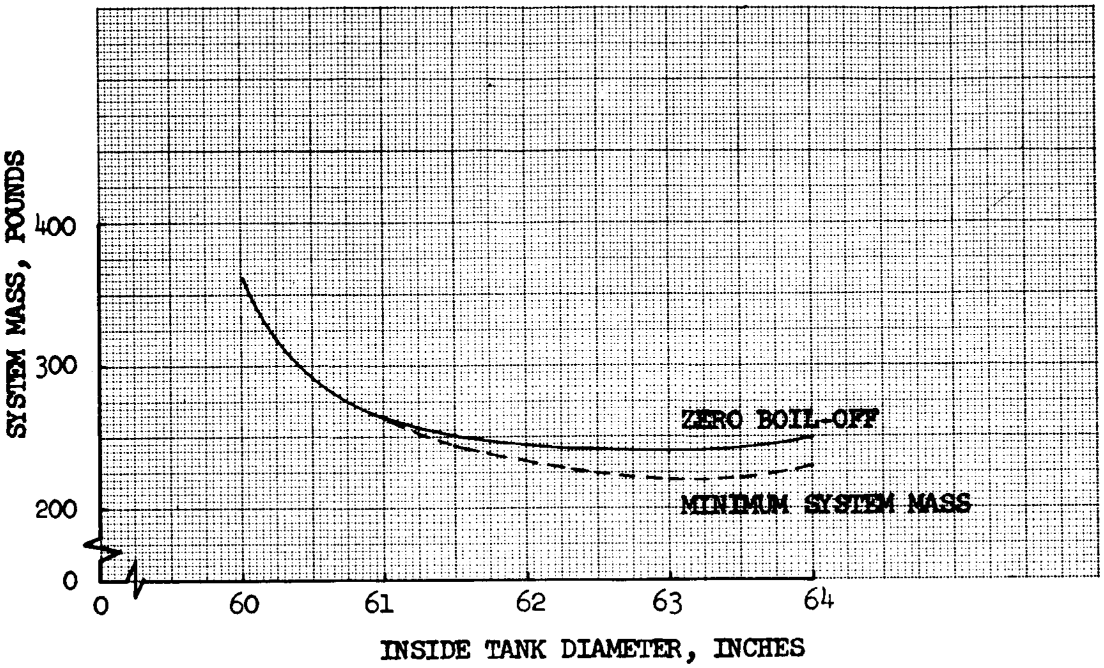


Figure 3.8-4

OPTIMIZATION OF HYDROGEN TANKAGE

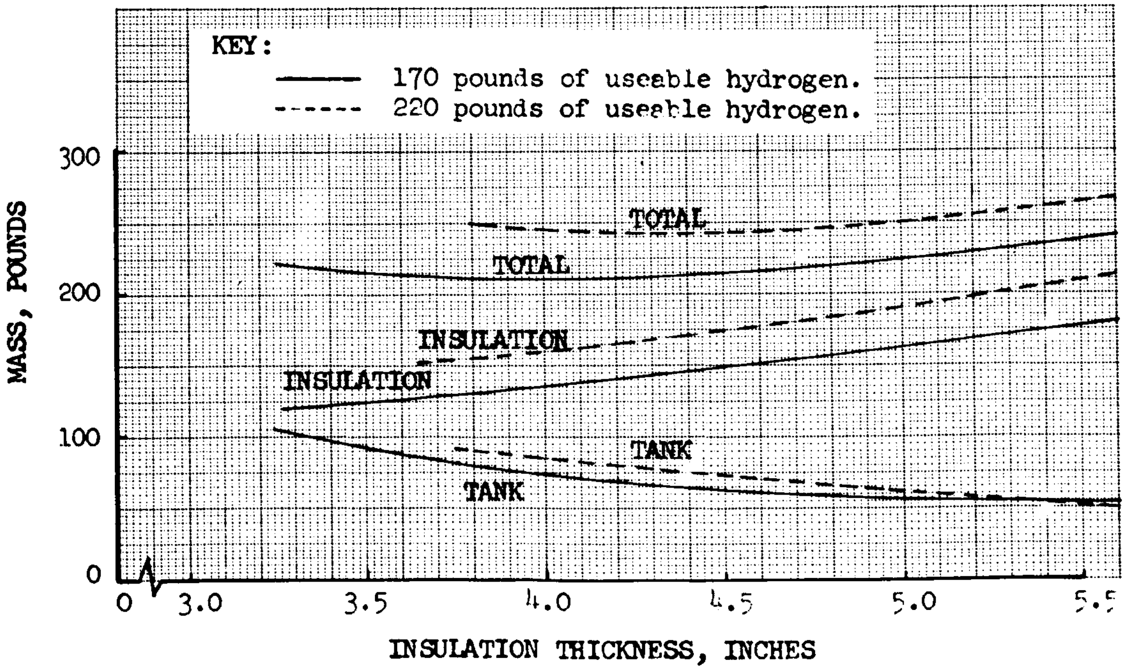
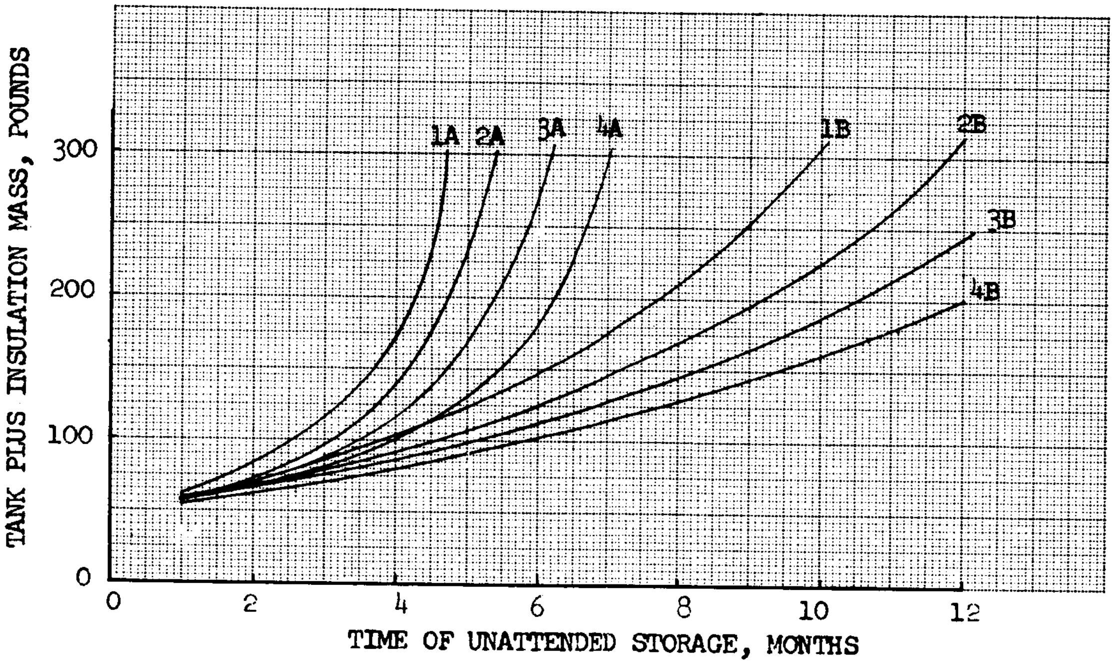


Figure 3.8-5

LIQUID HYDROGEN STORAGE

PENALTIES INCURRED AS A FUNCTION OF TIME

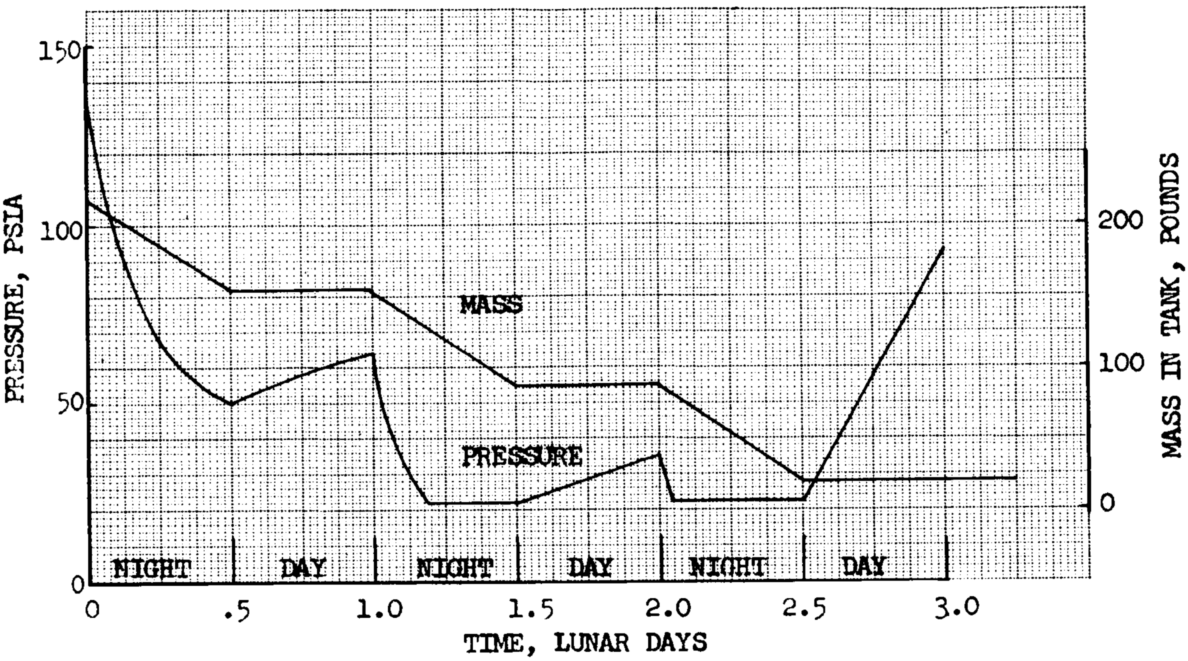


KEY: (Starting conditions of hydrogen)
1. Liquid at 14.7 psia (36.5°R).
2. Liquid at 5.2 psia (31.0°R).
3. Liquid at 1.07 psia (25.0°R).
4. Liquid and ice (50-50 by weight) at 1.07 psia (25.0°R).
A. Transfer plumbing connected.
B. Transfer plumbihg disconnected.

Figure 3.8-6

PRESSURE PROFILE FOR BASE 1 USAGE SCHEDULE

220-POUND LIQUID HYDROGEN TANK



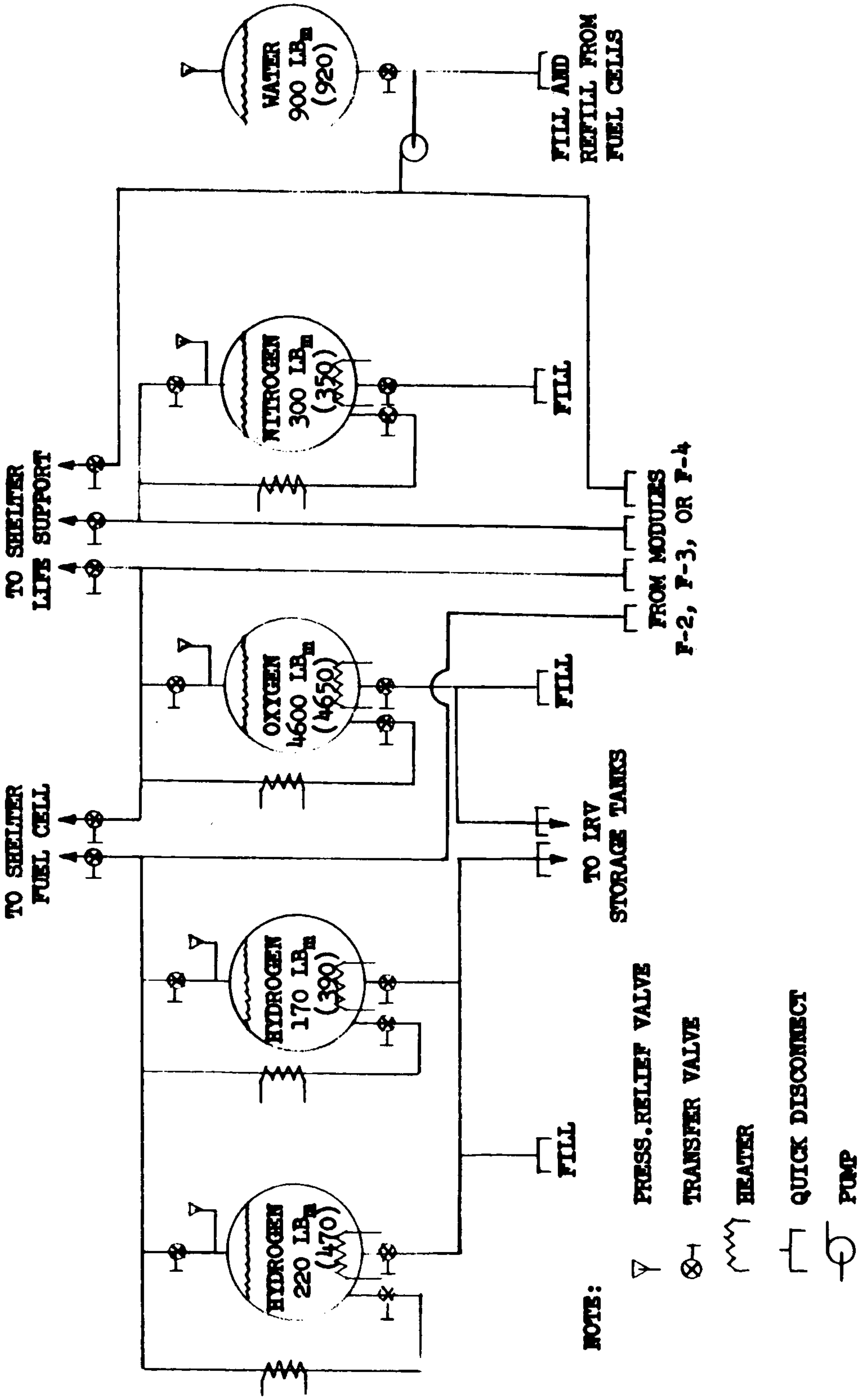
FUEL REGENERATION REQUIREMENTS

Amount Regenerated			System Mass			Volume
Liquid Hydrogen (pounds mass)	Liquid Oxygen (pounds mass)	Total (pounds mass)	Electrolyzer Plant (pounds)	Liquefaction Plant (pounds)	Total (pounds)	Electrolyzer and Liquefaction (cubic ft)
925	7405	8330	420	47	467	6

3.8.2 Fuel Storage and Transfer Module

The primary fuel storage and transfer module with storage capacity for the entire fuel requirements of Lunar Base 1 is shown in Figure 3.8-7. This module is used in all four lunar bases with additional fuel to meet total requirements being supplied in similar modules F-2, F-3, and F-4. The hydrogen and oxygen fuel regeneration module (F-5), designed by Allison Division, General Motors Corporation, is summarized in the preceding table, and shown in Figure 3.8-8. This module is used in Lunar Bases 3 and 4, requiring power supply from the central nuclear power supply.

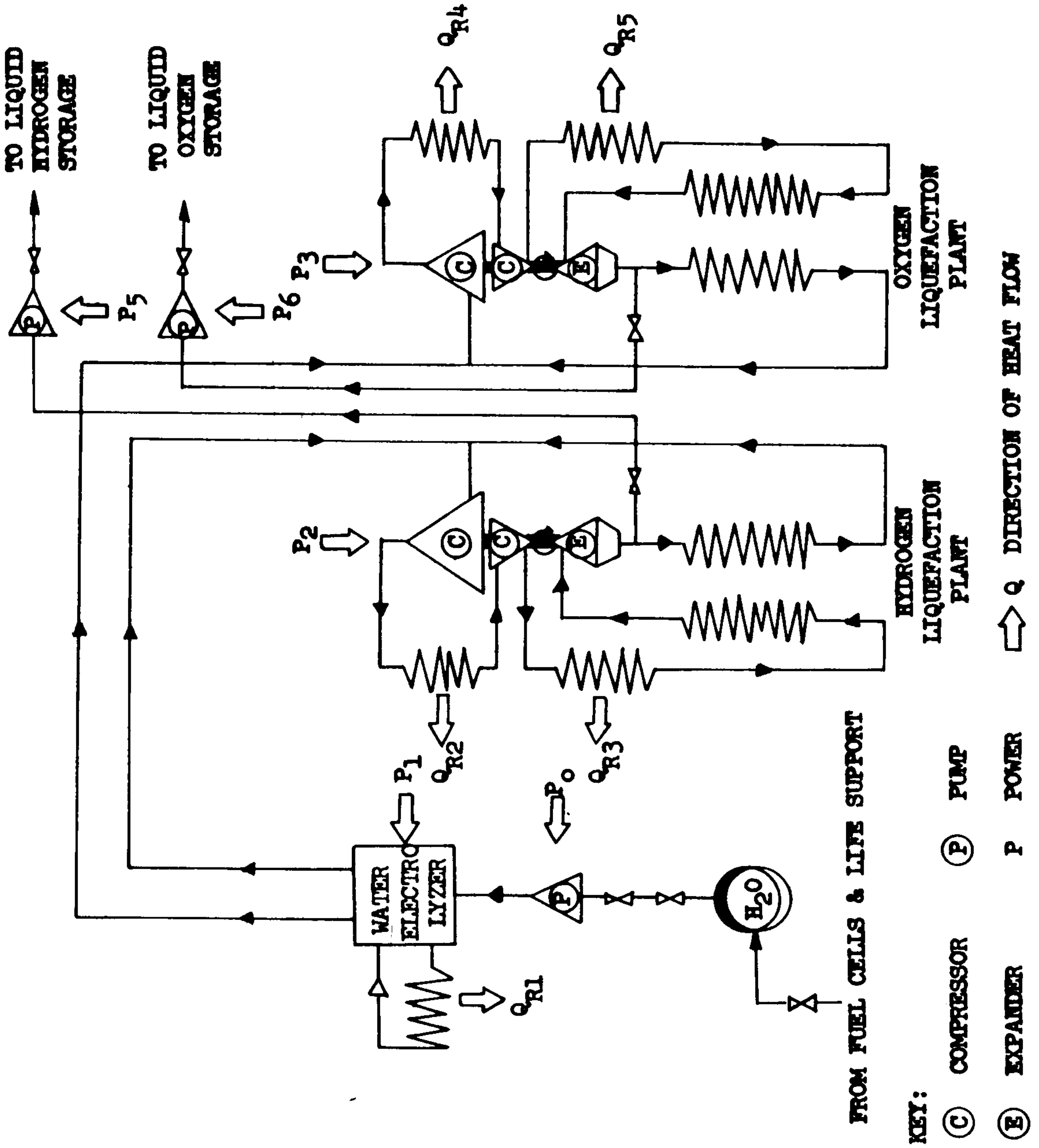
Figure 3.8-7
FUEL SUBSYSTEM MODULE F-1



FLUID MASS IS NOTED IN EACH TANK AND TOTAL TANK MASS IS IN PARENTHESIS

Figure 3.8-8

FUEL REGENERATION MODULE F-5



3.9 MAINTENANCE SUBSYSTEM

3.9.1 Maintenance Concept

A key concept of the entire lunar base implementation is reduction — or, ideally, elimination — of servicing or maintenance requirements. This concept is becoming increasingly common and successful on Earth for a variety of industrial products ranging from watches and small appliances to complete automobiles. The incentives for this approach are many times magnified when applied to operations on the Moon, despite the increased difficulty in meeting design goals. The necessity for maximum economy in the use of expendables applies even to such seemingly simple operations as lubrication, where the logistics investment in manhours and tools may be enormous relative to actual lubricant consumption.

Although "total reliability" without excessive redundancy may not be attainable, this goal, plus a modest fault-correction capability of the crew, has been chosen in preference to the opposite course of "total maintainability." Implicit in this goal is the elimination of preventive maintenance. With design for suitably high reliability, there should be no benefit — and only increased cost and risk — from disassembling or otherwise tampering with equipment that shows no evidence of failure or incipient failure.

With a few exceptions where a minor repair would restore a major module, such as in the case of a small leak in the pressure shell of a shelter structure, replacement at the module or submodule level is provided in lieu of repair, in instances where marginal reliability is indicated. Low-reliability designs are categorically eliminated.

3.9.2 Maintenance Modules

The highest degree of integration of a maintenance module would be a centralized unit comprising an environmentally controlled structure with doors suitable for receiving all equipment to be maintained; all necessary shop facilities, such as fixed work benches and tooling installations; all necessary powered or unpowered hand tools; a mobile work bench and tool chest; and a stock of all spare parts and standard shop items, such as fasteners, abrasives, solvents, lubricants, surface coatings, etc. An investment of this type does not appear necessary with the chosen doctrine of design for maximum reliability rather than for maximum maintainability.

The facility investments required for extensive maintenance can also be questioned on the basis of their effective utilization. The lunar mission should not be required to support a crew member on the basis of his skills in the various maintenance crafts. Normal crew selection would tend toward the choice of scientists with reasonable handyman talents, rather than scientifically inclined mechanics or repairmen.

Since most of the maintenance inventory will require environmental protection, and much of it would be used within the shelter, space will be provided for orderly stowage of maintenance gear in the normally pressurized volume. To make effective use of less-accessible spaces for infrequently needed items, the requirement of a unitized maintenance package is not recommended. To preserve the concept of maintenance modules, however, and to indicate the incremental requirements for the more advanced bases, the following weights (in pounds) are estimated.

ESTIMATED WEIGHTS OF MAINTENANCE MODULES

	Item	Weight
M-1	Spares and tools for each shelter	400
M-2	Construction equipment spares, tools, and additional shelter spares for Base 2	600
M-3	Additional construction equipment spares and tools for Base 3	400
M-4	Additional repair equipment, spares, and tools for Base 4	400

BASE EFFECTIVITY OF MODULES

	Base Number							
	1		2		3		4	
Module	Qty	Wt (Lb)	Qty	Wt (Lb)	Qty	Wt (Lb)	Qty	Wt (Lb)
M-1	1	400	1	400	2	800	3	1200
M-2			1	600	1	600	1	600
M-3					1	400	1	400
M-4							1	400
Total		400		1000		1800		2600

The maintenance inventory will consist of spares at the submodule or major component level, and the necessary tools for their installation. Since the task requirements are scaled to limited crew capability, the tools will be simple and basic in nature and, hence, multipurpose in application.

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GLOSSARY OF TERMS

AU	Astronomical Unit — average distance between Earth and Sun
Base Model	A specific example of a lunar exploration support system, connoting crew size, mission duration, and scope of exploration
Base Model 1	3 men, 3 months
Base Model 2	6 men, 6 months
Base Model 3	12 men, 12+ months
Base Model 4	18 men, 24+ months
Base Site	A specific example of a lunar base location, connoting surface and subsurface characteristics
Base Site A	5.6° N, 26.6° W
Base Site B	12.6° S, 2.9° W
Base Site C	40.9° S, 11.1° W
Boiloff	Amount of cryogenic fluid lost by venting to the surroundings
C-1	Communications module; also C-2, C-3, etc.
c.g.	Center of gravity
CRU	Combined Rotating Unit .
CSM	Command and Service Module of Apollo System
CTV	Crew Transport Vehicle — generalized reference to the manned elements of an Earth-Moon transportation system
ECS	Environment control system
EPUT	Events per unit time
F-1	Fuel supply module; also F-2, F-3, etc.
FIFO	First In — First Out: sequence of rotating crewman

IR	Infrared radiation
L-1	Life support system module; also L-2, L-3, etc.
LEM	Lunar excursion module of Apollo system
LF	Low frequency band communication system (30-300 kilocycles)
LH_2	Liquid hydrogen
LLV	Lunar logistics vehicle
LO_2	Liquid oxygen
LRV	Lunar roving vehicle — lunar surface mobility apparatus
LSS	Life support system
M-1	Maintenance module; also M-2, M-3, etc.
Module	A discrete embodiment of all or a portion of specified functional equipment
MTBF	Mean time between failures
N_2O_4-50/50	N_2O_4 oxidizer with 50% UDMH and 50% hydrazine fuel
NPSH	Net positive suction head: the hydrostatic head of liquid above saturation pressure required at the pump inlet to prevent cavitation
OWBU	One-way buildup
P-1	Power supply module; also P-2, P-3, etc.
parsec	Radial distance at which Earth's orbit subtends one second of arc
rem	Roentgen equivalent man: radiation unit
R.Q.	Respiratory quotient of man: ratio of carbon dioxide exhaled to oxygen consumed
Saturated Liquid	For the one component systems used in this study, liquid at the temperature of its boiling point

Saturated Vapor	For the one component systems used in this study, saturated vapor is the vapor in equilibrium with its saturated liquid
S-1	Shelter module; also S-2, S-3, etc.
S-band	Communication system frequency band between 2 and 3 kmc (10^9 cycles per second)
SFC	Specific fuel consumption
SM	Service module
Subsystem	The aggregate of equipment and materials which together performs all of a unique functional purpose, e. g., crew shelter, power generation, communications, etc.
Super-insulation	Linde SI-44 multilayer insulation consisting of 35 to 70 alternate layers of aluminum foil and submicron glass fiber paper with intervening spaces evacuated to a pressure of less than 1 micron of mercury.
V-1	Lunar roving vehicle
VHF	Very high frequency band communication system (30-300 megacycles)
VLF	Very low frequency band communication system (3-30 kilocycles)
UDMH	Unsymmetrical dimethylohydrazine
UV	Ultraviolet radiation
X-1	Mission support module: scientific experimental apparatus

SYMBOLS AND UNITS

A = surface area, square foot

A_s = surface area, square foot

a_1 = radius of monopole antenna element, meters

B_{rf} = radio frequency bandwidth, cycles per second

b/a = ratio of semiminor to semimajor axes of ellipse

b = footprint width, inch

c = crew capacity of spacecraft

C = sandwich structure core thickness, inch

C = velocity of sound in shield material

C_a/C_r = ratio of weight of cargo transported to number of crewmen, pounds per man

D = base diameter, foot

D = radiation dosage, rads

D = wheel diameter, inch

d = diameter of largest meteoroid protected against, inch

d = sandwich thickness, inch

Es = elastic modulus, psi.

F = communication system carrier frequency, mc

$F_>$ = meteoroid particle flux having mass m or greater, number/ft^2 second

f_m = modulation bandwidth, cycles per second

f_1 = coefficient in shield thickness to exposure ratio

G_R = receiving antenna gain, decibel

G_T = transmitting antenna gain, decibel

g = acceleration of gravity, ft/sec^2

H = gross tractive effort, pound

h = obstacle height, inch

h = sandwich structure thickness, inch

h = shelter height, foot

K = buckling coefficient, monocoque cylinder in compression

K_1 = power coefficient, LRV

K_2 = power coefficient, trailer

K_c = coefficient for compression

k = thermal conductivity, Btu in./hr. ft.^{2} °F

k = Boltzmann constant 1.38 x 10^{-23} joule 1 °K

k_ϕ = frictional modulus of deformation, lb/in.$^{n+2}$

L = launch rate, vehicles per month

L = quonset length, foot

L = wheel base, inch

L_{fs} = free space attenuation, decibel

L_s = total communication system losses, decibel

l = height of monopole antenna, meters

l = footprint length, inch

M = communication system power margin, decibel

m = meteoroid mass, slug

N = number of crewmen at base

N = $-\ln Po \approx 1 - Po$

$\bar{N}_{>}$ = meteoroid particle flux having mass m or greater number/ft^2 second

N_i = load per unit length of circumference, pound per inch

N_R = overall receiving system thermal noise power, decibel

n = number of particles

P_n = probability of n meteoroid strikes of mass m or greater

P_o = probability of no meteorite penetration

P_o = probability of not exceeding radiation dosage

P_T = transmitter power, kw

p = depth of meteoroid penetration, inch

p = pressure, psi

p_1, p_2 = load index ratios

Q = quality of a tuner

Q_{leak} = shelter heat leak, Btu in./hr ft^2 °F

R = radius of shelter, feet

R = range, nautical miles

R_α = meteoroid flux correction ratio

R_a = average of inner and outer radii, inch

R_b = bulldozing resistance, pounds

R_c = soil compaction resistance, pounds

R_G = grade resistance, pound

R_L = loss resistance due to ground system

R_R = radiation resistance, $18.3\,(\beta l)^2$

R_R = rolling resistance, pound

r = wheel radius, inch

r_s = single shield thickness, inch

S = crew stay time, month

$(S/N)_{in}$ = input signal-to-noise ratio

T = temperature, °F

T_s = total equivalent system noise temperature, °K

T_w = equilibrium wall temperature, °F

ΔT = temperature difference through cabin wall, °F

$\bar{t}$ = effective thickness of a sandwich structure, inch

t = insulation thickness, inch

t = thickness of material, inch

$\bar{t}$ = total shielding thickness, inch

t_{DS} = double shield thickness of aluminum, inch

t_s = shielding thickness, inch

t_{ss} = single shield thickness of aluminum, inch

t_x = face thickness, inch

V = velocity of meteoroid, ft/sec

V = volume, cubic feet

X_A = antenna reactance

W = weight per unit area, pound per square foot

W = weight, pound

W_B = ballast weight, pound

W_e = fuel and tank weight of power supply, pound

W_f = system fixed weight of power supply, pound

W_s = weight of shielding per unit surface area, pound per square foot

W_T = weight of vehicle, trailer and payload, pound

W_v = weight of vehicle, pound

X = crevice width, foot

Z = sinkage, inch

α = meteoroid environment parameter, slug/ft^2 second

α_s = solar absorptance

α_s = absorptivity

β = $2\pi/\lambda$, reciprocal meter

β = meteoroid environment parameter

β = slope of grade, degrees

γ = penetration parameter

γ = soil density, pounds per cubic inch

δ = solid angle "seen" by a point, steradians

δ = wheel deflection

ϵ = emissivity

ϵ_g = relative dielectric constant of lunar material

ϵ_o = permittivity of free space

θ = angle between sun's rays and normal to wall element, radians

θ = slope of grade, degrees

λ = performance indicator (drawbar pull/W_T)

λ = wavelength, meter

μ = coefficient of friction

σ = allowable stress, psi

σ = lunar surface conductivity mho/meter

σ_{cr} = critical stress, psi

σ_{cy} = allowable compression yield stress, psi

σ_{TU} = ultimate tensile strength, psi

ρ = material density, pound per cubic foot

ρc = core density, pound per cubic inch

ρm = density of meteoroid particle, pound per cubic foot

ρf = face density, pound per cubic inch

ρ_s = density of shielding, pound per cubic foot

ϕ = soil internal friction angle, degrees

NASA-Langley, 1964 CR-35