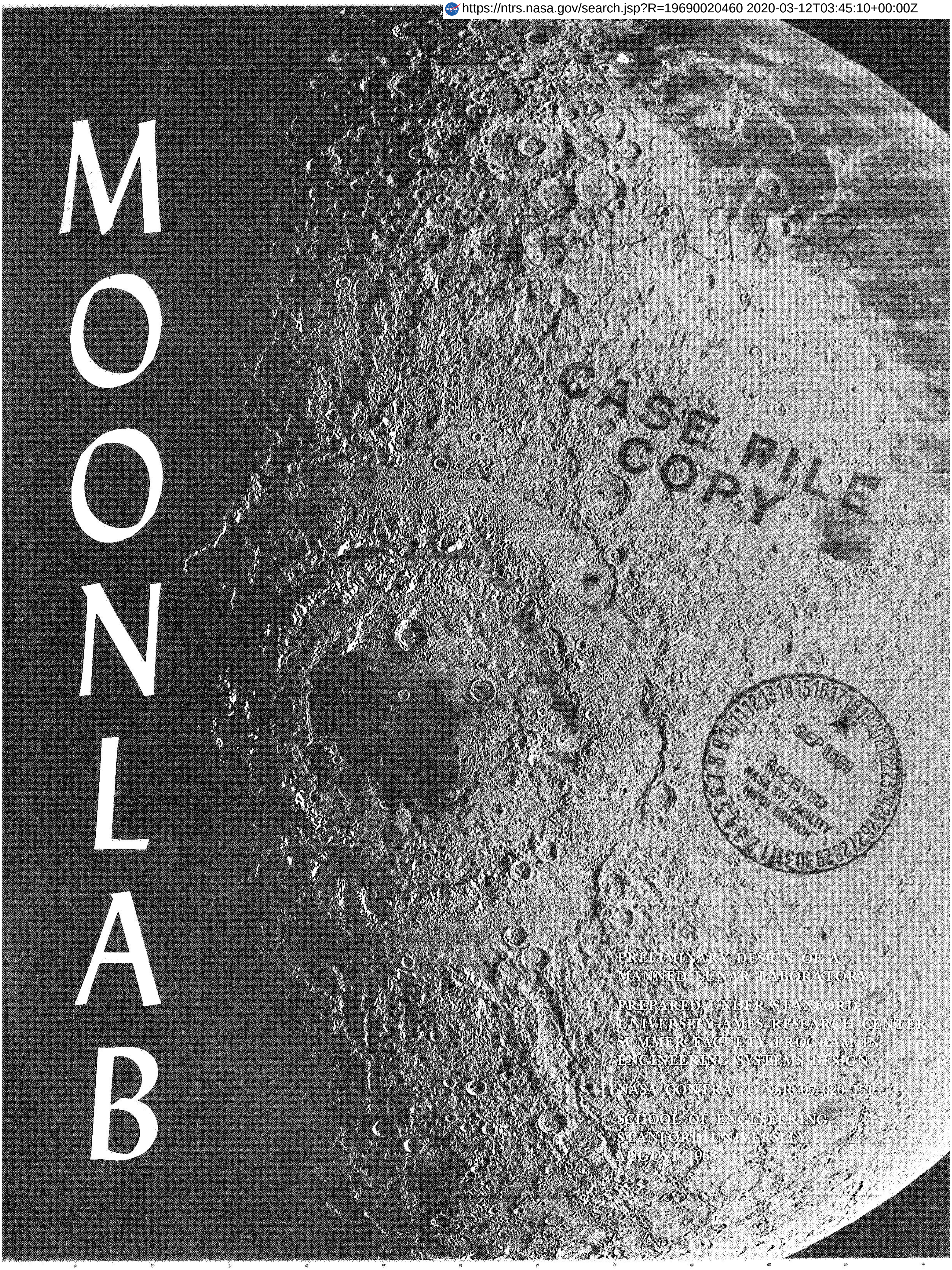

MOONLAB

N69-29838

PRELIMINARY DESIGN OF A MANNED LUNAR LABORATORY

PREPARED UNDER STANFORD
UNIVERSITY-AMES RESEARCH CENTER
SUMMER FACULTY PROGRAM IN
ENGINEERING SYSTEMS DESIGN

NASA CONTRACT NSR 05-020-151

SCHOOL OF ENGINEERING
STANFORD UNIVERSITY
AUGUST 1968

N69-29838

MOONLAB

A Study by the Stanford-Ames Summer Faculty Workshop in Engineering Systems Design

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June 24 - September 6, 1968

PREFACE

The problem originally assigned to the participants in this study was the design of "a semi-permanent lunar surface observatory." Although real and exciting, this was an extremely large problem. It was necessary for the participants to consider such factors as national goals, the U.S. space program, and the advantages of manned and unmanned space exploration, in addition to the many technical considerations required to reach the final design concept. Factors such as the Vietnamese war, poverty issues, urban problems, and general concerns about the levels of public debt and spending were uppermost in the minds of the participants and tended to make major design decisions more difficult.

Because of concern with overall national expenditures, a sizeable amount of effort was expended in cost-benefit analysis. Unfortunately, when benefits are primarily scientific knowledge, a rigorous cost-benefit analysis is extremely complex, if not impossible. All participants agreed that science in general has been a profitable investment for the U.S. and for the world. However, attempts to quantify benefits from specific investments proved frustrating.

The decision to include man in the lunar observatory was made early in the program. Human intelligence and skills are essential to accomplish the scientific investigations upon which the mission is based.

The task of defining the scientific objectives which become the MOONLAB mission was not simple. An important part of the mission-definition work was the review of a multitude of experiments suggested by the country's scientific community as being candidates for a lunar mission. The study group found that these were predominately in the physical sciences. Groups of biological and behavioral science experiments were added. The task of ranking the candidate experiments was difficult because measures of scientific merit, if they exist at all, are difficult to quantify.

Once the mission and its objectives were defined, the design of MOONLAB proceeded quite smoothly. As an exercise in multi-disciplinary communication, the study was successful. As the design evolved the areas of parametric conflict became apparent and resolution by tradeoff was accomplished where possible. This report represents the endpoint of the study. Part I discusses the criteria and assumptions used in the design and the evolution of MOONLAB up to 1985. Part II describes MOONLAB as it appears in 1985. Part III discusses prospects for MOONLAB after 1985.

FORWARD

This report presents the results of a preliminary design study undertaken in the summer of 1968 by a group of twenty visiting professors at Stanford University and Ames Laboratory as a part of the NASA-ASEE Engineering Systems Design Summer Faculty Fellowship Program.

The primary purpose of this study was to acquaint the participants with the educational methods in space systems engineering used at Stanford in the hope that they would introduce similar techniques at their home universities. A second purpose was to acquaint the participants with NASA activities in space technology and research in order to identify areas of importance to engineering students both in coursework and in graduate research. A third purpose was to perform a preliminary design of a Lunar scientific laboratory.

For the purposes of the study, the participants were divided into three working groups. Each group was given a Stanford-Ames advisor. A project manager was chosen to oversee the overall design objectives and to coordinate the three groups' activities; each group chose a group leader. In order to give more of the Fellows a chance to participate in the direction of the project, the management responsibilities were rotated at the beginning of each phase of the study.

The three project phases were as follows:

I	June 24 - July 24	Definition Phase	General background material was acquired and realistic alternative solutions were defined.
II	July 24 - August 16	Selection Phase	Best approaches were selected from the various alternatives.
III	August 16 - September 6	Completion Phase	Detailed calculations were completed and the final presentation and report were prepared.

During the study, lectures and discussions on topics pertinent to the design objectives were presented. The speakers and their topics are listed below:

Richard Allenby NASA headquarters	NASA Post-Apollo Lunar Exploration Plans
Harold Mazursky USGS	Geology and Geophysics of the Moon
Jack Green McDonald Douglas Co.	Lunar Exploitation
Harold Hornby NASA/Ames Research Center	Lunar Delivery Systems
Julian Allen, Donald Gault, William Quaide NASA/Ames Research Center, and Leonard Jaffe Jet Propulsion Laboratory	The Lunar Surface
Jack Kinsey USN	Psychiatry and Habitability
Hermann Schaeffer USN	Radiation Shielding
Douglas Grahn Argonne Labs	Radiation Damage to Humans
Jacob Shapira NASA/Ames Research Center	Closed Ecological Systems
Doris Calloway University of California	Nutrition
Steward Johnson USAF	Lunar Structural Design
Gordon Auguson NASA/Ames Research Center	Astronomy
Emmanual Roth Lovelace Foundation	Environmental Physiology and Optimization of Human Performance
Paul Miller NASA Headquarters	Nuclear Power
Rodney Johnson NASA Headquarters	Manned Lunar Operations
Cyril Ponnamperuma NASA/Ames Research Center	Exobiology

The study participants and advisors are indebted to these speakers for the time and effort they spent in preparing and presenting a uniformly outstanding series of lectures. The talks contributed immensely to the knowledge of the class and the success of the study.

As director of the Stanford portion of the program, I would like to thank all of the NASA, university, and industry people who participated in the various informal discussions and criticisms which helped form this report. I would like to thank NASA/Ames Research Center for its hospitality and for the enthusiasm it has shown for the program. I would like to thank Linda Lloyd and Betty Griffiths, who contributed truly outstanding secretarial help to the program. Without their attention to detail, organizational competence, consistent good humor, coffee, and mini-skirts, the summer would have been much less successful. I would like to thank Robert Wilson and Jack LaPatra for an excellent job of editing this report and Margie Watts for a beautiful job of organizing and typing. I would like to thank Professor Peter Bulkeley of Stanford for the time and energy which he spent in acting as an advisor to the group. A special note of thanks goes to Dr. John Billingham, my NASA/Ames Research Center counterpart, for the many hours he spent on this program above and beyond his busy schedule, for his many stimulating technical contributions, and for being an extremely pleasant person to work with. Lastly, I would like to thank the Faculty Fellows who participated in this project. I hope that they enjoyed the summer as much as I did and benefited sufficiently from the program to repay them for the many hours of work which they contributed.

J. L. Adams

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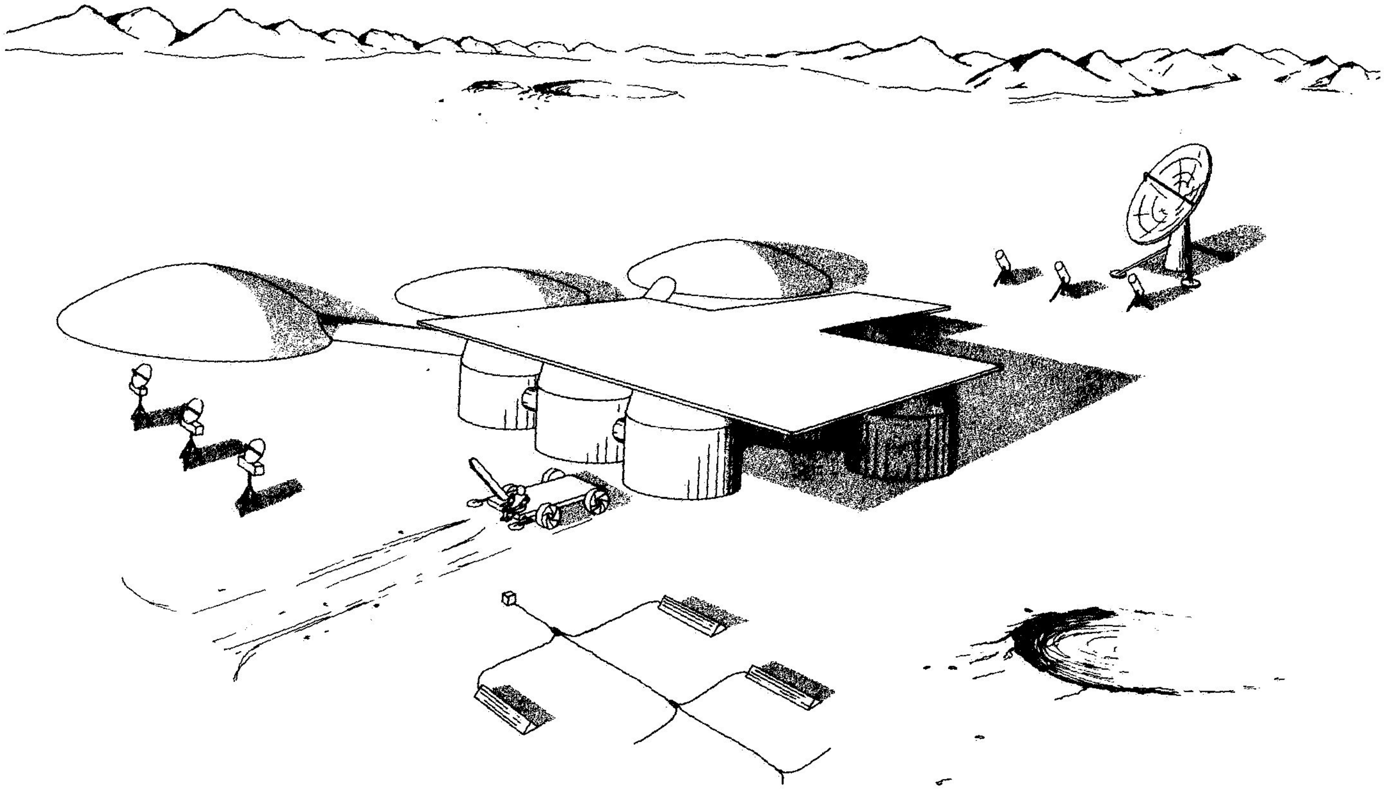

MOONLAB

Part I - DESIGN CRITERIA AND PROGRAM EVOLUTION

Chapter 1

DESIGN SUMMARY

1.1 MOONLAB Site

The MOONLAB is to be built in the crater Grimaldi, a "young" crater near the west limb. The site was chosen primarily for its suitability for astronomical observation. There are, moreover, nearby selenological features ranking high on the list of scientific curiosity.

Grimaldi is just south of the lunar equator, a location characterized by extremes in thermal conditions. The polar regions are much more favorable from thermal considerations, but were rejected on the grounds of poor astronomical promise and unfavorable abort capability and plane change requirements in those phases of the program where lunar orbit rendezvous will be used.

1.2 Evolution

The period from 1970 to 1985 will be one of hardware development and base evolution, with the first launch scheduled for 1976. The early launches, carrying three men for periods of 90 to 180 days, will carry out site preparation, preliminary construction, and data gathering on those experiments necessary to establish final design parameters. Intermediate launches will include the first shelter units, with emplacement and interconnection carried out as the shelters arrive. The launch schedule calls for a total of 37 launches through 1985.

The individual shelter units will, during the evolutionary period, have self-contained life support and power generation equipment. These two functions will eventually be centralized as deployment of solar energy converters and construction of the lunar farm permit.

Scientific investigation beyond construction parameter studies will commence early in the evolutionary period. The results of these early studies will have a considerable influence on the post-1985 lunar exploitation activities.

The evolutionary buildup schedule is governed in large part by such factors as hardware development times, launch rate limitations at Cape Kennedy, and the need to avoid extremes in the annual dollar budgeting of the program. Evolution cost has been determined to average 1.15 billion dollars per year.

1.3 Scientific Instruments

The principal scientific instrument of the MOONLAB will be the inquisitive human being. His judgment, his ability to observe objectively, his faculty for deduction, speculation, and extrapolation have yet to be reproduced in an inanimate instrument.

The MOONLAB scientists will be aided in their observations by a one-meter (40-inch) optical telescope in 1985. A 2.5-meter (100-inch) optical telescope may be added in the post-1985 years. Additional instrumentation will parallel equipment available on Earth for measurements in the many scientific areas.

Not the least of these measurements will be made upon the principal instrument, man himself. His mental and physical responses to prolonged low pressure, low gravity, and the stress of long duration confinement will answer many existing questions and raise many new ones.

1.4 Personnel

The MOONLAB staff will consist of 24 scientists and engineers who will carry out scientific and technological investigations in such areas as astronomy, biology, exobiology, human resources, agriculture, psychology, sociology, selenology, selenophysics, and particles and fields.

Individual staytime for staff members will range from 3 to 24 months. The longer staytime is highly desirable, since it will reduce the number of required yearly personnel rotation launches and hence the cost of maintaining the lab.

1.5 Life Support and the Lunar Farm

Perhaps the most novel aspect of the proposed MOONLAB will be its life support system. The system will be virtually "closed" except for water and gas makeup required to balance leakage. CO_2 and O_2 balances will be maintained by photosynthesis in the lunar farm, which will concurrently produce vegetable foodstuffs for the caloric requirements of the staff.

The growing areas will be enclosed by three inflatable structures and the top deck of one of the eight cylindrical modules. The inflatable bags will be held in lenticular shape by stiffening toroids at their peripheries. Sunlight will enter the growing area through the transparent window of each farm structure.

The MOONLAB atmosphere will be circulated through the farm enclosures for gas exchange and conditioning. Water transpired by the leaf surface will be condensed in a heat exchanger, yielding potable water and effecting rejection to cold space, through external radiators, of the considerable heat load in the farm areas.

Water and nutrients will be supplied to the farm soil in the form of diluted urine and processed fecal matter, thus closing the waste loop.

Principal crops will be high-protein grains and grasses selected to fit the fourteen-day growing season as annuals, perennials, or biennials. Some of these crops will grow to harvest in 14 sunlit days. After mowing, their roots will survive deep freezing, allowing that portion of the farm to be "shut off" for the lunar night period. One of the farm structures may be space-heated during the night to avoid freezing, allowing, if desired, the raising of biennials without cold damage to the dormant leaf.

The success of the farm as the keystone of the life support loop, is assured only if gastight inflatable materials and sealants can be developed. Also requiring careful development is a window material and structure that will have desirable optical/thermal properties. Methods for leaf processing and preparation of nutrient extracts must be developed so that palatability is not a problem. Two years is a long time to live on a nutritionally perfect but tasteless, formless, colorless, and unesthetic diet.

1.6 Shelter

The principal parameters and/or constraints encountered in the design of the lunar shelter include internal pressure, temperature extremes, protection against ionizing radiation and meteoroid impacts, the dynamic structural loading of launch and landing, and the man-hour construction load on the lunar surface. These factors interact directly with weight, size, and cost.

The shelter as designed will consist of eight habitat/work-area modules connected by short tunnels of inflatable rigidized material (Fig. 4-1). The modules will be completely prefabricated on Earth and configured to fit atop a standard, direct landing lunar descent stage. They will be cylindrical in shape, approximately 6 m in diameter and 9 m high. Raceways in the tunnel floors will house plumbing, power, and gas ducting.

Deployed over the eight-module cluster will be a flat shield, acting both as a meteoroid bumper and a heat moderator. One of the eight modules will be further shielded by a sleeve-contained jacket of lunar soil; this module will serve as the solar flare radiation shelter.

1.7 Power and Communications

Solar cells, solar thermionic converters, H_2-O_2 fuel cells, and a water electrolysis plant will be used to form a regenerative central power system for the MOONLAB. During the 336-hour lunar day, solar conversion will power the lab operations and the electrolysis plant. Cryogenic storage of H_2 and O_2 electrolysis products will be sufficient to power, by fuel cell conversion, all required lab operations during the ensuing 336-hour lunar night.

Electrolysis and cryogenic storage capacities are determined by the lunar night power load. Because of cascaded conversion inefficiencies, every nighttime kilowatt requires four to five kilowatts of solar conversion capacity. Due mainly to emergency life support system requirements and the nighttime heating load, night capacity could not be kept below 40 kW.

Daytime capacity may be considerably larger because of direct connection to solar converters. The bulk of scientific work requiring heavy power, such as deep drilling, will be scheduled for the lunar day.

Should rockbound lunar water be found, power for (daytime) crushing and roasting may be obtained by deployment of additional solar conversion modules. The availability of water would also require additional electrolysis capacity for producing roving and flying vehicle fuels. It is safe to say that unless lunar water is found, excursions in the lunar flying vehicle will be infrequent since the H_2O reaction product of the cryogenic thrusters will not be recoverable.

The literature on nuclear reactor power systems development for space applications indicates that presently contemplated systems have a design life of from one to two years. It is felt that for extended semi-permanent missions such as the MOONLAB a design life of at least five years is desirable or, alternatively, designs and methods by which nuclear fuel elements may be replaced with a minimum of labor and radiation exposure.

Communications will include voice, TV, and data channels. A traverse party will be kept in constant voice communication with MOONLAB by line-of-sight relay links. Communication with earth will be constant, requiring at least three stations spaced evenly on Earth's surface.

Some data reduction and processing will be done with the MOONLAB's computer, with subsequent relay to earth. It is anticipated that the MOONLAB scientists will have readily available channels (voice and picture) for consultation with their earthbound colleagues and families.

1.8 Mobility

Vehicle landing sites will have to be dispersed about the MOONLAB area for safety reasons. This decision requires means for moving such large and heavy loads as the shelter modules over considerable distances. Collection and transfer of large volumes of lunar soil will have to be done to charge the lunar farm and to fill the shield sleeve of the radiation shelter module. These functions will be performed by a multipurpose vehicle combining drag, crane, backhoe, and cargo capability.

Much of the selenological and selenodisic investigation will require large traverses of men and equipment about the Grimaldi site. Surface transportation for these distances over the anticipated terrains has been judged to be hazardous and impractical. Two three-man flying vehicles will be available for these traverses, each with a maximum one-way range of 800 km. The second of these vehicles is required for back-up and rescue purposes.

1.9 Lunar Exploitation

Exploitation of the Moon involves utilization of the unusual properties of low gravitational forces, high vacuum, large temperature variation from night to day, and radiation availability (thermal, galactic, solar flare). Thus, vacuum technology and cryogenic technology, application of surface chemistry and physics and utilization of particle physics will be possible MOONLAB activities. Gravity, magnetic field effects, and thermal solar energy will also be utilized where possible. Lunar soil and rock may serve as the source of water and elements such as silicon and its compounds.

1.10 Weight and Cost

The total weight of evolution phase launches will be 276,000 kg. Program cost to 1985 will be 17.4 billion dollars. Post-1985 costs will be largely a function of the personnel rotation schedule and the availability of lunar water. A six-man personnel launch will cost about 400 million dollars, a cargo launch about 325 million dollars.

Chapter 2

OBJECTIVES AND BENEFITS

2.1 Background

With the exception of twentieth century warfare, no single project in history has been as expensive as the manned conquest of space is proving to be. The ability of the United States of America to accomplish this conquest is not at issue. The question is simply whether the United States should now or in the future pay the price.

Why go to the Moon? What is our purpose? After considerable discussion, the objectives of developing a lunar laboratory or base were classified into the following broad categories:

(1) Advancement of science,
(2) Advancement of technology,
(3) National prestige, goals, and security,

As with any venture, MOONLAB must justify the enormous quantity of human talent and economic resources required for its implementation. However there is no benchmark by which we can extrapolate the value of having conquered an extraterrestrial body. To be qualitative is difficult, to be quantitative is virtually a pipe dream. For an engineer this is a frustrating situation.

To put an objectives-benefits analysis of the proposed program into perspective it is worthwhile to sketch the history of the national objectives of the space program. The earliest list is contained in the first report of the President's Science Advisory Committee (PSAC). This committee was formed in late 1957 in the wake of Sputnik I and at that time was reacting largely to the challenge of that event. It listed "four factors which give importance, urgency, and inevitability to the advancement of space technology,"

> "The first of these factors is the compelling urge of man to explore and to discover, the thrust of curiosity...
>
> "Second, there is the defense objective for the development of space technology...

> "Third, there is the factor of national prestige...
>
> "Fourth, space technology affords new opportunities for scientific observation and experiment which will add to our knowledge and understanding of the earth, the solar system, and the universe." [1]

Interesting and significant shifts can be ascertained from a January 12, 1961, statement, "Report to the President-Elect of the Ad Hoc Committee on Space." [2] As discussed by Golovin [3], "National prestige" now leads the list, "the compelling urge of man to explore and to discover" has been omitted, and the following objectives have been introduced:

(1) Practical civilian applications,

(2) "Exciting possibilities for international cooperation... particularly in fields of communications and in the exploration of our solar system."

On April 12, 1961, the Soviet Union placed the first man into orbit. Six weeks later, on May 25, President Kennedy proposed the expansion of the nation's space effort with the goal of a manned lunar-landing during the decade of the 1960's.

A more recent analysis of the goals of the United States space program is contained in the February 1967 PSAC report, "The Space Program in the Post-Apollo Period." The principal objectives enunciated were

(1) Leadership in space,

(2) Practical uses of space, and

(3) Space science and exploration.

With each objective is included a discussion of the associated benefits in broad, qualitative terms. The possibility of a quantitative cost-benefit analysis is discounted: "Nonetheless, the scale of costs in the present Apollo program or in other manned endeavors of similar magnitude cannot be proved commensurate with the direct benefits to be derived from them in the future." [4]

Additional "indirect benefits" also considered by the report are

(1) Technological excellence,

(2) National self-confidence, and

(3) A peaceful space posture and international cooperation.

Having considered the progress, history, and rationale of the United States space program, the February 1967 PSAC report contains the recommendations summarized in the following paragraph:

> "Therefore, the Panels favor a balanced program based on the expectation of eventual manned planetary exploration, integrating manned and unmanned efforts to arrive at the following five major objectives:
>
> 1. A limited but important extension of Apollo in order to exploit our anticipated capability to explore the Moon.
> 2. A strongly upgraded program of early unmanned exploration of the nearby planets on a scale of time and effort consistent with the requirements for planning future manned expeditions.
> 3. A program of technology development and of qualification of man for long duration space flight in anticipation of manned planetary exploration.
> 4. The vigorous exploitation (by all appropriate agencies of Government) of space applications for national security and the social and economic well-being of the Nation.
> 5. The exploitation of our capability to carry out complex technical operations in near Earth orbit (and on the Moon) for the advance of science, particularly astronomy." [4]

The following more detailed statement concerning lunar exploration was also included as part of the February 1967 PSAC report:

> "Recommendations.--In the period after the initial two Apollo lunar landings we recommend that a sustained program of lunar exploration proceed as follows:
>
> a. Continue manned expeditions at the rate of between one and two per year.
>
> b. Provide each manned expedition with logistics support as recommended above, shifting over to any alternative system (for example, one based on a direct trip to the moon without rendezvous) when the economics clearly favor it.
>
> c. Provide supplemental unmanned lunar exploration systems. One important component of this program during the early 1970's will be unmanned spacecraft capable of landing significant scientific payloads anywhere on the moon, particularly the lunar poles.
>
> d. Since we expect that it may prove valuable to send manned expeditions to parts of the moon not accessible to

> the present Apollo system (e.g., the polar regions), planning should be initiated to enable the achievement of this capability in the 1975-80 period." [4]

Considering developments in the year and a half since the February 1967 PSAC report was completed, it has been concluded that the recommendations and objectives presented have been essentially accepted by the political, scientific, and technological communities. If anything, the pressures of other national problems have led to an increased emphasis on the "applications" aspects of the program with implied delays in longer-range scientific programs, particularly those which are manned. In summary, while there is considerable difference of opinion about relative importance, in all analyses the broad objectives fall into the categories listed on the first page of this chapter: advancement of science, advancement of technology, and national prestige, goals, and security.

The status of the exploration and exploitation of the lunar environs is rather similar to the status of near-Earth operations 10 years ago. At that time various schemes for exploitation of Earth-orbital capabilities had been discussed. However, their technical and economic feasibility was still very much in question. How ironic it would be should the realization of the capability to exploit near-Earth space prove to be the deterrent for development of the next logical step in our space capabilities. The benefits to communications, meteorology, navigation, Earth-resources location and analysis, geodesy, and military surveillance from application of Earth orbital capabilities are manifold [5], but were not anticipated as recently as 10 years ago. There is every reason to anticipate similar if not greater rewards from a program to explore and exploit the first extraterrestrial body within our reach.

Despite admonitions that quantitative cost-benefits analyses were not feasible, each person involved in this study was asked to make estimates of the benefits to be gained from implementation of the MOONLAB program. The results of this poll are presented in Table 2-1. Each person was asked to submit an "optimistic" estimate of the benefits in each category and a "pessimistic" estimate. The wide variation between "optimistic" and "pessimistic" values, and the range in each category,

Table 2-1

EXPECTED BENEFITS FROM LUNAR VENTURE
(Billions of Dollars/Year)

	Optimistic Value Range[†]		Pessimistic Value Range	
	High	Low	High	Low
National Effects	57.0	0.035	5.6	0.0
Education	10.0	10^{-4}	0.5	0.0
Economic	10.0	10^{-2}	1.0	0.0
Prestige	5.0	0.0	1.0	0.0
Security	50.0	0.0	5.0	0.0
Other	3.0	0.0	1.0	0.0
	8.1*	0.035*	-	-
Advancement of Science	35.0	0.0	4.4	0.0
Astronomy	4.0	0.0	0.5	0.0
Physics	20.0	0.0	1.0	0.0
Chemistry	14.0	0.0	1.0	0.0
Life Sciences	8.0	0.0	1.0	0.0
Other	5.0	0.0	1.0	0.0
	4.4*	0.0	-	-
Advancement of Technology	135.0	0.002	8.0	0.001
Energy	100.0	10^{-3}	1.0	0.0
Medical	4.0	10^{-4}	0.5	0.0
Communications	20.0	10^{-3}	0.5	0.0
Vacuum	5.0	0.0	2.0	0.0
Cryogenics	10.0	0.0	1.0	0.0
Agriculture	2.0	0.0	1.0	0.0
Electronics and computers	3.0	0.0	1.0	0.0
Other	3.0	0.0	1.0	0.0
	33.0*	0.0015*	-	-

[†] Range based on 14 replies to circulated questionnaire.

[*] The sum of optimistic values weighted by a probability estimate.

illustrates the highly intuitive and subjective nature of the estimates and tends to confirm the inadequacy of the quantitative approach. The most interesting aspect of Table 2-1 is the relative ranking of the benefits ascribed to the three main categories: national effects, advancement of science, and advancement of technology.

2.2 Advantages and Disadvantages

An alternate approach to determining the merits of MOONLAB is to compare its advantages and disadvantages with those of other options available to the United States during the 1976-85 period. The principal broad comparisons involved might be characterized as follows:

(1) Lunar vs Earth-orbital,
(2) Lunar vs planetary,
(3) Manned vs unmanned,
(4) Base size.

It should be noted that it is not necessary to choose one possible program at the expense of all others. This section attempts to demonstrate that a manned lunar program offers enough significant advantages over other options to be included as part of the total United States space effort. As discussed in Chapter 4, it is anticipated that as the primary lunar space program MOONLAB would receive approximately 25 percent of the NASA budget during the 1976-85 period.

Lunar vs Earth-Orbital

Based primarily on the relative ability of the Saturn V system to deliver mass either onto the lunar surface or into Earth orbit, the cost of sending manned or unmanned payloads to the lunar surface is estimated to be initially three times as great as into Earth orbit. Earth-orbit presents obvious advantages in experiments and applications which involve measuring and monitoring conditions on the Earth's surface or in its atmosphere. Even in such circumstances, however, similar measurements from the lunar surface would provide an overall perspective which could enhance the utility of both types of experiments.

Astronomy is considered a principal function of the lunar base and, indeed, one of the prime scientific justifications of the overall space effort. Tifft has discussed and summarized the pros and cons of Earth-orbital vs lunar base astronomy. His analysis strongly favors the latter approach despite the logistics penalty [6].

No real comparison can be made with respect to geo (seleno) scientific studies which comprise the second major area of scientific work. Many of the experiments anticipated simply cannot be done except on the lunar surface.

Two other benefit areas, considered as indirect by the PSAC report, are worthy of mention. The first is termed "technological excellence." Because of space-related demands on engineering and production, United States industry is capable of attaining increasingly higher quality levels. The lunar program seems to offer the optimum level of effort which maintains a "strong pressure against the technological state of the art...important to the technical vitality of the program." [4] The military aspects of Earth-orbital studies seem to hinder the possibility for extensive international cooperation. However, development of East-West cooperation on a strictly scientific lunar program such as MOONLAB appears more feasible.

In summary, the scientific and technological program planned for MOONLAB has been specifically designed to take advantage of the lunar environment. Except for some work intended to supplement and check other experiments, the program consists of experiments which cannot be undertaken as efficiently, if at all, elsewhere.

Lunar vs Planetary

The cost of delivering payloads to nearby planets is estimated to approach a factor of 10 over that for lunar delivery. With such a ratio manned planetary flights do not appear feasible considering economic constraints and the state of technology assumed for the period through 1985. Unmanned probes and, possibly, a Voyager-type landing on Mars are the maximum capability projected for this period. It is anticipated that the delivery and soft-landing capabilities developed from a lunar program during the next decade will provide the basis for the planetary equipment of the post-1985 era. Therefore, lunar exploration provides a logical stepping-stone to eventual manned exploration of the planets.

Manned vs Unmanned

The APOLLO program has been considered to have been "man-oriented" to the exclusion of scientific and technological objectives. MOONLAB adopted the attitude that the program would be manned only to the extent that man's presence and capabilities would contribute to the overall efficiency of the operation. The scientific and technological program was developed by augmenting the experiment list compiled by North American [7]. The North American compilation is an excellent summary of physical science investigations which should be carried out. However, this list is too closely oriented to translating the way similar "earthbound" experiments would be conducted. For example, man-hour requirements have been developed based on Earth experience for similar experiments with a penalty factor introduced to reflect the relative difficulty of manned operation on the lunar surface. Insufficient attention seems to have been devoted to the extremely high cost of manned operation. It is felt that experiments should be designed to be as automatic as possible with data transmission and operation on a routine basis not requiring the intervention of the lunar staff. In particular, the use of the telefactors [8] or similar devices should be carefully considered. This would leave the staff free to handle the non-routine, unanticipated situations as well as the experimental setup and maintenance situations which often cannot be efficiently automated.

Size of Base

As pointed out in this chapter, the February 1967 PSAC report recommended one or two manned lunar expeditions annually to exploit Apollo-developed capabilities. Because of extremely large sustaining costs for the Saturn V, it is estimated that one launch annually, without unmanned support launches, will cost approximately 750 million dollars per year. By increasing the level of the lunar program above that recommended by PSAC it is possible to markedly increase the amount of science obtainable per dollar of investment.

The MOONLAB program described in this report requires an approximate doubling of the manned launch rate suggested in the PSAC report. In addition, considerable unmanned experimental and support equipment must be transferred to the lunar surface. However, scientific capability per dollar invested increases manifoldly. The efficiency of the lunar operation increases because the introduction of lunar agriculture and the exploitation of lunar resources can become economically feasible. Since lunar staytimes can be increased with a large base, launch costs per man-year of lunar staytime decrease. It should be pointed out that the evolutionary phase (Chapter 4) can be terminated at any level should continued expansion not be warranted. At this point, however, it appears that benefits accruing to the MOONLAB program will develop quickly and be sufficient to justify the expansion from 3 to 24 men.

Morgenstern [9] has provided an excellent discussion of the economics of space programs, including the difficulties in applying the more traditional cost-benefits analyses. He suggests evaluating the space program by studying these four areas:

(1) Effects on the economy of the level of spending,

(2) Byproducts of the main purpose (technical fallout),

(3) Direct impact on economy--such as from weather or communications satellites, and

(4) Scientific results.

His concluding statement is noteworthy:

> "It is a well-known phenomenon of the last 25 years that most of our important companies find that the majority of their currently offered products did not exist 25, or even 10, years ago. Their profits stem mostly from the new products, so they push research and development as far as their

means will allow. The government, constantly prodded by the scientific community, also begins to believe that research is needed for the purpose of the general well-being of the community.

It is then difficult to see why these expectations should not also apply to space exploration, especially when one remembers that some of the most vital discoveries ever made by man have come precisely from watching the stars and planets. Now that we are able to break through the obscuring shield of the Earth's atmosphere, how could we but expect that discoveries will be made of a magnitude that will astonish even this generation, which has seen so much and is prepared to expect that our knowledge will increase without limit." [9]

--February 1968

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Chapter 3

FACTORS INFLUENCING BASE DESIGN

3.1 Site Selection

The landing site selected for the proposed lunar base is in the crater Grimaldi at lunar coordinates 68 deg 00'W, 3 deg 30'S. (Fig. 3-1.) The selected site is within the lunar equatorial landing zone (at 5 deg latitude), thus making the site accessible to the 1970-75 lunar landing vehicles and also accessible by line-of-sight to earth bases for the purpose of direct radio and TV communication.

Several other locations, such as Copernicus, Alphonsus, Tycho, and the poles, have been considered as possible sites for the proposed lunar base. Each location has specific features of scientific interest [1]. The landing site at Grimaldi was chosen primarily for its suitability as an astronomical site. The establishment and maintenance of an astronomical laboratory, with both optical and radio instruments, is one of the broad objectives of the lunar base program. Astronomers would like to have a major lunar laboratory located at a site near the lunar limb or slightly over the limb in order to eliminate or minimize Earth disturbances. A near equatorial site, perhaps slightly southern to place the Magellanic Clouds in the circumpolar sky, is desirable [2]. The selected site satisfies these requirements. The site will furnish visibility of the southern celestial hemisphere as well as visibility of the planets. The near-limb location is intended to reduce Earth-shine interference. Grimaldi is a crater 150 km in diameter and is thought to be filled with mare material. The rather flat surface of the floor of Grimaldi will furnish unimpeded telescopic viewing from the zenith to the horizon.

The site has many geologic features of interest in addition to its suitability as an astronomical location. (Figure 3-1.) Grimaldi is photographically one of the darkest craters. It will be of interest to geologists to examine the structure, age, composition, and origin of a very dark mare material. The walls of Grimaldi are observed to be discontinuous and to consist of a mass of cliffs. On the east the walls average about 1300 m in height, with debris along the inner east slope,

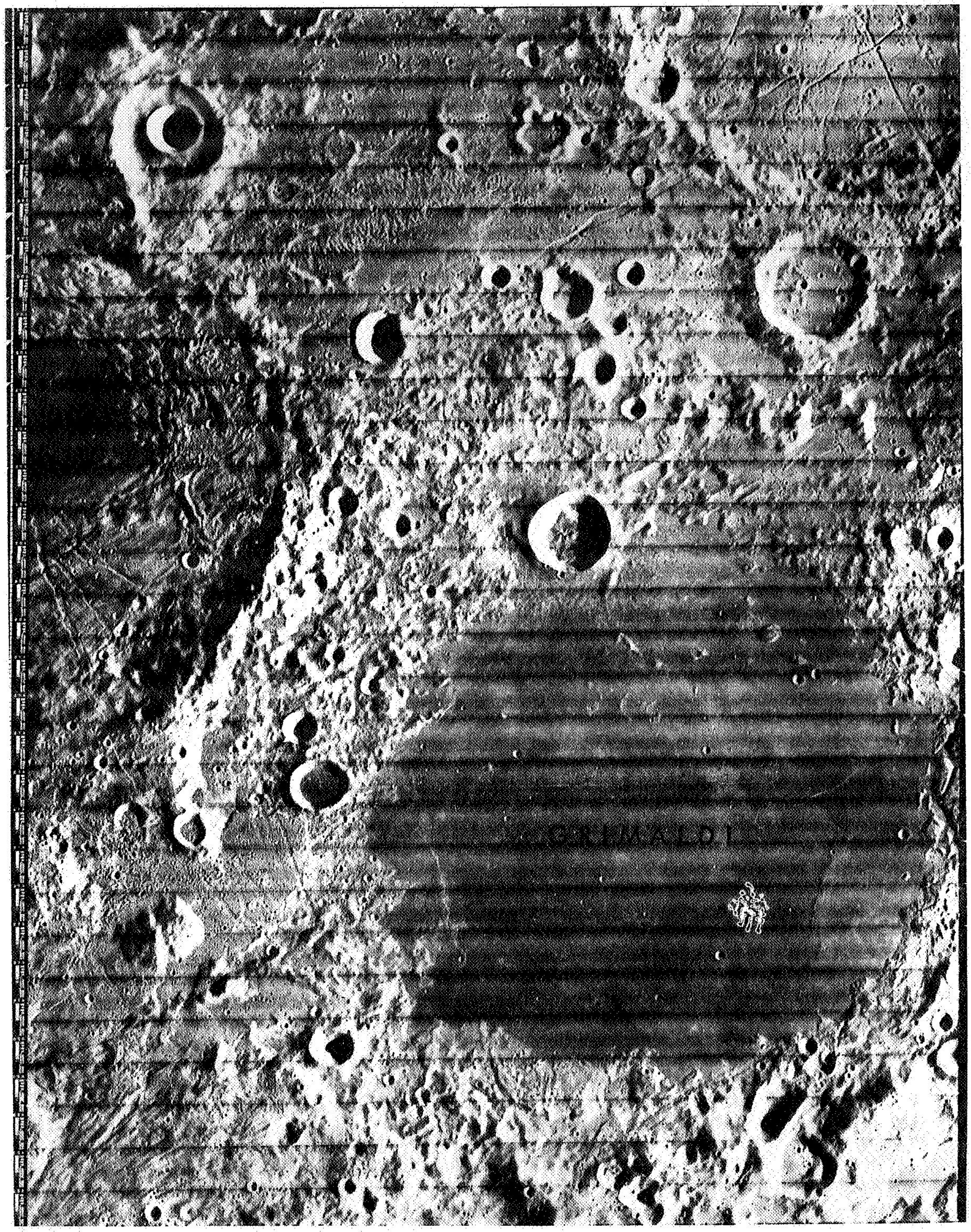

Fig. 3-1. GRIMALDI, Site for Lunar Base.

and also some peculiar semicircular plateaus. On the west the walls are very broken, with a peak of approximately 2700 m on the southwest. There is a lower portion halfway along the southern portion of the east wall. Two clefts cut through the south wall. On the northeast portion is a bright crater, Saheki (formerly known as Grimaldi B), which is connected by ridges to the north wall. South of Saheki is a low, dark hill. There are also three hills to the east and some old rings, now mere curved ridges, on the south, another ridge near the west wall and one from the south, also two craters near the east wall. There is also a craterlet to the south of Saheki, and another on the rim of an old ring under the northwest wall. A peak on the west wall of Grimaldi has four summits, the highest being on the south. From the south wall are many capes and projecting ridges on to the floor. There is also a cleft on the southeast of the interior. The existence of clefts at the walls of Grimaldi would enable the passage of lunar roving vehicles for extended exploration of areas outside of Grimaldi.

There are evidences of a variety of geologic features in the vicinity of the chosen landing site, such as volcanic domes, volcanic flows, and rill formations which are worthy of exploration and detailed studies. Narrow and shallow channels have been observed to connect the east part of Grimaldi to Oceanus Procellarum (Ocean of Storms, the largest of all the great dark plains with an area of about 2 million square miles). It will be of interest to geologists to examine the mare material of Grimaldi and to decide if this material rises from within the moon or if it was overflow from Oceanus Procellarum.

The criteria for a specific landing site for the development of the lunar base will be constrained, among other things, by topography. At the present time, the best photograph of Grimaldi is the one from the Lunar Orbiter IV. However, this photograph has an extremely low resolution (about 1 mm to 638 m). It is therefore recommended that plans should be made to obtain photographs of Grimaldi of higher resolutions at an earlier date in order to obtain sufficient information regarding the topography of the landing area. A site-certification flight to the landing area is required prior to the establishment of the proposed lunar base.

During the site-certification flight, a detailed study of soil conditions at the proposed lunar base should be carried out. The strength and compressibility characteristics of the soils and rocks which will underlie the base must be determined before the structural design can be finalized. Since the base will be composed of individual pre-fabricated modules with connecting tunnels, differential settlements of any appreciable magnitude are undesirable. Obviously, the problem of differential settlement can be minimized if the base is constructed on rock. On the other hand, soil is needed for the proposed farm and transporting it over any appreciable distance would be extremely costly. It would seem, then, that the optimum site would have a shallow depth of soil (less than 1 m) overlaying rock. It is important to point out that should later information show the chosen site to be scientifically undesirable for the construction of the proposed base, the basic design and the physical layout of the base, as outlined in this report, will remain essentially the same for another site.

3.2 Study Assumptions and Guidelines

The United States is committed to send men to the Moon in the APOLLO program. Some science will be done on these first flights. Presumably future programs will continue this science. The magnitude of these programs depends on several factors,

(1) The overall objectives of future lunar programs,

(2) The level of NASA funding for the next several decades, and

(3) The role the Moon will play in the development of the capability to undertake future planetary exploration.

These factors are considered in Chapters 2, 4, and in Part III. The major guidelines used in designing the base are given below, while detailed guidelines which are concerned with the design of particular components of the lunar base are contained within the individual chapters.

3.2.1 Physical Conditions of the Lunar Surface.

The following conditions are assumed to exist in the lunar environment and on the surface:

(1) Temperature variations from a maximum surface temperature of 390°K (117°C) at the subsolar point to a nocturnal value of 105°K (-153°C). Changes in surface temperature occur very rapidly with the transition from day to night or night to day. Less than a meter below the surface, the temperature is relatively constant at 233°K (-40°C).

(2) The lunar atmosphere has a density of less than 1×10^{-12} that of the earth's atmosphere at sea level.

(3) Gravitational attraction at the surface is 1.62 m/sec^2.

(4) The lunar magnetic field is weak, probably not exceeding 6×10^{-4} G (the earth's field is about 0.5 G).

(5) Cosmic-rays are primarily protons with energies ranging from less than 10 MeV up to several GeV. During solar flares the intensity of cosmic-ray flux may increase, for intervals of one or two days, to many thousand times greater than the normal galactic flux intensity of 1.5 to 4 particles/cm^2/sec.

An integrated annual dose of 5-12 roentgens results from the normal $0.5\text{-}1.2 \times 10^8$ particles/cm^2 (with an estimated specific ionization of 3 times the minimum flux intensity). During the period 1956 to 1961, the annual dose was increased by solar flares by a factor of 2.5 for particles above 100 MeV and by a factor of 15 for particles above 30 MeV.

(6) The size of meteoritic particles striking the lunar surface range upward from 1 μm in diameter. Velocities range from 11 to 72 km/sec. Concentration of particles ranging in size from 1 to 300 μm is estimated at 5×10^{-21} g/cm^2. The data given in Table 3-1 and Fig. 3-2 were used for estimating micrometeoroid shielding necessary for the design of MOONLAB.

(7) The lunar surface material is similar in composition in all lowland areas. The material is similar to silts in particle size (2-60 μm) and has a permeability similar to that of silts. The material ranges from 1-20 m thick and is compacted due to lack of air. The estimated cohesion is 0.07 psi and the material has an angle of repose of approximately 31 deg ± 2 deg. The material is most probably basalt in origin.

Table 3-1

PROBABILITY OF MICROMETEOROID PENETRATION†

(Body of 1 m^2 Cross Section)

Meteor Visual Magnitude	Kinetic Energy erg	M Mass grams	Particle Radius mm at 0.44 gm/cc (assume spherical shape)	No. of Particles of M or Greater per m^2-sec Neglecting Earth Shielding			Penetration (D) of Aluminum mm
				N/m^2 sec	N/m^2-24 hrs	N/m^2-2 yrs	
0	1.0^{13*}	1.25	8.8	4.9^{-15}	4.23^{-10}	3.09^{-7}	3.9^{5}
1	4.0^{12*}	0.5	6.5	1.67^{-14}	1.44^{-9}	1.05^{-6}	2.9^{5}
2	1.6^{12*}	0.198	4.8	5.78^{-14}	4.99^{-9}	3.65^{-6}	2.1^{5}
3	0.63^{12}	0.079	3.5	1.98^{-13}	1.71^{-8}	1.25^{-5}	1.5^{5}
4	0.25^{12}	0.031	2.6	6.92^{-13}	5.98^{-8}	4.36^{-5}	1.1^{5}
5	0.10^{12}	0.012	1.9	2.48^{-12}	2.14^{-7}	1.56^{-4}	8.4^{4}
6	40.0^{9}	5.0^{-3}	1.4	8.0^{-12}	6.91^{-7}	5.05^{-4}	6.2^{4}
7	16.0^{9}	2.0^{-3}	1.0	2.56^{-12}	5.67^{-7}	4.14^{-4}	4.4^{4}
8	6.3^{9}	0.79^{-3}	.75	9.48^{-11}	8.19^{-6}	5.98^{-3}	3.3^{4}
9	2.5^{9}	0.31^{-3}	.55	3.31^{-10}	2.86^{-5}	2.09^{-2}	2.4^{4}
10	1.0^{9}	0.12^{-3}	.40	1.18^{-9}	1.02^{-4}	7.44^{-2}	1.8^{4}
11	4.0^{8}	50.0^{-6}	.30	3.83^{-9}	3.3^{-4}	2.42^{-1}	1.3^{4}
12	1.6^{8}	20.0^{-6}	.22	1.3^{-8}	1.12^{-3}	8.2^{-1}	9.7^{3}
13	6.3^{7}	7.9^{-6}	.16	4.54^{-8}	3.92^{-3}	2.86	7.0^{3}
14	2.5^{7}	3.1^{-6}	.12	1.59^{-7}	1.37^{-2}	10	5.3^{3}
15	1.0^{7}	1.2^{-6}	.09	5.6^{-7}	4.9^{-2}	35.8	4.0^{3}

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† From "TRW Space Data," 1967-B7, TRW Systems Group, TRW Inc.

*Note: Superscripts are exponents of 10; i.e., $4.0^{12} = 4.0 \times 10^{12}$.

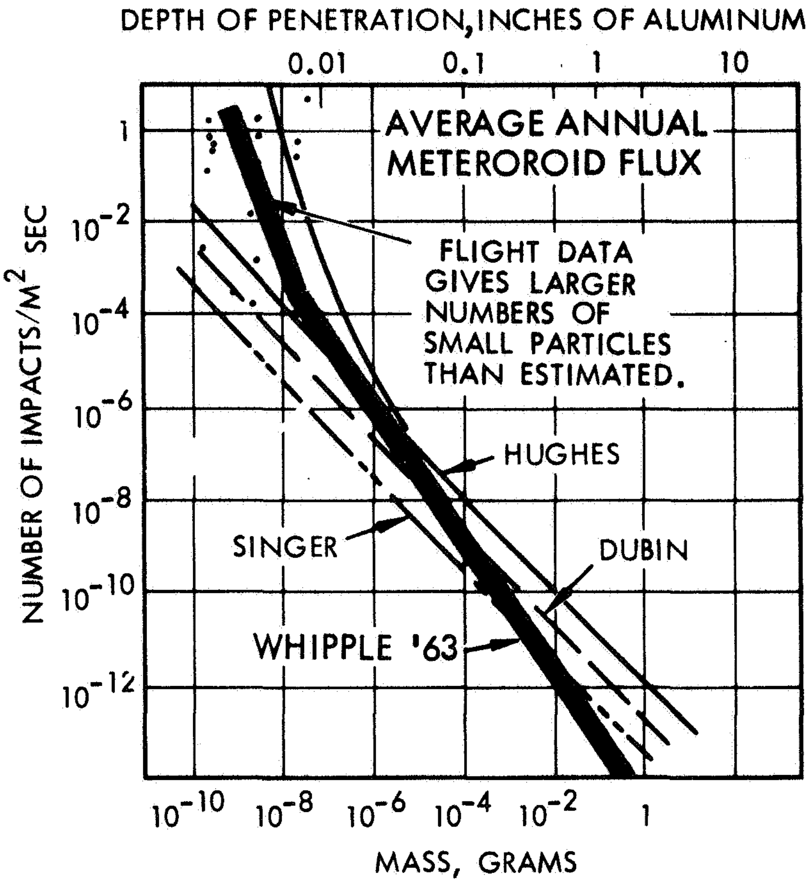

Fig. 3-2. Average Annual Meteoroid Flux.

3.2.2 Site Certification

The development of a manned scientific laboratory on the lunar surface appears to be the primary function of the lunar base during the 1970-1990 time period. Of the science to be conducted astronomy most significantly influences the site selection. As discussed in Section 3.1, the crater Grimaldi appears to be an excellent site for a lunar base. The following assumptions are made concerning the development of the Grimaldi site:

(1) A flight of 14-day staytime will be made to Grimaldi in the period 1971-73 for site certification.

(2) A signal tower will be erected in Grimaldi by 1976 to direct later flights.

(3) Any vehicles, flying and/or roving, landed at Grimaldi between 1973 and 1976 will be usable during the early stages of the base development.

3.2.3 MOONLAB Hard Design Criteria

(1) Development effort starts in 1970 (i.e., the site certification, development of new vehicles, scientific instruments, shelters, etc.).

(2) The metabolic needs and life support functions of the occupants are as given in Table 3-2. The values in this table were chosen after study of the literature and consideration of the difficulty of enviornmental control. They were then treated as design assumptions.

Table 3-2

METABOLIC SPECIFICATIONS

(Basis: per man)

Inputs	kg	
Oxygen uptake	0.85	
Carbon dioxide output	1.05	
Food, ashless, dry basis	0.63	
Total water allowance outputs	3.5	
Water of oxidation	0.33	
Urine water, average	1.5	
Fecal water	0.25	
Fecal and urine solids	0.10	
Respired and evaporated water	2.70	
Latent heat - k cal/day		1560
Sensible heat - k cal/day		2140
Miscellaneous		
Dry bulb	18.3-29.5 °C	
Relative humidity	45-55%	
Volumetric displacement	125 cfm/man	
Radiation dose not to exceed that which would cause a 144-day decrease in life expectancy.		

(3) No technological breakthroughs are assumed necessary to complete this proposed program. Estimates of technological developments and upratings used in the study are considered to be conservative.

(4) The evolution of the base will make maximum reuse of previous lunar flights, and thus the development of all future lunar hardware should reflect this assumption. For example, the proposed 2 kW fuel cells used in the guidance system of the delivery vehicles should be designed for reuse as the power supply for the lunar base during the lunar night.

(5) It is assumed that the equipment and vehicles previously landed at the site of the MOONLAB will have been designed and protected so that they will be useful during the earlier phase of the base evolution. Thus, care should be taken to protect the earlier equipment from deterioration due to the existing environmental conditions.

(6) The launch and landing vehicle configurations proposed by the Lockheed Missile and Space Company [3] were adopted as those available during the evolution of MOONLAB. An uprating on the staytime capability on the Moon surface for the return vehicles has been assumed. LOR vehicles with staytimes of 180 days and direct-mode vehicles with a 270 day staytime have been postulated. These staytimes represent a 90-day increase over the values given in the Lockheed report. However, if continuous abort capability of all MOONLAB personnel is required the staytime of the return vehicles must be extended to one year. MOONLAB off-loading equipment and lunar mobility were taken from the LESA and MIMOSA studies [1,4].

(7) The power subsystem choice (a solar cell/regenerative/fuel cell) was influenced by the assumptions that (a) large quantities of fuel for Radioisotope Thermoelectric Generator's (RTG's) will not be available, and (b) the useful life of a SNAP 8 reactor system at full power is approximately one year. If either of the above conditions is changed significantly, the power subsystem choice might be altered.

(8) Continuous S-band radio and video contact with Earth is assumed.

(9) Because of the high dollar cost of man-hours on the lunar surface ($60,000-$100,000 of investment per man-hour) the base has been designed where possible to be automatically deployable, thus requiring a minimum amount of labor on the lunar surface. As a result the use of lunar materials

has been kept at an absolute minimum except for the use of dirt as solar flare shielding around the initial three-man habitat.

The high cost of lunar man-hours also makes it imperative that all experiment equipment be designed with a high degree of automation. This is particularly true for equipment remote from the main base and equipment which typically requires many man hours on the Earth such as astronomical apparatus.

(10) The base has been designed on the assumption that lunar water will not be available. However, all systems being designed for the lunar program should make maximum use of H_2-O_2 as the common fuel (i.e., rocket engines, power supply, metabolic system).

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Chapter 4

MOONLAB EVOLUTION 1970-1985

In the period from 1970 to 1985 the proposed MOONLAB will grow from a 200 million dollar concept and planning stage to a 24-man laboratory requiring an annual budget in excess of a billion dollars. The objective of the evolutionary phase of MOONLAB development is to secure a science-oriented lunar laboratory by 1985 which will yield early feedback to the scientific community and to the general public. As discussed in the previous chapter, the site chosen is Grimaldi. Because of this selection of site, virtually on the lunar equator, the early stages of the evolutionary phase employ the Lunar Orbit Rendezvous (LOR) technique for personnel delivery and return. Two assumptions concerning the personnel delivery vehicles were made which are of paramount importance in establishing the abort capability and personnel rotation for the base. These assumptions are that,

(1) The LOR personnel carriers [1] are capable of 180-day duration operation, and

(2) The direct-mode personnel carrier [1] is capable of 270-day dormancy on the lunar surface.

Use of the LOR technique makes the evolutionary program extremely vulnerable to changes in site latitude. For example, if a polar site were selected the evolutionary phase could not start until the direct-mode vehicle becomes available in 1980 unless the abort constraints (continuous during first three years) were changed. Thus an alternate program was also investigated which had no constraints as to lunar latitude. The results of that study indicated the total cost of a direct-mode-only evolutionary program would be the same as the program described in the following pages; however, as the manned operations occur over five years (instead of nine), the peak annual funding of such a program would be larger, and there would be no science feedback until 1982. Accordingly, the 9-year evolutionary program using LOR was selected.

4.1 MOONLAB Evolution Programs

The evolutionary phase is subdivided into several programs including hardware development, site certification, and acquisition and logistics. A site certification mission which will survey and map Grimaldi, select a site within Grimaldi, provide design information on soils and foundations, and locate radar targets for later landings is scheduled for 1973 at the latest. With the desired information obtained in this mission, the evolutionary program will begin continuous manned operation in 1976. Table 4-1 gives the major milestones of the 1970 to 1985 period.

Table 4-1

MAJOR MILESTONES IN THE EVOLUTIONARY PROGRAM

Year	Development
1970	Start Development Programs
1973	Site Certification Mission
1976	Deliver First Cargo Establish 3-Man, 3-Month Staytime Base
1977	Staytime Extended to 6 Months Science Program Starts
1978	Base Grows to 6 Men Hygiene Shelter Delivered
1979	Staytime Extended to 9 Months
1981	Staytime Extended to 12 Months Base Grows to 12 Men Sleeping and Command Shelters Delivered Direct-Mode Personnel and Advanced LLV Used
1982	Physical Science and Off-Site Activities Shelters Delivered Start Phase C Science Program
1983	Agriculture Shelter Delivered Base Grows to 18 Men Deliver Lunar Surface Transportation
1984	Astronomy Shelter Delivered Farms Delivered 14 Metric Tons of Science Equipment Delivered
1985	Base Grows to 24 Men

The first shelter to be delivered to the lunar surface will be covered with lunar soil to increase the radiation protection of the habitat. During the nine years of MOONLAB evolution seven more shelter modules and three "farm" structures will be delivered. The deployment of these shelters and farms is illustrated in Fig. 4-1. Also indicated is the post-evolutionary function of each shelter. After 1985 the first shelter, which is a solar flare refuge, will become the area for medical services and biological and psychological experiments.

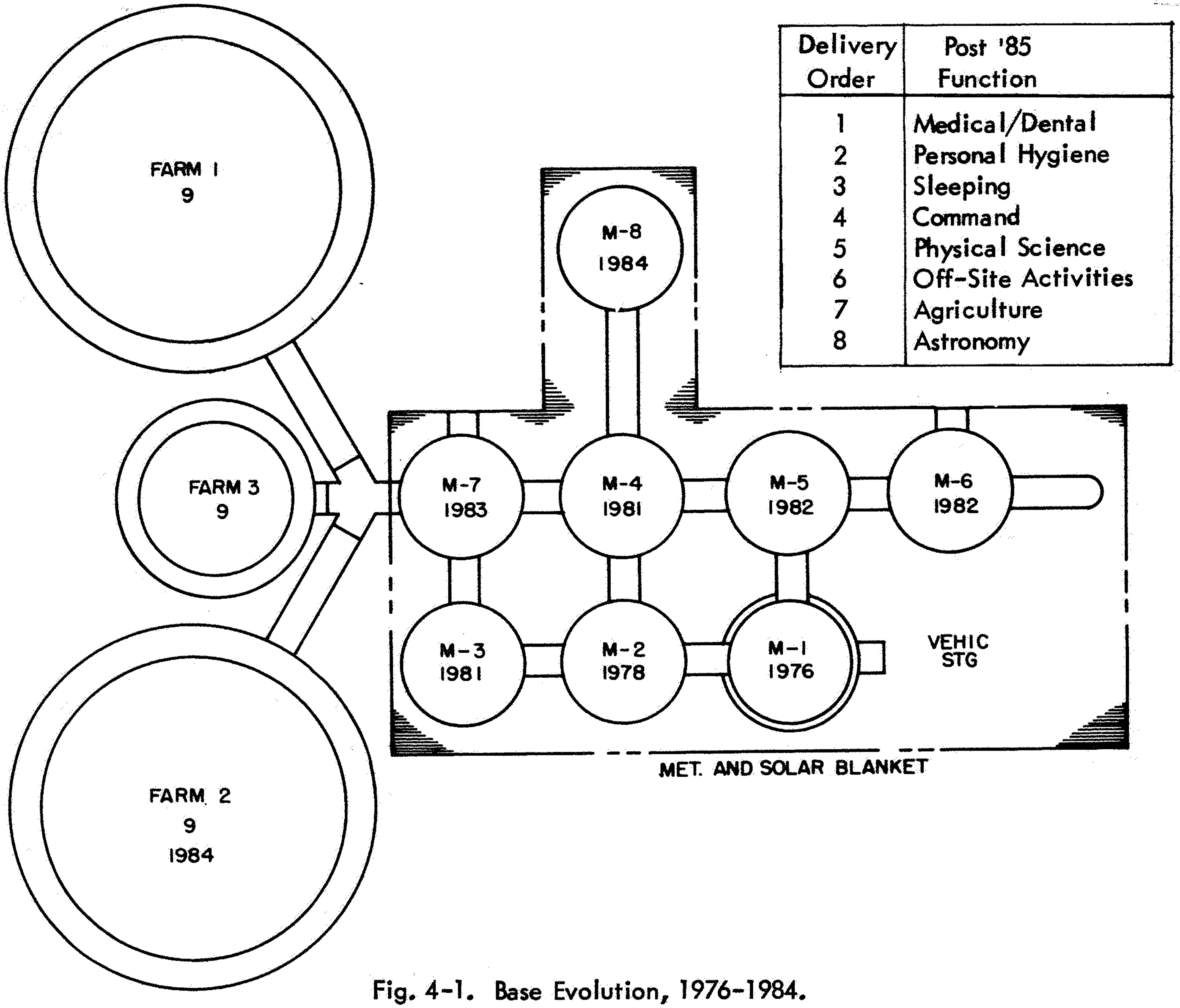
A profile of the MOONLAB buildup is given in Table 4-2. The scheduling of crew arrivals has been overlapped, starting in 1978, to distribute the launches over the year. A total of 37 launches will be required, of which 23 will be manned launches and 14 will be cargo launches. The buildup of astronaut staytime from 6 months to a year is accomplished in three steps, with a period of one year of Earth post-mission observation of the astronauts before the lunar staytime is increased.

Abort during the first three years of the program is continuous since the astronauts will be able to return to Earth via the same vehicle that delivered them. As personnel lunar staytime grows beyond the vehicle staytime in mid-1979, return from the Moon is accomplished by launching a personnel carrier from Earth. In the case of abort the launch time reaction capability of this method (minimum of three days) may be unacceptable. By developing vehicles with staytimes equal to personnel staytimes, or vice versa, this problem may be avoided.

The total mass delivered in the evolution of MOONLAB is shown in Table 4-3. Detailed descriptions of the various categories are given in Part II of this report.

Table 4-4 gives the delivery requirements during evolution. Since the requirements do not fall exactly into units deliverable by the cargo vehicles (16,000 and 23,000 kg), early delivery, particularly of expendables, allows the cargo to be partitioned into the specified units.

Figure 4-2 gives the science and power profiles during evolution. The science program, described in Chapter 5, accounts for 75 percent of the total man-years of occupancy of MOONLAB in the 1976-1984



Delivery Order	Post '85 Function
1	Medical/Dental
2	Personal Hygiene
3	Sleeping
4	Command
5	Physical Science
6	Off-Site Activities
7	Agriculture
8	Astronomy

Fig. 4-1. Base Evolution, 1976-1984.

Table 4-2

MOONLAB EVOLUTION PROFILE 1976-85

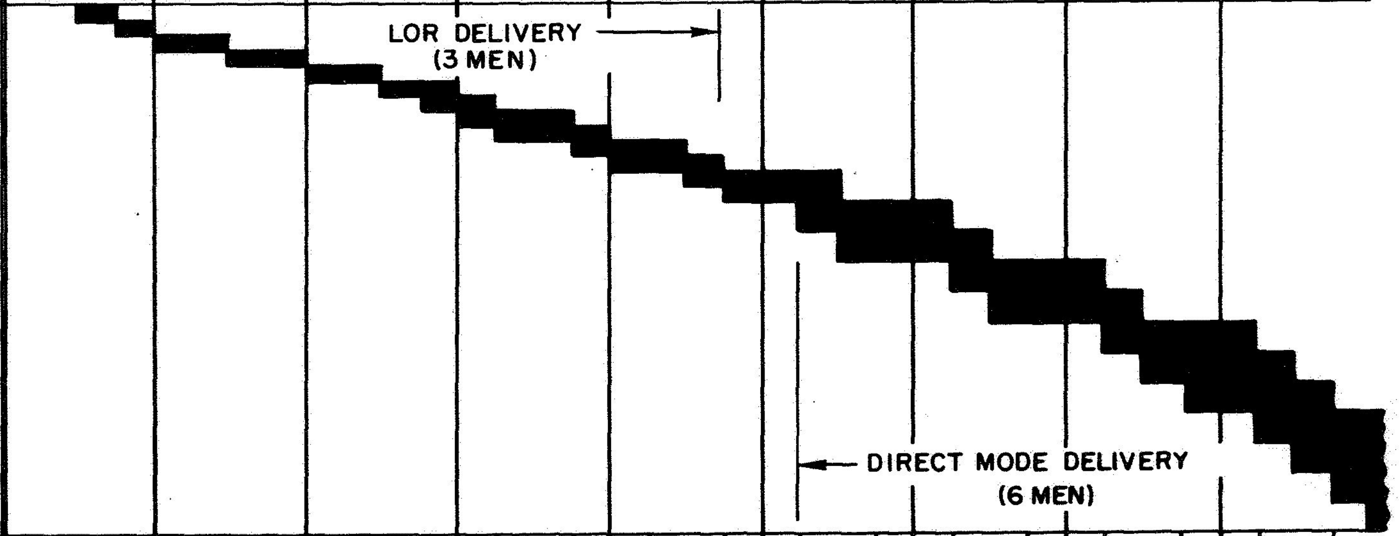
YEAR	76				77				78				79				80				81				82				83				84			
MEN	0	0	3	3	3	3	3	3	3	3	3	6	6	6	6	6	6	6	6	6	6	12	12	12	12	12	12	12	12	12	12	18	18	18	18	18
STAYTIME, MONTHS			3		6		6		6		6		9		9		9		12/9		12		12		12		12		12		12		12		12	
MAN YEARS	1.5				3				3.75				6				6				10.5				12				13.5				18			
PROFILE OF CREW DELIVERY & STAYTIME																																				
LAUNCHES																																				
MANNED			1	1	1		1		1		1	1	1	1		1	1		1	1		1	1			1	1			1	1	1		1	1	1
CARGO		2				1				1					1			1			1			1				1	1	1			2		1	
SHELTERS (TOTAL)		1								2											4							6	7				7 +FARMS			8 +FARMS

Table 4-3

MASS BUDGET FOR MOONLAB EVOLUTION

System	Weight (kg)	Percent of Total
Shelters, Life Support, Farm and Radiator	99,000	36
Water: Use, Reserves and Packaging	45,000	16
Power Equipment and Replacement	31,300	11
Lunar Transportation and Off-Loading Equip.	26,600	10
Gas: Use, Leakage, Reserves and Packaging	30,400	11
Food: Use, Reserves and Packaging	19,400	7
Science Equipment	19,200	7
Tunnels	2,700	1
Communications Replacement	2,400	1
TOTAL	276,000	

Table 4-4

MOONLAB EVOLUTION ANNUAL DELIVERY REQUIREMENTS
(Mass Are Given in Units of 10^3 kg)

Item Year	Shelters, Farm and Life Support	Water	Power	Atm.	Off-Loading and Lunar Trans.	Food	Science Equip.	Misc.	TOTAL†
1976	16	*	*	*	10	*	2.4		28.4
1977		4	.6	2.8		0.8		.3	8.5
1978	8	5	3.6	2.8		1.0		.6	21.0
1979		8	1.2	4.4	5	1.6		.3	20.5
1980		8	1.2	4.4		1.6		.3	15.5
1981	18	8	7.2	4.4		2.8		1.2	41.6
1982	16	8	2.4	3.6		3.2	2.8	1.2	37.2
1983	10	2	7.8	3.6	11.6	3.6		.9	39.5
1984	31	2	7.3	4.4		4.8	14	.3	63.8

† Included in First Shelter.

* Payload Constraints Enforce Early Delivery of Cargo. See Table 4-2 for Schedule.

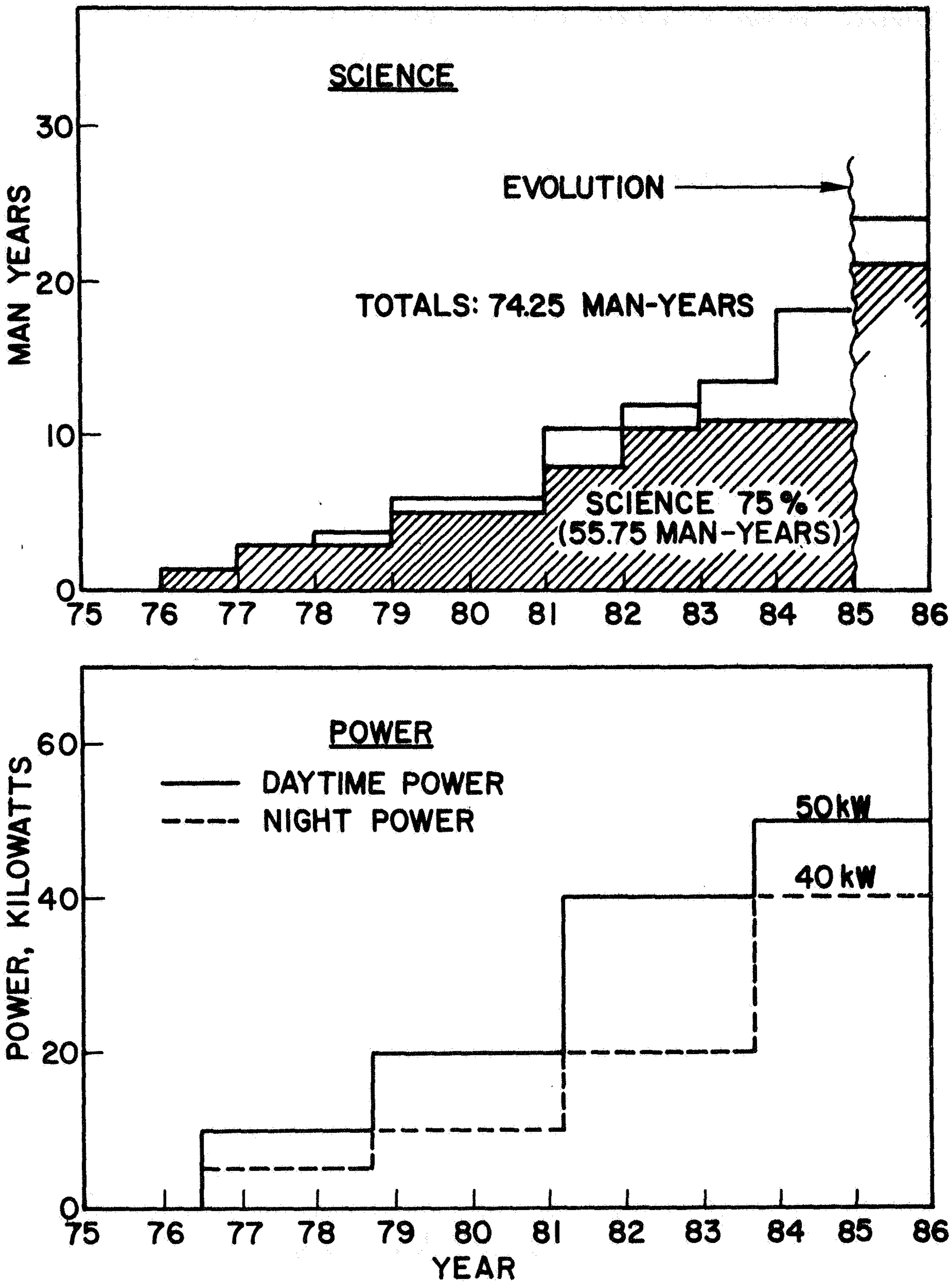


Fig. 4-2. Science and Power During Evolution.

period. In the fully developed state science accounts for 87 percent of the occupancy. It is to be noted that the man-years discussed above include sleeping, eating, etc., so that the actual on-the-job time is approximately 1/3 of the occupancy time. The program is scheduled to give early and continuous science feedback starting in 1977, a consideration adopted to enhance the program image with the general public and to enlist the support of the scientific community.

The power system (Chapter 11) utilizes solar cells during the lunar day and a regenerative system for lunar night. The power system was assumed to require a 20 percent annual replacement starting with the second year of operation.

4.2 MOONLAB Evolution Costs

The cost of establishing MOONLAB has been divided into development costs and acquisition costs. The development of hardware for the MOONLAB extends from 1970 through 1985. The development costs were assumed to be distributed uniformly over the development period which is, of course, contrary to the usual polygonal development funding profile. The costs are shown in Table 4-5 and the annual funding in Fig. 4-3. The major item in the development program is for delivery vehicles, and within these costs the development estimate for a major uprating of the Saturn V (170 percent) has the greatest uncertainty. The delivery vehicle development costs are referenced in Table 4-5 while development costs for the other areas are contained within the corresponding chapters in Part II.

The acquisition costs were based on the schedules given in Tables 4-6 and 4-7. The site certification mission occurring in 1973 was estimated at 300 million dollars, a sum which is perhaps too optimistic. Two other items in the acquisition schedule that warrant discussion are the launch operation costs which are estimated at 300 million dollars annually, and the vehicle manufacuturing sustaining costs at 240 million dollars. Current estimates for these items for all NASA operations are 370 million dollars for the launch operations and 385 million dollars for Saturn V, LEM and CSM sustaining costs. The figures used

Table 4-5

DEVELOPMENT PROGRAM FUNDING
(millions of dollars)

Item	Year	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	Totals ($)	
Shelter and Life Support	Shelter	25	25	25	25	25	25											(150)	
	Life Support		8	9	9	9	9											(44)	194
Lunar Vehicles	Off-loading Equip.	50	50	50	50	50	50	50										(350)	
	Lunar Flying Vehicle			15	15	15	15	15	15	15	15							(120)	
	Lunar Rover			33	33	33	33	33	33	33	33	37	33	33	33			(400)	
	Trailer									9	9	9	9	9	9			(54)	924
Science Equipment	Phase B					100	100											(200)	
	Phase C										31	31	31					(93)	
	Phase D											50	50	50	50			(200)	
	Phase E												56	58	56	56	56	(282)	775
Delivery Vehicles [1]	J2-S Engines	9	9	9	9	9												(45)	
	Early Cargo Vehicle	38	38	38	38	38	41											(231)	
	Early Personnel (LOR)	29	29	29	29	29												(145)	
	Uprated Saturn V				70	72	72	72	72	72	70							(500)	
	Advanced Cargo							13	13	13	11							(50)	
	Direct Mode Personnel	46	100	100	100	100	100	100	100	100	100	100						(1046)	2,017
Power	Power	10	20	20	20	20	20												110
Communications	Communication		9	9	9	9													36
ANNUAL TOTALS		207	288	337	407	509	465	283	233	242	269	227	179	150	148	56	56		4,058

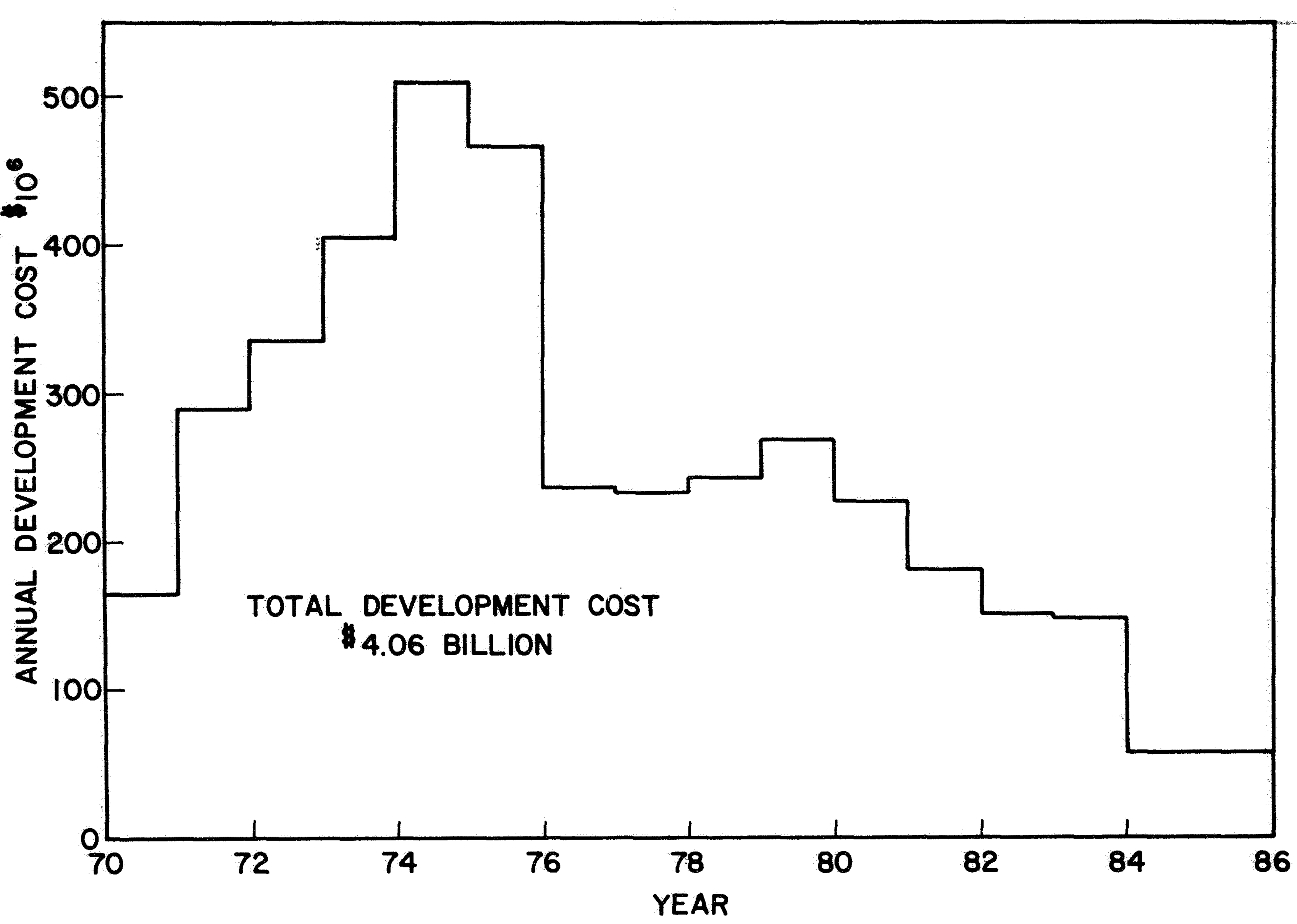


Fig. 4-3. MOONLAB Development Funding 1970 to 1986.

Table 4-6

MAJOR ACQUISITION COSTS

Item	Unit Cost (millions $)
Shelter and Life Support	
First shelter (includes power and communications	78
Subsequent shelters	32
Power	
Lunar day	0.57*
Lunar night	3.16*
Launch Vehicles, Recurring Costs	
Uprated Saturn V (J2-S Engines) (2)	125
Advanced LOR Delivery (3 men) (1,2)	72
Early Cargo LLV (16,000 kg payload) (1)	19
Uprated Saturn V (170 percent) (Estimated)	160
Advanced Cargo LLV (23,000 kg payload) (1)	26
Direct Personnel Delivery (6 men) (1)	103

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*per kW

in Table 4-7 represent that portion of the total costs which are charged to the MOONLAB program. Items such as MSF support, currently a 30 million dollar plus item, are not included.

The total cost of the MOONLAB is 17.4 million dollars, an average of slightly over a billion dollars per year for the 15 years of evolution. The funding schedule is shown in Fig. 4-4. Using an 8-hour workday, the investment cost per man-hour of work on the Moon is slightly over 100 thousand dollars per man-hour.

4.3 Economic Considerations

4.3.1 Introduction

Since the magnitude of the post-Apollo program will depend on the funding available, a look at the possible levels of funding is necessary. Perhaps the best single indicator of our growth as a nation is

Table 4-7

MOONLAB ACQUISITION SCHEDULE

Item	YEAR 70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	Totals (million $)	
Site Cert. Mission		50	100	100	50												300
Shelters and Life Support						78			32			64	64	32	32		302
Power								4	26	8	8	51	17	56	52		222
LOR Vehicles							394	394	591	591	591					(2,561)	7,725
Direct Mode Vehicles												526	526	789	789	(2,630)	
Cargo (16,000 kg)							322	161	161	161	161					(966)	
Cargo (23,000 kg)												392	196	392	588	(1,568)	
Launch Operations							300	300	300	300	300	300	300	300	300		2,700
Vehicle Sustaining Costs							240	240	240	240	240	240	240	240	240		2,160
TOTALS		50	100	100	50	78	1256	1099	1350	1300	1300	1573	1343	1809	2001	13.4 billion $	

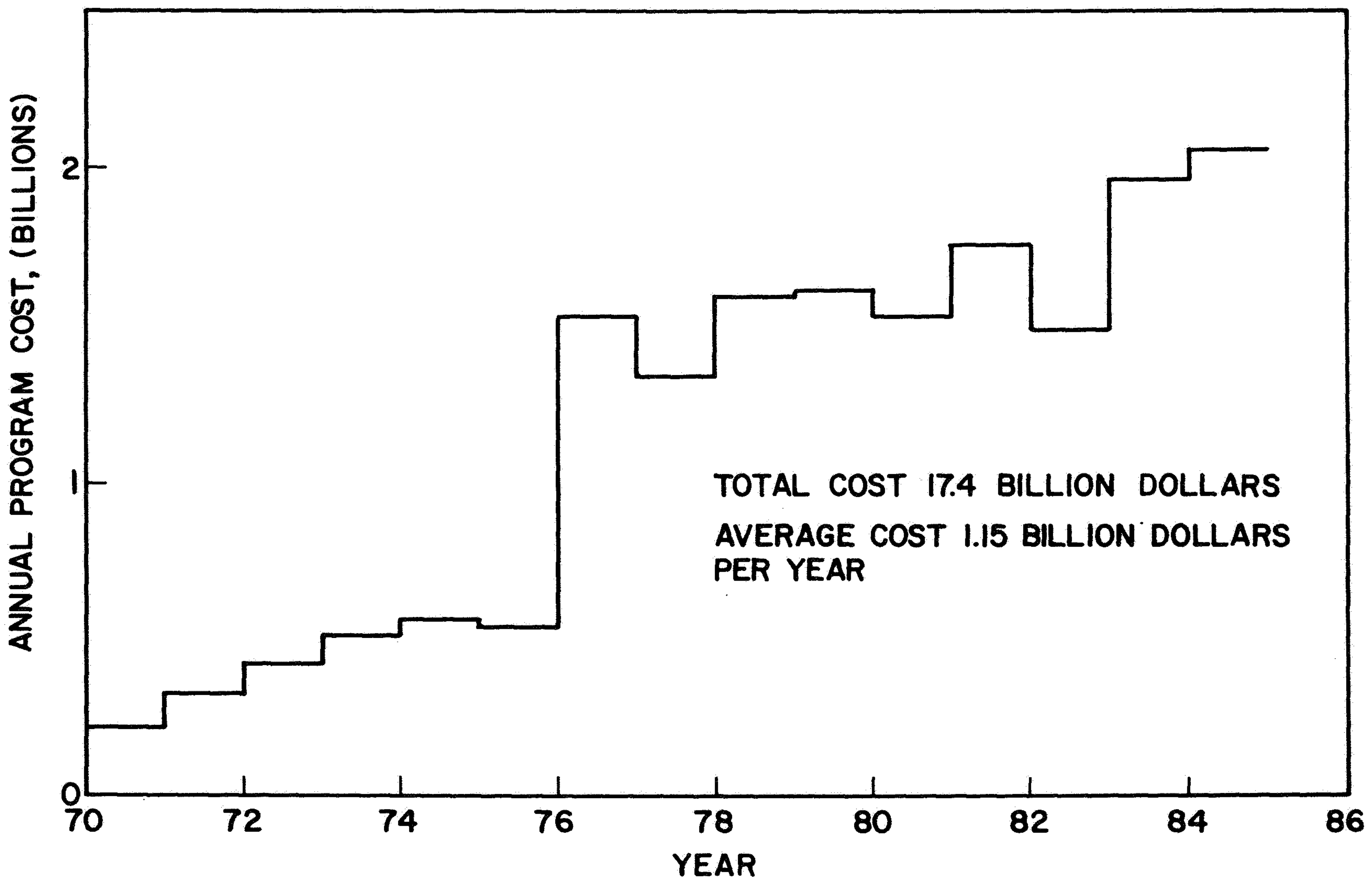

Fig. 4-4. MOONLAB Funding Schedule 1970 to 1985.

the Gross National Product (GNP). When total GNP is converted to constant 1958 dollars, effects of monetary inflation are removed and the difference in the rate of growth before "Sputnik" and since can be observed (Fig. 4-5).

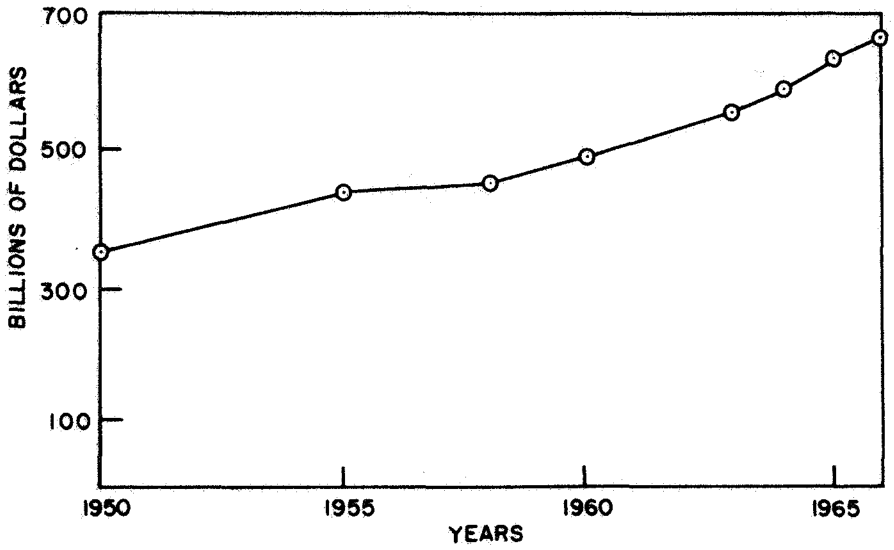

Fig. 4-5. USA Gross National Product Constant Dollars 1958 =100.

The post-World War II increase in population could have provided much of the stimulus for the jump in GNP. If so, the per capita GNP would have stabilized; however, the growth rate appears undiminished. Fig. 4-6 again removes the effects of inflation with constant dollars. The change (increase) in rate of growth after our entry into the space race is particularly noticeable.

Did this growth happen because of the space program? Even if statistics were available separately, and they are not, it is doubtful if the answer could be justified quantitatively. Perhaps the visible trend upward at this time is more important than the question of how much any one activity influenced it.

The national goal to develop and demonstrate lunar travel capability represented one of the largest single research and development efforts in the years of the space age following Sputnik. There also seems to be a continuing relationship between this kind of research and

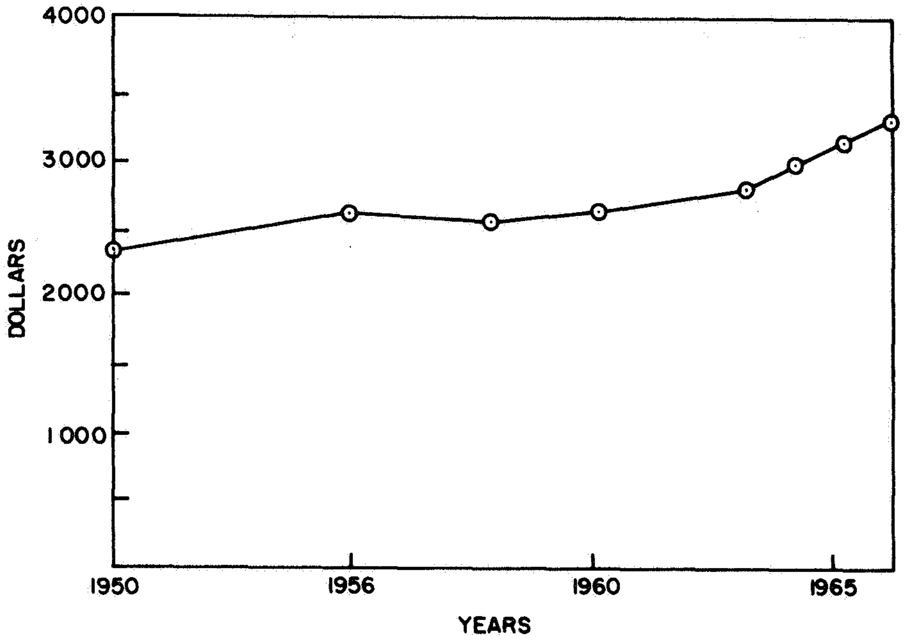

Fig. 4-6. USA Per Capita Gross National Product Constant Dollars 1958=100.

development and the growth of the GNP. Figure 4-7 shows a remarkable similarity in rates of growth during the past few years. Based on such sparse data, it would be presumptuous to make claims about cause or effect. The relationship is, however, striking.

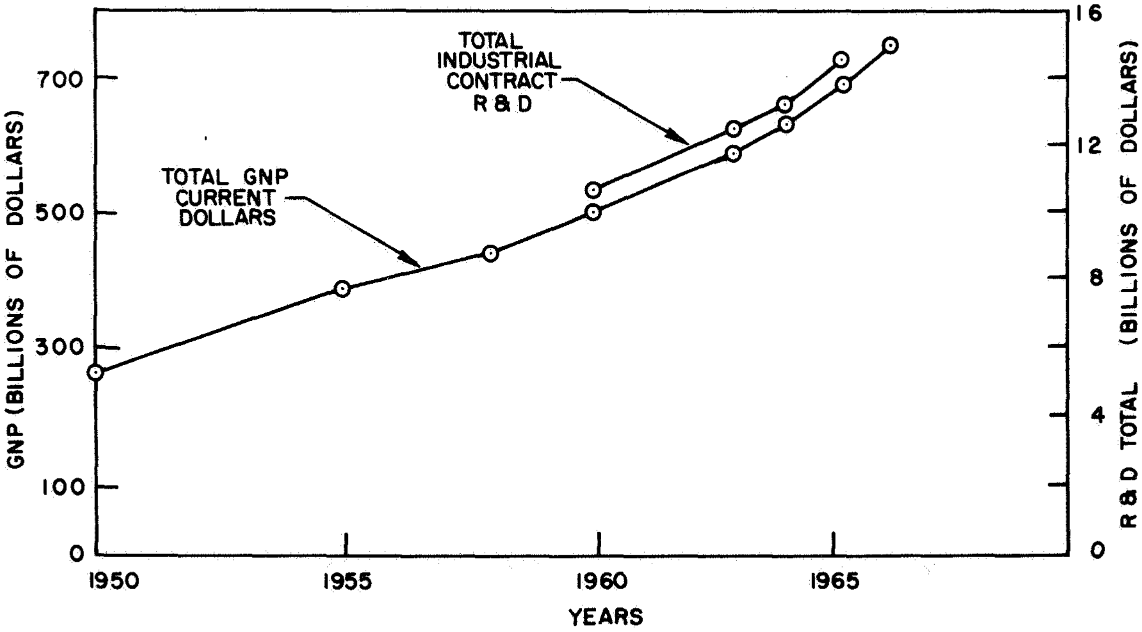

Fig. 4-7. Total Industrial Contract Research and Development.

Because of the uncertainty of future NASA funding, the funding likely to be available for a manned lunar program has been considered from two points of view,

(1) <u>Constant Dollar Budget</u>

If the NASA budget is maintained at a constant level of 4 billion (1968) dollars per year, then a 15 billion dollar lunar program could be funded during the time period 1970 to 1985 by spending about 1/4 of the total NASA budget on the program. This funding level would allow the undertaking of the program shown in Table 4-8 during the 1970-1975 period, and the development of a small semi-permanent base by 1985.

Table 4-8

LUNAR PROGRAM

BUDGET LEVEL (billion $ per year)	69	70	71	72	73	74	75
Additional Apollo/ALSEP		VVV					
Titan/Field Asst./LFV			V	VV	V		
LM Shelter/Taxi/Rover					VV	VV	VV

(2) <u>Constant Percentage of GNP</u>

Assuming the current NASA budget of approximately 1/2 percent of the GNP is maintained through 1985 and that 1/4 of the NASA budget would be spent on the lunar program, a total of approximately 22 billion dollars could be spent on the lunar program. This funding level would permit the undertaking of the program given in Table 4-8 as well as the development of a 24-man semi-permanent base by 1985. However, an average of only 1.85 billion dollars per year (1986-1990) could be spent to maintain the base.

Thus, it appears that, provided the NASA budget is not cut significantly below its current level, a semi-permanent base of some size (6-24 men) can be developed during the 1970-1985 period. It is interesting to note that the calculation of the 22 billion dollars above was based on the 3 percent per year growth in GNP which has occurred since the 1930's. If the growth rate that has occurred over the past decade was used instead (between 6 and 7 percent), a significantly larger lunar program would not be unreasonable.

4.3.2 Cost Factors Significantly Affecting the Design of MOONLAB

During the evolutionary phase of MOONLAB approximately 75 man-years are available to perform activities on the lunar surface. If each scientist who goes to the Moon works approximately 60 hours per week and the resulting man-hours are divided into those costs associated with the delivery and sustaining of personnel on the lunar surface, the result is an average cost of approximately 50 thousand dollars per man-hour. Thus, any system that is being developed for manned lunar program should be developed so that the work involved in deployment, construction, and initiation of operation are kept to a minimum. This is true for all major components of the MOONLAB base, but especially any operation which must be repeated more than once including experiments.

In contrast to the need for automation, the need for miniaturization is not nearly as critical. For example, a kilogram of payload can be delivered to the lunar surface by 10 to 15 thousand dollars. Thus, unless miniaturization can be accomplished for less than 10 thousand per kilogram it, in all likelihood, should be undertaken.

One other factor that must be considered in the base and experiment design is that, except for the small amount of material that can be returned to Earth in a command module, no vehicle exists for returning substantial scientific payloads to the Earth for further analysis.

Many previous studies have assumed that during the course of operation of a lunar program a great deal of surface mobility to explore the lunar surface would be available. If the mobility is provided by a flying vehicle similar to those given in Chapter 12, which expend 4,000 kg to make an 800 km one-way flight, the cost of expendables per flight would be 40 to 60 million dollars. At this cost level mobility will be limited to that which is absolutely necessary for the operation of the main base. The concept of placing many dispersed instruments and revisiting them on a routine basis is out of the question. While surface travel is cheaper in terms of expendables used, it is very slow and may not even be possible over many parts of the lunar surface. Thus, surface travel does not appear to provide a very attractive alternate to flying, indicating that lunar mobility will be limited until either new methods of providing mobility are developed or fuel is found on the lunar surface.

Finally, the length of staytime on the Moon for each person has a decisive effect on the cost of Earth-to-Moon transportation for the purpose of personnel rotation. With the availability of 6-man spacecraft (at approximately 0.4 billion dollars per launch) in the post-1985 period, it will require four launches per year if the staytime for each person on the Moon is limited to one year. Fewer launches per year will be required if the staytime is lengthened. Figure 4-8 shows the relationship between the number of launches per year, and the cost per year required for personnel rotation, and the length of staytime for each person on the Moon. This relationship is in the form of a hyperbolic curve:

$$N = 4/y ,$$

where

N = the number of launches per year required for the purpose of personnel rotation,

y = the corresponding length of staytime (years) of each person on the Moon.

The derivative, $dN/dy - 4/y^2$, represents the rate of change in the number of launches per year with respect to the rate of change of the length of staytime. The value of dN/dy decreases very rapidly as the value of y increases and becomes asymptotic to zero. This implies that the cost of personnel rotation rapidly approaches a rather stable level as the staytime becomes very long. For example, it is interesting to note that if the length of staytime for each person on the Moon is increased from one year to two years, the cost of personnel rotation will

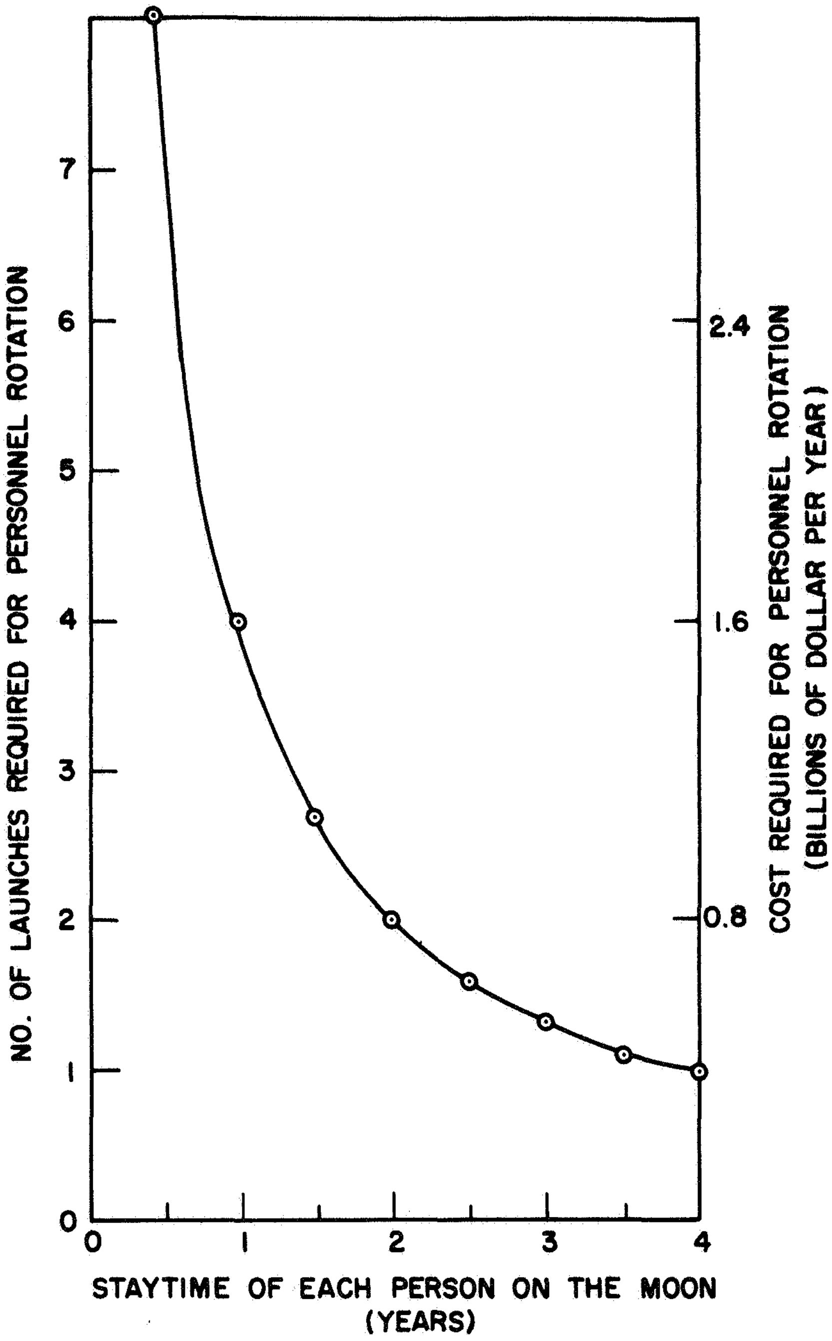

Fig. 4-8. Staytime of Each Person on the Moon (Years) vs Cost.

be reduced from 1.8 billion dollars to 0.8 billion dollars per year. This is equivalent to a savings of approximately 33 million dollars per person per year. If the staytime is lengthened from two to three years, the additional cost reduction would amount of 11 million dollars per person per year. If the staytime is lengthened from three to four years, the corresponding cost reduction is 5.5 million dollars per year. From the viewpoint of economy, the length of staytime on the Moon should ideally be at least two to three years.

However, it is also important to consider the health hazard to which a person is subjected during his stay on the lunar surface. At the present time, little is known about the psychological and sociological effects of living on the Moon. A detailed study of psychological and sociological effects on the well-being of lunar base personnel is an important subject of research. Another important consideration is the

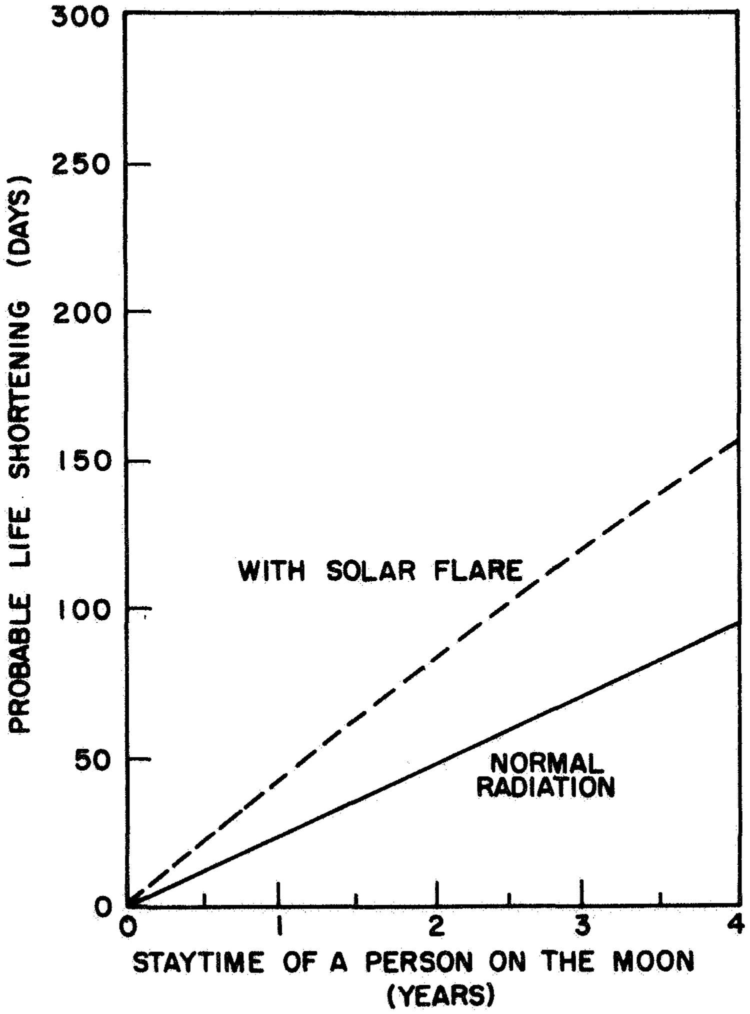

Fig. 4-9. Staytime of Each Person on the Moon (Years).

radiation exposure of lunar base personnel. Extrapolation of experimental findings indicates that at the normal level of radiation on the lunar surface there is a probable life shortening of about six days for every 30-day staytime on the Moon. Thus, a life shortening of about 75 days would be incurred for each year of staytime on the Moon (Fig. 4-9). Radiation from solar flares will cause additional damage to the base personnel. Therefore, radiation hazard must be carefully considered in the final determination of the length of staytime on the Moon. Nevertheless, a staytime greater than one year is clearly indicated if the cost of the post-1985 MOONLAB program is to be kept within acceptable limits of approximately 1.5 billion dollars per year.

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2. Hornby, Harold, "Lunar Delivery Systems," Lecture to NASA/ASEE Workshop, Ames Research Center, Mountain View, California, July 1968.

Part II - MOONLAB JANUARY 1, 1985

Chapter 5

SCIENTIFIC MISSION ACTIVITIES

5.1 Introduction

With the establishment of a 24-man semi-permanent base on the Moon in 1985, the base personnel should be organized to carry out scientific activities which will allow the exploration and study of the Moon. The organization of the base personnel will be discussed in Chapter 6. It is important to remember that the MOONLAB program is a part of the exploration and study of the solar system in the United States long-range space program. As stated in the Space Science Board report, Space Research, "the exploration of the solar system bears on three central scientific problems of our time: the origin and evolution of the Earth, Sun, and planets, the origin and evolution of life, and the dynamic processes that shape man's terrestrial environment. Not only do these problems directly bear on man's place in the universe, but they are closely related to the question of the origin of the universe itself... Of the underlying problems of natural philosophy, the question of the origin of life and the origin of the solar system have received the greatest attention from the public. It is highly appropriate that the prime goals of the nation's space program should be the elucidation of these fundamental cosmological and biological questions." [1]

In the manned lunar mission, the scientific community feels that a primary goal of lunar-oriented studies is to obtain data which will permit (1) determination of the present structure and activity of the lunar interior, (2) determination of the composition of the lunar surface and the processes primarily responsible for the present appearance of the Moon, (3) determination of the history or evolutionary sequence of events by which the Moon arrived at its present configuration, and if possible, (4) the generalization of the knowledge, thus obtained, concerning the Moon to other regions of the solar system and to other specific planetary satellites [2]. Thus, physical sciences in the traditional areas of geology, geophysics, geochemistry, astronomy, and astrophysics, offer obvious gains in science to be accomplished by the presence of man on the Moon.

Technological studies concerned with the description of the lunar surface environment and its effects on both biotic and abiotic materials and systems will also be of high priority in the MOONLAB program. The very presence of men on the lunar base will be an experiment, for nowhere on Earth could one simulate a highly motivated group with a rational, exciting task, operating in a confined, stressful, non-abortive, and long-term natural environment. The results of biological, physiological and psychological studies of men in this scientific mission will be useful to future space missions of longer duration to other planets.

The establishment of the proposed farm on the surface of the Moon, with the expressed purpose of supplying 75 percent of the caloric metabolic needs of the occupants, provides an opportunity for studying lunar agriculture and its possible effects on future space programs. The successful establishment of a lunar farm will have a tremendous impact on the development of activities on the lunar surface, as well as future space exploration. Agricultural activities will provide life support for the lunar population and thus form the basis for permanent colonization of the Moon. In addition to supplying food for lunar population, agricultural activities can also satisfy the following life support objectives: (1) closure of O_2-CO_2 chain by photosynthesis of higher plants, (2) closure of food-waste chain by crops, soil organisms and soil invertebrates, and (3) waste water purification by transpiration and recondensation. The techniques developed for lunar agriculture can be transferred to similar activities on other planets in the future.

To outline the scientific activities of the personnel of the established lunar base from 1985 on, it is important to point out that a gradual buildup of the base will occur in the period 1976-1984 and that during this buildup period short-term exploration of the Moon will have established a bank of information sufficient to understand lunar surface mechanical properties. Thus, in the post-1985 era this base will be primarily for conducting long-term experiments in the sciences and for exploration of technology in the unique lunar environment. Following is a brief discussion of the scientific and technological studies which will be conducted in the MOONLAB program.

Appendix A contains more detail on the MOONLAB scientific mission activities. Where possible, specific experiment information has been taken from the North American Aviation Report [3]. Experiments have been added to the North American list in the areas of biological, agricultural, and behavioral sciences. Time estimates for the experiments in the North American Report assumed five repetitions of each experiment and factors of two to four to convert Earth time requirements into Moon time requirements. Although not considered an integral part of this study, the lunar orbital experiments from the North American Report are also included in Appendix A (Table A-3).

The experiments in the appendix are divided into five phases to be carried out sequentially. Figure A-1 shows the scheduling of these phases with approximate dates. There will undoubtedly be some overlap of activities between phases, and it is anticipated that new or revised scheduling will be made as the program progresses. However for the purposes of this study, it was assumed that the activities listed under phase D will occur in 1986-1988.

The experiments are further divided into three groups in each phase to agree with the division of personnel as discussed in Section 5.7. Table 5-4 summarizes the total scientific time requirements by phase and by experimental group.

5.2 Physical Sciences

Some investigation of physical sciences will have been accomplished in the base buildup period, 1976-1984. However, some experiments in physical sciences will be programmed on a continuing basis. In addition, new areas of investigation will be created as a result of experiments which have been carried out since the initial establishment and operation of the lunar base.

5.2.1 Lunar Atmosphere

Lunar atmospheric studies will involve the determination of the composition and concentrations of neutral species in the lunar atmosphere, and determination of the mass and concentrations of ionized species in the lunar atmosphere. Continuous monitoring of the lunar atmosphere at different locations should be maintained to study the time and spatial distribution and variation of the composition and concentrations of neutral and ionized species in the atmosphere. Special attention should be directed to the gaseous emission from the lunar surface and the absorption of free radicals by the lunar surface. The problem of contamination of the lunar atmosphere by rocket exhaust deserves a major effort in the monitoring program.

5.2.2 Selenodesy (Geodesy)

Selenodetic surveys are concerned with the establishment of an accurate coordinate system for performing detail mapping of the Moon; the determination of size, shape, and motion of the lunar body; and the determination of the gravitational field of the Moon. Continuous survey and mapping activities are required to provide additional details for constructing maps of the lunar surface. Long-range observations of lunar surface gravity and Earth-Moon distances are required in the establishment of an accurate selenodetic coordinate system.

5.2.3 Selenology

Selenological investigations involve reconnaissance and surveying activities to obtain information which will aid in answering basic scientific questions regarding the origin of the Moon, its age, internal structure and internal phenomena. Selenological investigations will include selenomorphology, structural selenology, petrology, volcanology, and field relationships. These investigations will involve mapping of field relationships, sampling of lunar materials and meteorites, and studying meteorite and micrometeoric flux and erosional characteristics. In the post-1985 era, selenological surveys will be extended to outlying areas to search for special characteristics and distribution of the lunar surface, subsurface, tectonic activities, and selenologic structure. With the availability of deep-drilling equipment, a program of systematic selenological investigations at greater depths can be scheduled.

5.2.4 Selenochemistry

Selenochemical investigations include mineralogy, phase composition, elemental composition, isotopic composition, selenochronometry, moisture, and thermoluminescence. These investigations will involve gross chemical mapping, sample analysis, age determination, selenochronology of selenomorphic features, studies of time of material deposition, relationships of time, conditions at time of deposition, studies of crater mineralization, disorder in surface materials due to meteorite bombardment, and analysis of biogenic or carbon materials. A long-range, continuous program of sampling and chemical analysis of lunar materials obtained at different locations should be scheduled in the years following 1985. Special attention should be directed to search for special deposits at prospective sites.

5.2.5 Selenophysics

Selenophysical investigations include seismometry, thermal measurements, gravimetry, magnetrometry, and tellurimetry. These investigations will involve passive, short-period seismic monitoring of natural events, passive, long-period seismic deep interior studies, active seismic studies of lunar surface structure, magnetic surveys, gravitational surveys, tidal movement studies, telluric current studies, thermal studies, and studies to determine the lunar moment of intertia, librations, and orbital perturbations. Emplacement of selenophysical equipment during the buildup period will allow continuous monitoring of lunar seismic activities, lunar librations and orbital perturbation, lunar thermal phenomena, and lunar gravity and magnetic field.

5.2.6 Particles and Fields

Particles and fields studies include determination of the cosmic solar particle radiation environment on the Moon and the lunar interaction with the geomagnetosphere and solar wind. A better understanding of solar radiation is of critical importance for the safety of lunar base personnel. The categories of particles and fields investigations are (a) charged-particle investigations, (b) magnetic-field investigations, and (c) radiation-astronomy experiments. The charged-particle investigations include studies of the electrons and nuclear flux with energy ranges of 10 to 500 keV that are associated with solar activities; time-dependent angular distribution of solar-charged particles with energy ranges of 0.5 to 1000 MeV, including flux vs energy; direction of charged particles of galactic nucleous, flux vs energy; direction of galactic electrons; high-energy particle physics of galactic particle scattering; and the solar wind (10 eV to 10 keV), involving simultaneous observation of the north and south auroral zones during magnetic storms. The magnetic field investigations are concerned with solar and interplanetary fields, including the tail of the Earth's magnetic field. Radiation-astronomy investigations are concerned with measurements of the ultraviolet and x-ray spectra (50 to 0.1 A) of the Sun, stars, and galaxies; measurements of the gamma-ray spectra (0.1 to 10 MeV) of the Sun, stars, galaxies, novae, and supernovae; a study of high-energy gamma-rays (greater than 10 MeV); collisions in an interstellar medium; and a search for celestial sources of neutrinos and measurement of their energy spectra. With the availability of radio-astronomical equipment on the lunar base in 1985, most of the activities in this area will probably be in the category of radiation-astronomy investigations. However, continuous monitoring of the lunar interaction with the solar wind and selenomagnetosphere will be maintained in order to obtain information concerning the time and spatial variation of solar particle radiation environment at the Moon.

5.2.7 Remote Observation of the Earth

Observation of Earth from space will continue to be valuable for purposes such as meteorology and resource utilization. The majority of this work will be from Earth orbit. However, Earth observations will be made from MOOLAB for purposes of obtaining coverage which is difficult to obtain from Earth orbit, for calibrating orbital observations, and in any case of economic advantage.

5.2.8 Astronomy

Activities in astronomy will form a major portion of scientific work to be performed at the lunar base in the post-1985 period. With the availability of both the optical and radio astronomy equipment, a wealth of information in astronomy could be expected from such activities. The unique visual environment on the lunar surface greatly extends the viewing capability of telescopes. A 40-inch telescope on the lunar surface is equal in faintness limit to a 200-inch telescope on Earth. Optical astronomy investigations include photographic studies of extended surfaces consisting gegenschein, zodiacal light, lunar libration clouds, structure and time changes in the Earth's magnetosphere, outer solar atmospheres, and comets; photoelectric studies of unique objects with emphasis on ultraviolet and infrared regions of the spectrum; narrow- and wide-band photoelectric photometry; photographic and spectrographic observations of faint and bright objects; wide-band photographic photometry to very faint limits; solar spectroscopic and photographic observations; high-resolution photographic and spectroscopic studies of outer planets; systematic studies of high-energy phenomena in stars; high-resolution studies of the solar surface and very high dispersion spectroscopy of the Sun; studies of the outer envelopes of stars and galaxies; surveys for detection of planets and other systems; high-resolution photography of stars, planets, galaxies; high-dispersion spectroscopy of peculiar objects; and photoelectric photometry at high-precision accuracy. In addition, lunar telescopes can be used in Earth-directed investigations in the areas of meteorology and oceanography. Earth-directed observations from lunar telescopes can be made to determine (a) atmospheric heat balance; (b) reflectivity and albedo; (c) heat flux measurements of ocean surface and cloud cover involving the determination of sea surface temperatures over large areas for determination of thermal content of the Earth's oceans; (d) sequential photography to obtain information and measurements on sea surface glitter, contrasts, and colors, and ice pack information concerning degradation and movement; and (e) sea-surface height measurements for measurement of slope and ellipticity of of the geoid. Radio-astronomy investigations will be of major importance during the post-1985 period. No other scientific area is expected to yield as much broad scientific information for the effort expended. The lunar station will provide opportunity for sensitive, long-term, detailed radio-astronomy studies of the universe.

5.3 Technology

Lunar environmental conditions provide unique advantages for the performance of basic and applied research. Basic and applied research in basic knowledge areas, such as physics, chemistry, biology, materials, etc. can be performed to take advantage of such unique properties of the Moon and of the lunar laboratory as (a) extensive vacuum; (b) low gravity; (c) focusable, unfiltered thermal energy from the Sun; and (d) the availability of deep space and subsurface as a heat sink.

The technological investigations are related to basic scientific research with application to engineering problems. These investigations involve physics experiments to make use of the unique lunar environment, materials research, lunar and Earth, in the lunar environment, and exploration of lunar resources.

The physics experiments are of a fundamental type to further knowledge in molecular and atomic beams, relativity, cryogenics, satellites, and plasmas. The Moon may offer a site for a very large particle acceleration installation, which will extend the present status of knowledge in fundamental particles.

Lunar materials research experiments involve dating possibilities by thermoluminescence in lunar materials, methods of extracting the useful materials from lunar raw materials, and studies of the effects of the lunar environment on Earth materials.

Technology concerning the utilization of lunar resources will be explored at the lunar base. A program of lunar resources utilization includes lunar resources survey, prospecting, and analysis; lunar mining and materials handling technology; lunar materials extraction and process technology; and lunar manufacturing techniques.

5.4 Biological and Biomedical Research

The categories of biological investigations are exobiology, evaluation of proposed ecological system components, and effects of lunar conditions on living systems.

Exobiology investigations relate to studies of induced prebiotic chemistry and evidence of existing life. These studies would involve experiments to determine the effect of exposure of chemical mixtures to lunar conditions, synthesis of complex molecules, and the origin of biological molecules. Identifying the absence or presence of living forms on the lunar surface or subsurface will also be an aspect of these studies.

Evaluation of proposed ecological system components involves the analysis of farm plants including growth, photosynthesis, and gas exchange efficiencies of selected plants under lunar conditions; evaluation of hydrocarbon utilizing organisms including the valuation of bacteria using hydrocarbons to produce carbohydrates, fats, proteins, etc.; photolysis of water involving the utilization of lunar solar insolation for energetic reduction of H_2O; and the analysis of lunar materials with regard to their nutrient and toxic properties and the evaluation of their use for higher plant growth.

Investigations for determining the effects of lunar conditions on living systems involve experiments for determination of the sterilizing capacity of the lunar environment regarding spore and microorganism survival. Experiments will be conducted to determine growth, development, reproduction, and survival characteristics to identify long-term subtle effects of lunar habitation on organism behavior, rhythms, and genetics.

Biomedical investigations of interest will be studies of lunar gravity effects, general health and safety, mechanical efficiency of man in reduced gravity, crew work capability, and psychological effects. These studies involve the effects of prolonged habitation of 1/6 gravity on the physiology of lunar base personnel; metabolic, chemical and psychological monitoring; energy expenditure, and metabolic cost of work tasks; work efficiency; ability to perform standard tasks; and effects of confinement and isolation on crew interaction, mood changes, and motivations.

5.5 Behavioral Science Research

The presence of 24 men in the lunar base provides an opportunity to perform and document behavioral science research. Behavioral science research tasks include studies of man's response to sensory and social improverishment, personality adjustments during confinement, group organizations, interpersonal relationships, techniques of arbitration, motivation during extended confinement, general psychological impairment during confinement, authority relationships during long confinement, group relations in multisized groups, performance decrement in lunar environment, sex-related tensions in a monosexual group during confinement, the effect of failure to satisfy normal emotional needs, and use of post-hypnotic suggestion to reduce emotional stress. The behavioral science research tasks, as outlined above, should be initiated early and should be programmed on a long-term basis.

5.6 Agricultural Science Research

Agricultural research is expected to be of primary importance in successful continuous operation and improvement of the lunar farm. A research farm should be set aside for experimental work in lunar agriculture. Agricultural research experiments include studies of the growth rate of different plants in the lunar farm environment, genetic effects on plants resulting from exposure to lunar conditions, effects of lunar conditions on the behavior and rhythms (28-day lunar day-night cycle) of farm plants, performance of hydrogenomonas in the synthesis of organic compounds from CO_2 and inorganic materials, use of hydrocarbon utilizing organisms for the biological synthesis of hydrogen and carbon dioxide into edible food, use of lunar materials as plant nutrient, and seed improvement in lunar agriculture. Research on the feasibility of raising livestock in the lunar farm should be initiated as soon as possible. This phase of research work should be coordinated with the studies of ecological system evaluation discussed in Section 5.4.

5.7 Personnel

The personnel at MOONLAB in 1985-1986 will consist of three functional groups of eight men each; a physical science and technology group, a biological and behavioral science group, and an astronomy group. The suggested types of individuals in each of these groups is shown in Table 5-1. During the evolutionary period the personnel will gradually build up from three men in 1976 to 24 men in 1985. In this period the type of personnel will evolve to the grouping suggested in Table 5-1. Table A-1 in Appendix A shows the evolution of the base personnel.

In 1985-1986 the major efforts of the MOONLAB personnel will be scientific activities. It is estimated, however, that 3 men will be required for life support activities (including the farm), communications, and other non-scientific duties. During the evolutionary period the non-scientific activities will represent a larger portion of the total activities. Table A-2 in Appendix A indicates a suggested breakdown of duties during the evolutionary period.

The activities of the 24 men in 1985-1986 have been further broken down into general categories such as setting up experiments, and making observations. This breakdown is shown in Table 5-2.

Table 5-1

PERSONNEL AT MOONLAB IN 1985-1986

Physical Science and Technology Group

1	Geophysicist
1	Geologist (geochemistry)
1	Physicist (particles and fields)
1	Engineer (materials and chemistry)
1	Engineer (soils, construction, drilling techniques)
1	Communications Expert (Electronics)
2	Engineering and Research Support Personnel

Biological and Behavioral Sciences Group

1	Experimental Social Psychologist (MD, Psychiatrist)
1	MD Psychologist (Surgeon, Physiology)
1	Biologist
1	Micrcbiologist (Exobiology)
1	Agronomist (Farm and Life Support)
1	Agriscientist
1	Engineering and Research Support Personnel
1	Communications Expert (Electronics)

Astronomy Group

5	Astronomers
3	Engineering and Research Support Personnel

Total Personnel at MOONLAB = 24

Table 5-2

TYPICAL TYPES OF ACTIVITIES BY PERSONNEL IN 1985-1986

		Percent of Time
1.	**Communications Experts**	
	Repairing equipment	30
	Modifying equipment	35
	Planning new systems	35
2.	**Physicist, Geologist, Geophysicist**	
	Setting up experiments	15
	Organizing and developing experimental programs	70
	Analysis of data and samples	15
3.	**Engineers**	
	Construction of facilities	10
	Drilling, collecting samples, field surveys	65
	Analysis of samples and data	25
4.	**Astronomers**	
	Setting up equipment	5
	Making observations and astronomical measurements	85
	Analysis of data	10
5.	**Microbiologist, Biologist, Agriscientist**	
	Setting up experiments	5
	Developing and maintaining experiments	70
	Analysis of data	25
6.	**Agronomist**	
	Operating farm	60
	Operating atmosphere system	20
	Operating water and waste systems	20
7.	**Engineering and Research Support Personnel**	
	Setting up equipment	10
	Taking data and samples; repairing and modifying equipment	45
	Analysis and recording of data and samples	45

Table 5-2 (cont)

	Percent of Time
8. **Experimental Social Psychologist**	
Medical emergencies and treatment	10
Psychological counseling	40
Social-psychological experiments	50
9. **MD Psychologist**	
Physical fitness program	20
Human factors and environmental experiments	80

Table 5-3

SCHEDULING OF SCIENTIFIC ACTIVITIES

Activity Phase	Estimated Beginning Date	Estimated Completion Date
A	First Apollo Landing	1976
B	1977	1982
C	1982	1985
D	1985	1987
E	1987	1988

Table 5-4

TIME REQUIREMENTS FOR SCIENTIFIC ACTIVITIES
(Time in Man-Years)

Phase	Physical Sciences and Technology	Biological and Behavioral Sciences	Astronomy
A	0.6	0.1	0.0
B	11.0	5.2	8.2
C	7.3	17.8	9.9
D	10.1	10.4	19.8
E	9.0	10.0	19.0
TOTAL	38.0	43.5	56.9
	Total Man-Years of Science = 138.4		

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2. Van Driest, E. R., and D. F. Mitchell, "Scientific Missions for Manned Lunar Operations," Astronautica Acta, Vol. 12, No. 5-6, pp. 405-415, 1966.

3. North American Aviation Report, "A Study of Scientific Mission Support for Extended Lunar Exploration."

Chapter 6

PERSONNEL

6.1 General

While the literature on the performance of isolated small groups is fairly large, there appears to be little conceptual agreement on many matters. However, some factors have been observed and replicated and these will be useful in determining the selection, training, and organization of lunar base personnel.

The isolation factor, of major concern in the selection of personnel, will be discussed first. The isolation to which a group on the Moon will be exposed will be an absolute physical isolation in a hostile environment from which there may be very limited possibility of escape, and very limited possibility of receiving physical assistance from the Earth. In addition, a degree of sensory deprivation and cultural isolation will be present depending upon the design of the lunar mission.

The time factor in isolation is very important. For the MOONLAB it will be a specified time period based on the time required to accomplish all scientific objectives economically. It will be essential to schedule the research activities so that each person has a definite feeling of worth and involvement during the entire period. It is very likely that the circumstances of technology and economy in 1985 will make a premature termination of the fixed isolation period of low probability. An extremely important bias on the functioning of the indiviiduals and the organization will be a continuous, large capacity communication system. The influence of this continuous tie to families, libraries, professional assistance, and to Earth functions in general should be carefully examined in confinement studies prior to the actual mission. It is especially important to determine the effect of an existing or interrupted Earth communication link on group interpersonal relationships.

At this point in time it appears that the major limiting factor in long-term extra-terrestrial activities is the problem of interpersonal relationships for the isolated individuals. Studies indicate that there is a phasic nature of those relationships for the lunar group size during the period of isolation.

Referring to the "people pool" at the left of Fig. 6-1 we shall assume these men are all Americans, but the possibility of making the MOONLAB international should not be ruled out in future studies. Another more remote possibility is that the people pool will contain "modified people"; that is, at a later extremely mature stage of MOONLAB people who have had extensive conditioning, either psychological, physiological, or both, will be available for particular tasks not easily accomplished by normals.

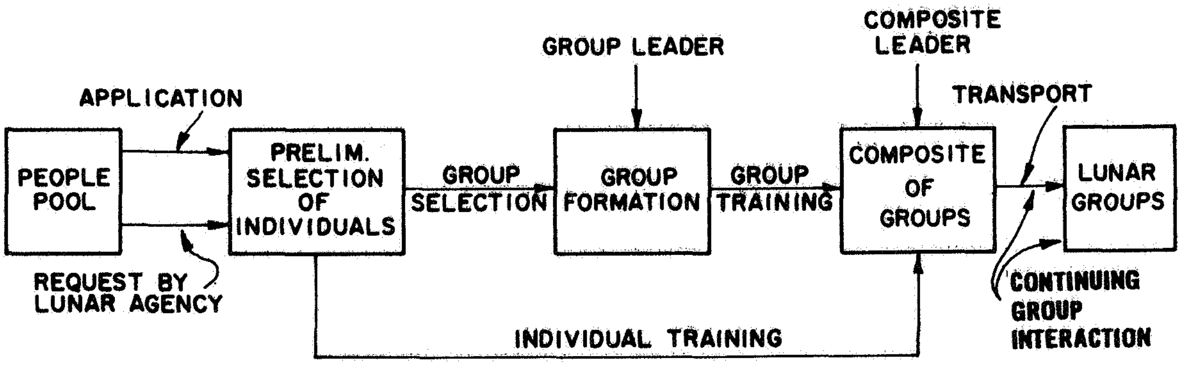

Fig. 6-1. Flow Graph to Display a Possible Process for Selecting, Organizing, and Training the MOONLAB Personnel.

In the preliminary selection of individuals, the following items will be considered:

(1) History, and clinical examination,
(2) Skills,
(3) Testing: psychological and physiological,
(4) Psychiatric exam (capacity for growth),
(5) Aptitude to acquire other skills,
(6) Interviews, and
(7) Leadership qualities.

It is anticipated that the selection criteria will change through various stages in the history of the MOONLAB. In the early construction stage the emphasis will be on astronaut-engineer types chosen during a "high prestige" period. At a later stage this will change to purely scientific personnel working in a more routine laboratory environment. Clearly, the inducement and motivation of the people will reflect this transition. At the outset the prime inducements will be the challenge, the money, and the prestige. Later it will be a group of scientific investigators who are very excited about doing something in their specialty that cannot be done on Earth.

Following the preliminary selection the eight-man teams will be formed by grouping individuals according to specialties, then using group dynamics techniques to stabilize the combination. This will be discussed further under Section 6.5.

Phase 1: Heightened anxiety as a function of the sense of danger a given individual perceives at the outset.

The problems of Phase 1 have been dealt with in other situations by ensuring that individuals are kept very busy with tasks requiring a great deal of bodily activity.

Phase 2: The long settled-down period during which anxiety lessens and there is an increase in depression.

In Phase 2 each man has settled into his routine; generally controls his depression, and functions adequately, but not superlatively, in his job. The depression appears unavoidable and may be a serious problem for personnel performing critical tasks. Studies should be made to determine a means of measuring performance degradation during depression. In addition, methods of alleviating depression should be determined.

Phase 3: Near the end of the isolation period there is increased affect and anticipatory behavior, and a higher probability of aggressive behavior.

In many confinement studies the Phase 3 behavior has been duplicated. There is a distinct reduction of performance levels, housekeeping and daily routine chores tend to be neglected, and anxieties seem to rise. Earth studies must be directed toward finding ways to handle these problems.

Related to tenseness and anxiety in small groups is the problem of sleeplessness. People in stress studies have tended to go for several days with only an hour of sleep a day. On the Moon, where each person's activities may be critical, this could be a serious problem. Chemical means or techniques, such as hypnosis, should be investigated for inducing sleep.

Though leisure time is frequently anticipated to be spent in intellectual and cultural pursuits "never quite gotten to" before isolation, the general recreation of small isolated groups invariably tends to become very simple and basic. Recreational activities must be planned accordingly.

Closest interpersonal relationships tend to be established between people doing similar kinds of work. On this basis the organization of the lunar personnel will consist of three groups each oriented around the type of work to be done, i.e., a physical sciences group, an astronomical group, and a biomedical, biological and behavioral sciences group.

Before sending men to the Moon for an extended stay, a great deal more study is required of groups totally committed to complete physical isolation (with reliable communications) in determining what occurs in interpersonal relationships. This is particularly important since the literature has dealt exclusively with groups formed immediately before isolation took place. Unless a great deal more is learned, it must be assumed that lunar personnel will be selected and organized for an extended training period prior to actually occupying the MOONLAB.

6.2 Personnel Selection

Since we will not take "captives" to the Moon, and will not allow situational events to choose the Moon men, it is assumed that all personnel will be volunteers.

The following motivations have been identified for people who volunteer [1]:

1. Desire for prestige,
2. Desire to escape an unpleasant situation,
3. Feelings of inadequacy that spur them to prove themselves,
4. Financial reward,
5. Curiosity (intellectual),
6. Challenge of the unknown.

These are general motivations, and to the list we can add the desire of a researcher to achieve scientific goals in his professional work on the Moon not possible on Earth. In the selection process a weighting criteria must be established for the several motivations, and means evolved for determining the extent of a given motivation in an individual.

Based on the comments in the introductory section of this chapter, and in coordination with other constraints on the development of the MOONLAB, the general design assumption is that there will be an evolutionary period during which the MOONLAB personnel will build to a steady-state number of 24 men. They will function in three groups of eight and will remain at least a year. Depending on the scientific work to be done, stays can be longer; for the longer stays, study and consideration should be given to the inclusion of women among MOONLAB personnel.

6.3 Group Formation Criteria

The small group literature is large and varied. Because the MOONLAB personnel will be part of a confined small group, it is essential to isolate the salient knowledge (or be aware of the lack of it) so that successful MOONLAB groups may be formed. The following material represents a compendium of research results abstracted from the literature to be used as a guide in group formation. The characteristics of both the group members and the group itself are given.

6.3.1 Group Members

Abilities and experience: In general there is a distinct correlation between capabilities and skills of group members and their individual performance. However, knowing these relationships it still may not be possible to predict the performance of the group. Group performance is not a simple summing of individual performance. It has been found that group members are not good judges of one another's capabilities, except with respect to judgments of leadership potential.

Personality and biographical characteristics: These characteristics of group members have been studied little, and for the work that has been done no general propositions have appeared.

Attitudes: There is some indication that member attitudes toward the group task are associated with an overall personal success in the situation. However, these attitudes do not seem to relate to individual task performance or to the quality of group interpersonal relationships.

Status: Members who have high social or task status in the group are likely to have high power, to use it, and to react favorably to the group. However, understanding of an individual's performance cannot be gained solely from knowledge of his position in the group.

6.3.2 Group Characteristics

Capabilities and experience: The more task training and experience groups and group members have the better they will perform as individuals and groups. Little is known about how capabilities and training accomplish their impact on group performance.

Group size: The general proposition that the smaller the group the more effective its performance appears frequently in the literature. However, this point is not at all clear. For small groups a few consistent relationships have been observed. Small groups require less guidance and leadership capability, but perceive themselves with less ability as a whole. Ideas and attitude changes will be fewer. Small groups will be intensely aware of group task success.

Composition of group: Unfortunately this critical group characteristic can not be effectively handled with what the literature has to offer. There are such variables to consider as interests, values, personality, background, abilities, etc. However, realistic guidelines for synthesizing groups containing these variables in a specified form do not exist. One may speculate that for some variables both high and low levels are required, and for other variables either high or low levels would be desirable.

Group interpersonal relations: The literature indicates a complicated situation. Interpersonal attractions, interpersonal communication, and perceptions of task success may vary interdependently. Thus when one is analyzing a variable, changes in the other two must be included. A great deal of work needs to be done on these three variables and their interdependence.

Leadership: Most of the literature on leadership performance has come from leaderless group situations where leaders were identified in a dynamic way. Desirable leadership characteristics appear to be: individual personality characteristics, education, intelligence, ability, high group status, and leadership training. Age and biographical characteristics do not seem to contribute. Much less is known about the behavior of a good leader or the difference in the behavior of leaders and non-leaders.

If we are successful in using these research results to synthesize MOONLAB task groups, we may anticipate that our groups will possess the following characteristics:

(1) A common purpose,

(2) Common recognition by members of the group of the boundaries of the group and their position and function in relation to those of larger units or groups,

(3) A flexible group character having the capacity to absorb new members and to lose members without threatening group individuality,

(4) Freedom from internal subgroups with rigid boundaries,

(5) A relationship in which each group member is valued for his contribution to the group and has free movement within it, limited only by the generally accepted group conditions, and

(6) The capacity to face and cope with discontent.

It will be no easy task to use the existing research results to attempt to form stable groups possessing the desired group and individual characteristics. The detailed selection program must allow for careful formation of over-populated groups which will settle to a stabilized eight-man size after training.

6.4 Training

As in Fig. 6-1, individuals will undergo training, and the groups of 12-16 will be trained together. The type of activities individuals will be doing is indicated by the following partial list:

(1) Designing their lunar research,
(2) Learning the details of all lunar equipment,
(3) Participating in group dynamics,
(4) Refining the general mission,
(5) Relating to the scientific community,
(6) Strengthening existing skills,
(7) Acquiring new skills,
(8) Physical conditioning, and
(9) Experiencing low-gravity simulators.

The groups of eight people will be involved with

(1) Preparing cooperative scientific ventures,
(2) Sensory awareness training,
(3) T-groups (encountering), and
(4) Relaxation techniques including meditation, self-hypnosis, and yoga.

The preceding training requirements are intended to apply primarily to the steady state post-1985 period, and must be modified for the short staytimes of the MOONLAB evolutionary period. However, it is the long staytimes of the later periods which appear to have the most serious potential personnel problems. The training program may be variable in length for the evolutionary period, but should be at least one year long for the post-1985 period.

6.5 MOONLAB Organization

The term "group dynamics" has become familiar only in recent years, and in popular imprecise usage has come to mean one of three different versions. In the first version group dynamics refers to the means by which groups should be organized and managed. The emphasis on means is to stress the importance of democratic leadership, the participation of members in decisions, and the gains both to society and to individuals to be obtained through cooperative activities in groups. This version has been criticized as making "togetherness" a prime virtue and advocating leaderless groups participating fully and equally in everything.

A second version of group dynamics has the connotation of role playing, observation, and feedback of group process. This version has been used widely to improve skill in human relations.

The third more formal version of group dynamics refers to a field of inquiry concerned with the nature of groups, the laws of their development, and their interrelations with individuals, other groups, and larger institutions. Clearly, all three definitions have something to offer in organizing MOONLAB personnel.

The following list indicates significant aspects of group dynamical procedures:

(1) Groups will include 8 men,

(2) Roles of men in the group will be the same, regardless of external status,

(3) There will be no formal organization for functioning as a group,

(4) There will be no prearranged agenda or goals,

(5) The group will begin together to organize, regulate its own conduct, and establish its direction and goals,

(6) The content of group discussion will be general MOONLAB topics; however, of prime importance will be how the discussion takes place, and how the group sees itself working together regardless of content,

(7) Power relations (picking order) will be clearly on view in a group,

(8) Issues will be clarified, problem-solving atmosphere maintained, ideas tested for feasibility and consequences, and decisions made.

Institutions of all types and sizes have been using group dynamics successfully for years. Group dynamics permitted people with a common goal to interact more completely and efficiently in task-oriented groups.

During the training period, it is anticipated that three group leaders will "emerge." It is possible that the leadership role may change depending upon the emphasis of the work at a given period. A "composite" leader of all three groups could be appointed externally, but he would be required to successfully lead MOONLAB people during the training period.

Review of status, resolution of difficulties, and planning will be done by the group leader and the several peers of his group on a regular basis through frequent meetings. The composite leader will coordinate the three groups and arrange the necessary hybrid meetings. The atmosphere during dynamic group meetings must be open, honest, and candid.

6.6 Daily Schedule

Table 6-1 represents the work-rest-sleep schedule for a sample day on the Moon. The division of the workday into approximately four two-hour periods should contribute to both morale and work performance. The frequent exercise periods are essential to prevent excessive physiological debilitation.

Table 6-1

SAMPLE DAY

Hours	Activity
1 2 3 4 5 6 7	Sleeping
8	Exercise
9	Eating Hygiene
10 11	Work
12	Exercise
13	Hygiene Eating
14	Free time
15	Work
16	Exercise
17 18	Work
19	Eating Exercise
20	Hygiene
21	Free time
22 23	Work
24	Exercise

Chapter 7

LUNAR BASE LAYOUT AND DESIGN

The unique aspects of the manned lunar observatory, both in mission and in environment, provide a strong impetus for consideration of the man-base relationships. If man-machine interaction is deserving of consideration for Earth systems development and evaluation, then indeed the combined effects of isolating the man from his home planet, imposing reduced gravitational fields, and operation within an extremely hostile environment add yet undefined complexities to this interaction. It has been stated that the human isolation factor is probably the greatest single psychological barrier to prolonged human space travel or in this case lunar staytime. The problems associated with the effects of isolation can be alleviated by the application of human engineering principles to the lunar base design, layout, and facility arrangement.

The purpose of this section is to analyze the spatial requirements and their relationship to the man-operators and other site conditions over which the designers have control. In addition, consideration has been placed upon equipment placement and arrangement with respect to maximizing the total mission effectiveness. Habitability factors (odor, noise, illumination, temperature, humidity, living space, recreation, etc.) will be considered where it is demonstrated they will be potentially significant to the lunar base operator's total performance.

7.1 Spatial Requirements

The spatial requirements of the lunar base must be viewed with respect to the base evolution cited earlier. The requirements, however, are dictated during any phase of development by the activities and functions of the base personnel and the physical equipment requirements necessary to provide life support, mission execution, and expansion of base operations.

It has been agreed that the habitat, or base module, used for all base operations shall be the space canister employed to carry cargo and men to the Moon. Figure 7-1 presents the configuration of the proposed lunar module.

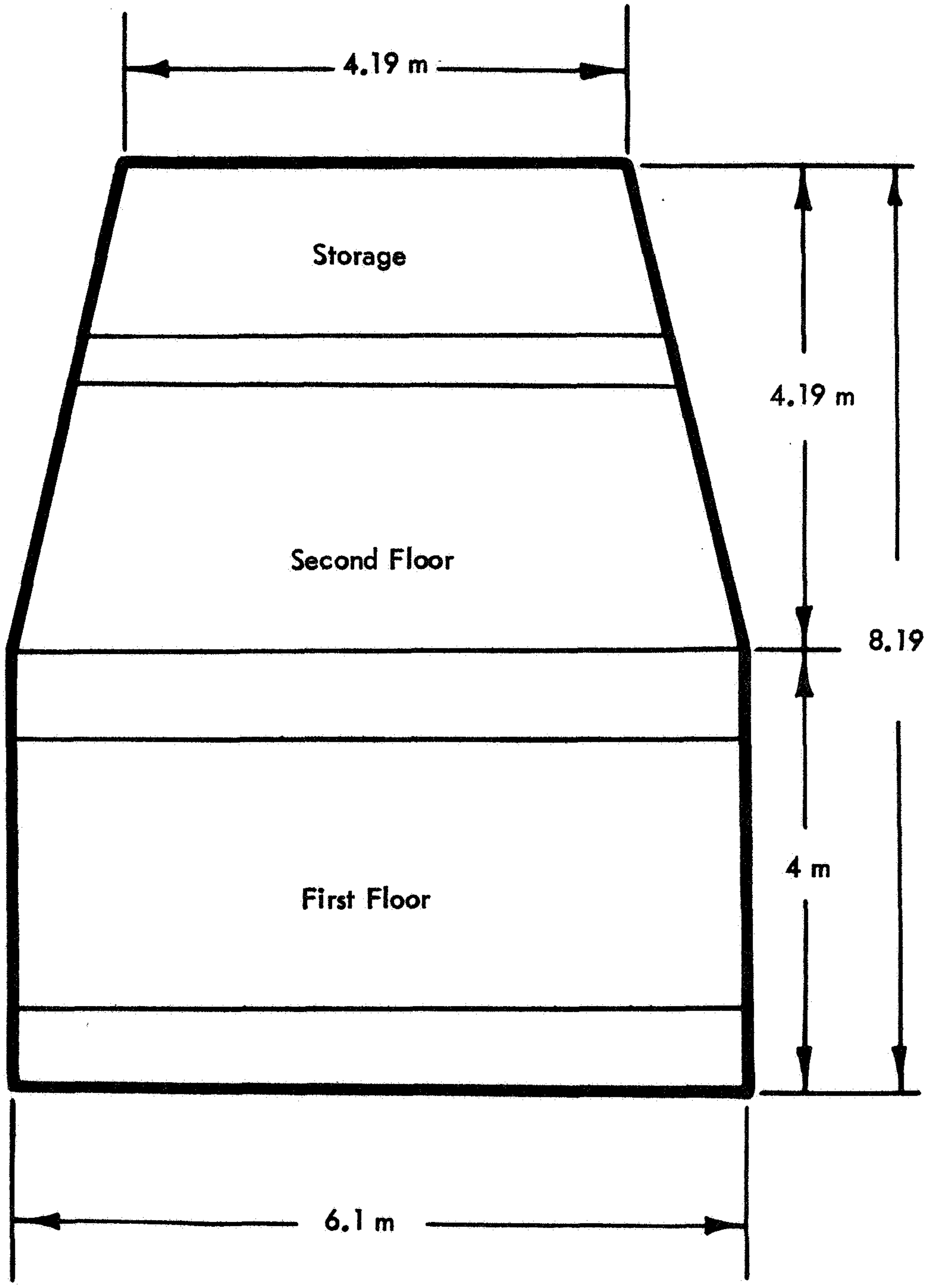

Fig. 7-1. Shelter Dimensions.

After 1985 eight such modules will be available at the lunar base. Further elaboration and detail of the lunar module will be presented in Chapter 10.

7.2 Evolutionary Spatial Requirements

The first canister (M-1, Fig. 4-1) will be launched in 1976 and will contain life support and science equipment and facilities to accommodate 3 to 6 men. All requirements of man-base needs must be met for these men over an extended period of time. As the base is progressively developed and the space within M-1 is expanded to meet additional manpower requirements, the canister will change in function. At the time of steady state operation (1985) this canister will be used as the bioscience laboratory, hospital, and maximum security habitat for the 24 man-base operation. As this canister will have the greatest lunar staytime, and therefore greatest potential threat to environment hazards, e.g., micrometeorite and radiation damage, the entire structure will be covered with lunar soil to a minimum depth of one meter.

Table 7-1 reflects the available canisters for habitation and the associated manpower increase. As expansion of the base is made, alterations of the space modules will be made. Effort has been made, however, to design the modules with respect to the total steady-state condition so that minimal effort will be required for such modifications.

Table 7-1

MODULE LAYOUT SCHEDULE

Module	Activities	Year	Manpower Cum.
M-1	Medical/Dental	1976	3
M-2	Personal Hygiene	1978	6
M-3	Sleeping	1981	6
M-4	Command	1981	9
M-5	Phys. Science	1982	9
M-6	Offsite Activities - Common	1982	12
M-7	Agriculture	1983	24
M-8	Astronomy	1984	18
F-1	Fruit and Veg. Farm	1984	24
F-2	Perennial Farm	1984	24
F-3	Ann/Bienn. Farm	1984	24

7.3 Steady State Requirements

For the purpose of grouping spatial requirements, the lunar space which man will occupy, regardless of the evolutionary stage, can be separated into three main categories (Fig. 7-2).

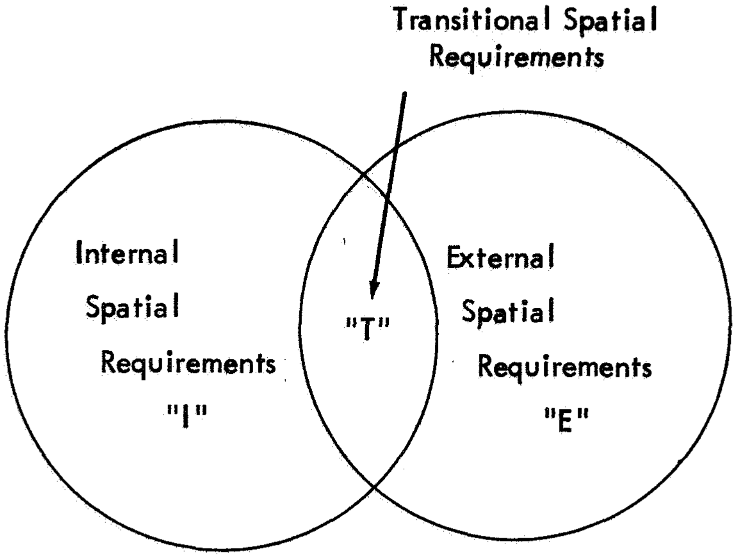

Fig. 7-2. Spatial Requirements.

7.3.1 Internal Spatial Requirements ("I")

This space category will be provided by the space modules. It will be maintained in essentially a "shirt sleeve" environment. It is recognized that there will be some risk of loss of structural integrity to the shelter module. In addition, there will undoubtedly be a range of radiation protection for the inhabitants in this area. The potential hazards associated with the variations in protection must be accounted for to provide maximum safety.

7.3.2 Transitional Spatial Requirements ("T")

This category includes all space that connects or separates the Internal living space from the lunar void. Air locks, passageways, life support tethers, etc., are examples of such space.

7.3.3 External Spatial Requirements ("E")

This represents the space man will occupy on the lunar surface or subsurface which is not associated with a life support atmosphere. Vehicular storage, power generation equipment, and agriculture are examples of activities utilizing such space. Meteorite and/or solar protection may be included in this area, but the environment will not support human life without individual life support equipment.

7.4 Spatial Allotments

Table 7-2 lists those activities which the crew will engage in that will require particular spatial allotments. The spatial categories defined above have been (Internal, Transitory and External) used to define gross area/volume requirements needed in each case. As the total available free volume per individual in MOONLAB is well above the value normally associated with confinement-isolation studies, no psychological problems are expected to result from minimum volume conditions.

Review of the literature discussing space-activities proportions that occur naturally or through design yielded rather consistent values. Figure 7-3 represents an average proportional breakdown based upon many survival shelter and space cabin studies. It is believed that these approximate proportions should also exist in the design of the lunar base.

7.5 Module Layout

Working from the premise that eight space canisters would sustain a steady state lunar base capable of providing the environment and equipment for a 24-man observatory, the primary concern is with canister arrangement. Many tradeoffs are necessary to allow a buildup of man-machine components to occur and to result in a steady state base that is also functionally operable. For example, the M-1 module originally designed as a three-man habitat must eventually serve as the base hospital and for other activities unforeseen at the time of development. Figure 4-1 represents the lunar base after 1985.

Table 7-2

ACTIVITY/SPACE IDENTIFICATION

Basic Crew Activities	Spatial Requirement Categories		
	I	T	E
Command and Control Operations			
Mission Operations	X		
Logistics	X		
Communications	X	X	X
Data Recording	X	X	X
Launch and Land Operations	X		X
Storage	X		X
Computation	X		
Crew Records and Files			
Systems Control/Base Operations			
Environmental Control	X	X	
Energy Production and Management	X	X	X
Subsystems Monitoring	X	X	
Waste Control	X		
Space Suit Storage		X	
Crew Locomotion	X	X	X
Research or Special Mission Operations			
Planning	X		
Equipment Operation*	X	X	X
Laboratory Operations	X		X
Data Recording and Handling	X	X	
Analyses	X		
Vehicular Storage			X
Physical Equipment Storage	X		X
Agriculture	X	X	X
Maintenance			
Inspection	X	X	
Servicing			
Fault Detection	X	X	
Equipment Repair	X		
Structural Repair	X	X	X
Base Housekeeping	X	X	
Power Equipment	X	X	X
Vehicular Repair	X		X
Offsite Activity Equipment			

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*See detailed list.

Table 7-2 (cont)

Basic Crew Activities	Spatial Requirement Categories		
	I	T	E
Crew Personal Operations			
Food Processing	X	X	X
Food Preparation	X		
Food Consumption	X		
Defecation and Urination	X		
Bathing	X		
Personal Hygiene	X		
Clothing Change and Storage	X	X	
Exercise	X		X
Recreation	X		
Biomonitoring	X	X	X
Medical/Dental Care	X		
Rest	X		
Personal Storage	X	X	X
Water Management	X	X	X
Laundering	X		
Service Storage	X		X
Crew Skill Maintenance			
Emergency Procedure Drill	X	X	X
Specialty Training	X		
Data Storage and Retrieval	X		
Sleep and Privacy			
Sleeping	X		
Reading	X		
Personal Storage	X	X	X

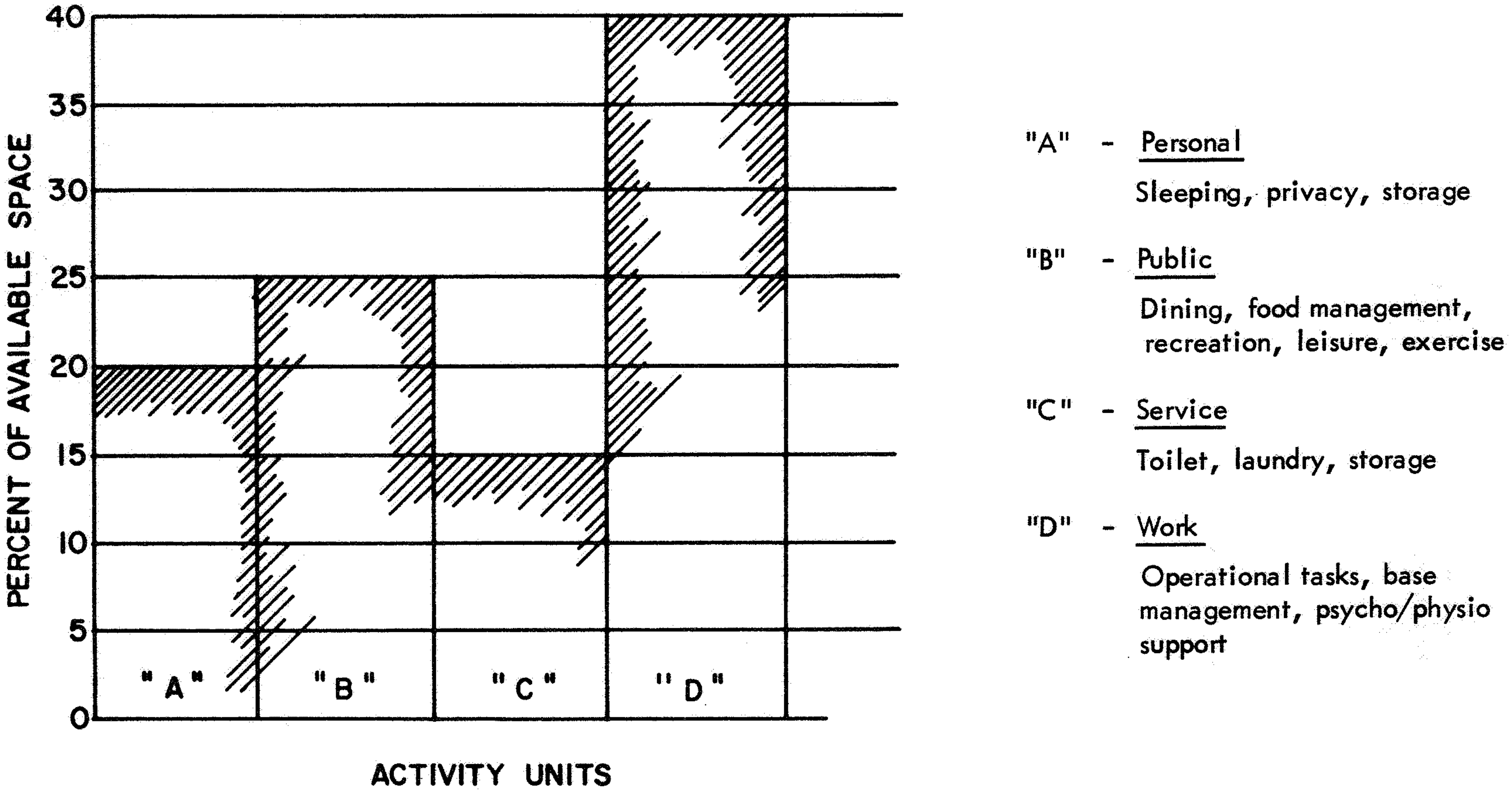


Fig. 7-3. Space/Activity Proportions.

7.5.1 Consideration of Human Factors

The eight pressure vessel canisters, although launched separately with temporary individual functions must operate as a single base with a larger total mission function. The arrangement of the modules, their associated activities, and the operators of the equipment can mean the difference between accomplishing and not accomplishing the mission. Proper arrangement of the components (man and machine) and their interrelationship with other modules should be based upon the visual, auditory, and control links and upon an analysis of the tasks to be performed. The arrangement shown in Fig. 4-1 has been developed with those principle tasks in mind.

Some of the important design features which have resulted from consideration of human factors are listed below:

(1) Separation of noisy (off-site activities module) from quiet zones (sleeping),

(2) Emergency ingress-egress passageways in the event of adjacent structural damage,

(3) Normal activity "flow" routines have been designed into adjacent canisters (e.g., sleeping, personal hygiene, eating),

(4) Farm and food preparation,

(5) The command module is centrally located,

(6) Provision has been made for a continuum of social activity (individual quarters in M-3 to 24-man group meetings in dining/conference area M-4). Allotments have also been made for individual and group recreation.

(7) Work stations all radiate out from the central command station allowing easy accessibility for records, files, and computation.

(8) The primary water storage (M-2) is located adjacent to the maximum security habitat (M-1). This module also contains all emergency medical facilities in the event of disaster.

(9) Emergency air locks are provided to and from every shelter. Emergency monitoring of all shelters for air pressure fluctuations is planned. Additional emergency backup procedures are covered in Chapter 13.

7.5.2 General Design Considerations

The following design considerations/recommendations for the base are believed to have an effect on total operator performance. No attempt has been made here to give specifics on separate modules. Specific detailed arrangement of work station layout and other interrelationships are presented in Section 7.6.

Design of Workspace and Equipment Layout

To date many handbooks and guides have been published providing the engineer with recommendations and general principles for the design of workspace and equipment layout. The design of this lunar observatory has made use of this information for problem solutions. Many of the problems associated with space travel will not necessarily affect the inhabitants after landing on the lunar surface. Many limiting design factors such as high "g" loads, noise and vibration, weightlessness, etc., will exist only prior to lunar operation and return to Earth. Therefore the high performance/design criteria will naturally benefit from the less stressful lunar operations. Those design considerations that relate specifically to the lunar base layout or the base conditions generally are included in Appendix B.

Illumination

A considerable amount of data is available for general and specific illumination levels for various tasks and conditions. Tables B-1 and B-2 in Appendix B provide recommendations, both general and specific, which can be used for space lighting in the lunar shelters. Psychologists have not studied extensively this perceptual effect of the sharp contrast in illumination found in the vacuum of space on the lunar surface. Hinged sun visors have been suggested for space suit helmets to counteract the rapid change from extreme illumination to total darkness which may be experienced.

Color

It is believed that color, as a sensory stimulus, will aid the lunar inhabitants in various ways. Color for safety, "see-ability," cleanliness, and morale has a definite role and relationship to human engineering. With the absence of color on the Moon, it is suggested that color scheme principles applied to the base structures, interior, and equipment follow aesthetic rather than pure utilitarian standards. The choice of color to suit the purpose of a room is considered quite important on the lunar base. Restful colors, such as greens and blues and certain shades of brown should be used for places of relaxation. More saturated colors which tend to stimulate are suggested for work areas. Other colors lend warmth to an area (reds, yellows, browns) while others create a feeling of coolness (blues, greens).

Noise Control

Effort has been made to separate areas of high and low noise levels. There will be acoustical treatment for such areas as sleeping, communications center, and areas within the command module.

Consideration has been given to desired sounds for enhancement of personal sensory input. Music should be available on an individual basis and selection of music made from sleeping-rest quarters and recreation areas. (See Fig. B-1.)

Temperature

The determination of human thermal constants in atmospheres other than air is difficult to assess. General comfort zones for air atmospheres are presented in Fig. B-2 of Appendix B. Extrapolation of comfort zones to the proposed 5 psia O_2N_2 atmosphere must be made. Psychosomatic charts are also available for various atmospheres.

Passageways, Ingress, and Egress

Passageways connecting the lunar modules serve two primary purposes: (1) to provide canister ingress-egress, and (2) to provide life support service inducts for module supply. The passageways will have essentially the same environment as the adjacent habitat. Air locks will be provided for each of the three lunar environment hatches.

The portal extending from the off-site activities canister (M-6) to the vehicular positioning track is located at the second floor level for direct access into the lunar roving vehicles. This passageway will make unnecessary maintenance of two airlocks between the base and the cab of the vehicles.

7.6 Module Floor Plans

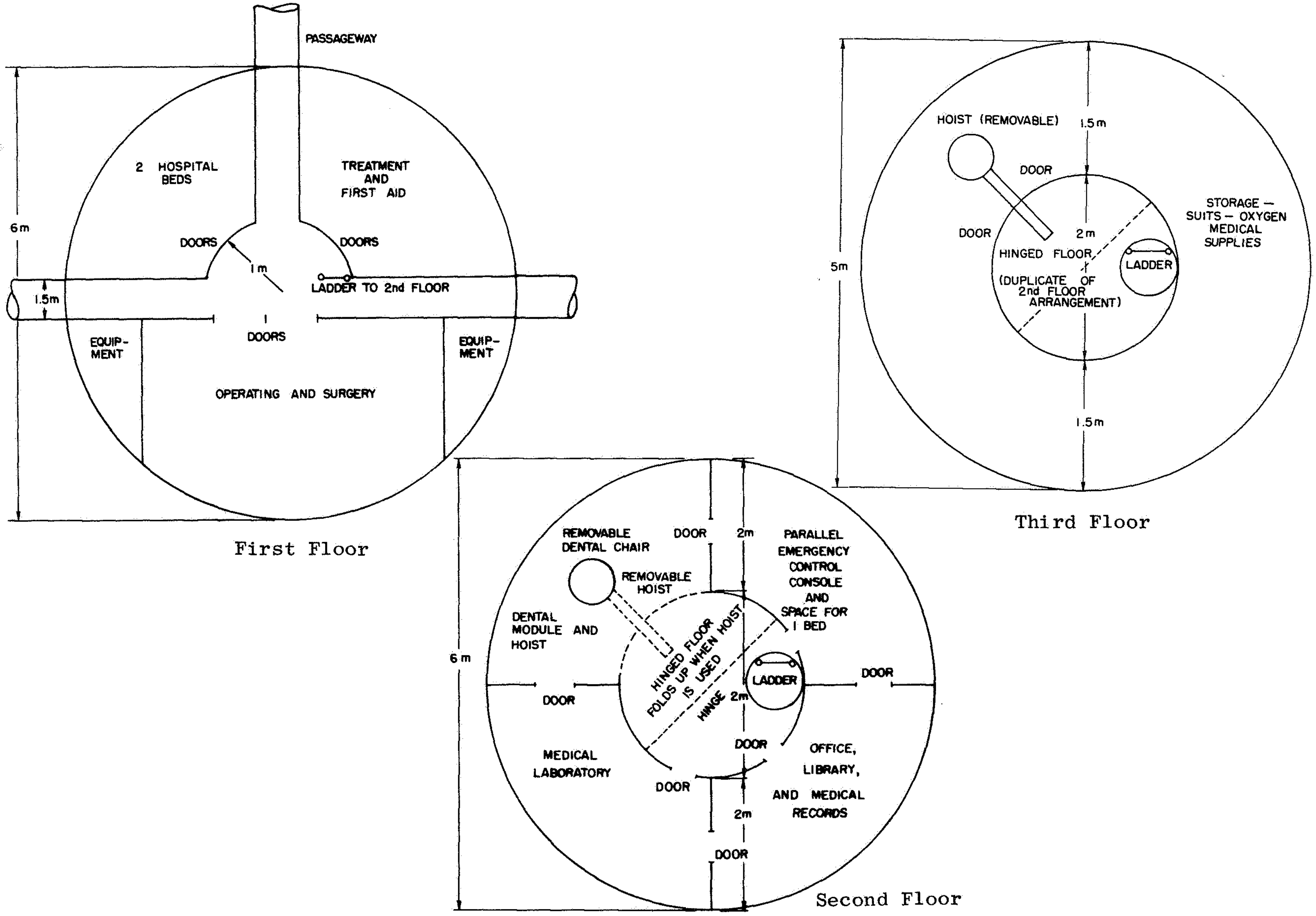
The floor plans of the individual modules illustrated in Fig. 4-1 are shown in Figs. 7-4 through 7-11.

7.7 General Physical Considerations

Tables B-3 and B-4, Appendix B, contain a general discussion of the population stereotype reactions, safety considerations, and the relative advantages of man and machine which are pertinent to the design of MOONLAB equipment.

REFERENCE

1. Rohrer, John H., "Interpersonal Relationships in Isolated Small Group Psycho-physiological Aspects of Space Flight," B. E. Flaherty (ed.), Columbia University Press, 1961.

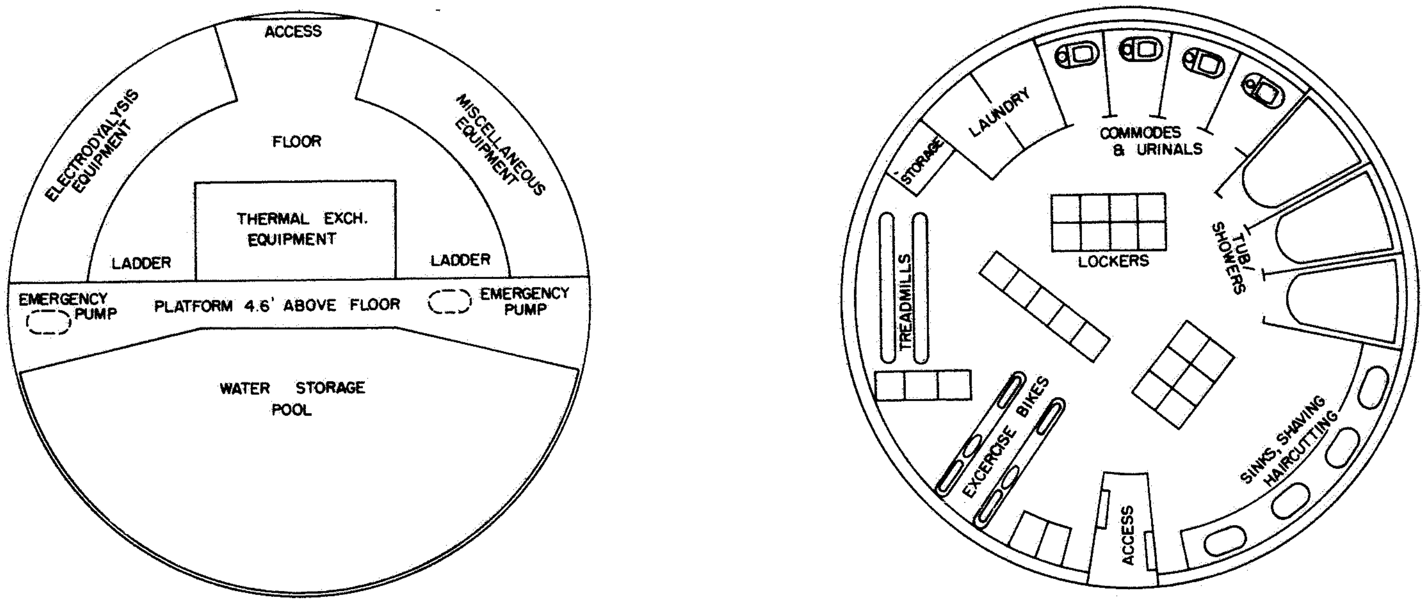


First Floor

Third Floor

Second Floor

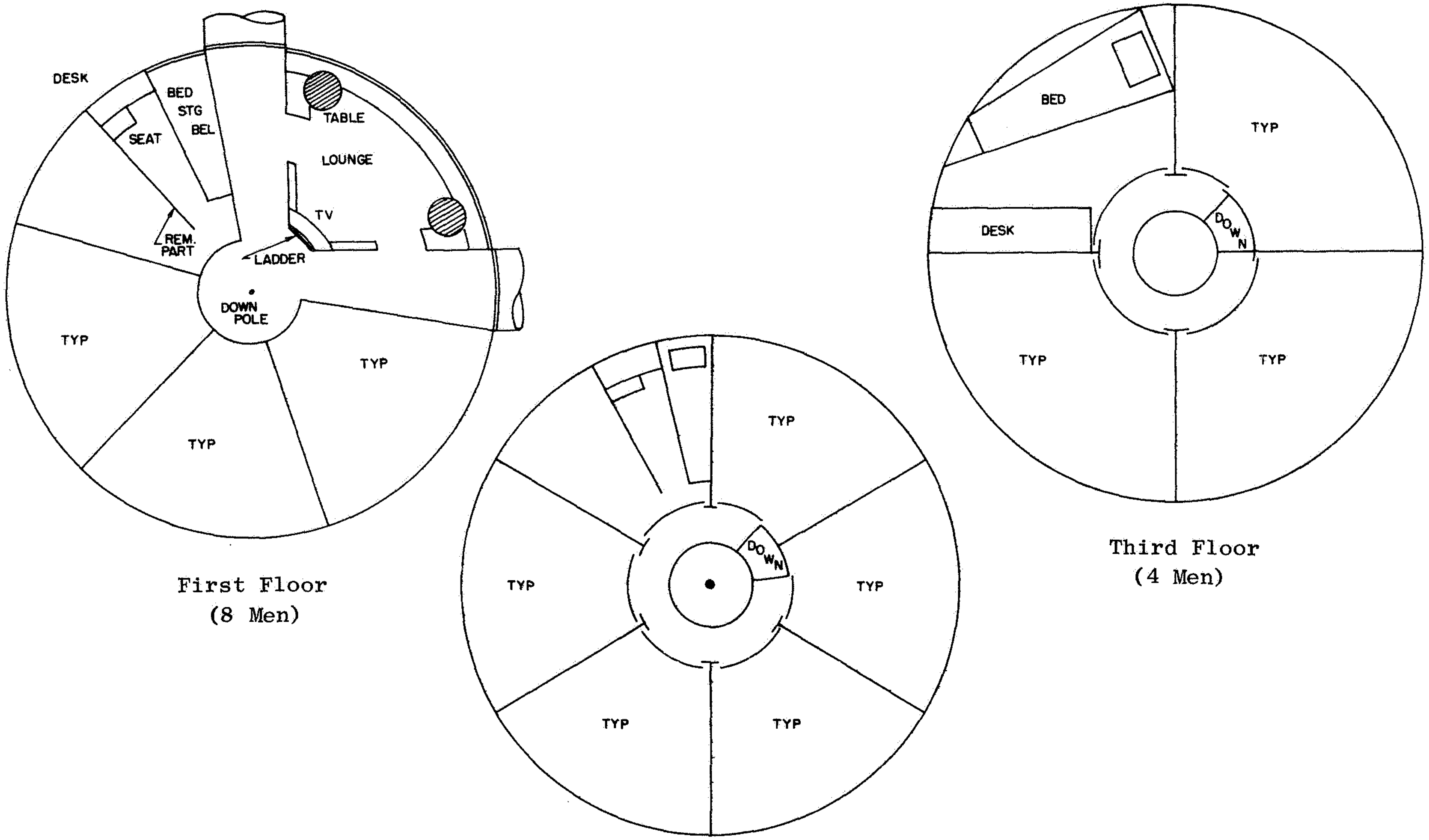
Fig. 7-4. Module No. 1 (Hospital and Emergency).



First Floor

Second Floor

Fig. 7-5. Module No. 2 (Personal Hygiene).



First Floor
(8 Men)

Second Floor
(12 Men)

Third Floor
(4 Men)

Fig. 7-6. Module No. 3 (Sleeping Module).

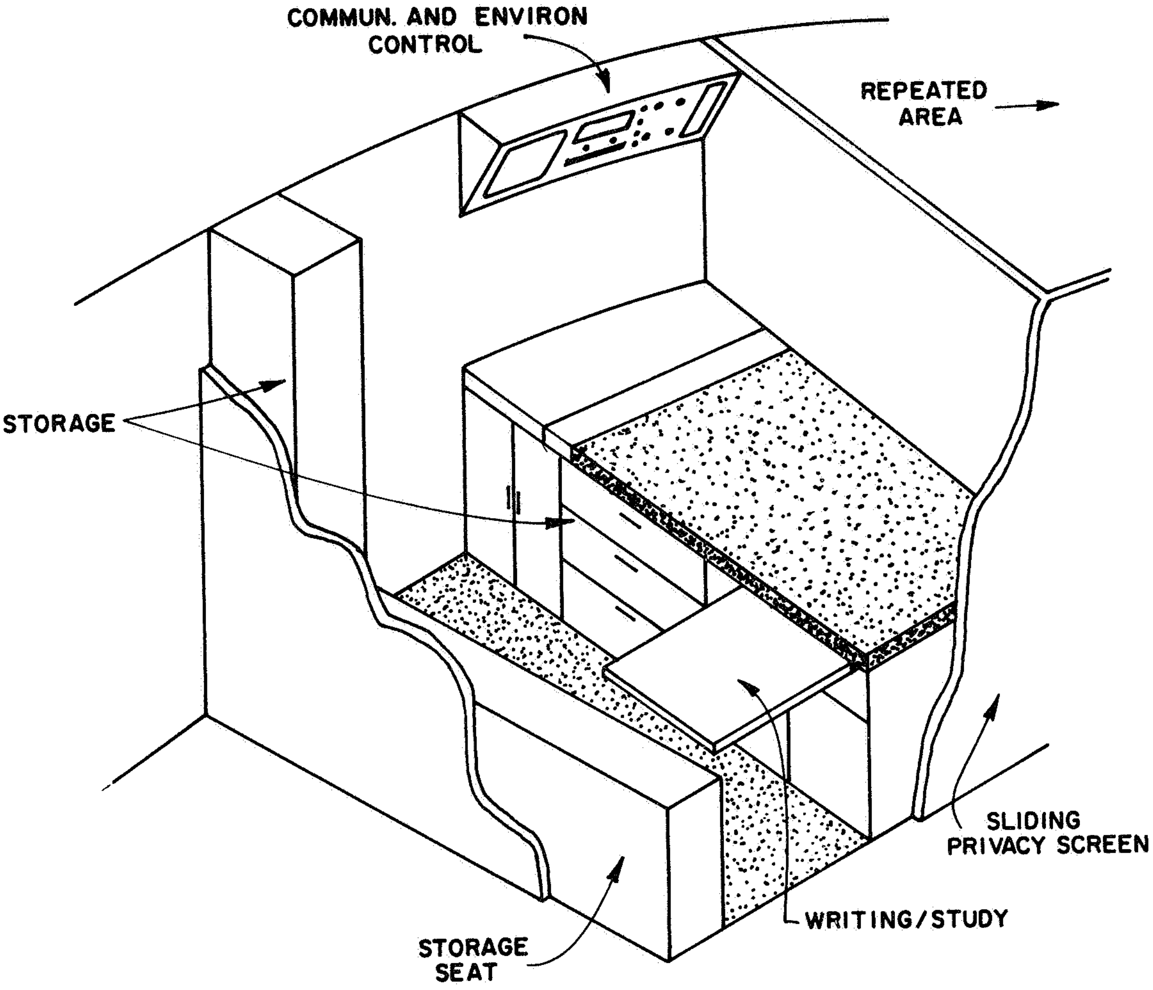
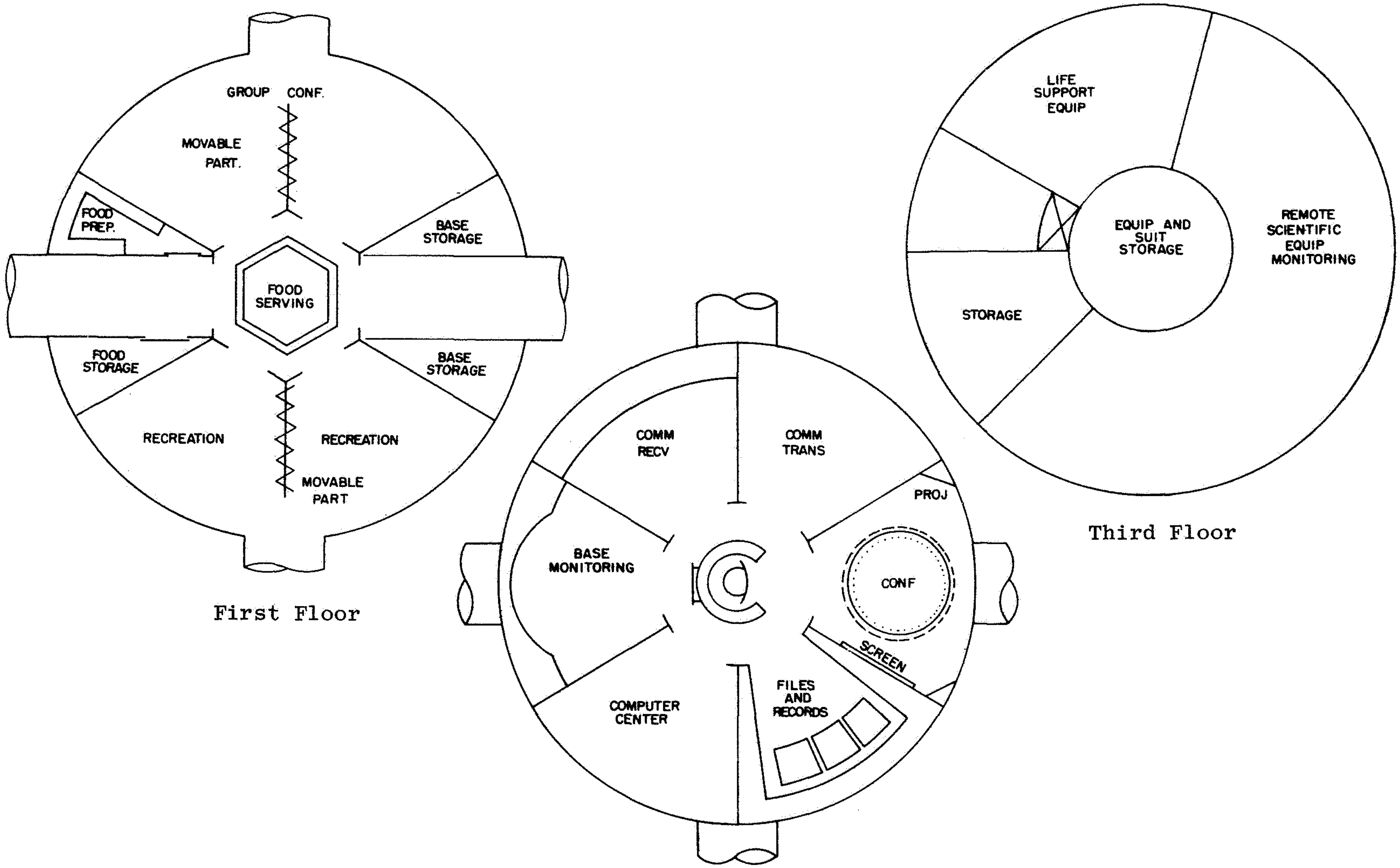


Fig. 7-7. Sleeping Module Detail.

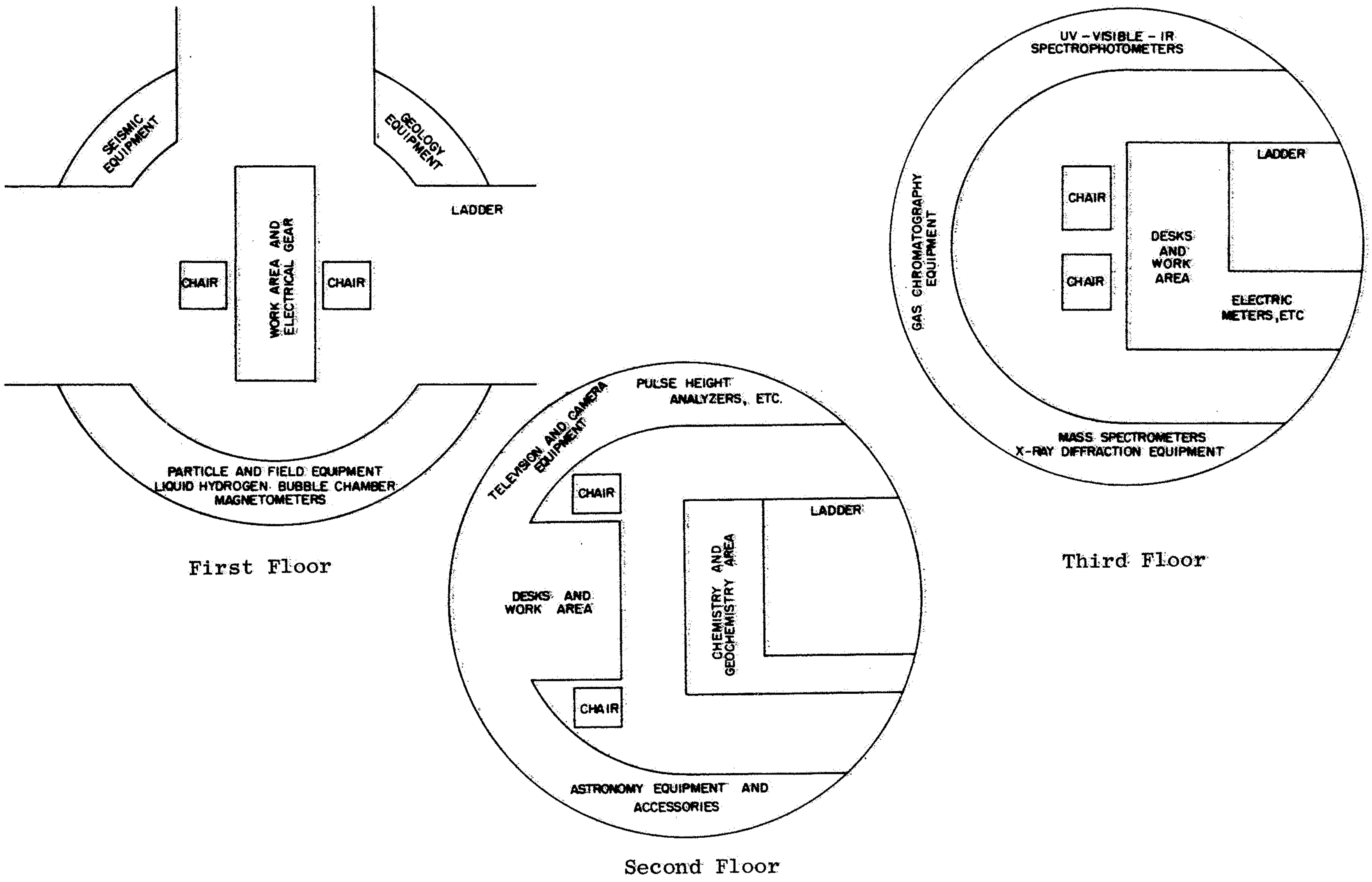


First Floor

Second Floor

Third Floor

Fig. 7-8. Module No. 4 (Command).

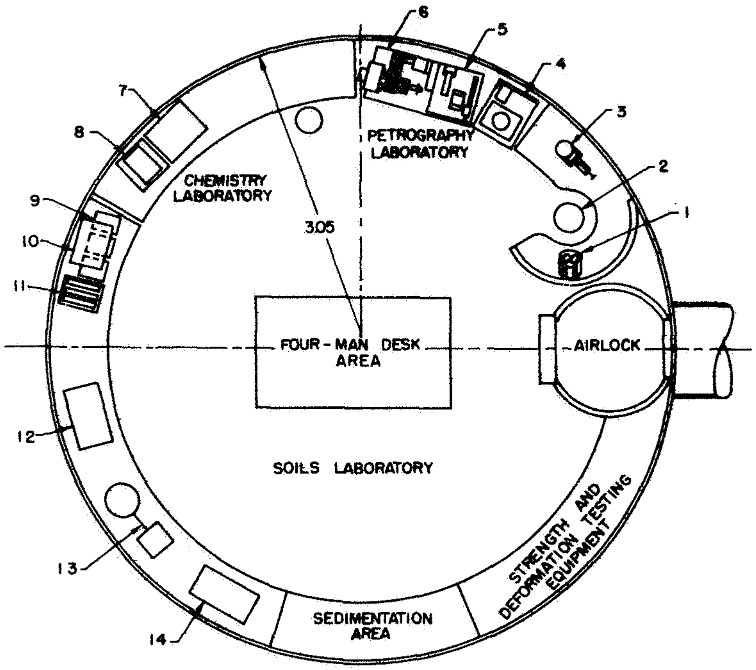


First Floor

Second Floor

Third Floor

Fig. 7-9. Module No. 5 (Physical Science).



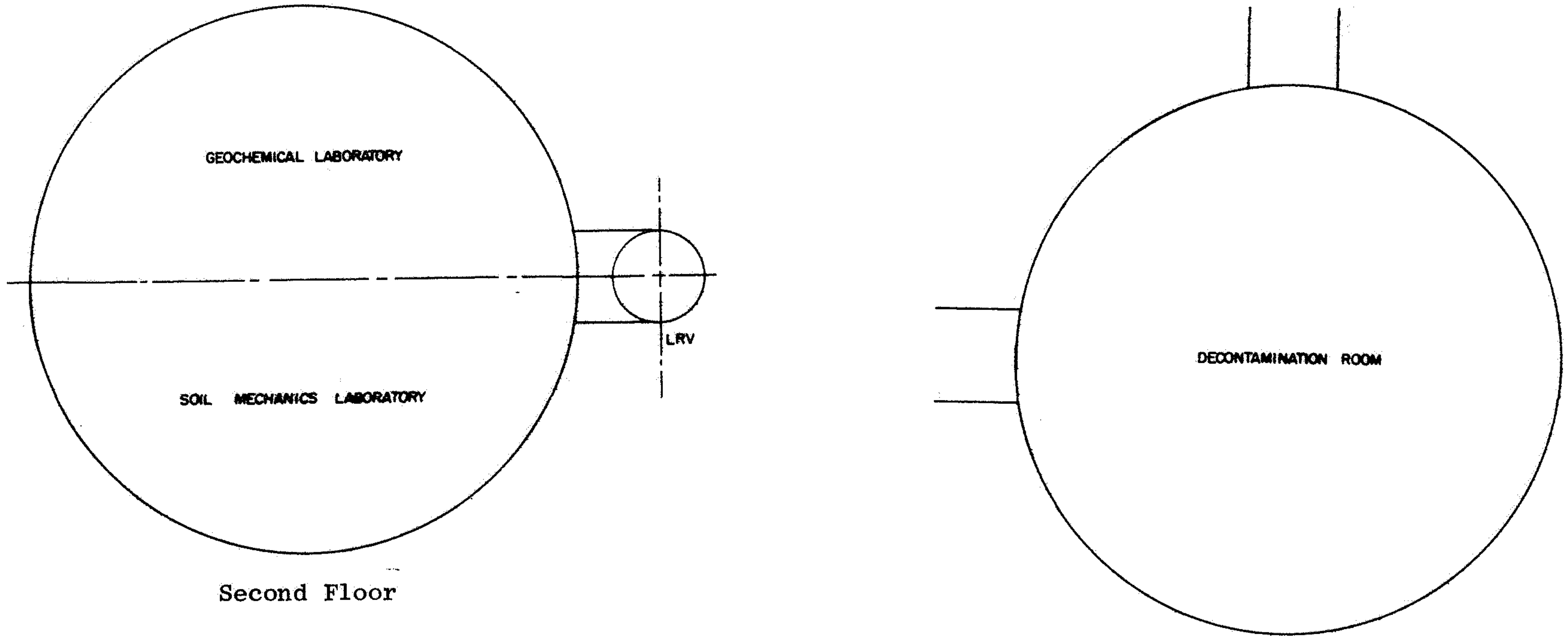
SYSTEM LAYOUT

Second Floor

KEY

1. Microscope
2. Stool
3. Balance
4. Polisher
5. Cutter & Sectioner
6. Pulverizer
7. Infrared Spectrometer
8. Mass Spectrometer
9. X-Ray Spectrometer
10. X-Ray Diffractometer
11. Neutron Activation
12. 200°C Oven
13. Sleeve Shaker
14. Atterberg Limits Equip.

Fig. 7-10. Module No. 6 (Offsite Activities).



Second Floor

First Floor

The second floor of this unit contains the Geochemical Laboratory on one side and the Soil Mechanics Laboratory on the other. Soil and rock samples will be off-loaded directly into this area where they are stored and processed. There is to be desk space for four persons provided in this area also.

The first floor is to be used for decontamination of persons entering the space station. Consequently, it contains facilities for cleaning and repairing space suits and for cleaning any equipment brought inside.

Fig. 7-10 (cont). Module No. 6 (Offsite Activities).

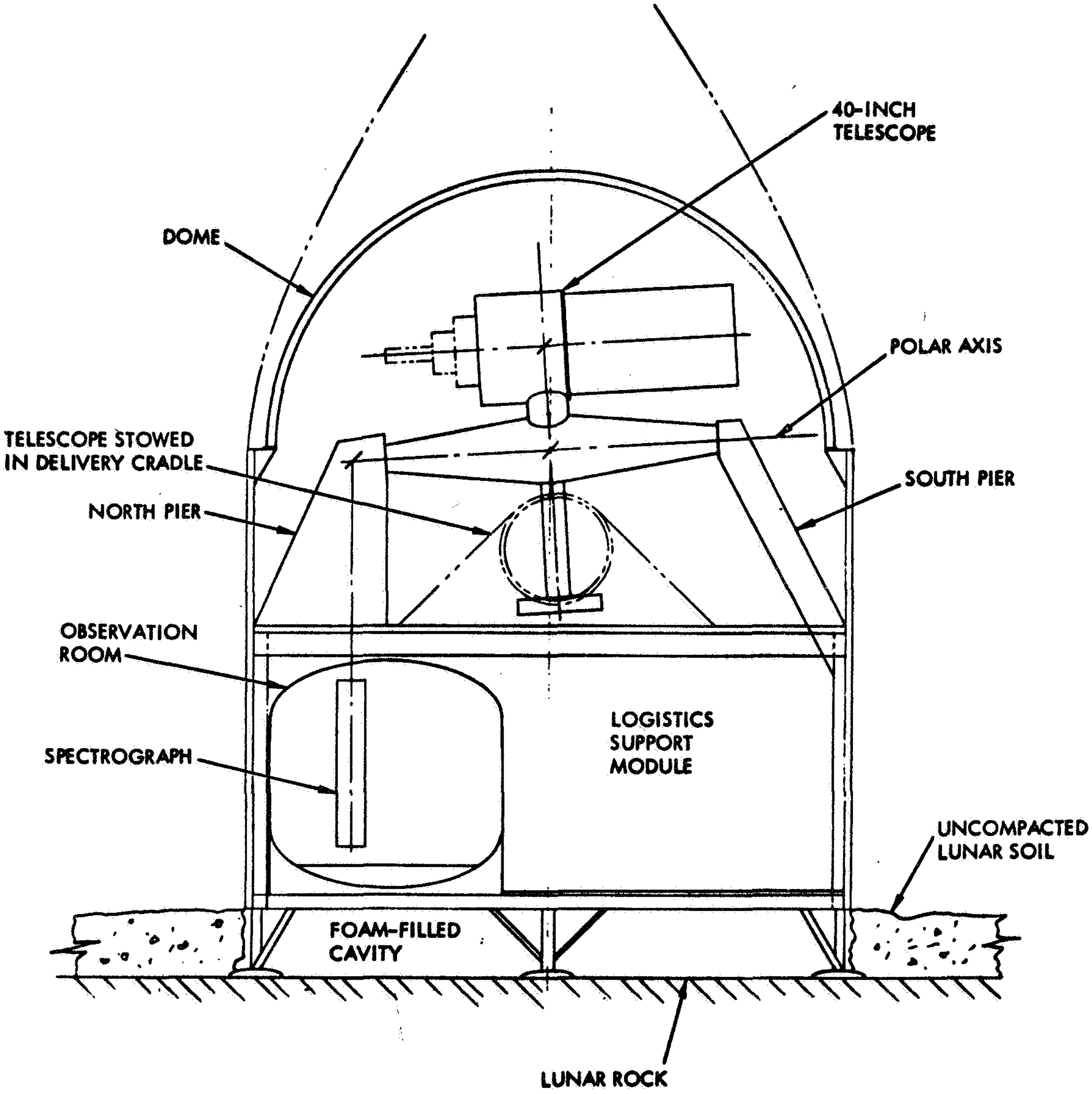


Fig. 7-11. Forty-Inch Lunar Telescope.

Chapter 8

LIFE SUPPORT SYSTEMS AND PROTECTION

8.1 Design Bases

The life support system for MOONLAB is unique for several reasons,

(1) It uses higher agriculture to both close the O_2-CO_2 cycle, and to provide food.

(2) Because higher plants are used, man's waste products are almost all completely used efficiently.

(3) By careful choice of crops, it is possible to operate with a minimum of mechanical equipment. Fundamentally only a fan and a dehumidifier are needed.

(4) A large fraction (75%) of the total food available is in a relatively fresh and aesthetic form.

(5) Resupply from earth is greatly reduced.

(6) Water purification is greatly simplified, and as a consequence more water for washing and laundry is available because of the multiple use.

The design specifications are based on man's metabolic needs as presented in Table 8-1.

Table 8-1

METABOLIC SPECIFICATIONS
(Basis: per man/day)

Inputs	kg	
Oxygen uptake	0.85	
Carbon dioxide output	1.05	
Food, ashless, dry basis	0.63	
Ingestible water allowance	3.5	
Outputs		
Water of oxidation	0.33	
Urine water, average	1.5	
Fecal water	0.25	
Fecal and urine solids	0.10	
Respired and evaporated water	2.70	
Latent heat k-cal/day		1560
Sensible heat k-cal/day		1240
Miscellaneous		
Dry bulb	18.3-29.5 °C	
Relative humidity	45 to 55 percent	
Volumetric displacement	125 cfm/man	

8.2 Atmosphere

The shelter and agricultural units will have the same nominal composition, namely a 5 psi (34,400 N/m^2) oxygen-nitrogen mixture as detailed in Table 8-2.

Table 8-2

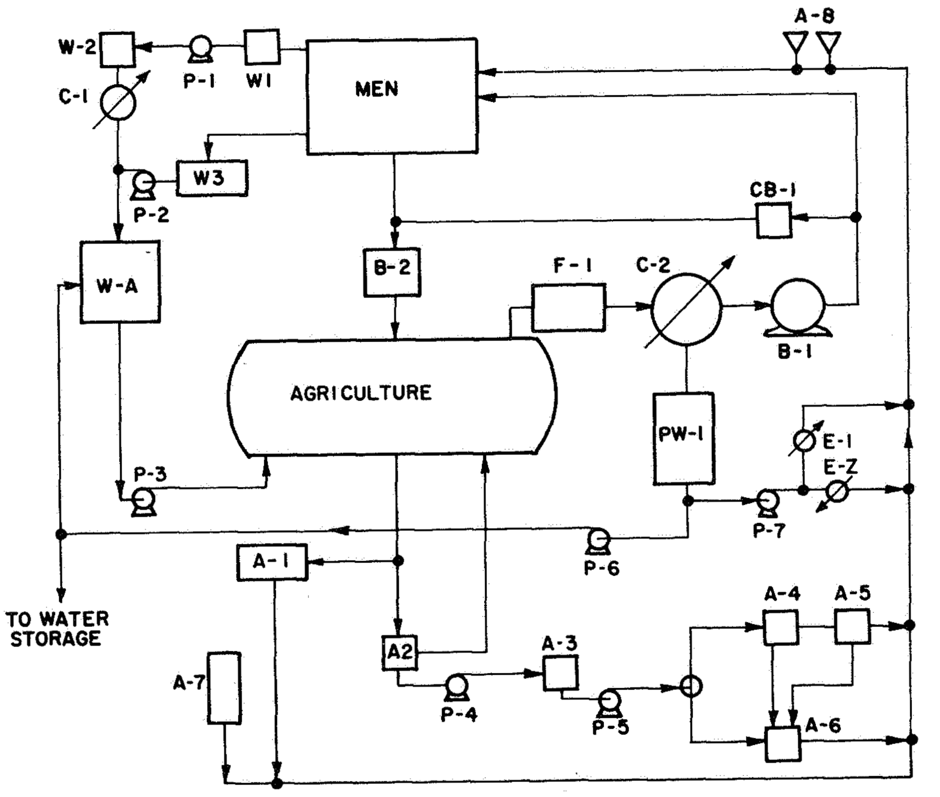
COMPOSITION OF SHELTER AND AGRICULTURAL UNITS

Gas	Pressure (N/m^2)	(mm Hg)	Volume Percent	Weight Percent	Average Molecular Weight
O_2	21,400	(160)	62.0	65.2	
N_2	11,490	(86)	33.4	30.7	
CO_2	535	(4)	1.5	2.3	
H_2O	1,070	(8)	3.1	1.8	
					30.42

Note: Design temperature is 24°C. Partial pressure of water corresponds to 50 percent relative humidity (RH).

Assumed O_2 uptake per man is 0.85 kg/d and expired CO_2 is 1.05 kg/d. The gas exchange capability of the agricultural system is based on these values.

During the lunar night agriculture will be dormant. Shelter air will be bypassed through an adsorber bed using Ag_2O as the active material. If the agriculture can function to reduce the CO_2 content of the atmosphere from 1.5 percent to 0.5 percent by weight at the end of the lunar day, approximately 600 kg of Ag_2O can maintain the CO_2 below a concentration of 1.5 percent by the end of the lunar night. Only 0.05 kW is necessary for regeneration. The CO_2 will be desorbed into the agriculture at a high enough rate to again lower the shelter atmosphere to 0.5 percent at the end of the lunar day. Some idea of the interrelationships can be obtained from Fig. 8-1. A material balance is given in Fig. 8-2. In case of agricultural failure the backup system of Fig. 8-3 will operate. The backup system requires standby electrical power. Requirements are detailed in Table 8-3.



A-1	Freezer
A-2	Crusher
A-3	Cooker
A-4	Coagulum Washer
A-5	Dryer
A-6	Serum Freezer
A-7	Stored Food
A-8	Flavors
B-1	Circulation Fans
B-2	Adsorption System
C-1	Condenser
C-2	Dehumidifier
CB-1	Contaminant Removal
E-1	Water Cooler
E-2	Water Heater
F-1	Filter Sterilizer
P-1	Feces Pump
P-2	Urine Pump
P-3	Dilute Urine Pump
P-4	Juice Pump
P-5	Cooked Juice Pump
P-6	Water Recycle Pump
P-7	Potable Water Pump
PW-1	Potable Water Storage
W-1	Feces Storage
W-2	Feces Dryer
W-3	Urine Storage & Sterilization
W-4	Dilute Urine Storage

Fig. 8-1. MOONLAB 1985 Life Support System.

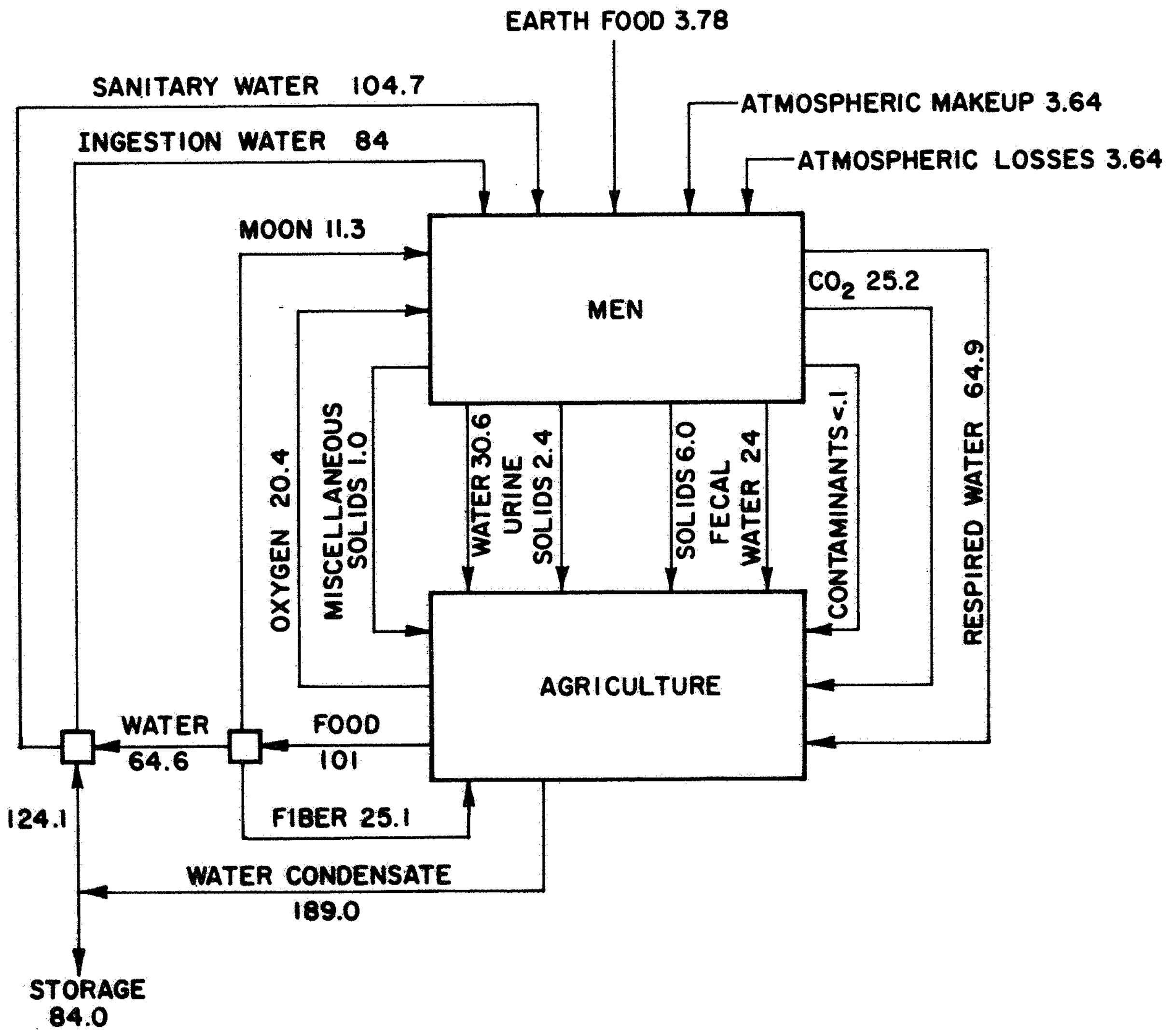


Fig. 8-2. Material Balance Relationships (kg/day).

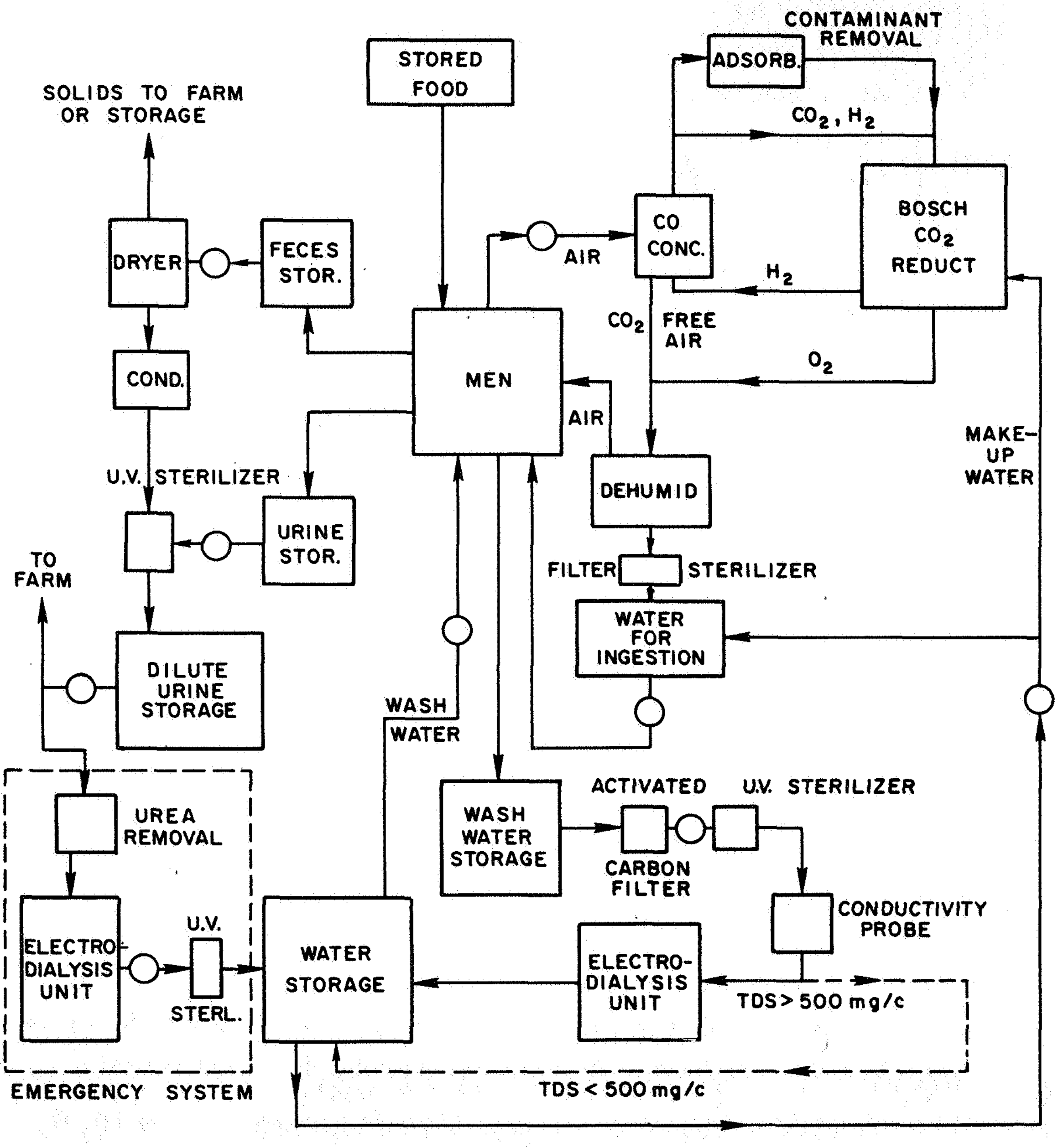


Fig. 8-3. Backup Life Support Systems.

Table 8-3

BACKUP LIFE SUPPORT SYSTEM POWER REQUIREMENTS

	kW
Feces Dryer	0.22
Water Heater	0.08
Air Circulation	2.00
Pumps at 0.093 kW each	0.84
Lighting and UV Sterilizers	5.36
CO_2 Concentrator	0.050
Bosch Regeneration System*	19.50
Wash Water System	0.50
TOTAL	29.00

---

*Mass 140 kg

Oxygen makeup will be partially from the replenishment for leakage, but in any case the very high O_2 concentration in the shelter atmosphere will prevent any serious physiological effects from the consumption of O_2. The slight decrease in O_2 concentration during the lunar night will be compensated by the increase during lunar day.

Leakage from the shelter will be principally due to air lock operation. Assuming that air locks will bound the tunnels and that there may be as many as three openings per day, losses have been calculated as 10 percent of a tunnel volume per day per opening. Farm leakage is based on probability of 3 punctures per year of meteorites 1.5 mm in diameter, and the loss of one shelter volume (18 m shelters) at each hit before repair can be made. Table 8-4 details the atmospheric requirements.

It will be essential to have sensors to monitor the CO_2-O_2 ratio distributed throughout the shelter and agricultural unit. These should automatically control equipment to keep the ratio within the prescribed limits. Gas chromatography will be used for analysis. It will be necessary to have portable sensors to monitor the CO_2-O_2 ratio in

Table 8-4

ATMOSPHERE WEIGHT REQUIREMENTS

		kg per year
Shelter charge (volume 1,770 m^2)		755
Farm charge (volume 1,300 m^2)		540
		1,295
Farm leakage[†]	119	
Shelter leakage[*] (3.11 kg/d)	1,135	
Suit loss[**]	73	
	1,328	
Suit oxygen 1.0 kg/d (including emergency back packs)		400
Emergency (60 days: O_2 only, no reuse) plus tunnels (1 day each)		1,532
Total gas needed at beginning of first year of full operation		4,554
Packaging weight at 15 percent		686
Total launch weight		5,240
Total O_2 (gas only)	3,700	
Total N_2 (gas only)	854	

[†] Based on loss of one shelter charge/day for each of three meteorite punctures.

[*] Based on loss of 10 percent of air lock volume/day (3 lock openings, 20 percent of one tunnel volume each).

[**] Based on a leakage rate of 200 mℓ/min of O_2 from suit.

spacesuits. Such sensors can be electrolytic in nature, i.e., make conductivity a function of CO_2 concentration. Warning to the men will be automatic if tolerance is exceeded.

8.3 Food

During the base evolution all food will be from Earth-supplied stores. The diet will be 2,800 k-cal with roughly 12 percent protein. As the agriculture develops, harvest of crops will begin to contribute to the diet. Eventually this will reach 75 percent of the caloric input. The form in which the Moon-grown food will be eaten depends to some extent on the crops (see Chapter 9). The food used from stores will be about half protein: freeze-dried meats, eggs, etc.

On the basis of 0.63 kg/day/man of dried food, the 24-man base will require 15.1 kg/day or 5,520 kg/yr. This relatively small weight makes it feasible to keep a year's supply of food on hand as backup for possible agricultural failure (Table 8-5).

Table 8-5

FOOD CONSUMPTION

A. Prior to Agriculture

Daily, kg	90-day Startup, kg	Source
15.1	1,360	Earth-supplied

B. With Agriculture

Daily, kg	Yearly	Source
11.3	4,134	Moon-grown
3.8	1,386	Earth-supplied
15.1	5,520	

C. Emergency Supply (30 days)

455 kg module = 3,640 kg

D. Total on hand beginning of 1985, kg 6,386*

---

*Packaging brings this to 6,700 kg.

Crops which will be harvested can be preserved by freezing and/or drying. For example, since the food will be harvested at the beginning of the lunar night, it may be placed in sealed containers and simply exposed to the lunar environment. The 125°K temperature should rapidly freeze any food. A portion might be processed to concentrate its protein and dried. Processing machinery is included in Fig. 8-1. Trace nutrients and vitamins will be supplied from Earth.

8.4 Water

Water use on the Moon will be more extensive than on space flights. Table 8-6 gives the detailed requirements. The water will be brought up in stages. There will be a net surplus of 5,100-360 = 4,740 kg/year. Resupply of water does not seem to be needed, though it would probably be desirable to renew some emergency supplies each year.

If only half the surplus were available, electrolysis would provide (at 90 percent efficiency) 1,880 kg/yr of O_2; thus, no resupply of atmospheric O_2 will be needed provided that energy is available for electrolysis.

Water for fire protection will be used for several purposes. Small amounts can be withdrawn and used for sanitary purposes. Such bleed-streams will be circulated through the wash water system of Fig. 8-3. Bathing by direct immersion will be possible. Since the tank is 4.55 m (15 ft) in diameter and 1.2 m (4 ft) deep it can also be used as an experimental facility for zero g simulation and recreation. The amount of contamination will be small, and a bleed-stream circulated continuously, as previously suggested, will be all that is required to keep the water free of contamination.

This same tank, if placed centrally, can serve as an emergency source of drinking water as well, using chemical purification if needed.

8.5 Waste Management System

Principal sources of waste are,

(1) Food containers and unconsumed food,

(2) Urine,

Table 8-6

WATER USES

	Daily	Yearly
Food and drinking	84	
Available from condensate[*]	98	
Net surplus		+5,100
Agricultural		
At 300 kg/man		7,200
Allowing 5 percent leakage		360
Hygienic needs		
Minimum at 1.5 kg/m-d	36	(reused)
Desired at 28 kg/m-d	670	
Fire protection[**]		24,000
Emergency		
Food and drink (60 days)	168	(5,040)
Minimum sanitary (60 days)	72	(2,160)
Total		(7,200)
Startup requirements (90 days food only)		315
Total		29,075

---

[*] Based on 90 percent recovery of respired moisture from men and plants.

[**] Provides about 5000 gallons or 30 minutes supply at 150 gal/min. Each Module will contain 500 kg for immediate needs.

(3) Feces

(4) Hair, skin excretions, fingernails and toenails,

(5) Paper.

The preferred containers will be those easily ground into small pieces and digestible to soil organisms on the farm. If materials cannot be developed for the purpose, then volume reduction and perhaps eventual incineration will be needed. Paper, hair, etc., will also be used as soil builders.

Feces will be collected through air converging system and stored in odor-free containers. Periodically the stored feces will be dried and sterilized in a fluidized bed dryer using superheated steam as the drying medium. If the feces can be stored without excessive contaminant generation, then the drying will be carried out during the lunar day to conserve power. The dried material will be spread on the farm as a soil conditioner. Water removal during the drying the process will be condensed and used to dilute the urine.

Urine will be sterilized with ultraviolet light and stored. It will be diluted with feces water and condensate from the farm. This diluted sterile urine will be metered to the farm as a water source and soil conditioner.

During construction and before the farm is in operation, or in case of failure of the farm, an electrodialysis system will be used for urine reclamation. In this system the urea must first be complexed to form a precipitate. The precipitate and other organic material in the urine will then be removed on activated carbon filters and the clarified urine will then be passed through a millipore filter to remove bacteria. The organic-free material will be stored and periodically pumped through an ultraviolet light sterilizer and the electrodialysis unit (see Figs. 8-4 and 8-5). The urine is recirculated through this system continuously until the conductivity probe indicates a desired level of total dissolved solids (70-100 mg/l, perhaps). When this level is reached the recovered water is pumped through activated carbon for final cleanup and stored as potable water. In the electrodialysis system some water is transported across the membrane with the ions. This endosmotic water is partially recovered by using a membrane permeation boiler and returned to the system for further processing. The residual concentrated waste is then handled in the solid waste management system for drying, etc. Small amounts of oxygen and hydrogen will be formed at the electrodes in the electrodialysis unit. These gases will be separated and discharged into the atmosphere system.

When the farm is not in operation, and during construction stages, solid wastes will be heat-dried, sterilized, and stored.

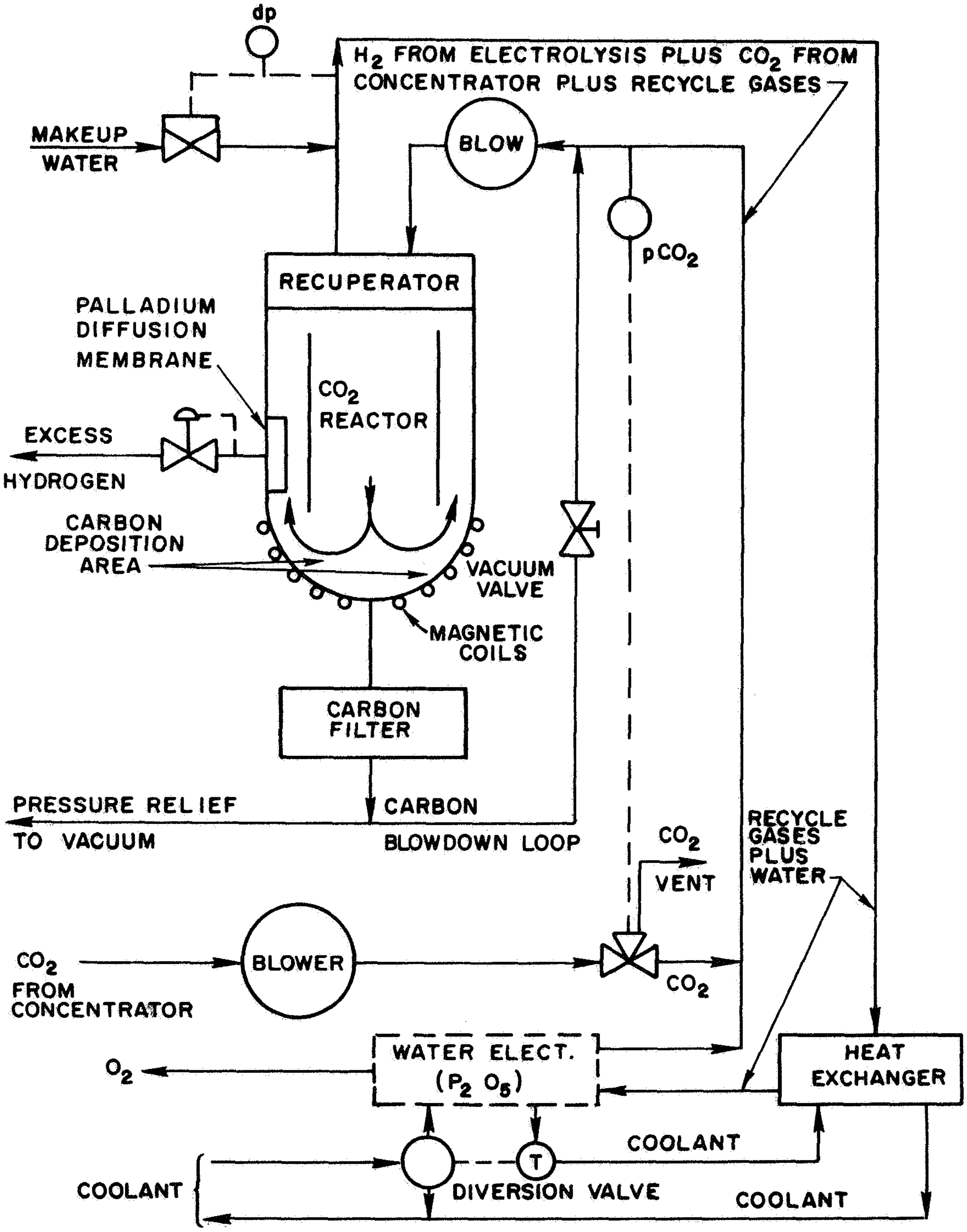


Fig. 8-4. MRD Bosch CO_2 Reduction System Flow Diagram.

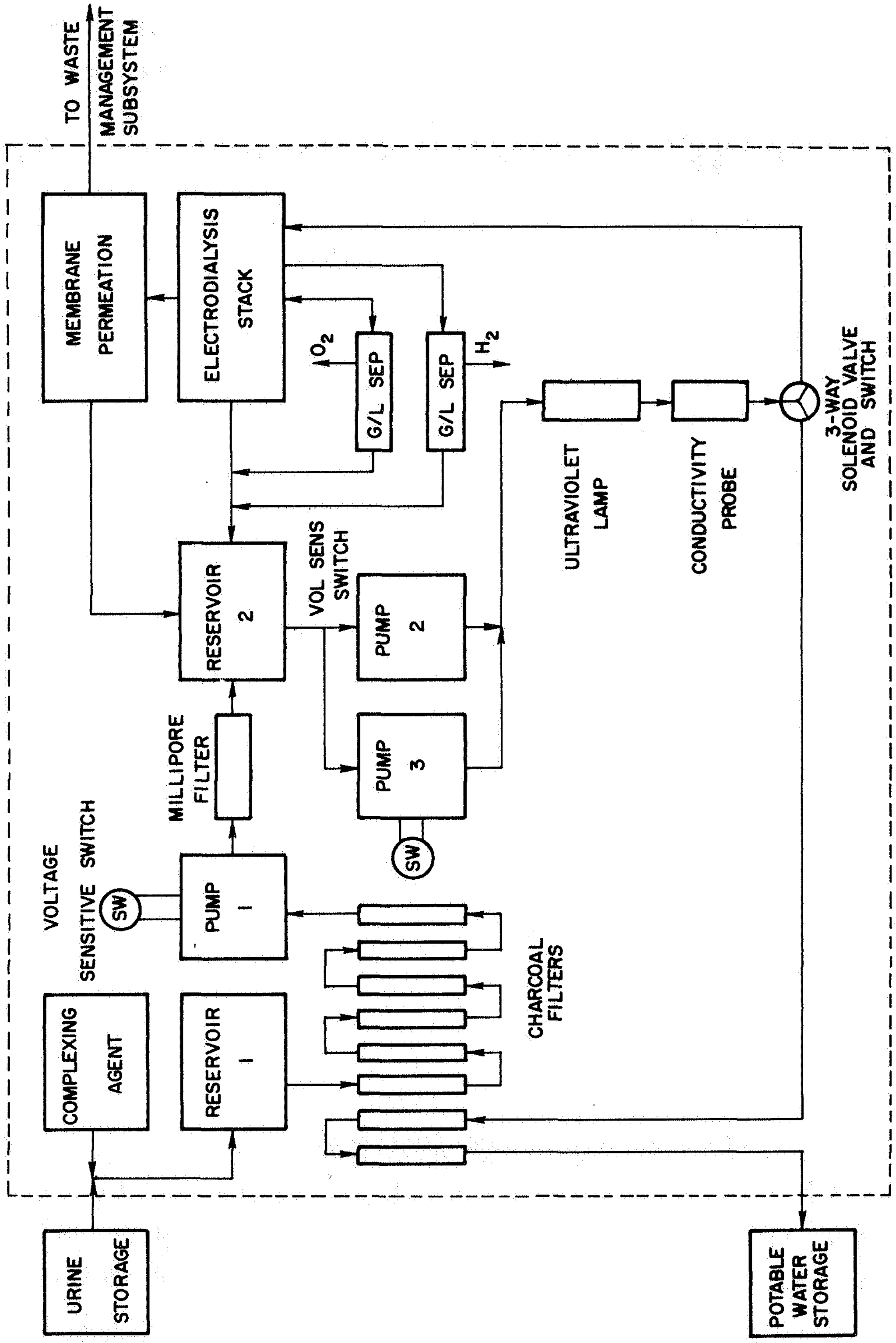


Fig. 8-5. Electrodialysis System for Urine Reclamation.

Wash water will also be reclaimed by an electrodialysis unit. The wash water will be collected and periodically passed through activated carbon filters, an ultraviolet sterilizer, and then back to water storage. When the conductivity probe indicates a total dissolved solids level of more than some predetermined amount (say 500 mg/ℓ), the water will be passed through an electrodialysis unit (one pass) before it is returned to water storage.

8.6 Thermal Control

The Sun, the agriculture, the equipment, and the men all impose thermal loads on the atmospheric conditioning system. These are shown schematically in Fig. 8-6 for the lunar day and in Fig. 8-7 for the lunar night. Both figures are based on the worst case approach. i.e., solar maximum in day and mid-night for the night (see Fig. 8-8).

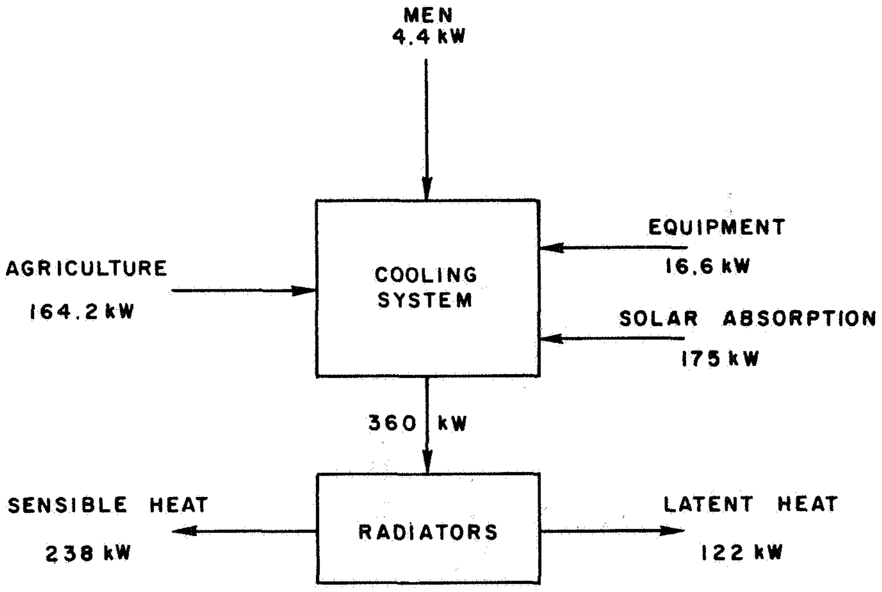


Fig. 8-6. Thermal Loads Lunar Day.

The calculations are approximate for the purpose of establishing order-of-magnitudes for the various inputs. Details are in Appendix C.

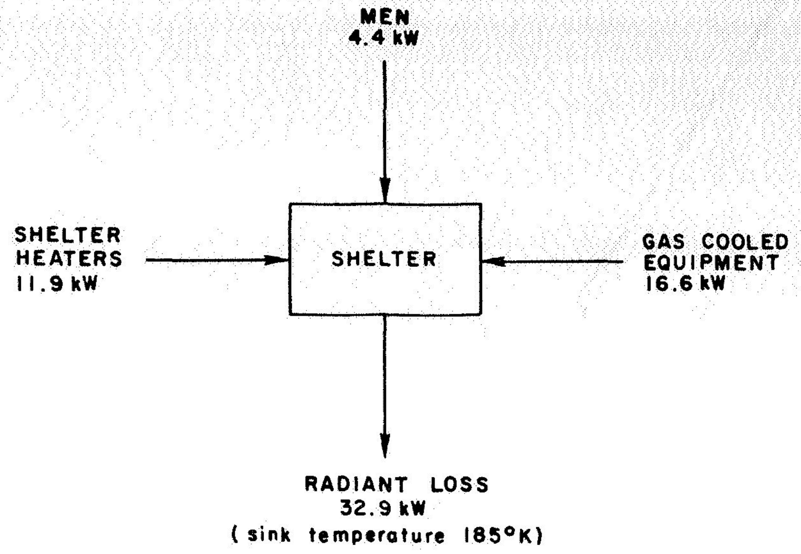


Fig. 8-7. Shelter Thermal Load Lunar Night.

By far the largest inputs during the day are those due to solar radiation (48.5 percent) and lunar agriculture (45.5 percent). Men contribute only 1.2 percent and equipment 4.8 percent. If the sink temperature under the shield drops below 260°K during the night, heating of the shelter areas is required. It seems likely that the sink temperature will be somewhere between the subsurface temperature and the upper shield surface temperature. This puts the range between 120°K and 240°K. As a zero order approximation the average is 180°K. The assumption is that the area is shielded in such a way so it does not see cold space. Obviously, once firm design is begun, a more rigorous approach will be used.

The heat transfer surface can be approximated by assuming overall coefficients for both the internal shelter coolers and the dehumidifiers. For the radiators themselves graphs in Appendix C give radiator areas as functions of thermal load and required coolant temperatures. Because the dehumidifier must reduce the air temperature to

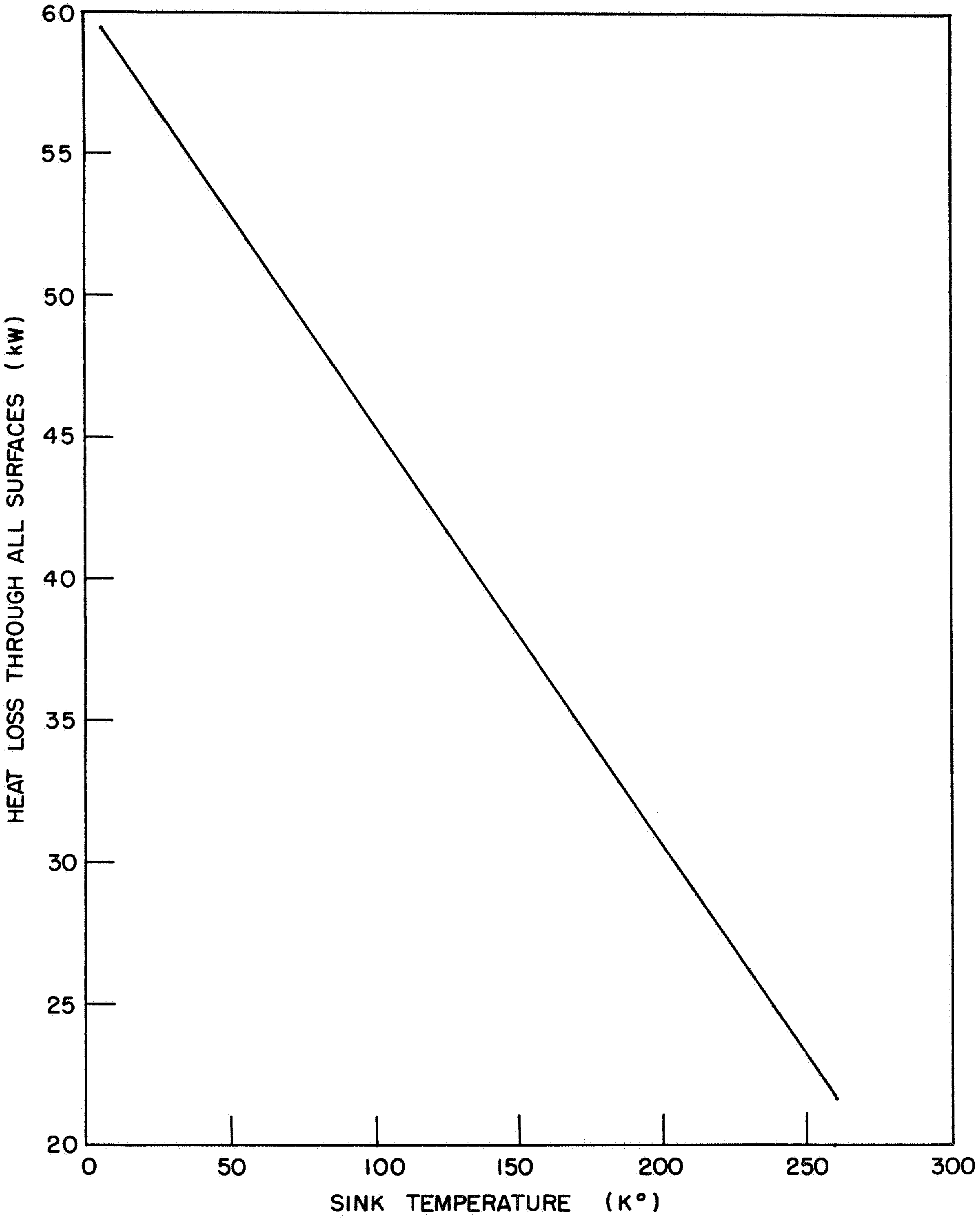


Fig. 8-8. Heat Loss From Shelter Surfaces. Internal Temperature 27°C, Overall Heat Transfer Coefficient 0.114 watts/m^2 (°C).

near the dew point (13.4°C), the coolant must enter at a lower temperature (4.5°C). Figure C-1 shows that the area is reduced with the increase in coolant temperature to the radiator. The maximum allowable (based on total heat load) is 21°C. The data of Table 8-7 are based on the above assumptions (see Table 8-8 also).

Table 8-7

THERMAL CONTROL SYSTEM DATA

	Area, m^2	Mass, kg
Radiators (50 ft^2/kW - 4.65 m^2/kW)	1,670	4,360
Dehumidifier (U = 50 Btu/h/ft^2°F - 0.284 kW/m^2°K)	28.6	74.8
Internal coolers (U = 10 Btu/h/ft^2°F - 0.0568 kW/m^2°K)	607	1,580
		5,915
With shells, supports, valves, etc.		~12,000 kg

Note: All tubing 0.635 cm aluminum, 0.3 ft^2/ft (0.0915 m^2/m) mass 0.0221 kg/m.

8.7 Contaminants Removal

Contaminants to the life support system can be divided into chemical and biological types. Both men and agriculture generate both types.

Because of the high oxygen concentration it is necessary to biologically sterilize feces and urine as soon as possible after expulsion from the body. It may be necessary to dry feces rapidly as well as add anti-oxidants to the urine. Storage of the feces for more than a day may cause significant generation of CO_2 and CH_4. If research proves that storage is possible, drying will be done only during the lunar day to conserve power. Otherwise, it will be done intermittently during the night. Some H_2 will also be present with some volatile sulphur compounds. Because the ambient pressure will correspond to a boiling temperature of only 72°C and because a large fraction of feces is

Table 8-8

HEAT INPUTS TO CIRCULATING ATMOSPHERE (NIGHT)

	kW
Men, metabolic output, respir., etc.*	4.4
Lights, sterilizers	10.0
Pumps	.8
Fans	2.0
Miscellaneous experiments	3.8
	21.0

---

*Circulation required to maintain 24°C dry bulb, 50 percent relative humidity (with no losses or gains to walls and with agriculture ignored) is 185 m^3/min (6,550 ft^3/min). The air must be supplied to inhabited areas at 14.5°C dry bulb, 13.3°C wet bulb. To maintain the humidity requires removal of 2.82 kg/h of moisture from the air (put there by respirations and perspiration). Latent heat removal is 6.55×10^6 J/h (6,200 Btu/h).

bacteria, the drying process will be carried out at elevated temperature and pressure (127°C, 24.2×10^3 N/m^2 [35 psia]).

Human flatus may add H_2 and small amounts of H_2S in addition to the more common components of CO_2, O_2 and N_2. Harvested crops may add CO and NH_3 as well as some other volatiles. These can be removed from the atmosphere by adsorption followed by catalytic incineration to CO_2 and H_2O (Fig. 8-1). Other chemical toxicants resulting from decomposition of polymers, evaporation of plasticizers or medicinals, volatilization of compounds secreted through the skin or through the leaves of plants will be handled through the same system. Ammonia may have to be handled separately by absorbing it in a liquid stream of low pH which can then be returned to the farm.

The leakage from both shelter and agriculture will serve to limit contaminant buildup in the atmosphere. Laboratory areas will be provided with separate adsorption units to prevent contamination of the entire system.

Food grown on the Moon which needs sterilization can be safely heated to boiling (72°C) for a short period. Potable water-streams pass through both bacterial filters and ultraviolet sterilizers. The bacterial filters can be thermally sterilized in place.

Smoke and other aerosols which could be troublesome in a low gravity field will be held to a minimum by the filters and dehumidifiers of the air circulation system. Smoke will only arise from accidental fires. Aerosols might arise from sneezing, coughing, washing, or fogging of the saturated agricultural atmosphere. After firm specification of materials of construction and the agricultural ecology, it will be possible to design a specific contaminant control system.

Once the group population has been fixed, there will be a short period of cross-contamination of bacteria and other flora, and then the system should reach a new equilibrium in which further upsets from microbial sources are less likely. As long as no pathogens were harbored initially, the likelihood of serious infectious disease is small.

Day-to-day housekeeping can be performed by use of vacuum cleaners to remove hair, nails, dust, etc. These materials can be conveyed to the feces drying unit and sent to the farm for soil conditioning. Spills will be cleaned with sponges which can then be ground up and also sent to the dryer and then to the farm.

8.8 Radiation

On the lunar surface there are two major sources of radiation, solar flares and galactic cosmic radiation. Cosmic radiation is about 50 mrad per day [1]. If it is assumed that the amount of shielding brings down the incident dose from solar flares to not more than about 1 rad per day, then it is reasonable to predict that the only effects from the combination of both types of radiation will be life shortening. In other words, the dosage to the men will be of the "chronic" type and will not produce any acute or sub-acute symptoms.

It is not proposed to provide any protection against cosmic radiation for the following reasons:

(1) Enormous thicknesses of shielding are required to stop the very high energy cosmic ray particles,

(2) As shielding is increased, the dose behind the shield initially rises, owing to the production of large amounts of secondary radiation, and

(3) The lunar laboratory is primarily an aboveground structure, and would be difficult to construct if all living quarters had to be shielded against the cosmic radiation.

The consequence of not shielding against cosmic radiation means that the occupants are exposed to the full 50 mrad per day at solar minimum. It has been calculated by Schaeffer [1] that this would produce a life shortening of 72 days per year spent on the lunar surface.

With regard to protection against solar flares, some shielding must be provided. If the walls of the modules only were relied on ($2\ g/cm^2$), then the total dose to the men would have been about 850 rads between May 10 and July 20, 1958 (Langham [2]). This would have been delivered in four doses and would probably have been sufficient to cause some acute symptoms. In addition, there would have been a very considerable increase in life shortening, amounting to many years.

Module 1 will therefore be a solar flare storm cellar, and the shielding will be 1 m of lunar soil compacted to a density of $2\ g/cm^3$. The shielding produced is $200\ g/cm^2$, and will reduce the dose of 850 rads, which was the worst period of the last solar cycle, to just under 5 rads.

The only chance that the men would be exposed to higher doses would be if they were caught outside the base during a flare or were forced to tend to equipment in an unshielded part of the structure. Since techniques are becoming available for predicting the occurrence of solar flare radiation hours before the peak flux, there should be plenty of warning for most personnel to be able to repair to the storm cellar. If someone were caught in a flare, it is improbable that he would be in acute danger because flares having a magnitude sufficiently great to produce acute symptoms are rare, and because he would probably be in a situation where at least some shielding could be provided. For example, any outposts some distance from the main base would be equipped with a small storm cellar with a $5\text{-}10\ g/cm^2$ of shielding.

At the peak of the solar cycle, the galactic radiation is reduced by the screening effect of the interplanetary magnetic field. Rough approximations to the total dose to base personnel is given in Table 8-9.

Table 8-9

TOTAL DOSE APPROXIMATIONS

	Galactic		Solar		Total	
	Annual Dose Rads	Life Shortening	Annual Dose Rads	Life Shortening	Annual Dose Rads	Life Shortening
Solar Minimum (Quiet Sun)	18	72	1	13	19	75
Solar Maximum (Peak of Flare Activity)	8	32	5	15	13	47

In either case the immediate hazard from radiation is extremely small, and the amount of life shortening very reasonable. It compares well with the life shortening sustained by the average smoker. For a two-year stay time, the life shortening figures would be doubled, but would still be acceptable.

8.9 Fire Protection

Until final choices for materials of construction are made, it is difficult to predict what will be possible sources of combustible materials. Since fire retardant chemicals do not appear to be effective in high concentration O_2 atmospheres, materials should be as noncombustible as is possible to make them. Fiberglass and teflon appear to be satisfactory for many applications. Noncombustible polymers can probably be developed for coating and other purposes. This is especially important for insulating and protecting electrical equipment which generates a great deal of heat. Any such equipment which must be gas-cooled should be provided with fail-safe power disconnect in the event of fire.

Sensors should be placed throughout the shelter and agricultural units to detect the appearance of flame and to give both warning and automatic response, i.e., dousing of flame. Currently (1968) under development for the purpose are ultraviolet sensors sensitive to a band of radiation present in flames (which may or may not be visible to the eye).

Water is the safest extinguishing agent for use in high O_2 concentrations such as in the shelter. Other agents considered give toxic products or irreversibly contaminate the life support system, or corrode equipment excessively. Furthermore, water is easily reclaimed for reuse in future emergencies. A central supply of 20,000 kg is recommended. In addition, each module will have 500 kg of water under pressure for fire fighting. This is sufficient to provide about 30 min of fire fighting time at a flow rate of 19,200 ℓ/min (150 gpm) for a single site fire.

8.10 Costs

Table 8-10 compares investment costs for a life support system using agriculture with a strictly chemical one. A two-year basis is used arbitrarily. Since the agricultural mass delivered includes shelters and material (biomass) which is not consumed, if the unit were to be amortized over its probable lifetime of five years then agriculture would be even more attractive. The table really represents, therefore, the breakeven point, i.e., agriculture becomes economically advantageous after two years. A more detailed analysis is required for firm design decision, but agriculture seems to be justified for a permanent base.

Table 8-10

COMPARISON OF INVESTMENT AND RESUPPLY COSTS FOR TWT LIFE SUPPORT SYSTEMS

Basis: 2 Years of Operation		
	Using Agriculture M$	Chemical M$
Research Development, and Acquisition	44.0*	62.0
Mass Delivered at $14,000/kg		
(1) Agriculture 14,300 kg	200.0**	
(2) Chemical 12,600 kg		176.0†
Power Equipment Acquisition at \$.2M/kW_e		
(1) Agriculture 5 kW	1.0	
(2) Chemical 29 kW		5.8
TOTALS	245.0	243.8

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* Includes development and acquisition of a backup chemical system.

** Includes food supplement and gas leakage supplied from Earth (2,000 kg).

† Includes food (11,600 kg) and additional expendables for backup (1,000 kg).

‡ Does not include an allowance for man-hours of labor necessary to operate either system.

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1. Schaeffer, H. S., A Note on the Galactic Radiation Exposure in Geomagnetically Unprotected Regions of Space, Naval Aerospace Medical Institute report NAMI 982, October 1966.

2. Langham, W. H., Radiobiological Factors in Manned Space Flight, National Academy of Sciences, National Research Council, Washington, D. C., 1967.

3. Ionics, Inc., Report No. SID 63-9, February 15, 1963.

Chapter 9

MOONLAB AGRICULTURE

9.1 Purpose

The purposes for developing MOONLAB agriculture may be classified as follows:

(1) The MOONLAB farm provides the basis for a pleasant, expandable permanent colony on the Moon, and is also economically justifiable. For 75 percent food recycle, about 2 years time at a base level of 24 men justifies the weight of the farm over the weight of required imported food and a CO_2 removal system.

(2) Development of a system for maximum photosynthesis with minimum space and labor requirements,

(3) Development of automated telemetering experimental packages for use in harsh agricultural environments,

(4) Development of new plant forms, new genetic makeup, and new soils by exposure to unusual light, hard radiation, gravity, magnetism, and atmospheric composition. Useful plants produced in such an environment may produce seeds which are advantageous elsewhere. Ecologic packages may develop for wider use.

(5) Crop adaptation and exploitation methods on the Moon may provide means for unlimited colonization of the Moon without dependence on Earth.

(6) Moon farming may yield knowledge and techniques which can be applied on Mars without the need for shelters. Mars farming could lead to eventual conversion of the entire planet to useful purposes. Water extraction methods with photosynthetic oxygen production might be enough to make Mars our first sizable extraterrestrial real estate development.

9.2 General Concepts of Farm Design

Several farms are needed for safety and for variation in growing conditions. The farms will be designed by consideration of such conceptual factors as crop content, closure of the O_2-CO_2 cycle, thermal balance, illumination, and soil conditioning and containment (see Fig. 9-1).

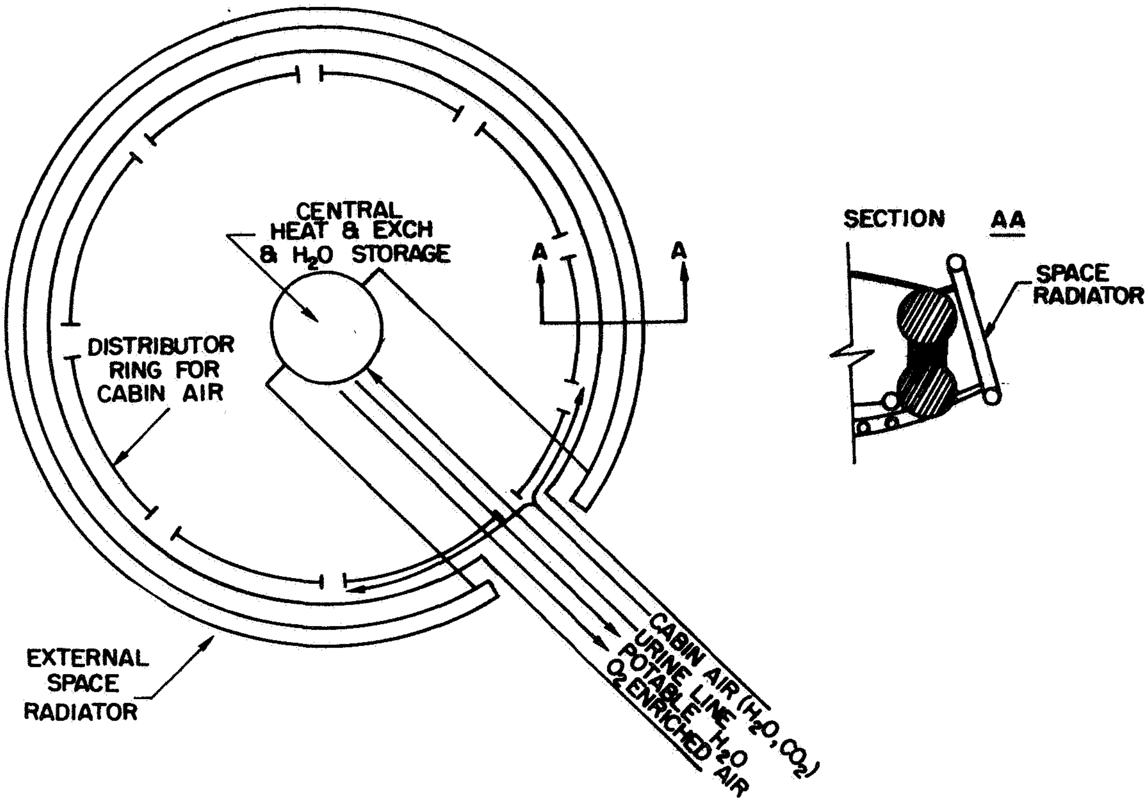

Fig. 9-1. Plan View of Typical Farm Unit.

One 18 m diameter farm will be programmed for perennials, one 18 m diameter farm for annuals and biannuals, one 10 m diameter farm for vegetable crops, and one 6 m diameter agrilab for new work in hydroponics and tissue culture.

An important design consideration is closure of the O_2-CO_2 cycle. Such closure of the O_2-CO_2 chain by photosynthesis of higher plants requires intensive culture at 5 m^2 farm area per man during an Earth day. Since the CO_2 level will be much higher on the Moon and light will be less filtered by atmosphere, fairly efficient conditions should be present for some plants. Since the most edible plants may not be the most efficient, a four-fold increase in allowed area to 20 m^2 per man is made. The result is a farm of 500 m^2 for the 24-man base. This is only 1/8 acre--a modest homestead. The four-fold increase is calculated to permit takeup of CO_2 from the chemical adsorber which regulates CO_2 level during night and is desorbed slowly during the day.

The farms will require heat rejection and transpired vapor condensation during the day to maintain 30° to 40°C atmosphere. Infrared rejection of the window will determine the extent of heat excess. The 18 m farms will hibernate at night, the leaf crop having been removed at dusk. Since soil temperature may fall below the ice point, the 10 m farm will be heated to stay above the ice point at night. About 2 kW will be needed. All farms will have highly reflective shades pulled over the windows at night to reduce heat losses.

All farms will be dark at night except the agrilab which will be lighted for at least minimum growth. About 2 kW is needed for this purpose. Since 60 W/m^2 will be needed to balance O_2-CO_2 use with the most efficient lights, extensive lighting is impossible.

Soil conditioning must be considered as a primary factor in designing the farm. Moon soil must be made from Moon dust since 160 tons are needed for the total farm assuming a 10-in. soil depth. Moon dust will be loaded before putting the window in place. Aggregate will be loaded first, followed by finer material. The soil will be watered by coarse sprays and drained into a sump. Water holdup of the entire farm in the soil will be 8,000 kg, assuming sand characteristics and 15-bar suction for the root area.

The floor of each farm consists of a sloping, gastight pan of high-density plastic. The floor (our C horizon) will be placed on properly contoured Moon dust. Thermal conduction between the farm and the surface should be minimized. The farm structure is further described in Chapter 10. Tables 9-1 and 9-2 summarize various characteristics of the agriculture complex. Figure 9-2 shows a cross section of one of the farms. Figures 9-3 and 9-4 show the floor plans for the agricultural laboratory module and the farm layout.

9.3 Life Support Details

The farm size permits total closure of the O_2-CO_2 cycle using higher plants, the CO_2 generated by men, equipment, and soil organisms. Three-quarters of the caloric needs of the men will be satisfied by 12 kg of dry matter per day from the farm, while the remaining quarter will be

Table 9-1

CHARACTERISTICS OF THE AGRICULTURAL COMPLEX

	18 m	18 m	10 m	6 m	TOTAL
Window Area	250 m^2	250 m^2	75 m^2	25 m^2	600 m^2
Enclosed Volume	800 m^3	800 m^3	450 m^3	50 m^3	2100 m^3
Window Mass	370 kg	370 kg	110 kg	37 kg	900 kg
Floor Mass	1000 kg	1000 kg	300 kg	n.a.	2300 kg
Beam Mass Number	1400 kg	1400 kg	800 kg	n.a.	3600 kg
Total Structure	2800 kg	2800 kg	1200 kg	40 kg	6800 kg
Night Power	0	0	2 kW	2 kW	4 kW
Soil Mass	65 tons	65 tons	25 tons	5 tons	160 tons
Soil Moisture	2000 kg	3000 kg	1200 kg	300 kg	7500 kg
Maximum Biomass					10,000 kg
Total Plant Dry Matter					1,000 kg
Nitrogen in Biomass					200 kg

Table 9-2

LIFE SUPPORT SYSTEM--AGRICULTURE PEAK POWER REQUIREMENTS

	kW	Mass
Feces Dryer	0.22	10.0
Water Heater	0.08	1.0
Agriculture Machinery	4.0	100.0
Wash Water System	0.50	12.0
Air Circulation	3.8	320.0
Pumps at 0.093 kW each*	1.6	20.0
Lighting, UV sterilizers, adsorber	10.0	800.0
TOTAL	20.2	1263.0

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*Includes agriculture processing pumps.

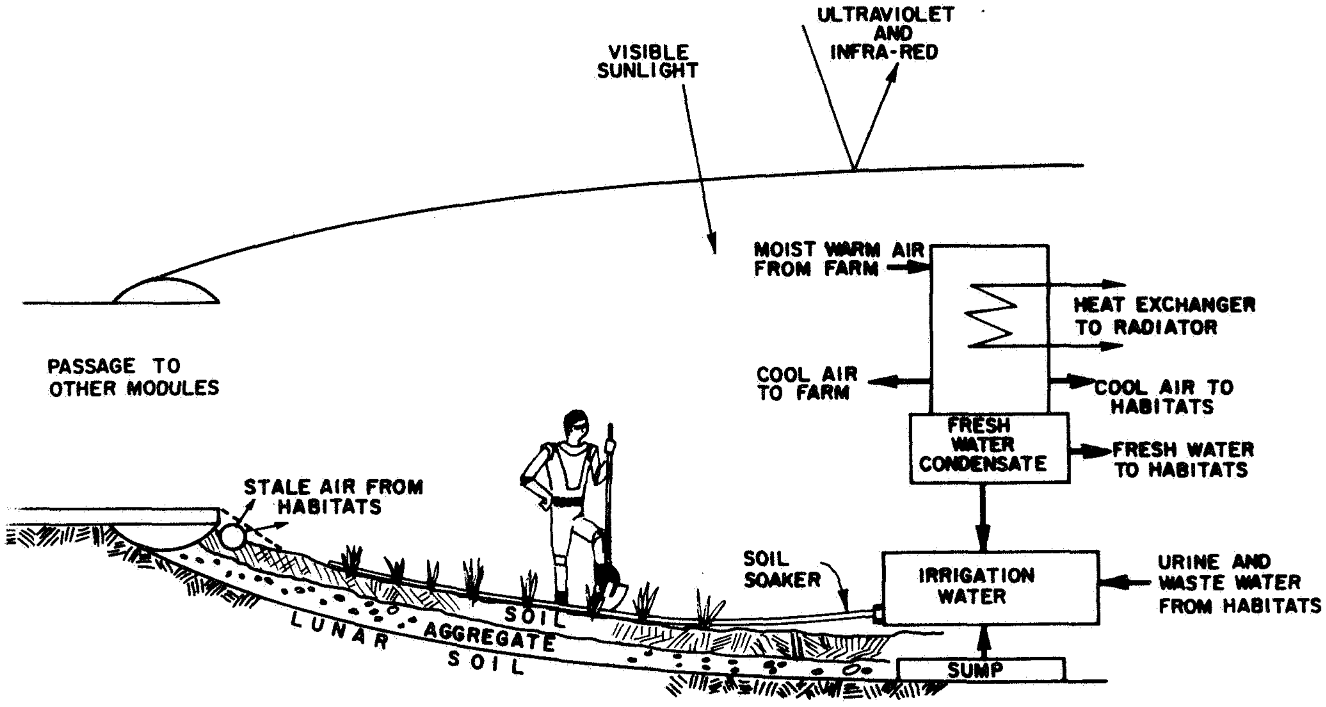


Fig. 9-2. Cross Section of the Farm.

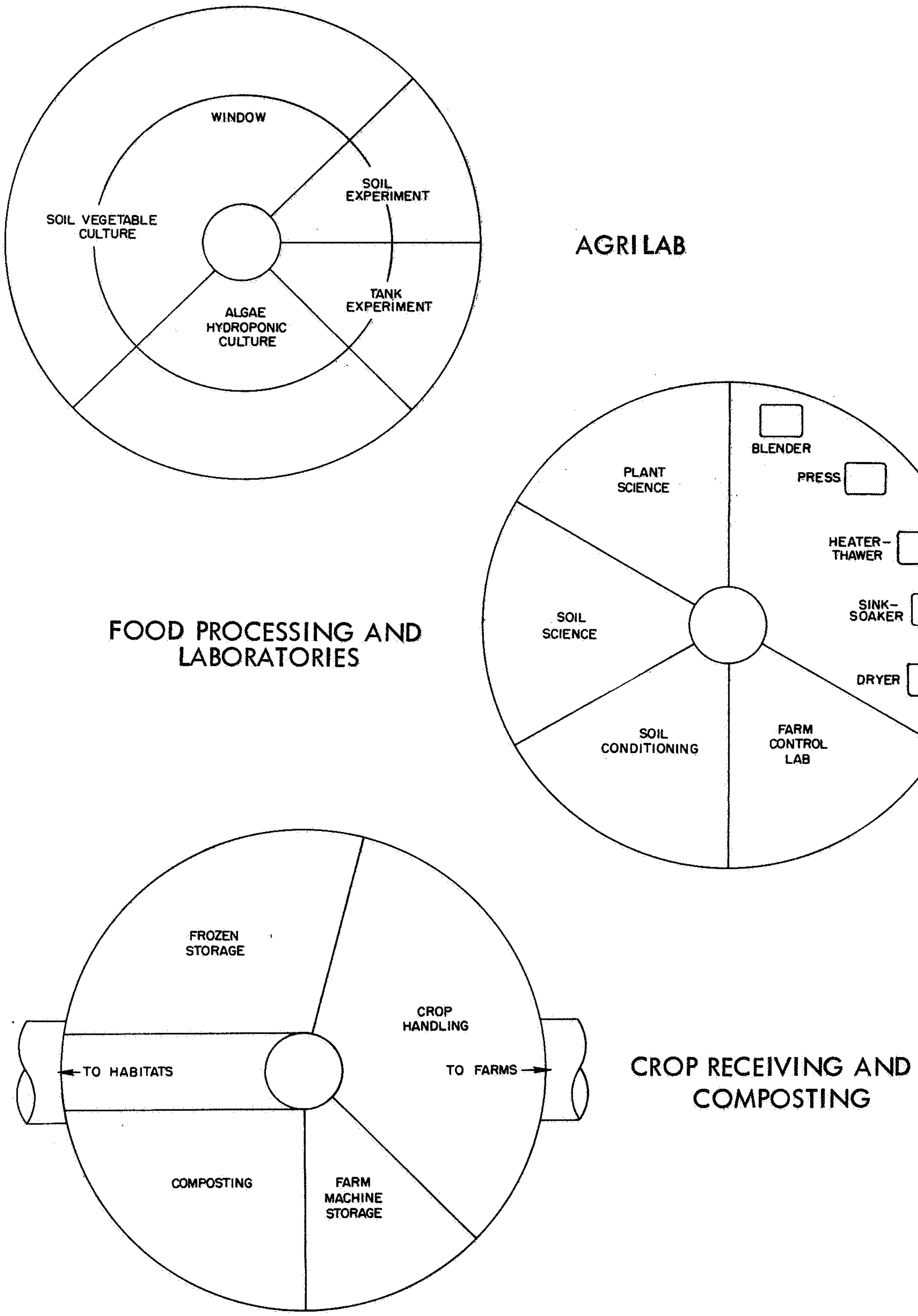
provided from Earth in freeze-dried form. All trace nutrients, fats, and mineral supplements will be imported.

Contribution to the farm water supply will come from condensed waste water, water transpired by plants, and sterilized urine.

Food wastes and dried sterilized feces will be added to the farm soil for the benefit of soil organisms. Wastes can be burned to CO_2 if detritus seems to build up.

9.4 Crop Details

Possible annual and biannual leafy crops which the farm will include are rye, swiss chard, endives, lettuce, and Chinese cabbage. Rye grows rapidly, is fairly sweet to the taste, and may lead to cereal production by overnight drilling of the grass to start fruiting. Swiss chard is extremely nutritious and totally edible except for the root mass. Endives, lettuce, and Chinese cabbage are believed to be suitable for lunar day growth and are almost totally edible.



AGRI LAB

FOOD PROCESSING AND LABORATORIES

CROP RECEIVING AND COMPOSTING

Fig. 9-3. Module 7 Floor Plan.

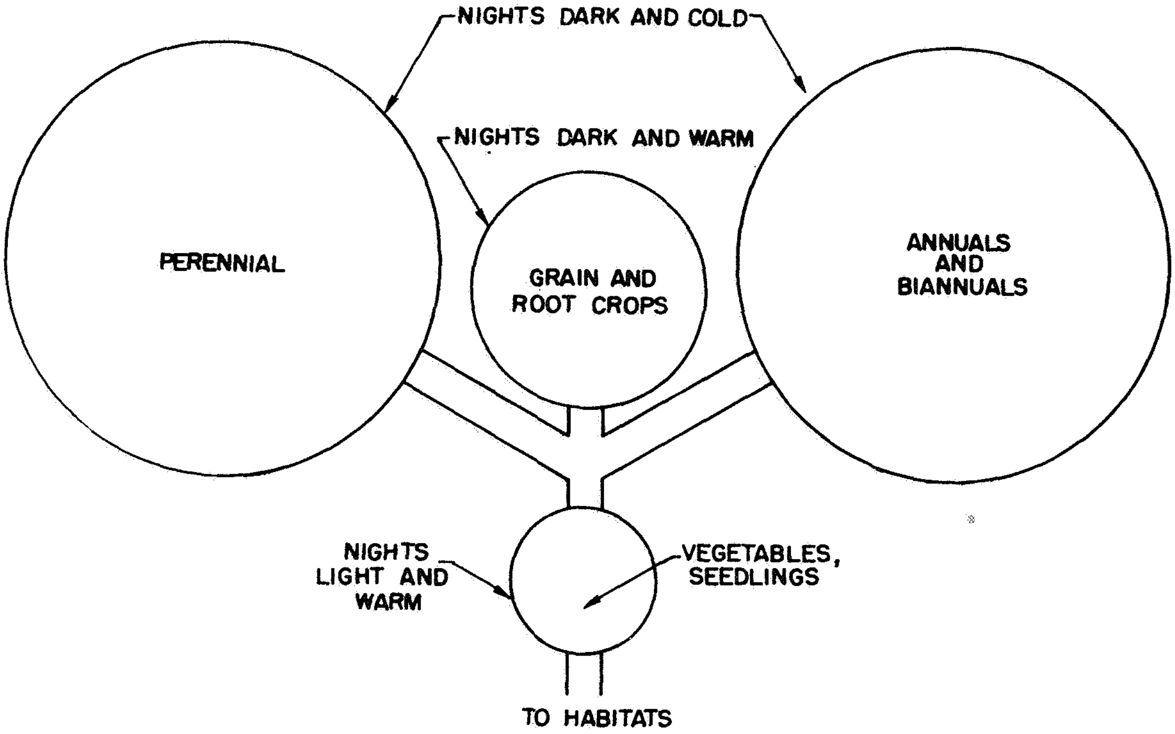


Fig. 9-4. Farm Layout.

Many other species of perennial plants are said to be capable of maturing enough during the 300 hours of light to yield good forage crops. Alfalfa is very vigorous and salt tolerant and has been optimized for rapid photosynthesis, but its edibility depends on further processing. It must, nevertheless, be considered as a candidate crop.

Tomatoes, peas, beans, etc. grow rapidly, are highly efficient and have a high yield inside the frost-free area. They will add desirable variety to the MOONLAB diet. Root crops may also be possible, especially in the frost-free areas. Sweet potatoes can provide the major nutrients for human groups, and all parts of the plant are believed edible. Peanuts are a good source of badly needed fats.

If crops with large proportions of non-edible mass are needed, a somewhat larger farm area can be used to provide the necessary atmosphere control. Since the biomass will grow with imported food supplements, the farm must expand if increasing water inventory is to be utilized.

9.5 Food Processing

The various foods to be processed are leaves, cereals, root crops, vegetables, and hydroponic crops.

Leaf processing will include harvesting, packaging, and freezing at dusk. Leaves not directly edible will be cooked with hot water (boiling point 60 °C) while fibrous leaves will be crushed and fiber pressed out for return to the soil. The serum will be frozen for direct consumption if palatable, and unplatable serum will be boiled to coagulate protein, which will be pressed out and dried. A safe scheme for removing leaf serum taste should be found as soon as possible.

Root crops and vegetables will be eaten after the usual preparation, and cereals will be boiled or dried and malted to improve taste. Hydroponic crops will be eaten as is or dried during the day, since dusk harvesting is not needed in this case. Tomatoes will be consumed immediately and sweet potatoes will not need preservation.

9.6 Farm Maintenance

The farm will be managed by an agronomist or botanist who will also conduct experiments in agriculture. He must be capable of directing the addition of nutrients, dried feces, conditioners, etc. into the soil. One man is capable of operating the lunar farm for 23 others.

Temperature control and water and atmosphere composition can be automated and provision made for an alarm system to warn of septic threats.

Personnel must minimize their time in the farms to decrease the radiation hazard, and no farming will take place during solar flares. Special shields may be emplaced when longer exposures are necessary.

All crops above ground in unlighted and unheated farms must be mowed or harvested at lunar dusk. A simple mower requiring a peak power of 1 kW will rapidly harvest the leaf matter, and an attached collector will accumulate the crop.

9.7 Evolution of Farm

9.7.1 Preliminary Development Work Required

Low-pressure, Earth-based greenhouses should be developed. The structures must be capable of containing 5 psi atmosphere, have intense visible artificial light sources, and be equipped with humidity, atmospheric composition, pressure, and temperature controls. These containers could initially be small (desktop size), and some should be provided with a very low terrestrial magnetic flux.

In addition, a material is needed for the window portion of the large inflatable farm structures. It must have good ultraviolet rejection, the best possible infrared rejection, and be at least 25 percent transparent to 2500° to 6500°A light. The material should have a tensile strength of at least 20,000 psi, be producible in large sheets, be capable of being bonded both to itself and to other materials used in inflatable structures, and have a very low water vapor and oxygen permeability.

9.7.2 Earth Tests Required

A number of tests must be conducted, methods developed, and studies made to ensure the success of the lunar farm.

The lunar farm soil must be formed from unweathered lunar basalt rock fragments by an Earth-devised technique. Necessary nutrients, soil organisms, and soil animals for higher plant growth must be identified. A B-soil horizon at 10 in. depth is required.

The most suitable crops for lunar conditions must be identified among crops completely or partially edible by man with emphasis on those already known to support large human populations. Annuals, biannuals, perennials, and small plants for hydroponic culture should be selected. Maximum yields of acceptable food, especially from the leaf crops, must be obtained by development of simple, solvent-free processing steps.

A food diet should be chosen based on the previous information, and the physiological and psychological effects of the diet tested on well-motivated subjects for extended periods.

9.7.3 Moon Tests Required Before 1985

Terraria with mixed cultures of soil organisms in typical soils should be flown to Grimaldi during the evolutionary period. These terraria will include the selected plant seeds and the chosen window material. Gas and temperature sensors to effect automatic control should be included, and soil pH, plant growth, etc. monitored.

Using these terraria, soil formation from Moon rock should be started and nutrient solution circulation supplied. Experiments combining soil formation and crop growth should be established. These latter experiments should be automated to simulate the kinds of inputs an attendant agronomist would make if he were present.

9.7.4 Farm Construction

As each window and floor section of the farm structure is landed, it is deployed as described in Chapter 10. The floor and its beam are emplaced, first loaded with coarse aggregate, then fine material, and finally seeded with earth organisms brought along in a dry state. The window and its beam are placed on the floor beam and bonded in place. Access ports through the floor beam are attached and connected by locks to habitats.

9.7.5 Soil Development and Crop Seeding

A successful lunar farm involves many factors. The O_2 atmosphere with CO_2 being generated by organisms will be introduced together with nutrient water sprays. Soil pH, osmotic load, etc. will be controlled as dictated by prior experiments.

Seeds will be encased in nutrient capsules before use, and when the soil is ready the seeds will be planted before a lunar dawn. After the atmosphere becomes correct the chemical system will be shut down, ducts from habitats opened, and fans started.

9.7.6 Farm Developments

In the post-1985 period soil and crop development will be expanded and new crops adapted to the crew's diet. Small animals such as chickens will be introduced to provide a better diet and permit easier use of leaf crops.

As flora becomes stabilized and simplified, effects of introducing various new beneficial life forms will be studied. The effects of lunar conditions on crops will be studied for insights on plant adaptability elsewhere. The influence of very long days will be examined to expose opportunities for more intense use of lighted greenhouses on Earth.

Moon organisms, if any, may show completely novel photosynthetic activity. Such forms will be cultivated in the Moon agricultural laboratory (agrilab). Heterotrophs using iron or manganese as electron acceptors should be sought. Shallow soil farming and hydroponics will be intensively developed.

9.8 Farm Operation

After the soil has been satisfactorily conditioned by nutrients, water, and microorganisms seedlings will be started in the agrilab. At lunar dawn these will be implanted in the larger farms according to the schematic farm layout. The annuals will be planted every lunar morning, perennials will be removed only occasionally. During the day, crops will be nourished and tended for intensive growth, CO_2 conversion, and water transpiration. Soil pH, osmotic load, moisture, and oxygen demand will be observed frequently by the agronomist.

At dusk the perennials and annuals will be mowed very close to the soil by the power clipper. If soil is too rich in organics the annuals will be completely uprooted. The crop will be collected directly by the mower. Leaf matter--that is, most of the perennials and annuals--will be collected in fairly small pieces. Salad-like crops such as endive, cabbage, or lettuce will be cut off in the usual way. The grain and root crops will be treated in Earth-fashion, except that the leaf matter will be separately mowed and collected. Those plants which have not fruited during the lunar day will be trimmed, if necessary, and prepared for fruiting the next day.

As dawn develops the reflective shades will be rolled out to cover each farm window. The fresh water in each farm will be directed to central storage. Irrigation water with its urine and nutrient content can be allowed to freeze, provided a sterile urine storage tank is available in the habitats.

9.9 Crop Handling

Leaf tissue can be first separated from stems, roots, etc. by blowing gas up through the crop mass. The leaf "chaff" will be washed and frozen for direct use if palatable (rye grass). If unpleasant in taste it will be extracted and/or cooked for consumption. The stems, etc. will be returned to the soil in the morning if the soil condition warrants it. If not, they will be composted if the oxygen supply permits it. If the oxygen supply is inadequate, supply will be converted to sugars and lignin by enzymatic hydrolysis. The lignin will be returned to the farm and the sugars eaten. If the lignin accumulates it will be oxidized.

9.10 Diet

If enough crops prove palatable and vigorous on the Moon the diet will become less dependent on freeze-dried meat, etc. from Earth. As tomatoes, sweet potatoes, lettuce, swiss chard, etc., adapt they will be, at best, partly edible and partly root, stem, or inedible leaf. These crops alone seem unlikely to become a large part of the biomass. They will, nevertheless, be prized for food. Grain, if it can be fruited over a lunar night, offers the best chance of a really intense caloric production. Because of the more complex life cycle of grains they will be slow to adapt. When they do, the diet will be truly complete, and agriculture will be ready to expand to larger areas (one-half acre). The grain, of course, can be baked, boiled, malted, or malted and fermented. Such an agriculture could be supplemented by chickens which can be shipped as fertile eggs. Alfalfa could become part of the poultry diet, but grain would be the mainstay.

Chapter 10

MOONLAB STRUCTURES

10.1 General

The overall requirement of living quarters for MOONLAB is to provide protective, sealed in spaces with independent ecological systems, capable of closely duplicating the terrestrial environment. The consideration here is to provide suitable safe shelters which can be transported to the Moon and which will be capable of withstanding the hazards of the trip and those of the lunar surface.

In the last decade many types of lunar structures have been proposed. Figure 10-1 shows that presented by Szilard [1] in 1959.

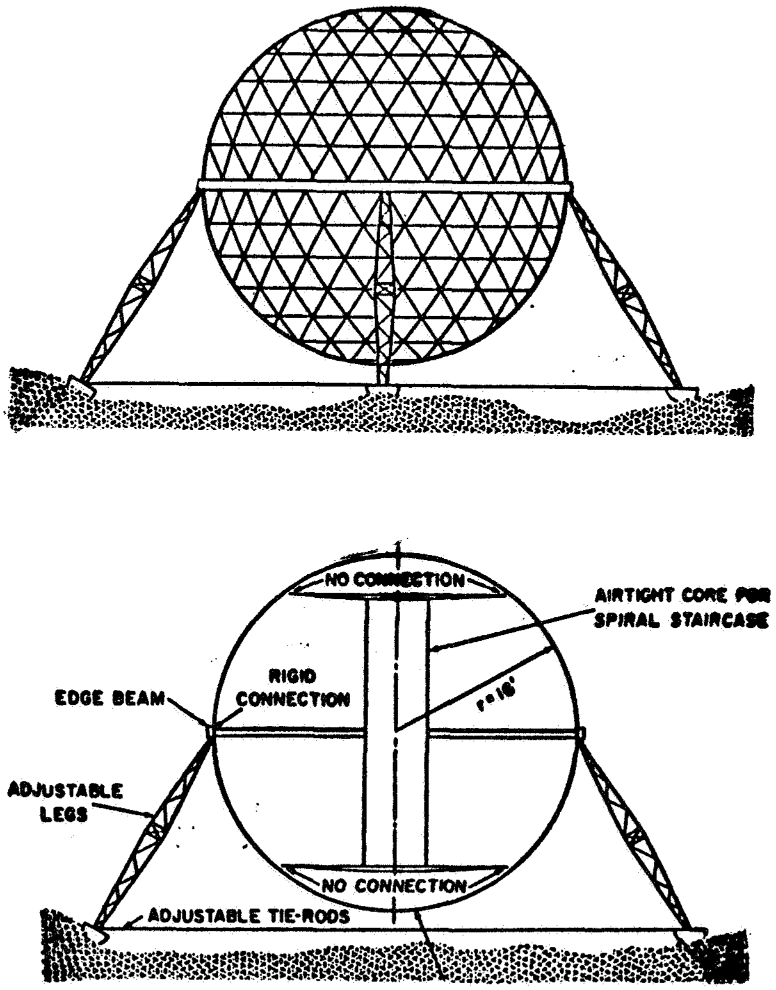


Fig. 10-1. Lunar Structures [1].

The shelter consists of a double-walled, rigid frame sphere of very light tensile members. The wall is of double skin construction to present an elastic meteoroid bumper and to let cooling fluid circulate between the walls.

Di Leonardo and Johnson [2] have proposed the use of inflatable membranes as shown in Fig. 10-2. In both cases protection against meteoroid puncture is provided by covering the shelter with a layer of lunar soil. In Fig. 10-2(b) the shape of the membrane is controlled by using load-carrying stiffeners in the shell. This concept provides a more useful contained volume. An inflatable cylindrical shelter has been

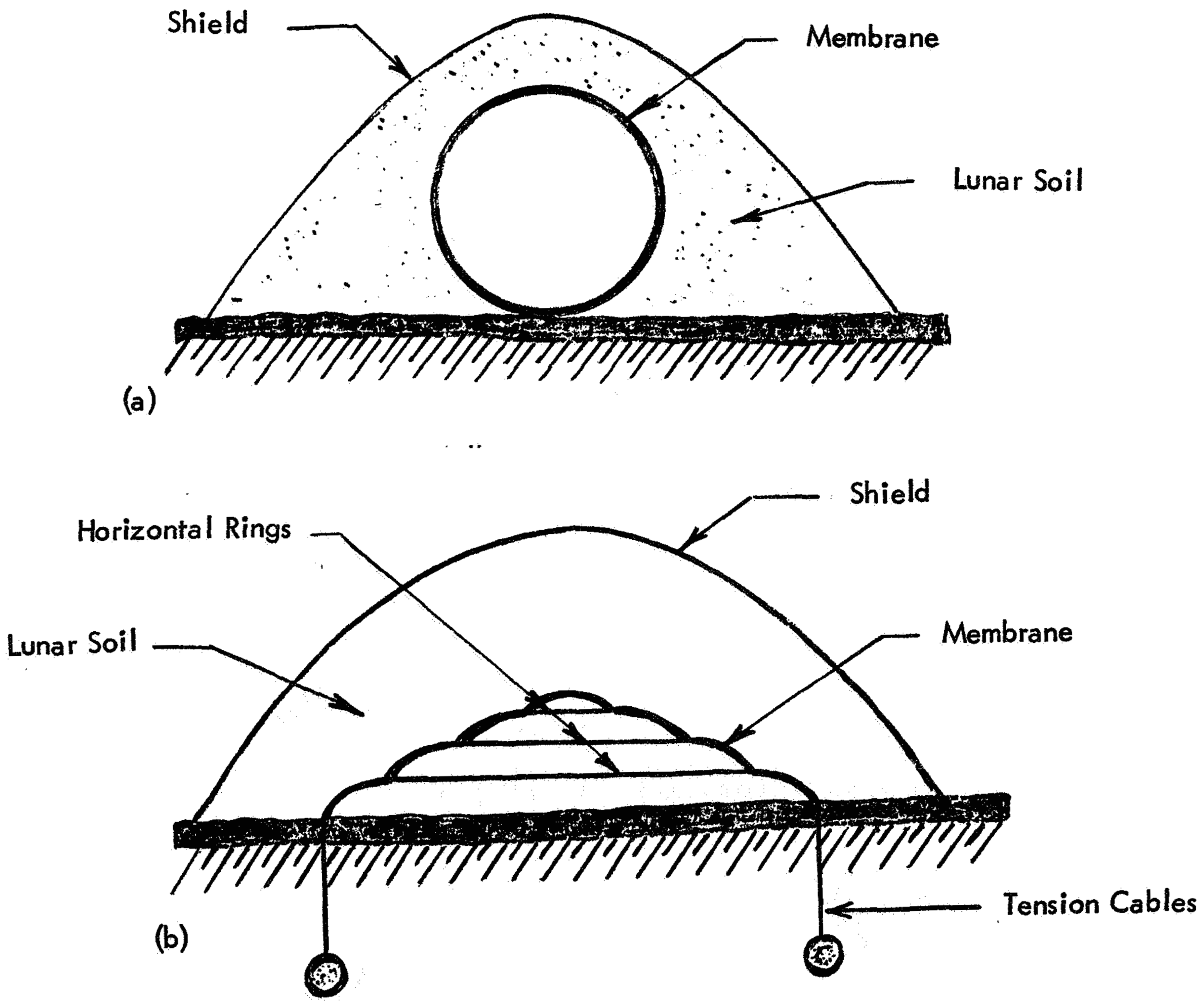


Fig. 10-2. Inflatable Structures.

fabricated by the Goodyear Company [3] and Earth-tested satisfactorily. The structure is of cylindrical form large enough to provide protection for two astronauts for a short staytime. In recent years studies by Boeing ("LESA," [4]) and Lockhead ("MIMOSA," [5]), have given a great deal of attention to prefabricated structures. For medium to long duration (3 years) staytimes the main basic form proposed is that first given in LESA, a vertical cylinder, landed and used in the upright position. Not all the proposed shelters are intended for the lunar surface.

Di Leonardo [6] has proposed an underground shelter, as shown in Fig. 10-3. The shaft and chamber are formed by using a shaped charge and after lining the "walls" with polyurethane foam, an expandable envelope is inflated in the cavity, making the shelter air-tight. Expansion of the base is obtained by connecting new chambers by a tunnel system. Exit to the lunar surface is through air-locks in surface "igloos."

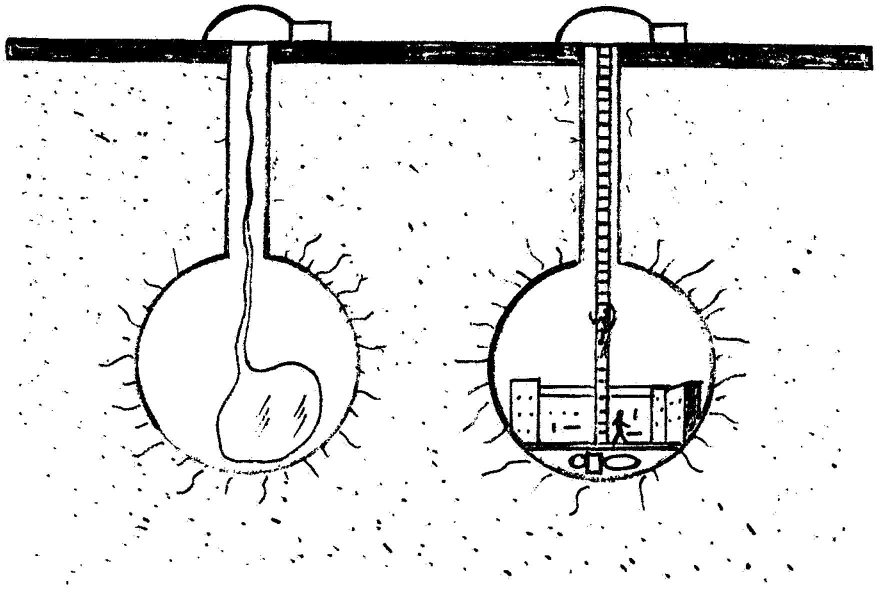


Fig. 10-3. Buried Structures [6].

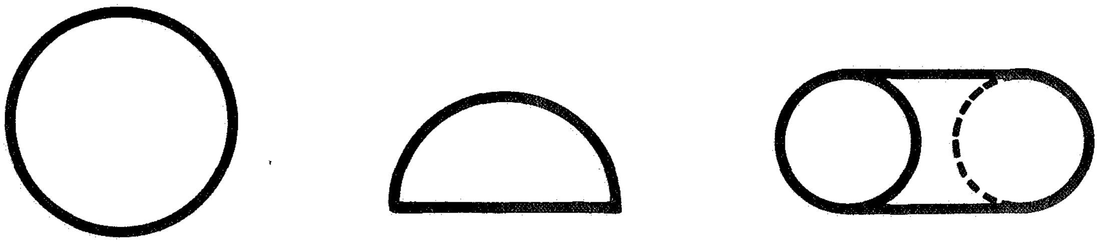
10.2 Design Constraints

The environment constraints for any lunar structure are as follows: vacuum, reduced gravity (1/6 g), meteoroids, radiation, temperature extremes, and unknown foundation conditions. Added to these we have the conditions of launching and landing, the specified contained atmosphere pressure of 34,400 N/m^2, the specified population of 24 and the cargo vehicle size of approximately 6 in. in diameter.

The main structures involved in the proposed lunar base are the manned shelters and the farm structure. These are considered separately.

10.3 Manned Shelter

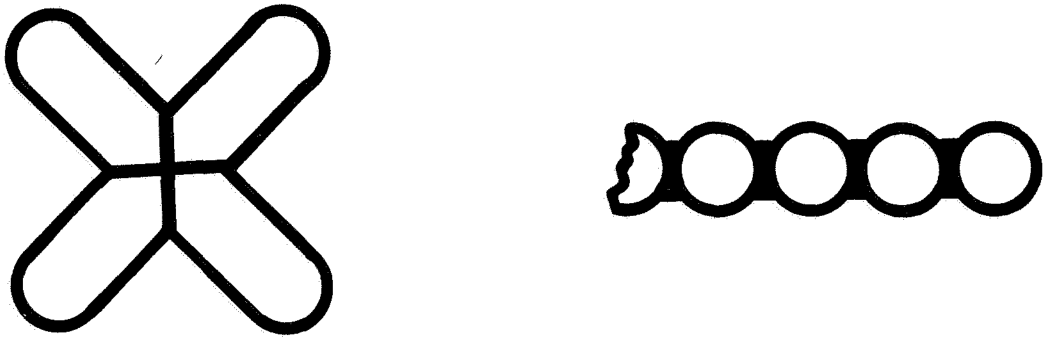
The feasible basic shelter shapes are shown in Fig. 10-4. Combinations of these are, of course, also useful as shown in Fig. 10-5. Figure 10-5(d) has been proposed by the LESA study [4]. Since MOONLAB will develop over a 9-year period (1976-1985), the best module shape is needed.



a. Sphere b. Hemisphere c. Cylinder

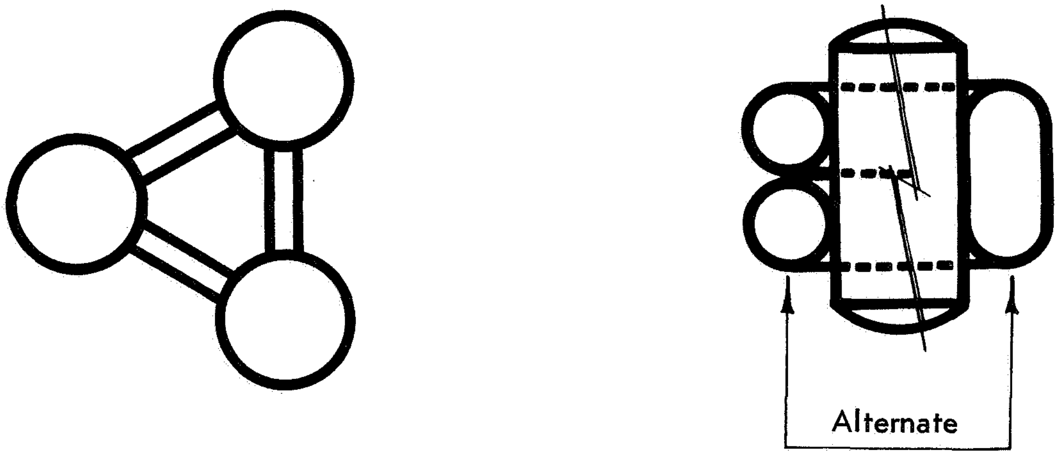
d. Quonset e. Toroid

Fig. 10-4. Feasible Basic Shapes.



a. Connected cylinders

b. Nested spheres



c. Spheres and cylinders

d. Toroid and cylinders

Fig. 10-5. Feasible Compound Shapes.

The main control used in choosing the basic shapes of Fig. 10-4 was that the structure be a pressure vessel. The simplest most efficient structural shape for withstanding internal pressure is the spherical membrane of Fig. 10-4(a). However, the sphere has one inherent disadvantage, an excessively high ratio of pressurized volume to usable, flat floor space for the typical requirements of manned quarters. The hemisphere form in Fig. 10-4(b) substantially reduces the ratio of pressurized volume to usable space but at the expense of requiring stiffeners to maintain the discontinuity at the junction of the roof and floor. Similarly with Fig. 10-4(d). The remaining configurations, the cylinder [Fig. 10-4(c)] and the toroid [Fig. 10-4(e)], while not the most efficient, from the point of view of required surface area for a given volume are, however, quite acceptable as useful pressurized shelter forms.

The toroid has the advantage over the cylinder in that it has no ends and for a reasonable mean diameter gives a considerable "alley" length. The end effect of the cylinder can, of course, be reduced by using suitable end forms.

10.3.1 Consideration of the Toroid and Cylinder Forms

Toroid. The first consideration is size. Although it is possible to house the entire base population (24) in a single structure, it is considered necessary that we build modules to protect against complete failure. Furthermore, the use of modules will allow the build-up to full capacity over the evolutionary period prior to 1985.

The suitable module crew size is 6 men. Using a gross volume of 28 m^3/man we are interested in the overall size for a suitable cross section. For a section diameter of 3.95 m we have a contained rectangle of 3.05 m by 2.44 m high, Fig. 10-6(a). The alley width could be increased if the desired 2.44 m headroom was measured to the circular shell of the toroid, Fig. 10-6(b). In either case the useful cross section area is acceptable and for a total volume of 169 m^3 the required mean diameter is 4.4 m and the overall size is 8.35 m. Such a toroidal structure would have to be transported in sections or inflated on site. Inflatable structures are a reality at present, but have the disadvantage that for a long duration on the lunar surface they require sufficient cover of lunar soil to protect against meteoroids and radiation. Further, the shelter would have to be "loaded" with life support, etc. in situ. All of this construction would carry the severe penalty of lunar labor--estimated at up to 100 thousand dollars of investment per hour (at least in the early years). The inflatable toroidal shell or any inflatable shell although suitable for a short stay for a small crew is presently unfeasible for "large" bases and long staytimes. Future availability of a larger diameter cargo rocket would, of course, allow the prefabrication and testing of the toroidal shelter on the Earth.

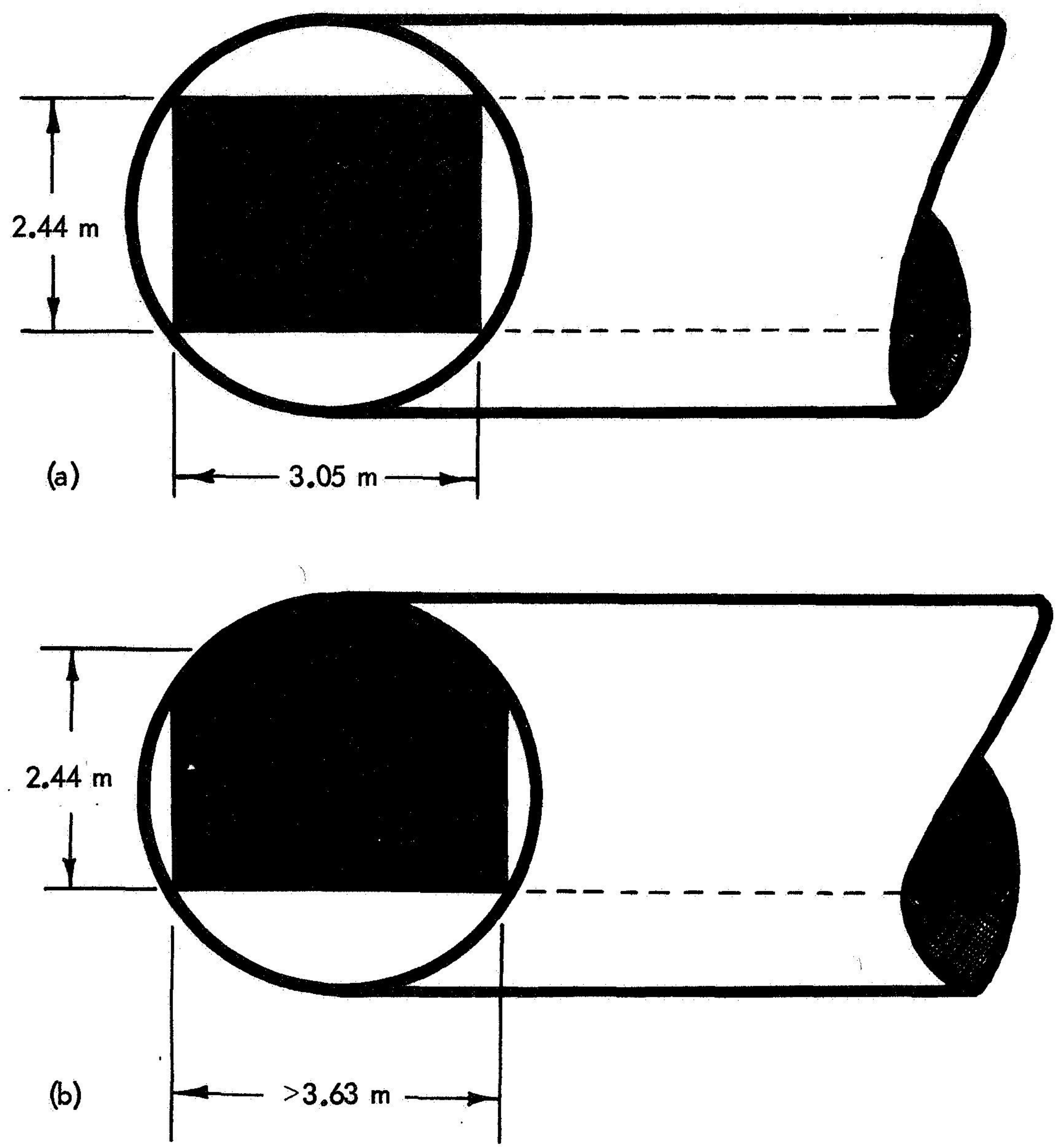


Fig. 10-6. Toroidial Space Utilization.

Cylinder. The cylindrical form can easily fit within the specified cargo vehicle dimensions (approximately 6 m in diameter) and thus can be prefabricated and tested on the Earth and landed on the Moon ready to use.

The cargo rocket dimensions are shown in Fig. 10-7. It is proposed that a prefabricated shelter be fitted in the cargo space

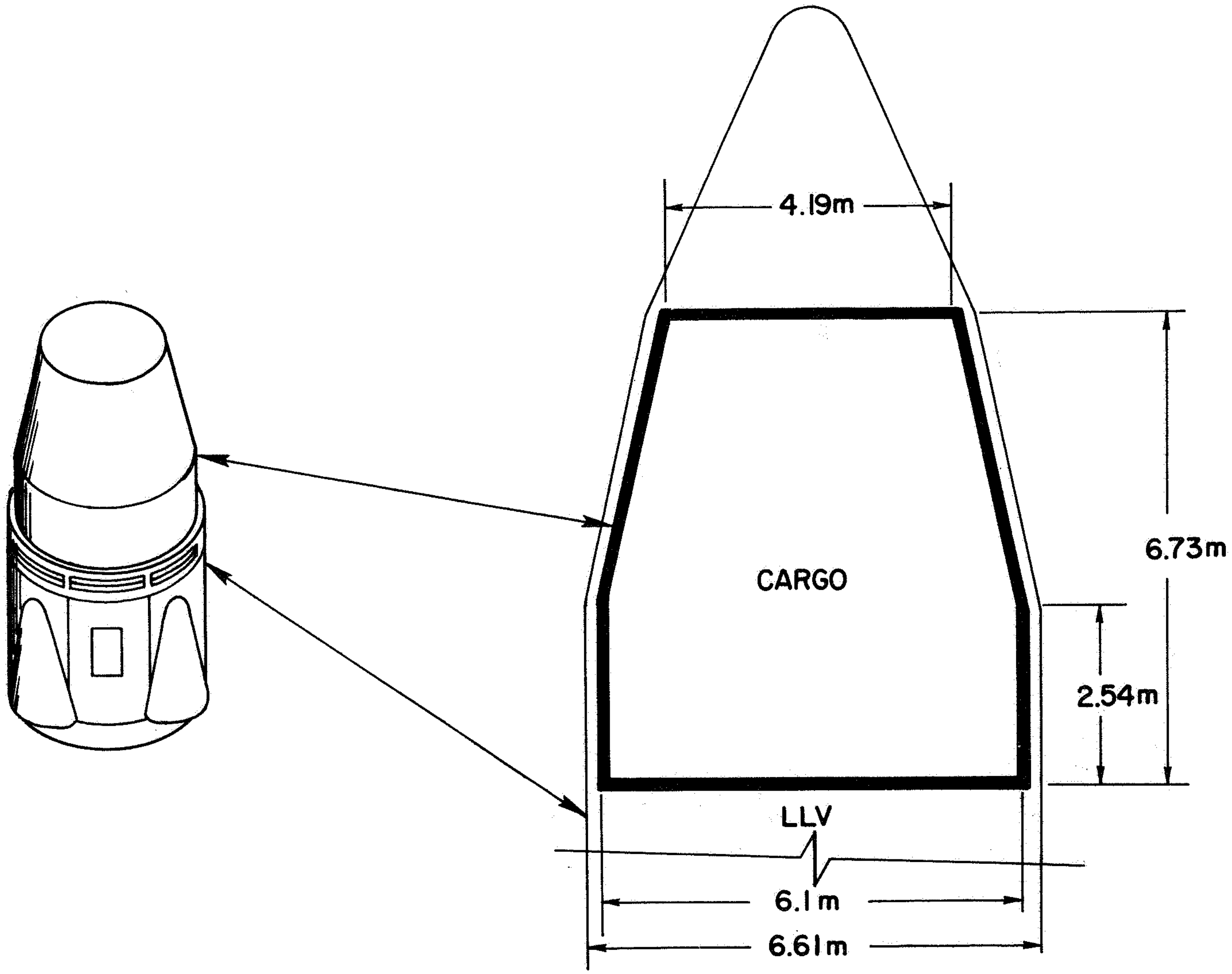


Fig. 10-7. Lunar Landing Vehicle Cargo Envelope.

shown, with extra straight length added between this and the LLV below (Fig. 7-1). It is not possible to carry out a complete design of the shelter in this study. However, because of the importance of the shell wall some consideration is given to this.

Shelter Shell Wall. Feasible wall systems are monocoque, skin-stringer, corrugated and honeycomb core sandwich as illustrated in Fig. 10-8.

The loads to be considered are buckling, due to launch and landing loads, and tension, due to the operating pressure. These are considered separately.

Buckling. Considering the cylindrical shape, the structural weight-to-unit volume relationships are given by

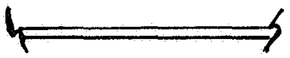
$$\frac{w}{v} = \frac{2\rho \bar{t}}{R}$$

where

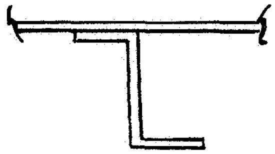
w = structural weight,
v = volume,
ρ = density,
$\bar{t}$ = effective thickness,

and

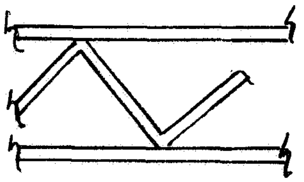
R = radius of shell.



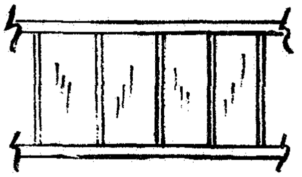
Monocoque



Skin-Stringer



Corrugated Core Sandwich



Honeycomb Core Sandwich

Fig. 10-8. Wall Systems.

For a monocoque system the wall thickness required is given by

$$t = \frac{N_i}{\sigma_{CR}} = \sqrt{\frac{N_i R}{KE}} \, ,$$

where

t = wall thickness,
N_i = load per unit length of circumference,
σ_{CR} = critical compressive stress,
K = buckling coefficient,

and

E = modulus of elasticity.

Since the equivalent thickness and the actual thickness are the same in this case, we have

$$\frac{w}{v} = \frac{2\rho}{\sqrt{KE}}\sqrt{\frac{N_i}{R}} .$$

The sandwich cylinder under compression can be treated in the same manner.

Assuming that the core carries none of the axial load the face thickness is given by

$$t_f = \frac{N_i}{2\sigma_{CR}} .$$

Considering the face thickness in terms of the sandwich thickness, d, we have

$$\frac{N_i}{\sigma_{CR}} = 2K_2 d ,$$

where

$$K_2 = \frac{t_f}{d} .$$

The effective thickness of the sandwich is given by

$$\bar{t} = 2t_f + c \frac{\rho_c}{\rho_f}$$

$$\cong 2\ t_f + d \frac{\rho_c}{\rho_f}$$

where

$\bar{t}$ = effective wall thickness,

c = core thickness,

ρ_c = core density,

and

ρ_f = face density.

Now, we have

$$t_f = K_2 d$$

then, the effective thickness becomes

$$\bar{t} = 2K_2 d + d \frac{\rho_c}{\rho_f}$$

$$= K_3 d,$$

where

$$K_3 = 2K_2 + \frac{\rho_c}{\rho_f} .$$

The critical stress for the sandwich cylinder in compression is given by

$$\sigma_{CR} = K_1 E \frac{d}{R} .$$

Substitution of this in the N_i/σ_{CR} expression gives

$$d = \sqrt{\frac{N_i R}{2K_1K_2E}} .$$

The structural weight to volume ratio is given by

$$\frac{w}{v} = \frac{2\rho\bar{t}}{R} = \frac{2\rho K_3 d}{R}$$

$$= \frac{2\rho K_3}{R}\sqrt{\frac{N_i R}{2K_1K_2E}}$$

$$= K_4\sqrt{\frac{\rho}{E}}\sqrt{\frac{N_i}{R}}$$

where

$$K_4 = \sqrt{\frac{2K_3^2}{K_1K_2}} .$$

Internal Pressure. The cylindrical pressure shell thickness is given by

$$t = \frac{pR}{\sigma} ,$$

where

t = required wall thickness,

p = internal pressure,

R = cylinder radius, and

σ = allowable tension stress.

For the monocoque system the equivalent wall thickness is equal to the actual thickness, i.e.,

$$\bar{t} = t .$$

For a sandwich wall we have

$$\bar{t} = 2t_f + \bar{t}_c$$

$$= Kt$$

where

t_f = single face thickness,

$\bar{t}_c$ = equivalent core thickness, and

K = constant.

The weight to volume ratio for a cylindrical shell is given by

$$\frac{w}{v} = \frac{2Kt\rho}{R} = \frac{2K\rho p}{\sigma}$$

For an assumed payload of 16,000 kg, the buckling design load of 2.1×10^5 N/m (max., due to 15 g vertical and 7.5 g horizontal--considered as ultimate landing load) and an internal operational pressure of 34,400 N/m^2 (design pressure taken as 86,000 N/m^2) the ratio of structural weight for axial load to structural weight for internal pressure is approximately 2.

It was decided that the wall system will be a honeycomb sandwich and although it is known that the buckling load due to landing is more serious than that due to internal pressure, there are other controls which must be considered, before decisions on wall weights can be made--i.e., those due to meteoroids, radiation and lunar temperature hazards.

Letting d/t vary from 50 to 75 and assuming honeycomb core is 2.5 lb/ft^3 and with a buckling coefficient of $K_1 = 0.42$ the maximum variation in K_4 is 6 percent. For aluminum alloy with density $(\rho) = 0.277$ kg/m^3 and modulus $(E) = 6{,}895 \times 10^4$ N/m^2, the slenderness ratio (d/t) used here is approximately 50.

The coefficient K_4 varies, of course, with sandwich geometry but the variation may be neglected for preliminary calculations.

Calculations for the skin-stringer and the corrugated core sandwich may be carried out in a similar manner. A comparison of all the systems is shown in Fig. 10-9. It is assumed here that the entire shelter payload is carried on the periphery.

10.3.2 Meteoroid Effects

The extent to which meteoroids are a hazard in space is uncertain because very little about their mass distribution, density, velocity and direction is known. However, structural design criteria have been developed based on high velocity impact of small projectiles, and on an assumed meteoroid flux [7,8,9].

The meteoroid flux is related to the mass distribution of the smallest meteoroid considered and is expressed as

$$F = \alpha m^{-\beta} ,$$

where

F = particle flux having mass m or greater (the units being number of particles per unit area per unit time).

α = a meteoroid environment parameter (units of mass per unit area per unit time)

= $10^{-9.955}$ kg/m^2 per sec,

β = a dimensionless environment parameter

= 1 for interplanetary space, and

m = meteoroid mass.

We have then $F = 10^{-9.955}\ m^{-1}$. The average number of meteoroids striking an area is given by

$$\overline{N} = TAF,$$

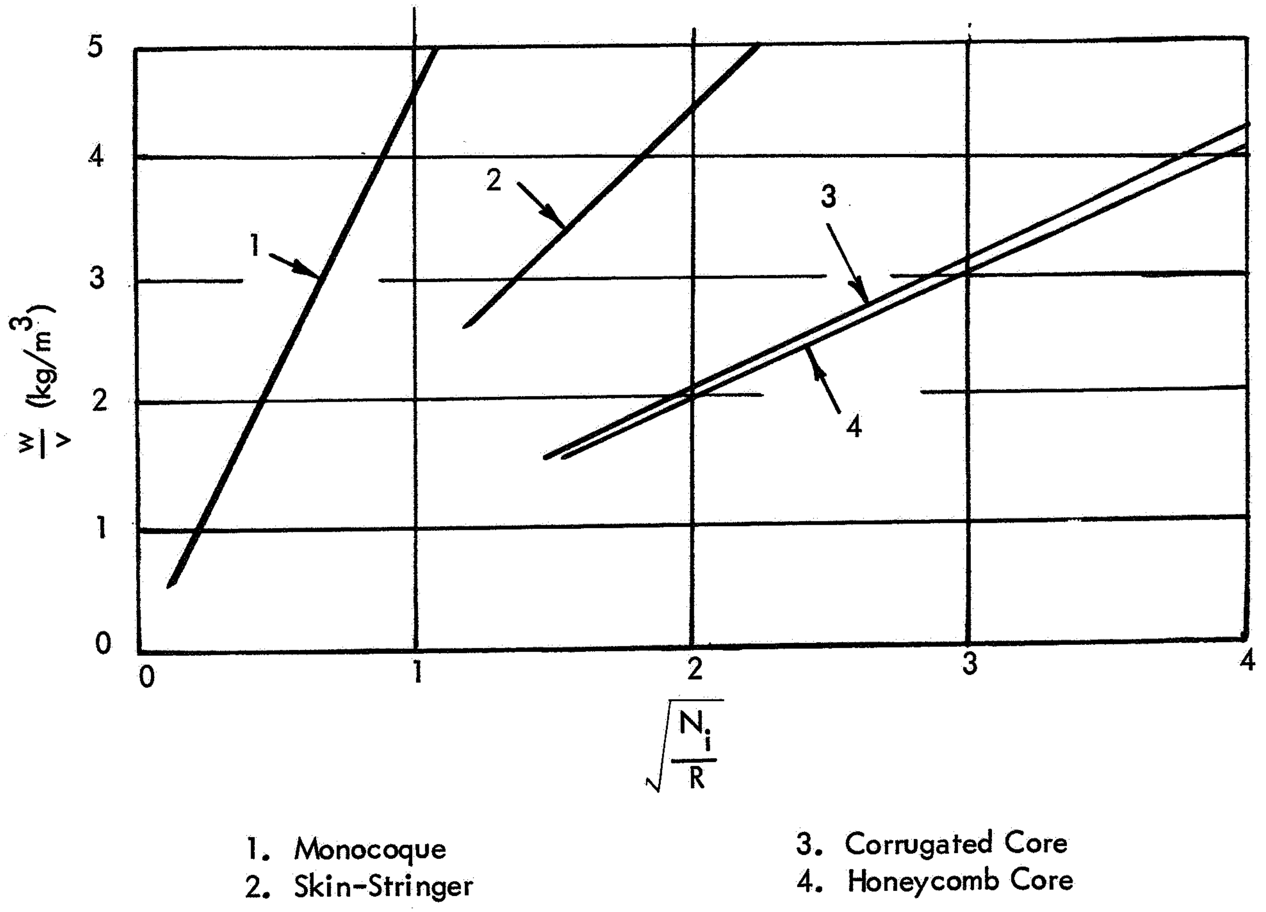


Fig. 10-9. Axial Loading Weight to Volume Ratio.

where

$\bar{N}$ = average number of meteoroids with mass equal to or greater than m, striking exposed area A during exposure time T.

Application of hypervelocity penetration theory results in the following expression for shielding thickness

$$t = f(AT)^{1/3\beta} ,$$

where

f = constant, depending on $\bar{N}$ and on the shielding material. For $\bar{N} = 0.010050$ (i.e., value corresponding to a 0.99 probability of zero penetrations) and for an aluminum shield we have

$$t = 10^{-2.005} (AT)^{1/3} .$$

This equation is given graphically in Fig. 10-10.

Experiments have shown that the shielding is most effective if used in multiple layers [10,11,12]. The outer layer ("bumper") breaks up the meteoroid and since the resulting smaller particles are scattered over a larger area the danger of penetration is reduced. The efficiency of the double wall is further increased if the wall space is filled. Fig. 10-11 allows the evaluation of the various wall systems shown.

Values of K (efficiency factor) are used to determine the total thickness of sheet required to replace a single plate.

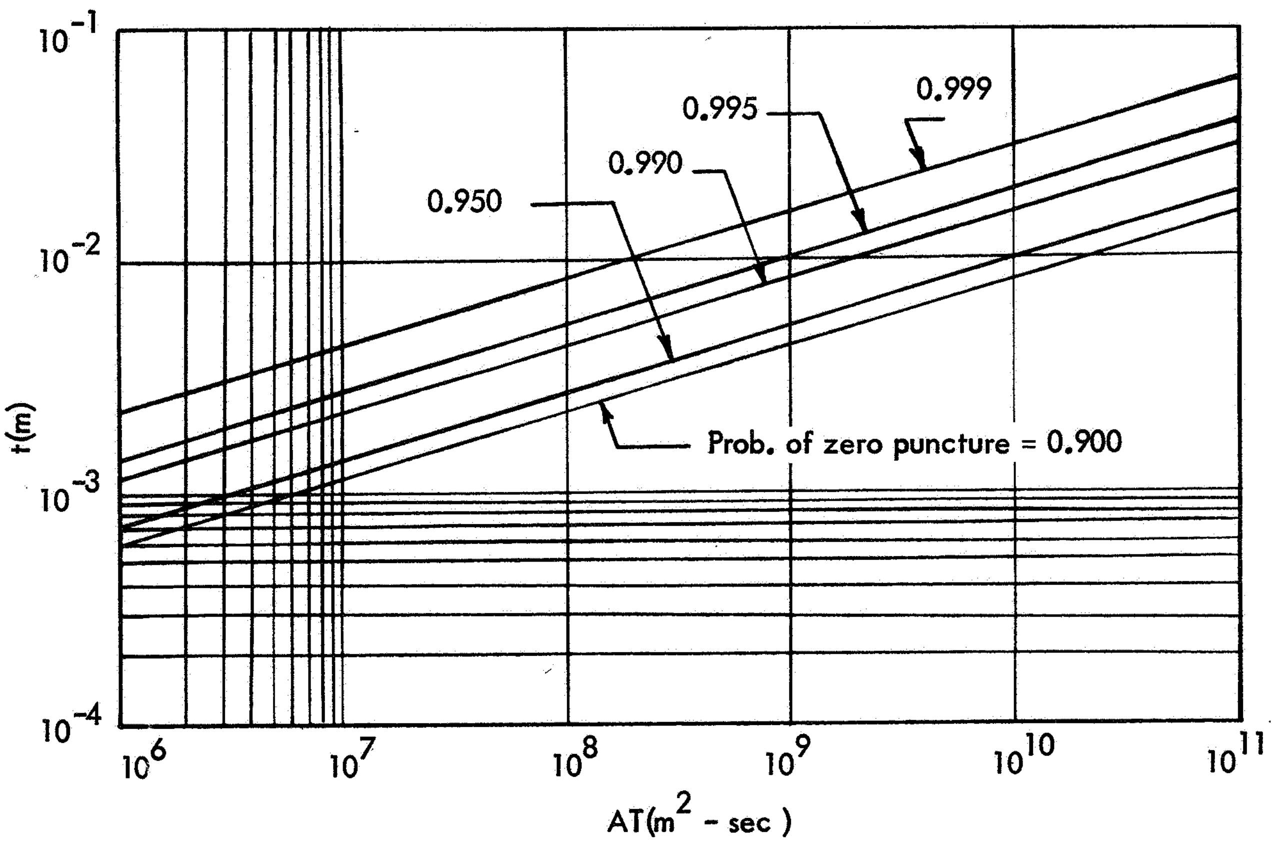
For two sheets we have

$$t_{TOTAL} = Kt_s$$

$$= t_1 + t_2 = 2t_f ,$$

where

t_f = face thickness ($t_1 = t_2 = t_f$) .



$$t = 10^{-2.005} (AT)^{1/3}$$

Fig. 10-10. Shielding Thickness Vs Exposure Time and Area.

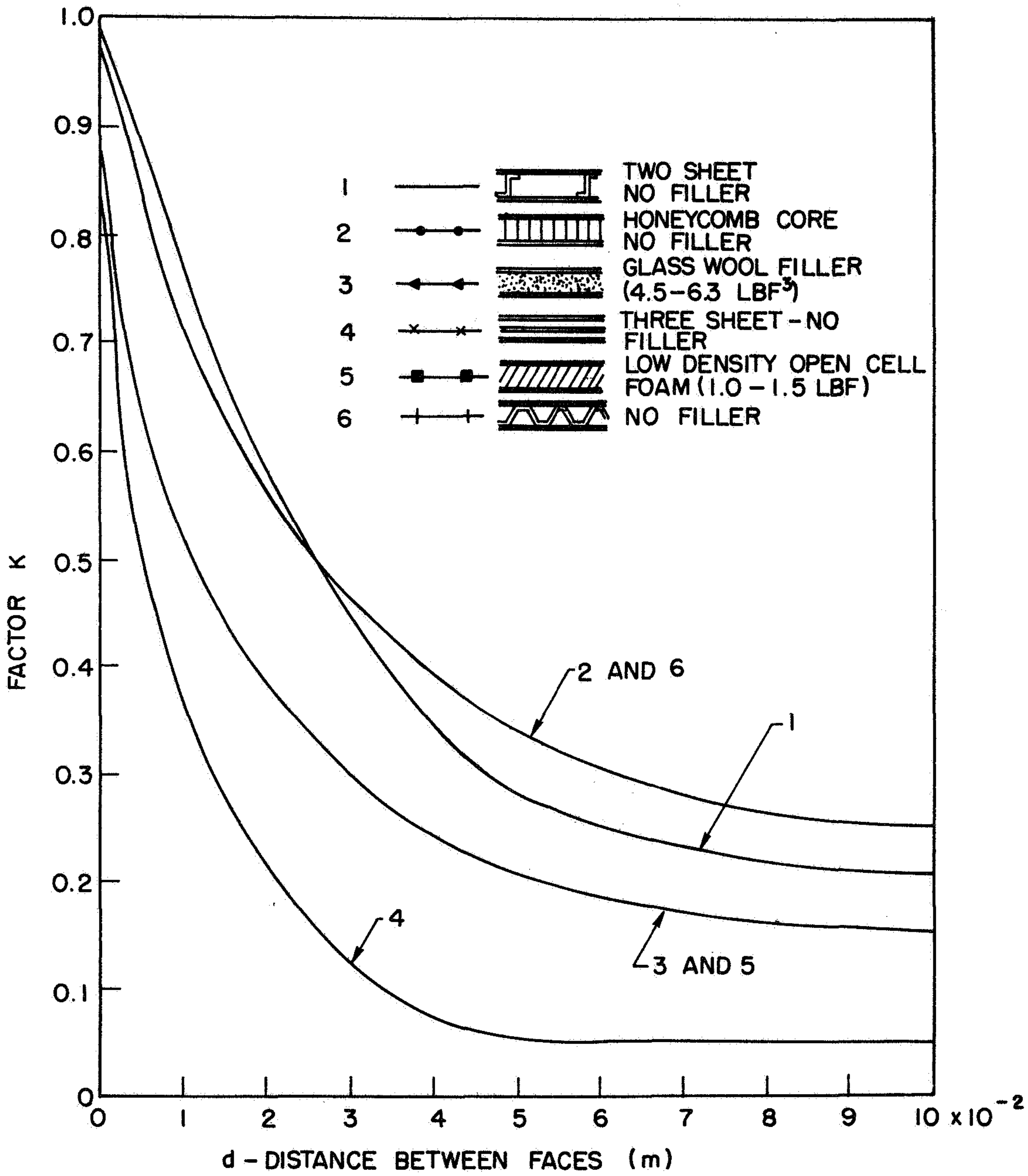


Fig. 10-11. Efficiency Factor K vs Plate Spacing for Various Configurations.

For three sheets we have

$$t_{TOTAL} = t_1 + t_2 + t_3 = 3t_f \ .$$

It is also possible to consider the equivalent thickness of a sandwich wall together with a single shield. Here we have

$$t_{TOTAL} = \bar{t} + t_s \ ,$$

where

$\bar{t}$ = equivalent thickness of sandwich wall.

Further, when a foam or glass wool filter is used with multiple sheet systems the improved efficiency factor may be calculated, e.g., for a triple wall system, we have

$$K_3F = K_3 \times \frac{K_2F}{K_2} \ ,$$

where

K_3F = factor for three walls with filler,

K_2F = factor for two walls with filler, and

K_2 = factor for two walls without filler.

10.3.3 Preliminary Selection of Shelter Wall

The minimum honeycomb wall to satisfy the axial buckling requirement has a core depth of 0.0254 m and a face thickness of 4.31×10^{-4} m of aluminum alloy.

The preliminary wall is shown in Fig. 10-12(a). The face thickness of 5.07×10^{-4} m is considered practical as a lower limit based on manufacturing and handling considerations. The wall thickness is taken arbitrarily as 0.0318 m (> 0.0254 m).

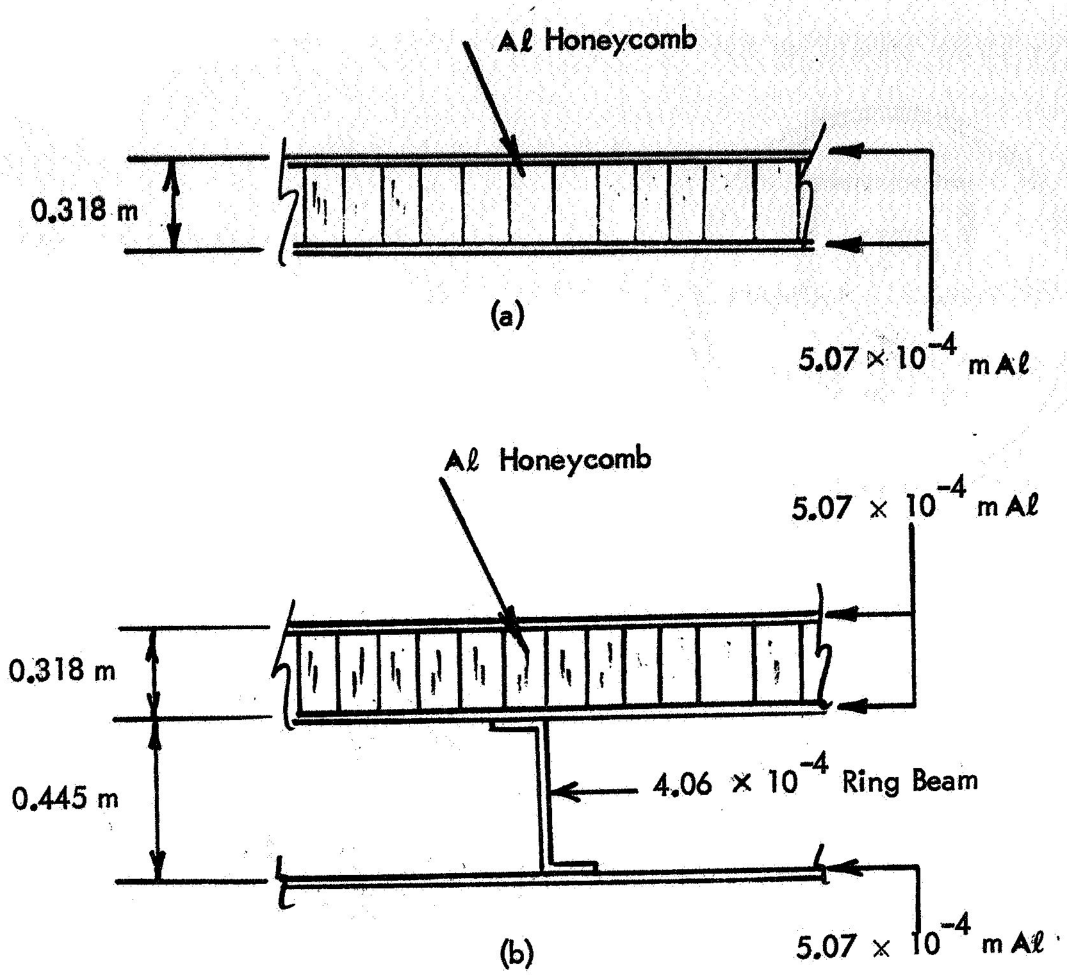


Fig. 10-12. Shelter Walls.

The effective thickness of the wall is given by

$$\bar{t}_{HC} = \frac{t_1 + t_2}{K} = \frac{2(5.07 \times 10^{-4})}{0.445} = 2.3 \times 10^{-3} \text{ m},$$

which is too small.

An improved wall is shown in Fig. 10-12(b) where we have

$$\bar{t} = \bar{t}_{HC} + t_{shield}$$

$$= \frac{2.3 \times 10^{-3} + 5.07 \times 10^{-4}}{0.305} = 9.0 \times 10^{-3} \text{ m}.$$

With filler between the sandwich wall and the single face the efficiency factor becomes 0.22 giving $\bar{t} = 12.2 \times 10^{-3}$ m.

10.3.4 Radiation

The extra-lunar sources of radiation are galactic radiation and solar flares. The former is small compared to the solar radiation and will, for the most part, be stopped by meteoroid shielding and structural detail required for strength. The special problems of solar flares will be solved by providing a "storm shelter." This shelter will be a shelter module itself with an extra cover provided for use of lunar soil. Approximately 1 m of compacted material is necessary for adequate protection.

There will be sufficient time after the onset of the solar flare to allow the astronauts to get to shelter and they will be required to remain under cover for a few hours at most.

Lunar Temperature Effect

The large temperature imbalance between light and shade, on the lunar surface will, of course, cause build up of stress in the shelter shell. The problem exists for any structure in space but our concern here is that the shelter continue to function as a safe pressure vessel.

The temperature problem is best solved by completely shielding the shelter. Figures 10-13 and 10-14 show two feasible solutions--in Fig. 10-13 a spent cargo shell (or shells) is split and spread to contain lunar soil. This outer shroud allows the compaction of the soil cover and minimizes the amount of soil required. In Fig. 10-14 the thermal shield is a flexible curtain draped from top hangers, deployed after setting the module in position. In both cases added protection against meteoroids is provided due to the extra bumper.

The problem of a solar flare shelter will also be solved if the soil cover in Fig. 10-13 is 1 m of compact material.

It is proposed that the first shelter module be established as shown in Fig. 10-13 and that future additions be as shown in Fig. 10-14.

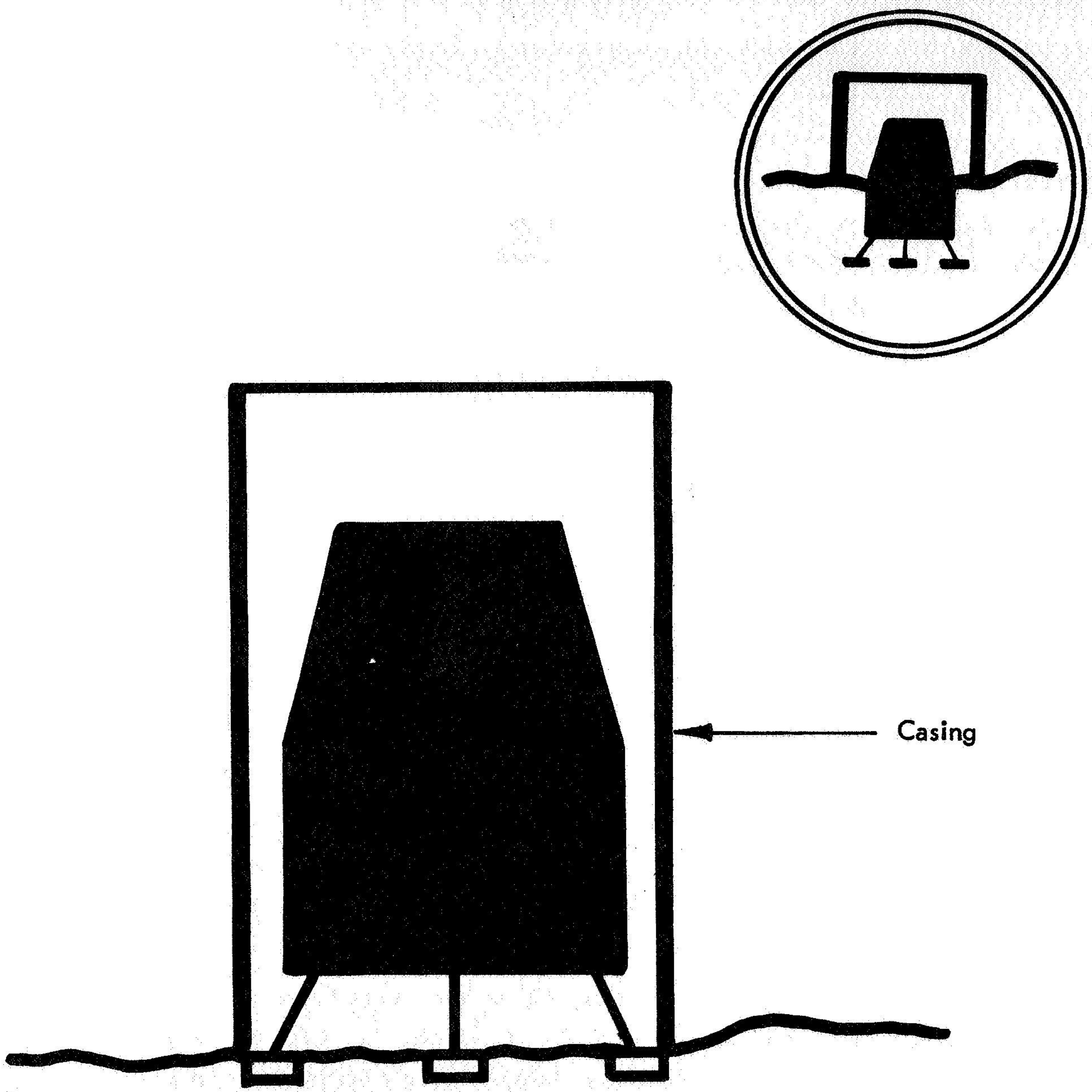


Fig. 10-13. Deployment of First Shelter.

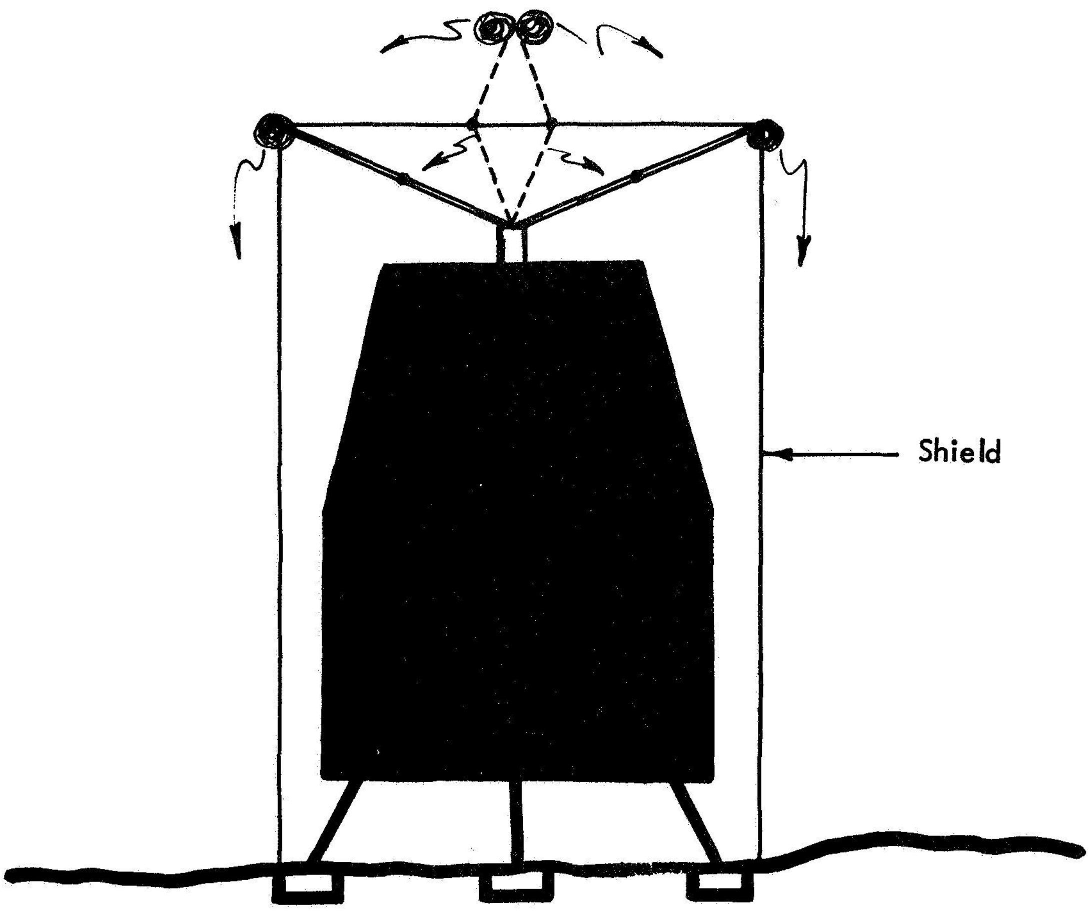


Fig. 10-14. Thermal Shield Deployment.

Of course, if lunar topsoil is available and if the filling and compacting operation is "easy" then all the future modules could be the same as the first.

The actual configuration of the flexible thermal shield shown in Fig. 10-15(b) has the advantage over Fig. 10-15(a) in that it allows future connection to the other modules and a possible saving of shield wall area.

A proposed description of the thermal shield weight is given in Table 10-1.

For the system(s) proposed the shelter wall shown in Fig. 10-12(b) will be adequate. This will satisfy loading requirements and

Table 10-1

THERMAL SHIELD

	kg/m^2
Thermal control surface	0.220
Laminated fabric	0.074
P.V.C. foam lining	0.205
TOTAL	0.499
Shield wt/shelter = 225 kg	

resist the meteoroid hazard until the module is operational. An estimate of the total shelter weight is given in Table 10-2. The structure weight estimate includes all structural elements.

Table 10-2

LAUNCHED SHELTER MASS (FIRST MODULE)

	kg
Non-Expendables:	
Structure	7,250
Ec/Life support	396
Power	6,000
Communications	500
Thermal shield	225
	15,370
Expendables:	
Atmosphere gas	814
Water	2,970
Food	393
	4,180
TOTAL (+10 percent)	20,000

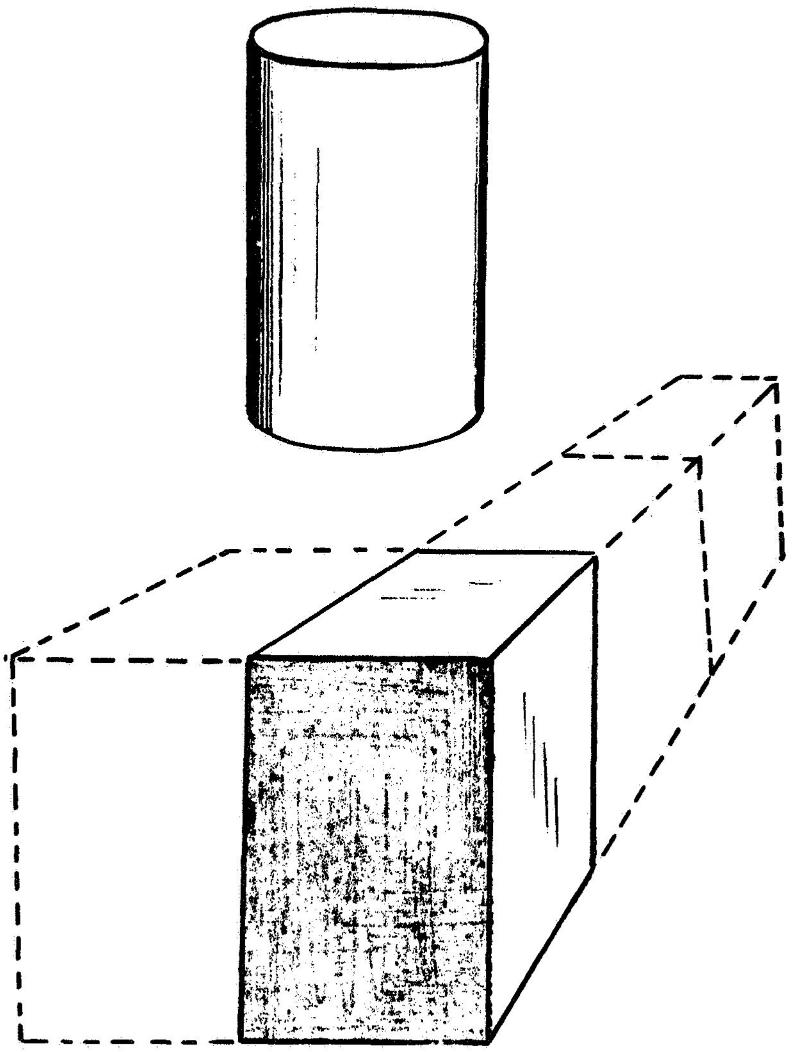


Fig. 10-15. Flexible Thermal Shield.

10.3.5 Foundations

Lack of definitive data regarding lunar soils prevents the design of a suitable foundation at this time. A preliminary solution is to use adjustable jacks under each module, each one resting on an attached pad. However, it is doubtful that this arrangement would allow sufficient adjustment to balance the differential settlement expected.

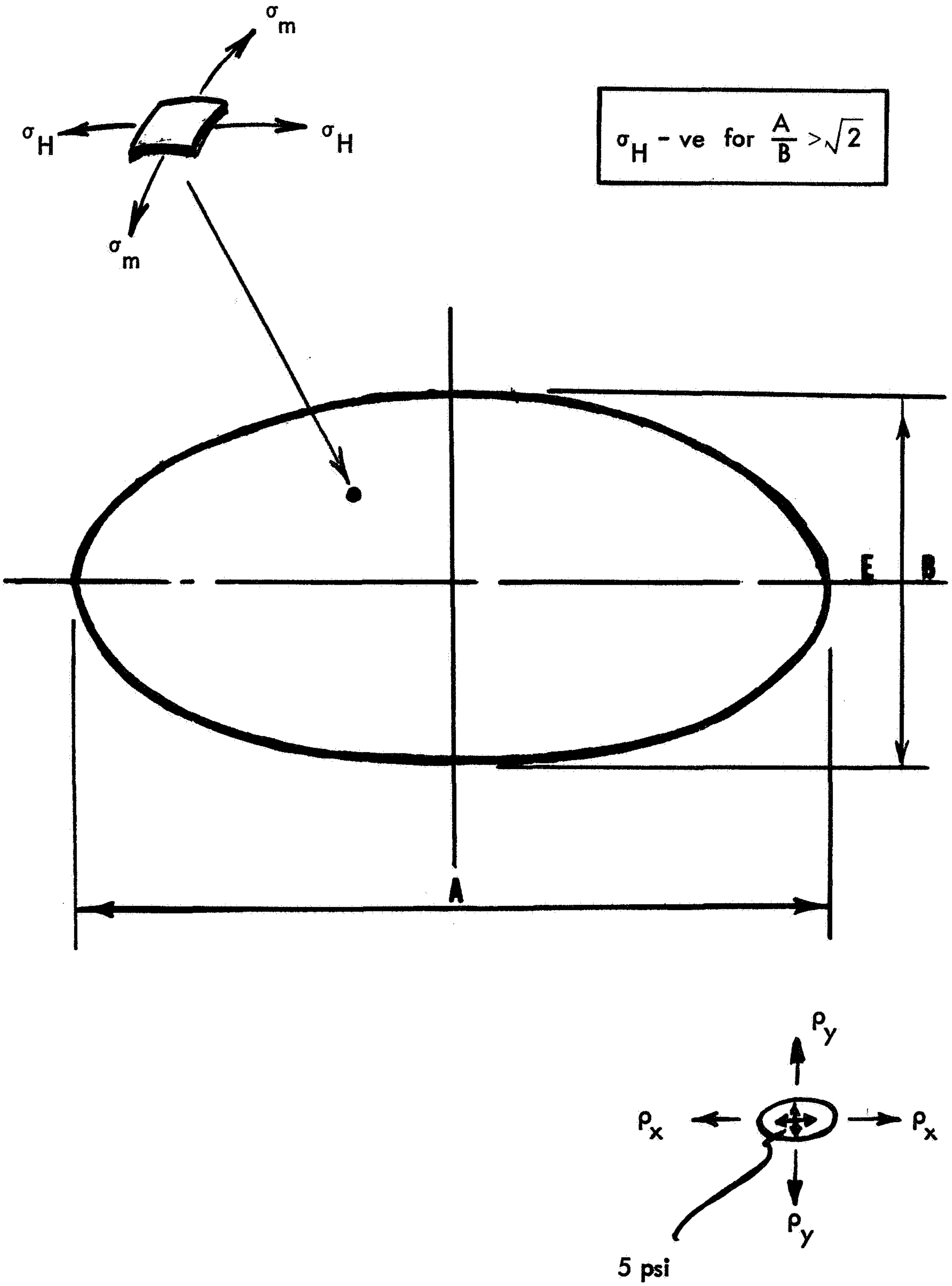
Other feasible solutions are to "float" the shelter modules on a large raft foundation (this could be a space truss system) or use piling down to lunar rock. Both these systems are considered unfeasible at this time.

The hope is that surface, or near-surface, rock will be available at the site in Grimaldi. Of course, this cannot be confirmed before arrival there in 1976 but information on the lunar surface will be gathered during the transition stage (pre-1976) and will allow the design of an acceptable alternate foundation system.

10.4 Farm Structure

The farm structure is special since beside satisfying the constraints given in Chapter 9, it must provide a large window area to allow the transmission of light and be sealed to hold the contained atmosphere and moisture change. Further, the configuration must be such that the soil base be easily placed, and that the crop be easily harvested.

Because of the size of the large farm units (18 m diameter) and considering the other constraints, it is proposed that the farm structure(s) be inflatable. With regard to the configuration and again considering the feasible basic shapes (Fig. 10-4) the logical candidates seem to be the sphere and the hemisphere; however, the former gives excessive headroom and drainage slope and the shell discontinuity of the latter still remains a problem. Since we require little more than 2 m headroom the solution shown in Fig. 10-16 is a suitable alternative. However, the oblate spheroid is not without its problems--for a ratio of $a/b > \sqrt{2}$ the hoop stress (σ_H) is negative at E and since this is so in our case we have to find some way of assisting force vector P_x in balancing P_y. The proposed solution is shown in Fig. 10-17. The toroidal ring beams will be inflated by filling with a self-rigidizing foam to balance the hoop stress in the membrane. The upper shell will be fabricated of a transparent plastic which satisfies the window specifications. The toroidal beams and the base will be made of an opaque material. This will be of greater strength than the window--in the former case to satisfy the greater pressure required in the beams and in the latter to resist wear and tear from the farming operation. The method of erecting and loading the farm shells is illustrated in Fig. 10-18.



σ_H - ve for $\frac{A}{B} > \sqrt{2}$

Fig. 10-16. Ellipsoid.

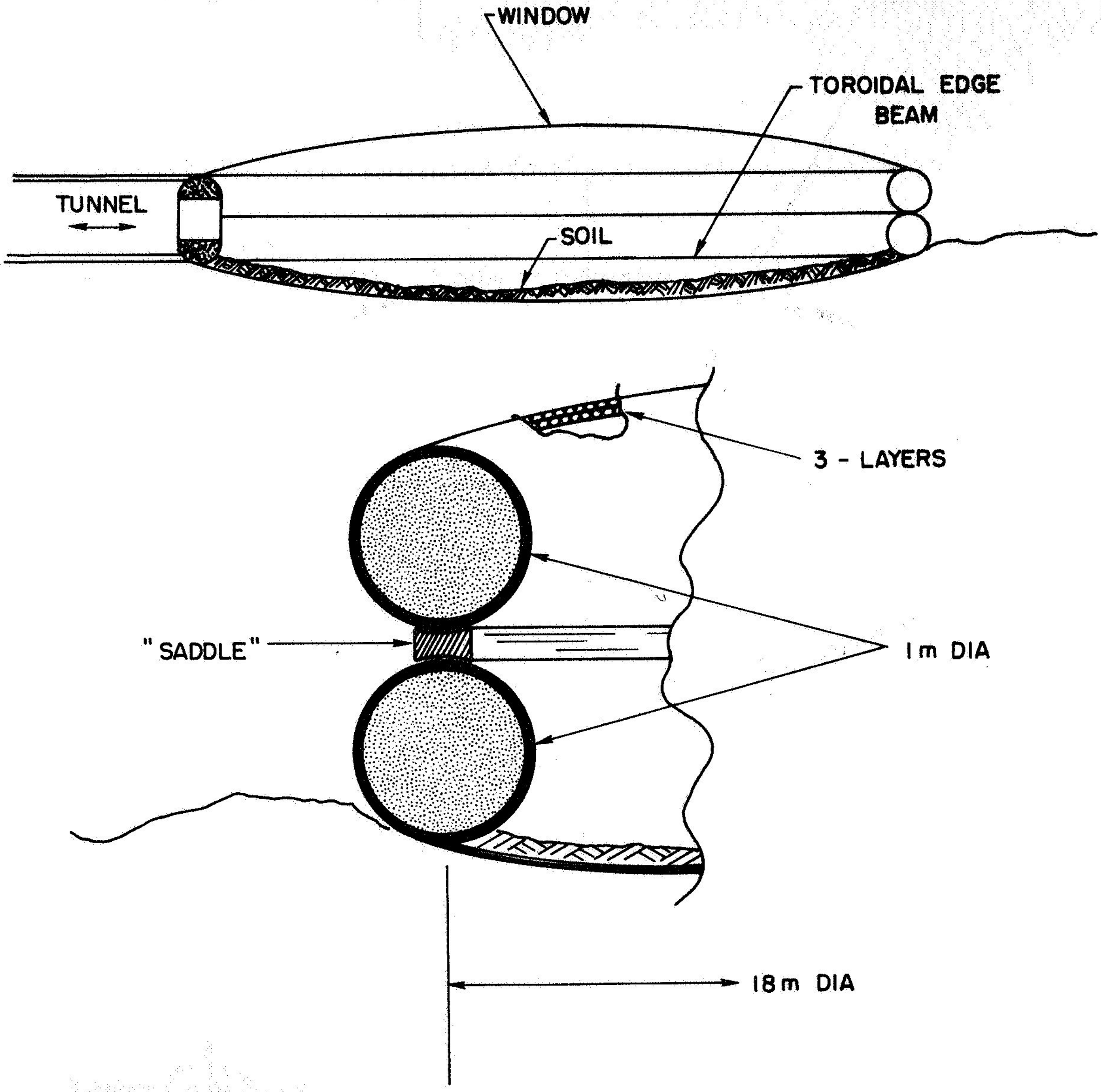


Fig. 10-17. Farm Structure.

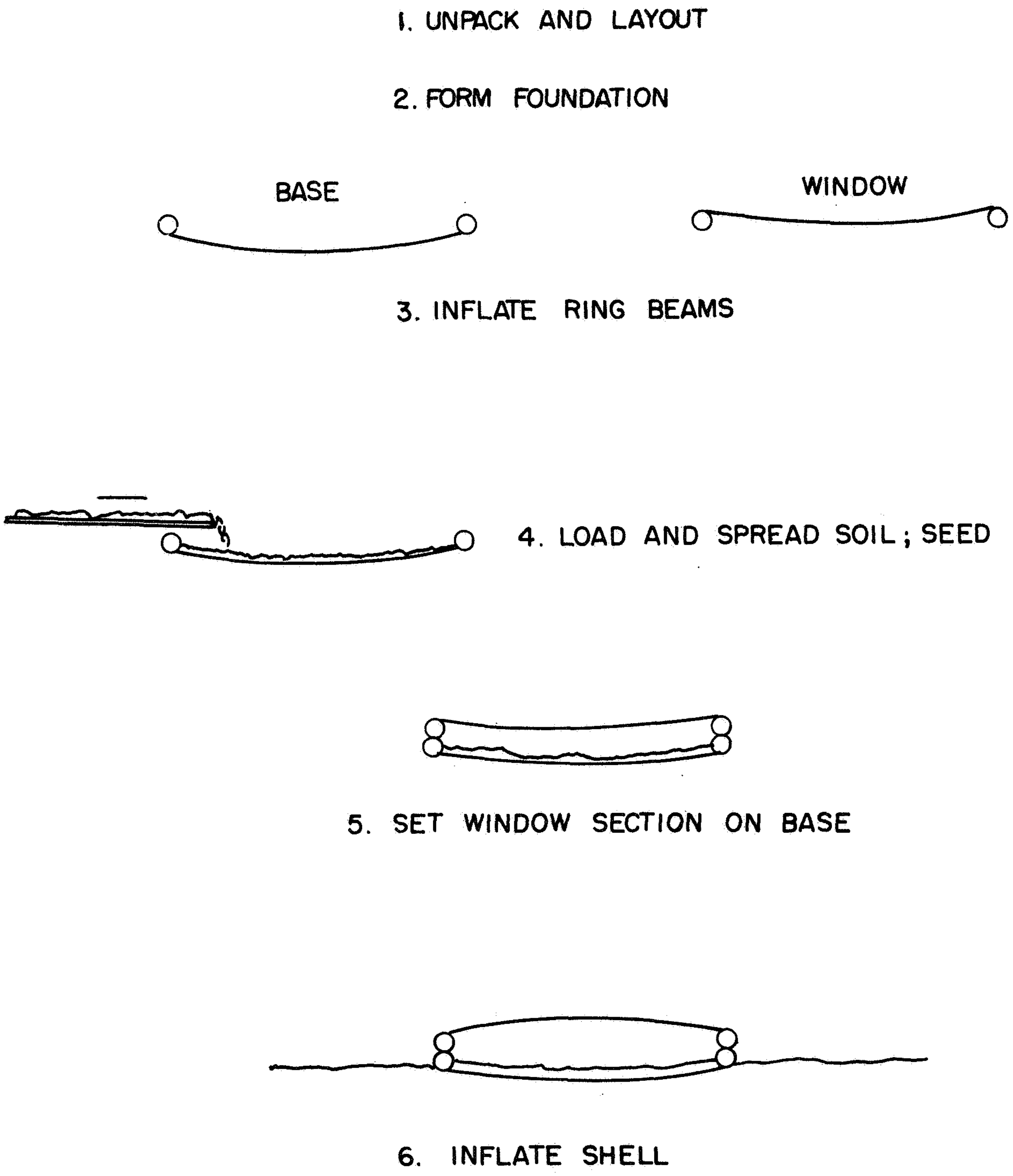


Fig. 10-18. Farm Structure Erection Sequence.

10.4.1 Farm Structure Materials

The largest window, 18 m, has to have at least 1 mm total thickness, if 5 psi atmosphere is used, and the window has a strength of 20,000 psi. To avoid light-limited growth, the windows must be 25 percent transparent to the 2500-6500 Å band. They must be almost totally opaque to ultraviolet and preferably reflective for infrared. Such a window is slightly beyond the state of the art at present. However, some work has been conducted on windows for expandable airlocks [13]. Since existing flexible transparent plastics do not possess sufficient strength to resist required design loads the approach has been to embed axial filaments within the flexible material, forming a flexible biaxially high-strength composite. Glass, steel and polyester filaments have been used successfully. The windows have been tested as to their optical clarity. Results of the tests are shown in Table 10-3.

Table 10-3

HUMAN FACTORS WINDOW EVALUATION [13]

	Human factors optical test (pressurized 7 psi [46,300 N/m^2])			
Panel No.	Blurriness	Ability to focus	Readability	Smallest legible print size, in. (points)
1	3.0	3.5	3.5	0.30 (14)
2	3.7	4.0	3.8	0.156 (11)
3	3.2	3.0	3.6	0.156 (11)
4	2.0	2.0	2.0	0.0937 (6)
5	3.1	3.2	3.4	0.30 (14)
6	3.0	3.0	3.0	0.156 (11)
9	2.5	2.5	2.5	0.156 (11)
13	2.5	2.5	2.5	0.0937 (6)

It is considered that the higher strength properties required for the ring beams and the base skin will cause no problem. At the present time structural techniques are available to supply high strength fabrics. A comparison of various materials is shown in Table 10-4. The estimated weight for the farm structures is given in Table 10-5.

Table 10-4

COMPARISON OF STRUCTURAL TECHNIQUES [13]

Technique	Design factor	Ultimate stress (psi)	Design stress (psi)	E modulus (psi × 10^6)	Relative weight
Woven dacron fabric	5	100,000	20,000	*	1.0
Dacron filament wind	5	112,000	22,000	1.4	0.62
Dacron structural tape	5	112,000	22,000	1.4	0.62
Steel filament wind	3	300,000	100,000	30.0	0.75
Steel structural tape	3	300,000	100,000	30.0	0.75

---

*270,000 fill direction; 115,000 warp direction

Table 10-5

FARM STRUCTURES ESTIMATED WEIGHT

	18 m	18 m	10 m	6 m	TOTAL
Window Area	250 m^2	250 m^2	75 m^2	25 m^2	600 m^2
Enclosed Volume	800 m^3	800 m^3	450 m^3	50 m^3	2100 m^3
Window Mass	370 kg	370 kg	110 kg	37 kg	900 kg
Floor Mass	1000 kg	1000 kg	300 kg	n.a.	2300 kg
Beam Mass Number/	1400 kg	1400 kg	800 kg	n.a.	3600 kg
Total Structure	2800 kg	2800 kg	1200 kg	40 kg	6800 kg

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Chapter 11

POWER AND COMMUNICATIONS

11.1 Power

The power system selected for the proposed base will supply electrical energy directly from solar cells during the lunar day. During the lunar night electrical energy will be produced from fuel cells. Hydrogen and oxygen for fuel cells will be obtained from electrolysis of water during the lunar day with cryogenic storage. Electrical power for electrolysis will be supplied from solar cells.

The power requirements of the base proper will be satisfied by 50 kW (electrical) during the lunar day and by 40 kW during the lunar night. This does not include power for electrolysis of water to supply fuel for mobile vehicles or for return to Earth. Specific requirements are shown in Table 11-1.

This system is the least expensive of the five systems considered (see Appendix D). The system has other inherent advantages,

(1) It is highly modular and can be supplied in units of essentially any size desired,

(2) Redundancy is readily achieved by adding units or by accepting a lower availability of power in event of failure of part of the system,

(3) Expansion of the system for additional power or for electrolyzing water to provide fuel for mobile vehicles or Earth return is readily achieved,

(4) Buildup of the system on the Moon is simple since components can be packaged in nearly any size desired and can be carried on any launch,

(5) There is no problem of radiation, thus allowing convenient location of the system relative to shelters,

(6) A peak power of 225 kW is possible if all electrolysis is shut off.

Fuel cells for the power system will be available from the navigational packages on the landing vehicles. Each vehicle has two cells, each of 2 kW capacity. With 40 or more landing vehicles there will be more than enough fuel cell capacity, including replacement

Table 11-1

MOONLAB POWER REQUIREMENTS

System	Power (kW)
Lunar Day	
Atmosphere circulation	5
Lighting	10
Heat rejection (living-working space and farm)	6
Water pumping (farm)	1
Harvesting and food processing	1
Waste processing	1
Communications	3
Experiments	15
Miscellaneous and contingency	8
	50
Lunar Night*	
Emergency life support	25
Lighting	4
Heating	10
Communications	1
	40

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*Requirements determined by emergency conditions in the event of loss of the farm.

as necessary. Also there will be ample cryogenic tankage which can be salvaged from landing vehicles. Fuel cells, tanks, and vehicles should be designed with this future use in mind.

Development cost of the electrolytic and liquifier system is estimated at 100 million dollars. Development cost of the solar cell array is 10 million dollars.

Hardware cost for producing electricity directly from the solar cell array (lunar day power) will be 0.57 millions of dollars per kW. The specific mass will be 82 kg/kW. For each kilowatt of electricity 32.4 m^2 of solar cells will be required. Hardware cost for producing electricity from fuel cells (lunar night power), including solar cells, electrolytic units, and liquefiers, will be 3.16 million dollars per kW. The specific mass will be 435 kg/kW. For each kilowatt of night-time electricity 142 m^2 of solar cell will be required. These figures for a kilowatt of electrical power during the lunar night apply to electrolyzing 150 kg H_2O per lunar cycle of 2000 kg H_2O/year. The products of electrolysis (H_2 and O_2) may also be needed for fueling mobile vehicles or for Earth return.

Table 11-2 shows pertinent quantities for the proposed lunar base (50 kW lunar day, 40 kW lunar night).

Table 11-2

MOONLAB POWER SYSTEM

Development cost	$110 million
Hardware cost	$115 million
System mass	21,500 kg
Deployment time	200 man-hr
Annual replacement rate	20 percent

The cost of electrolyzing 2000 kg of water per year will be 3.16 M$ and require a mass of 435 kg.

A schematic of a possible configuration for the solar cells is shown in Fig. 11-1.

11.2 Communications

11.2.1 Introduction

Because of the diversity of the operations on the Moon the communication system must also be diverse. It should be adaptable to special needs of the investigators as these needs develop. There must be redundancy and commonality between much of the equipment, so that it will be reliable and easy to maintain.

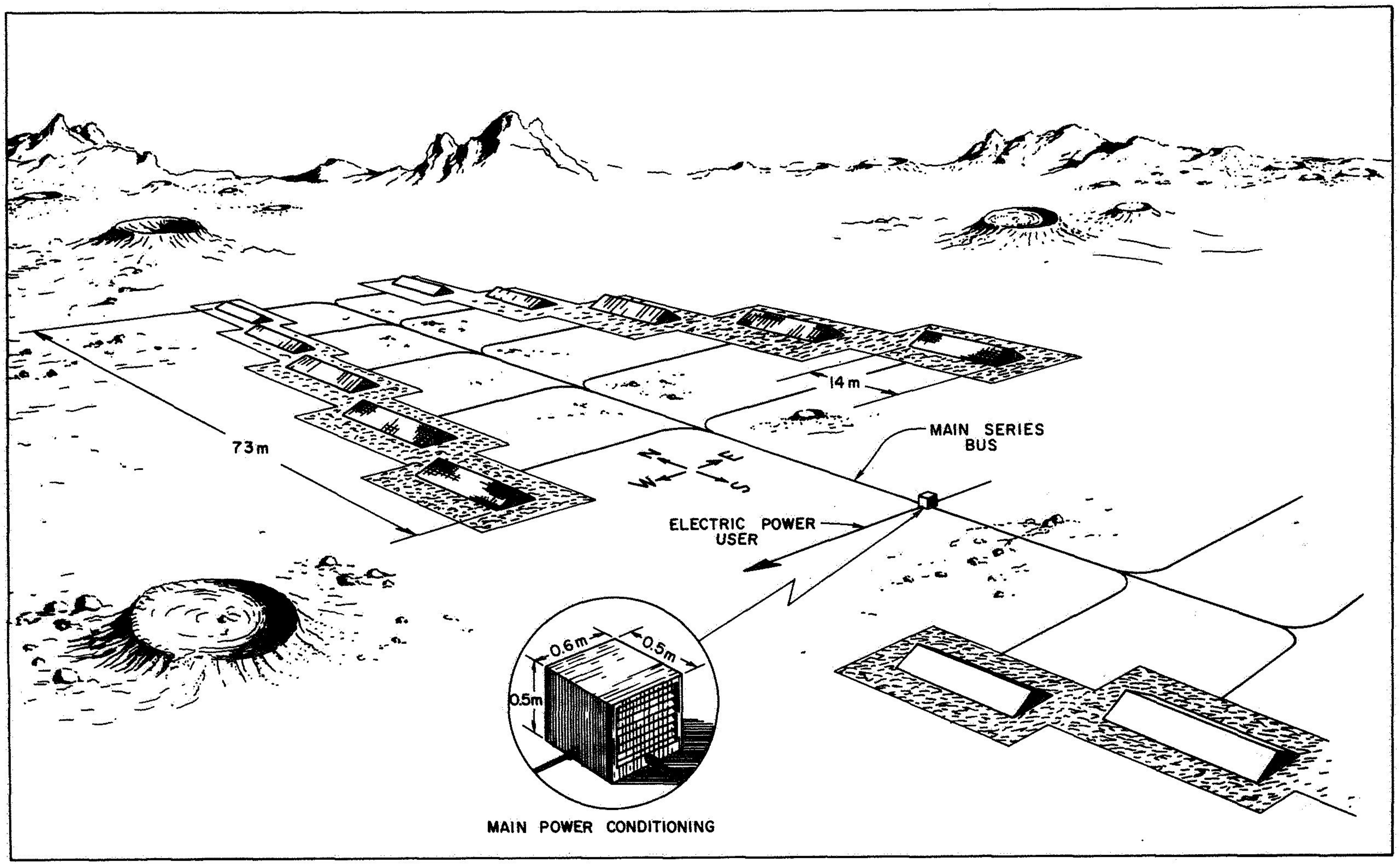

Fig. 11-1. General Arrangement of Lunar Surface Power System.

A new network of three ground stations, spaced approximately equally around the Earth, will be needed to maintain continuous communications with Earth. Antennas will be approximately 18 m in diameter, which will give them about 1/2 deg beamwidth. The Moon subtends about a 1/2 deg solid angle from Earth and therefore this antenna can handle communications from all parts of the Moon simultaneously. This is desirable from an equipment and safety standpoint. The frequency of operation will be in the 2.2 GHz telemetry band. This frequency band has many good features, such as availability of equipment and low cosmic noise.

On the Moon there will be direct communications from the main base to Earth, communications between the personnel on the Moon, and direct communications from a remote site to the Earth. The first link of communications from a moving vehicle or man outside the main base will have a carrier frequency of about 40 MHz. All other links will operate near 2.2 GHz. Figure 11-2 shows the various links included on the lunar surface.

Calculations giving the justification for antenna sizes and system powers are given in Appendix E. All of the equipment used in the communications system can be developed and delivered in three years from the letting of contracts. Table 11-3 summarizes equipment requirements for the communications system.

11.2.2 Ground Station Network

The Earth-based portion of the system will consist of three stations equally spaced around the Earth. The antennas will be 18 m in diameter with automatic tracking of the Moon. The operation of all the uplinks and downlinks between the Moon and Earth will be at a frequency near 2.2 GHz.

There will be one primary station and two secondary stations. The primary station will be located somewhere in the United States and will have TV links to laboratories around the United States. The secondary stations will be outside the United States, and because of the ground communication limitations will not have a real time video link

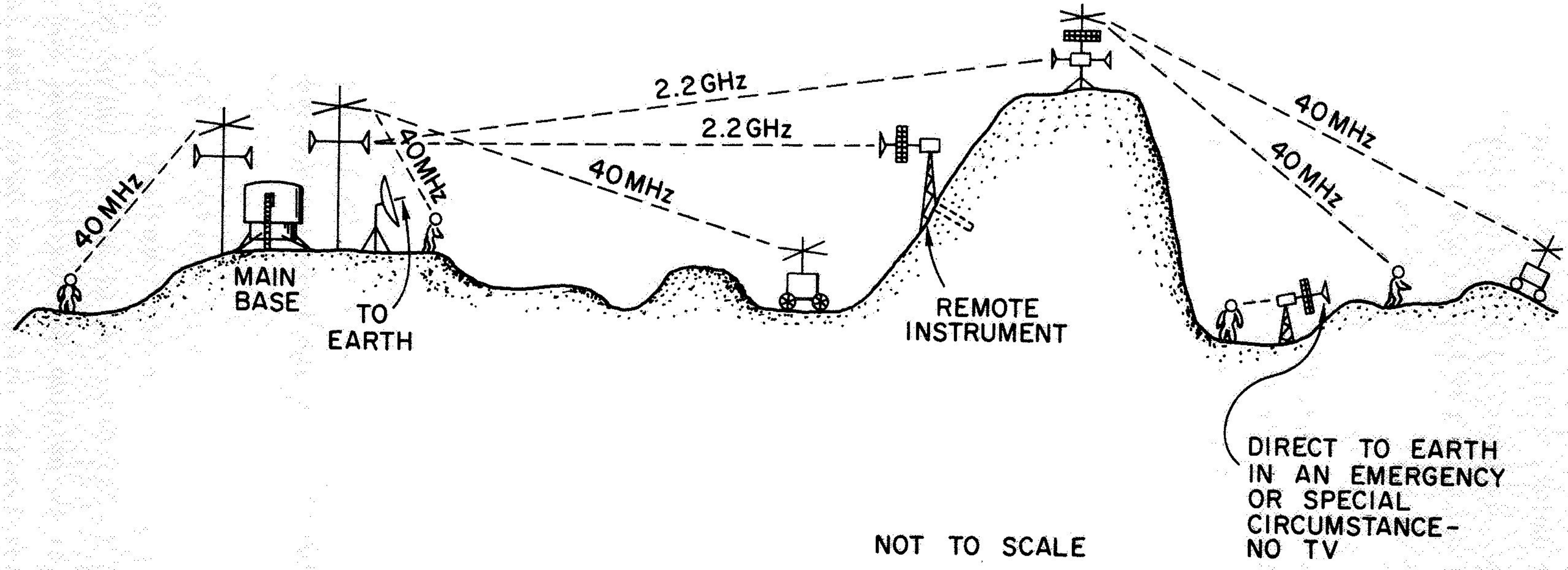

Fig. 11-2. Modes of Communications on the Lunar Surface.

Table 11-3

WEIGHT AND COSTS OF THE COMMUNICATION SYSTEM

Item	Number Required	Mass kg	Total mass kg	Development and delivery Costs	Maintenance cost, dollars per year
Earth Equipment					
Antennas	3	NA	NA	\$10 M*	1 M
Electronics	NA	NA	NA	20 M	2 M
Communications	NA	NA	NA	4 M	3 M
Lunar Equipment					
3 meter antenna	3	15	45	\$400 K**	0
40 MHz base antenna	2	50	100	60 K	0
2.2 GHz base antenna	2	2.5	5	15 K	0
TV terminal	4	12	48	400 K	40 K
Picture terminal	1	20	20	150 K	10 K
Control computer	1	20	20	800 K	40 K
Photo developing	1	15	15	100 K	10 K
Tape recorder	2	10	20	200 K	20 K
Relay stations	20	12	240	400 K	20 K
Miscellaneous cables, etc.	NA	NA	200	100 K	100 K
Portable TV cameras	5	2	10	50 K	10 K
High-speed printer	2	10	20	100 K	20 K
Computer terminal	1	20	20	100 K	20 K
Intercomm	-	-	20	50 K	10 K
Total			773	36,575 K	62,420 K

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*M - Million dollars

**K - Thousand dollars

with the United States. These stations will be able to have real time voice and telemetry with the United States laboratories and also be able to transmit and receive TV with video recording facilities. For special situations a satellite TV link will connect the non-United States ground station with the United States.

The new stations will be located near the present DSN (Deep Space Network) stations so that they can augment the new facility in case of an emergency.

The cost of the ground stations is shown below. The construction of the ground stations must be started as soon as the lunar base program is funded, because no matter how many men are on the Moon they will need continuous communication to the Earth for safety reasons.

	Initial Cost (millions)	Maintenance Cost (millions of dollars per year)
Antennas	$ 10	$ 1
Ground electronics	20	2
Interstation communication network	4	3
TOTAL	$ 34	$ 6

The ground stations will require no new breakthroughs to establish the initial communications link. Some new breakthrough might occur, but it seems unlikely at this time. Lasers cannot be used because the weather conditions on Earth would cause the system to be inoperable at times.

11.2.3 Main Lunar Base

Three 3-m antennas will be needed for communications to Earth. These antennas will automatically track Earth. Automatic tracking will be necessary because the librations of the Moon are about 18 deg in one direction and 16 deg in the other. The beamwidth of a 3-m antenna at 2.2 GHz is 3 deg. A clock mechanism will be adequate to point the antennas so the system need not be very complicated.

To communicate with men and instruments on the lunar surface outside of the main base two different systems will be used. When the communication distance is less than 10 km a 40 MHz system will be used. This frequency of operation is chosen because it results in a compromise between the physical size of the antenna required and the problems of reflections from lunar rocks, etc. For an object to have significant reflection or shielding effect, it has to be at least a wavelength in linear dimensions. At 48 MHz one wavelength is 7.5 m, but at 2.2 GHz a wavelength is 13.6 cm. So from an interference standpoint 40 MHz is better than 2.2 GHz. Going lower in frequency presents problems because of the antenna size. An antenna, in order to radiate, needs to be at least 1/10 of a wavelength long, or 0.75 m at 40 MHz. For communications within 10 km of the main base an omnidirectional antenna mounted on a 30 m pole will be used. This antenna must receive vertically and horizontally polarized waves to minimize communications loss when the men move around.

If communication is required beyond line-of-sight or behind an obstacle, a relay station must be used. The frequency for the relay stations will be near 2.2 GHz and therefore an omnidirectional, in azimuth, antenna will be installed on top of the 30 m pole. The vertical directivity of the antenna will be approximately 20 deg. The antennas to communicate with Earth will not be mounted on this 30 m pole.

A summary of the antenna requirements associated with the main lunar base is given in Table 11-4.

Below is a list of the major pieces of equipment to be located inside the main base:

(1) Four, 2-way television terminals (48 kg),
(2) Two high-speed printers for transmitting written material (20 kg),
(3) One high-resolution, high-linearity picture transmission system (20 kg),
(4) Data processing and control computer (20 kg),
(5) Photographic developing capability (15 kg),
(6) Two tape recorders (15 kg),
(7) One computer terminal (20 kg).

Table 11-4

ANTENNAS ASSOCIATED WITH THE MAIN LUNAR BASE [1]

Antenna	Use	Number Required	Pointing	Total* Weight, kg	Cost, Dollars
3 m diameter parabolic with tripod	Communication with Earth	3	Clock mechanism	45	100 K
40 MHz Omni with 30 m pole	Communication with lunar surface	2	Not required	100	60 K
2.2 GHz Omni to be mounted on 30 m pole	Communication with relay stations and instruments on the lunar surface	2	Not required	5	15 K

---

*Includes the last power amplifier of the transmitter feeding the antenna and the first stages of the receiver using the antenna.

The Moon-to-Earth TV channels will have a resolution equivalent to a United States commercial television, but a frame rate of only 1/sec. This will require 220 kHz modulation bandwidth of the Moon-to-Earth transmitters. The Earth-to-Moon link is not power-limited and will have both the standard commercial television frame rate and resolution under normal operation. This normal operation can be used for consultation with a person or group on Earth for entertainment, or for transmitting visual information such as graphs, pictures, etc. The Earth-to-Moon link will have the option of color or black and white.

The high-speed printers are required for sending printed material to the main base for use by the men. This material will consist mainly of books and papers from journals. This facility will also be used for recreational reading.

The data processing computer will be used to control all communications on the lunar surface. It will be programmed to do some simple real time data processing. Most of the data analysis or processing will be done on Earth. Figure 11-3 gives a drawing of the communications control console which has the computer control board in the center. A patch board is used to control the communications computer so an operator can see the total programming of the communication system. The patch board, therefore, has two functions,

(1) Readout of the status of the communications system,

(2) A simple and reliable method for modifying the communications system.

It is more efficient to transmit most data to the Earth for data processing since more and different computers can be brought into use if the processing is done on Earth. The lunar computer output terminal can be connected to any available computer on Earth and can be updated as new computing hardware becomes available during the evolution of MOONLAB. This is more efficient than continuously sending new equipment to the Moon.

The photographic developing capability is for the use of the astronomers and others who need high resolution, and high linearity

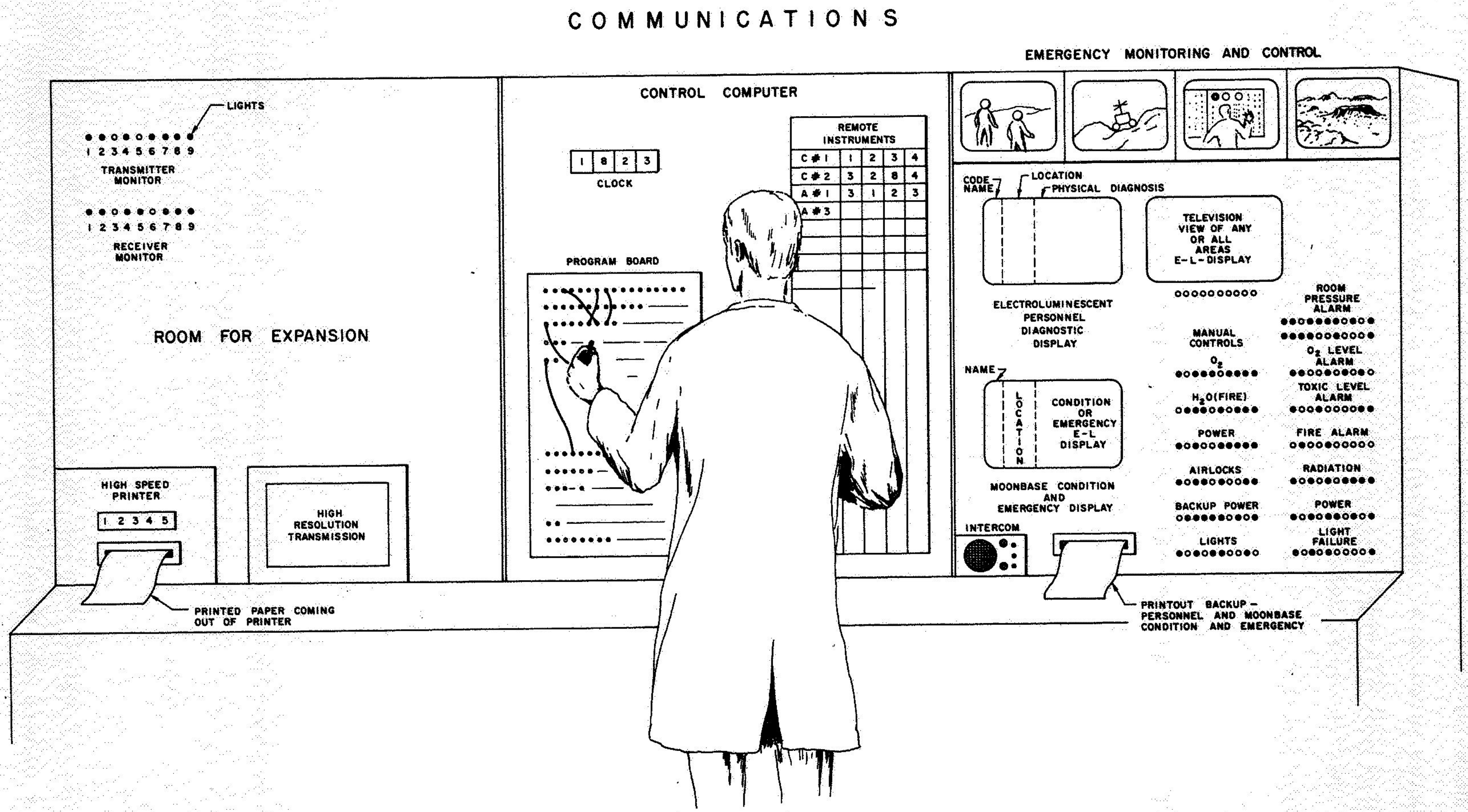

Fig. 11-3. Communications Control Console. Note there is a remote high-speed printer, high-resolution transmission system, and four TV terminals.

pictures. TV is not capable of giving high linearity because of the electron beam optics in the camera and picture tubes. Therefore a mechanical scanner must be used to obtain linearities in the order of one part in 10^6 as required by the astronomers. When in use, this facility will require the use of a 220 kHz channel and will take 10 to 15 min to transmit one picture. The high-resolution system will be used for transmitting pictures taken by the astronomical telescopes and any other case where high resolution and linearity are needed.

A block diagram of the equipment in the main base is given in Fig. 11-4.

11.2.4 Communications with Extra-Base Activity

Men operating in an extra-base activity mode will need maximum voice communication. A group of two or more men working as a team, say on a geological traverse, must be able to talk freely with one another and to people in the main base.

This type of communications can best be accomplished by using SSSC (single sideband suppressed carrier) transmitters and receivers. The transmitters should be VOX controlled (voice-controlled). This does not allow talking and listening at the same time, but with a little experience with VOX this should be no problem.

The basic carrier frequency will be near 40 MHz. Transmitter power at both ends will need to be at least 0.1 W. There will be six possible channels that a group can use. Before a group begins extra-base activity they will be given one of the six channels to operate on, and all members in the group will set the communication system in their space suits to operate on this channel. Once they are all set on the same channel, they will be able to talk together as a group directly from space suit to space suit.

If a group wants to talk to another group on another channel, a link will be established through the main base to the other group. Each space suit will have on it a call button which when pushed will call an operator. This operator will be able to establish links to

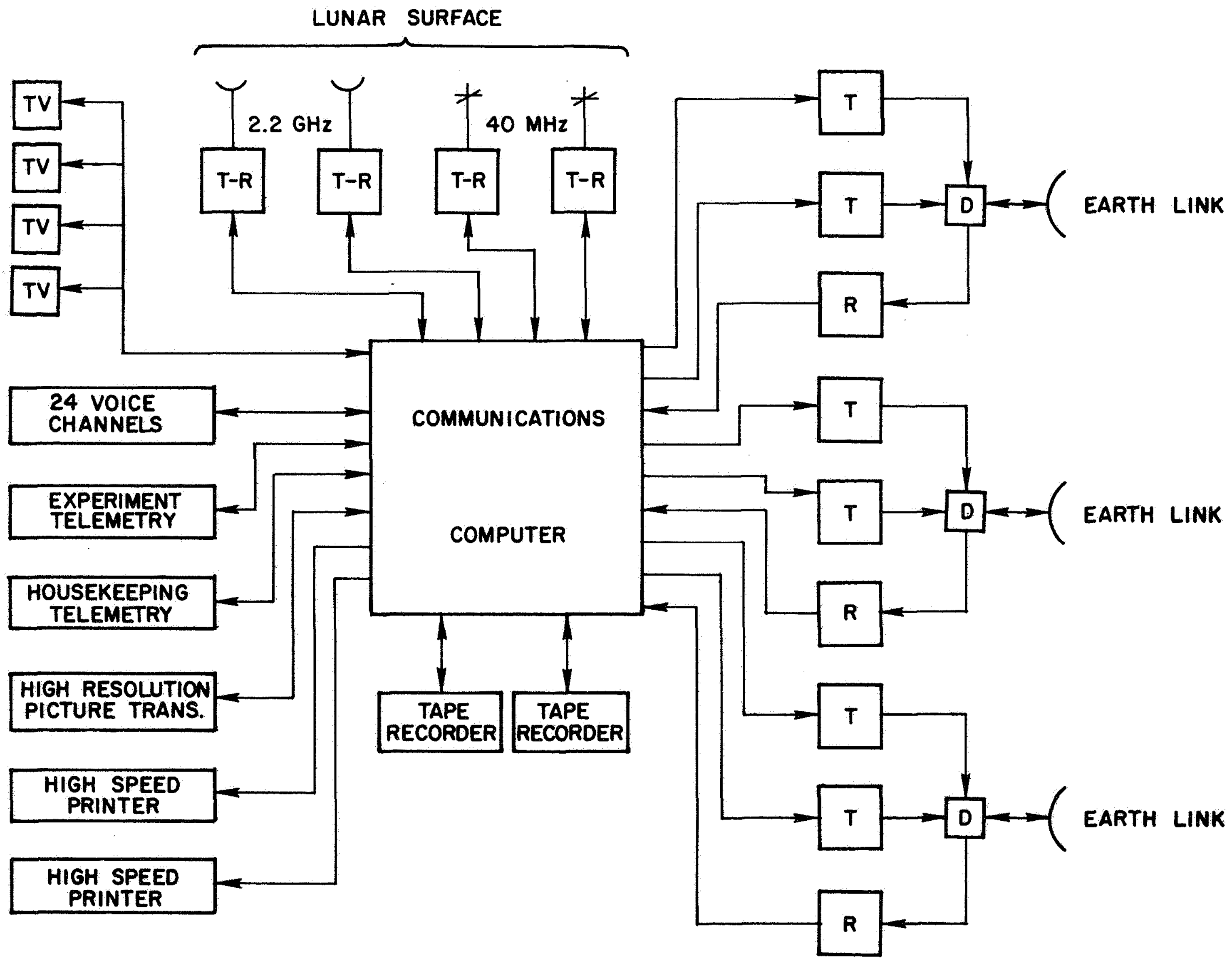

Fig. 11-4. Communications Computer Schematic.

other groups, to men in the main base, or to men on the Earth. It is important to have an operator standing by at all times in case of an emergency and to facilitate extra-base activities.

Direct communication from a space suit or a moving vehicle to the Earth will not be possible. The antenna on the space suit or moving vehicle must be omnidirectional so that motion is not restricted. With this type antenna, and under optimum conditions (i.e., using a 54-m antenna on Earth), it would take about a 100-W transmitter to establish a voice link with Earth, which makes it impractical because of weight.

If the group goes beyond the range of the 40-MHz system a repeater will be required. The same basic operating characteristics of the system will remain when using a repeater. A schematic of a relay station is shown in Fig. 11-5. Such a station can be set up in less than 10 min. The relay stations will have a solar cell-battery combination for primary power so that once a relay is set up it will operate continuously without further attention. The total weight of one relay station will be approximately 12 kg.

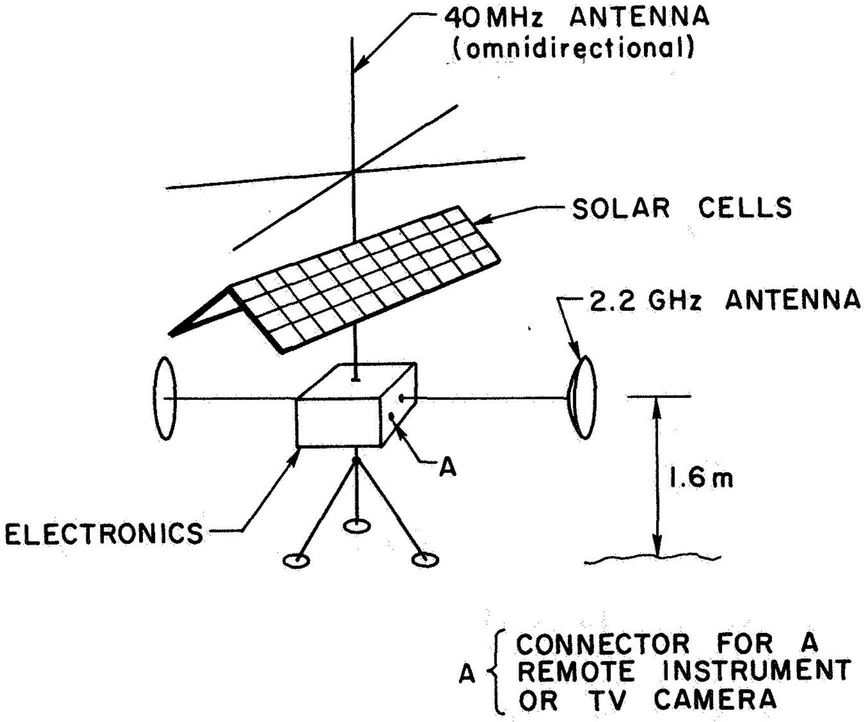

Fig. 11-5. A Relay Station for Use on the Lunar Surface.

11.2.5 Instrument Communications

The relay stations will also have inputs for the outputs of remote instruments or TV cameras. The instruments will be designed to receive a code from the communications control computer and then transmit back the reading of the instrument. In this way the sample period of an instrument can be changed without leaving the main base and a scientist in the main base can read any of his remote instruments at any time.

During normal operation the data from all the instruments will be recorded for a 24-hour period and then transferred into a main storage on Earth. This data will be stored in a central data storage on Earth and therefore no permanent storage will be required for recorded data on the Moon. Any part of this data stored in the central data storage on the Earth can be called back to the lunar base as it is needed. Users on the Earth can use the data as it is needed. Another important advantage of data storage on Earth is that if something happens to the lunar base the data will not be lost. From a weight standpoint it is better to send up facilities for short-term data storage and a transmitter than to try to store it on the Moon.

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Chapter 12

MOBILITY

12.1 Off-Loading and Deployment

The equipment for a lunar base can be separated into large components which represent either a complete payload for a launch or a major part of a payload, and other equipment which must be limited in size and weight so that it can be handled by the off-loading and deployment equipment. Table 12-1 summarizes these equipment requirements.

Table 12-1

EQUIPMENT FOR OFF-LOADING AND DEPLOYMENT

Equipment	Mass (kg)	Development Time	Development Cost in millions of dollars	Cargo Space
Wheels, axle and hitch for hauling complete Lunar Landing Vehicle	150	3 months	.10	6.6 m diameter 1 m high
Monorail	2,400	1 year	.25	Cone 6.6 m diameter 6 m high
Specialized Construction Equipment	2,700	2 years	250	6.6 m diameter 4 m high
Ginpole and winches	800	3 months	.1	6.6 m diameter ½ m high
Multipurpose Trailer	2,500	2 years	50	6.6 m diameter 2.8 m high
Material handling vehicle	1,500	2 years	50	6.6 m diameter 3 m high

12.1.1 Surface Movement of Landed Vehicles

It will be advantageous to land each Lunar Landing Vehicle (LLV) as precisely as possible with safety limits, and as close as possible to other LLVs. Studies [1] indicate that, with an adequate beacon system, it will be possible to soft-land an unmanned LLV with a 3σ-deviation of 90 m. The LLV will then be brought to the desired location by the moving concept shown in Fig. 12-1. This concept was originally suggested in Ref. [1].

Jacks will be used to raise both the payload and the LLV as a unit. If there is considerable tilt, one jack will be inserted first to plumb the centerline, the other two jacks will then be employed for level raising. Brackets with bearings are attached to the LLV and connected by an axle. Two large wheels with their own drive motors will be placed on the axle. A goose-neck bracket is attached to support part of the load on a Lunar Roving Vehicle (LRV). This will increase its tractive effort and drawbar pull. The speed of hauling will depend on the smoothness of the terrain (see graph in Fig. 12-1), but will not be of any serious consequence because distances are relatively small.

If it is desired to haul a complete load package to a distant site, it may become advantageous to prepare the path. At the desired location the carrier will be again jacked up and the wheels removed then lowered onto the landing gear of the LLV.

12.1.2 Off-Loading

In many instances the structural component of the LLV may become the support structure for the payload. However, if it is desirable to lower the payload to the Moon surface, a monorail such as that shown in Fig. 12-2 can be used [1]. Initially the monorail will be a part of the payload and subsequent payloads will utilize this monorail. Each payload must include the necessary hook and lifting device.

In this concept the complete monorail is contained within the payload nose cone and is deployed after removal of the cone. One end of the turret and actuator assembly is connected to an end of the monorail section, and the other end of the monorail assembly is latched to

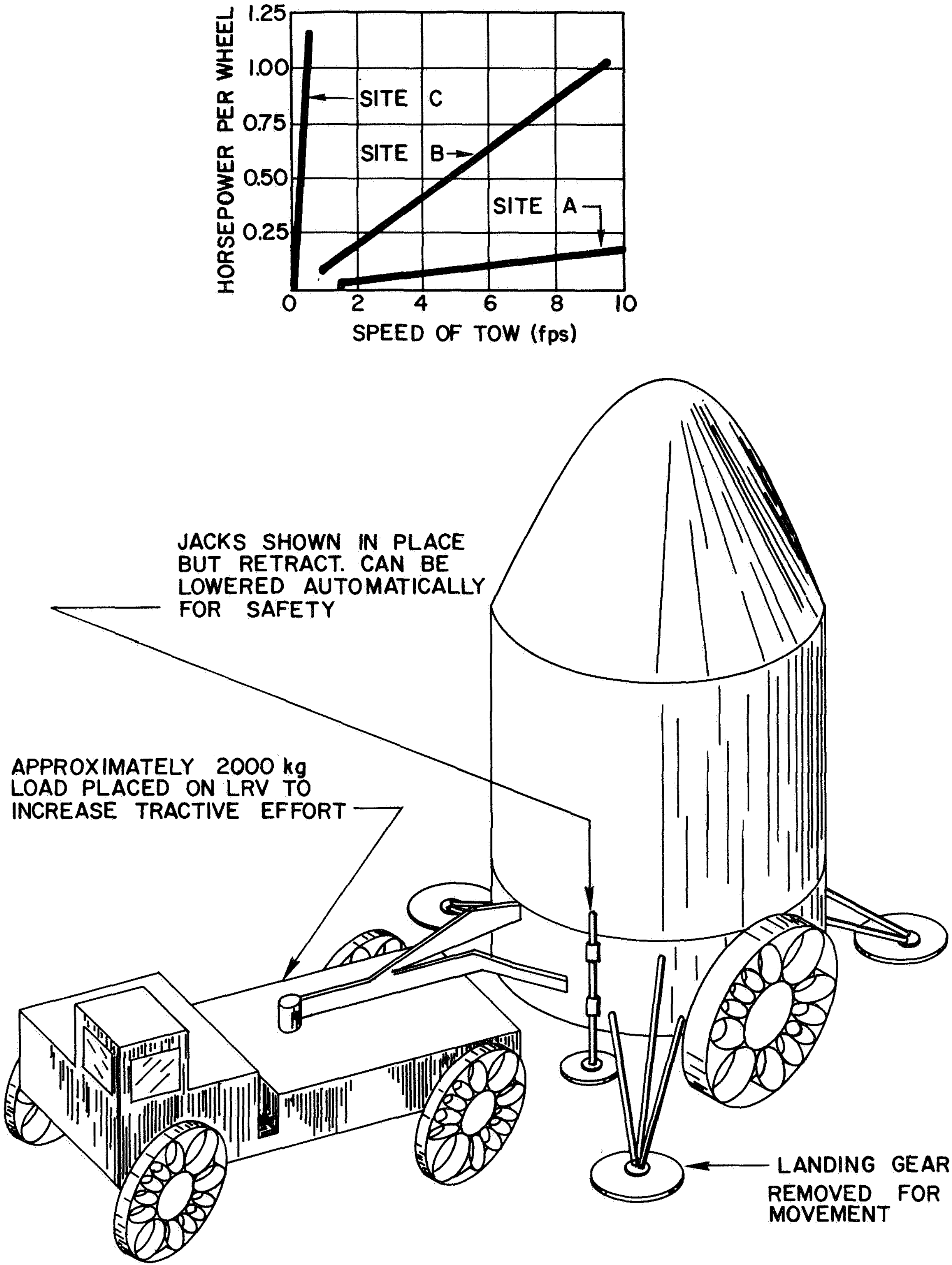


Fig. 12-1. Moving Concept [1].

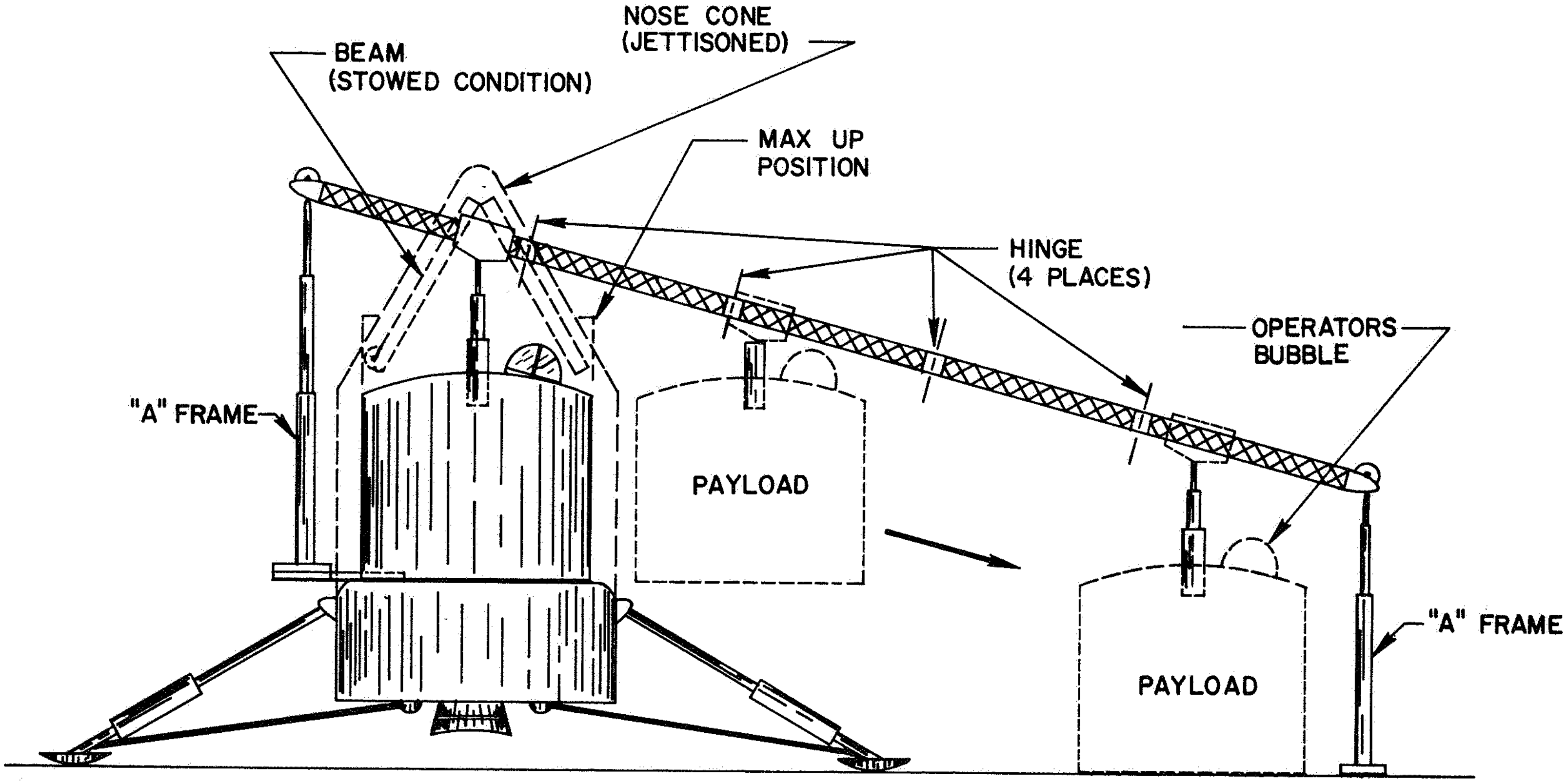
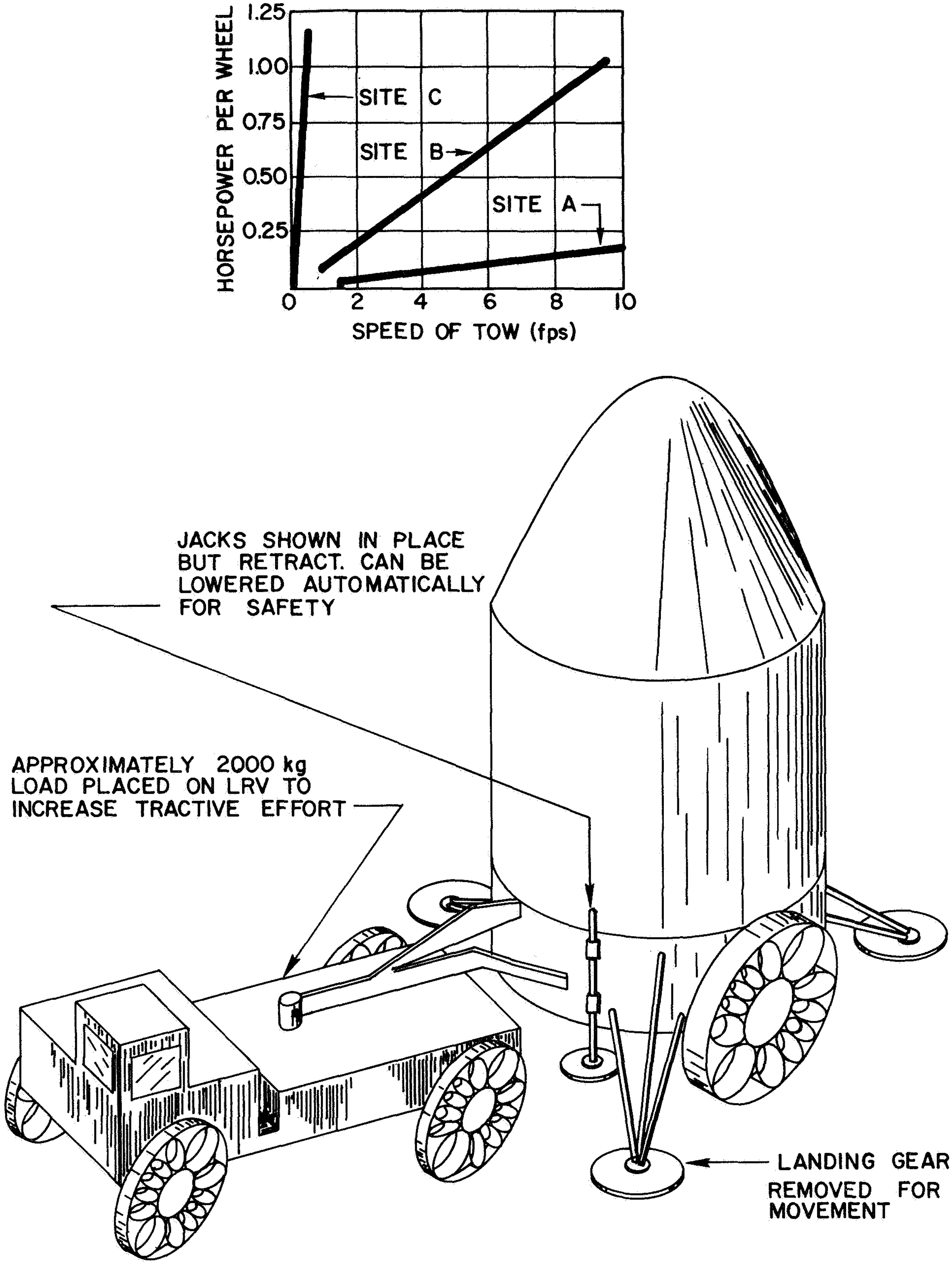


Fig. 12-2. Monorail [1].



JACKS SHOWN IN PLACE
BUT RETRACT. CAN BE
LOWERED AUTOMATICALLY
FOR SAFETY

APPROXIMATELY 2000 kg
LOAD PLACED ON LRV TO
INCREASE TRACTIVE EFFORT

LANDING GEAR
REMOVED FOR
MOVEMENT

Fig. 12-1. Moving Concept [1].

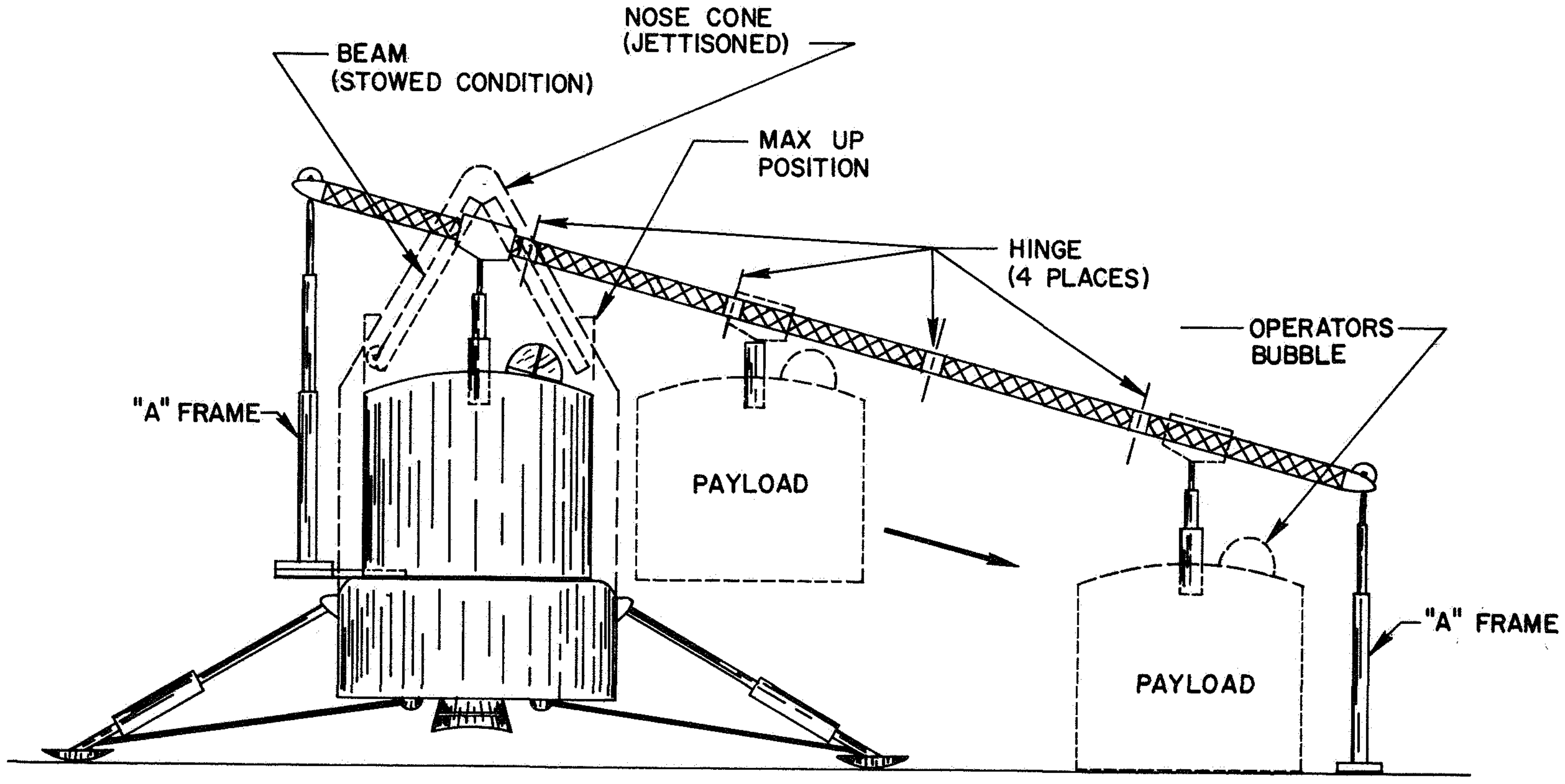


Fig. 12-2. Monorail [1].

the center portion of the payload dome. A transparent blister added to the dome permits visual observation of all rail movements from a manned control station inside the payload. The 24-m rail length consists of five hinged truss sections stowed teepee fashion in the conical nose with the A-frame legs hinged to the end sections. Each leg consists of a single tube 5 m long that has one telescoping extension to obtain a total length of approximately 10 m. Figure 12-2 shows the system set up and ready to lift the payload to the desired site.

The monorail is automatically extended and latched, and one pair of A-frame legs (at the extreme end) is deployed to touch the ground. This places the 24 m rail at an angle of approximately 15 deg with the horizontal. Two structural members to support the other two monorail legs hinge outward from the landing gear. The monorail legs are engaged with the support members, and the turret actuator retracts to raise the payload from the landing stage. It is moved down the monorail to the lower end and stopped. Then the actuator lowers the payload to the lunar surface.

Consideration was given to overhead cables such as are used in the logging industry. Such schemes do not appear attractive because of the erection effort involved and because they require substantial "deadmen" for anchoring guylines. There is no assurance at present that guyline anchors can be set securely enough in the lunar soil to resist the forces they must withstand, and automatic erection does not appear feasible.

12.1.3 Emplacement

The surface for off-loading of shelters will have to be smoothed and may have to be stabilized by scarifying and solidifying with a chemical such as self-setting cement.

After the shelter has been placed in its permanent location, a radiation barrier of lunar soil must be provided. In the LESA study [1] it is suggested that a shroud be placed around the shelter with the intervening space filled with soil and the structure covered with soil

(Fig. 12-3). A special vehicle, the Specialized Construction Vehicle shown in Fig. 12-4, is capable of performing this excavation and soil emplacement. In addition, it is designed to collect loose dirt from the lunar surface and to place it where it is needed, accomplish towing tasks, and do shallow excavation work. Normally the vehicle is operated by a two-man crew. One man drives and regulates cutter depth while the other directs the turret-mounted dirt-thrower for proper placement of the aggregate.

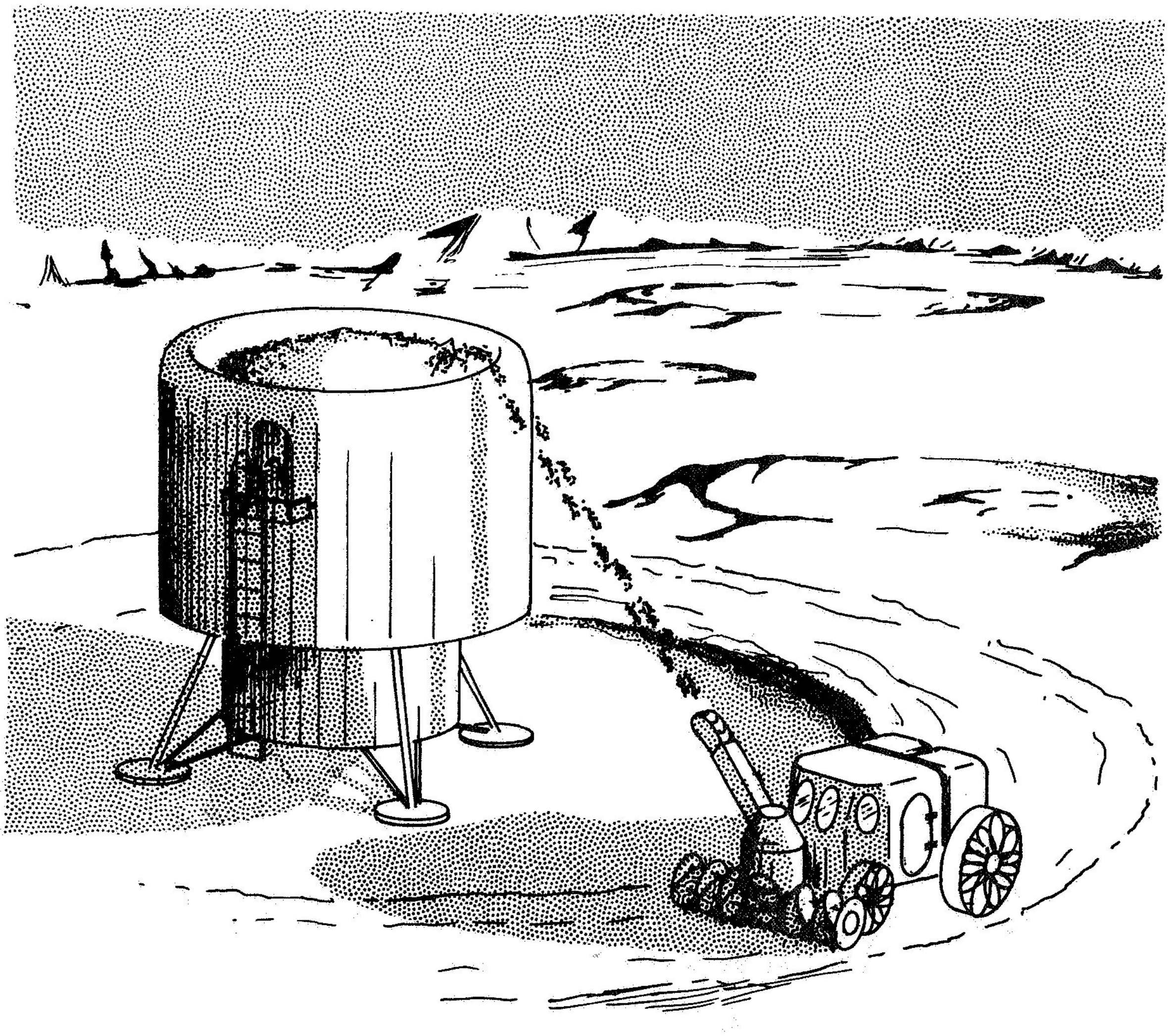


Fig. 12-3. Emplacement [1].

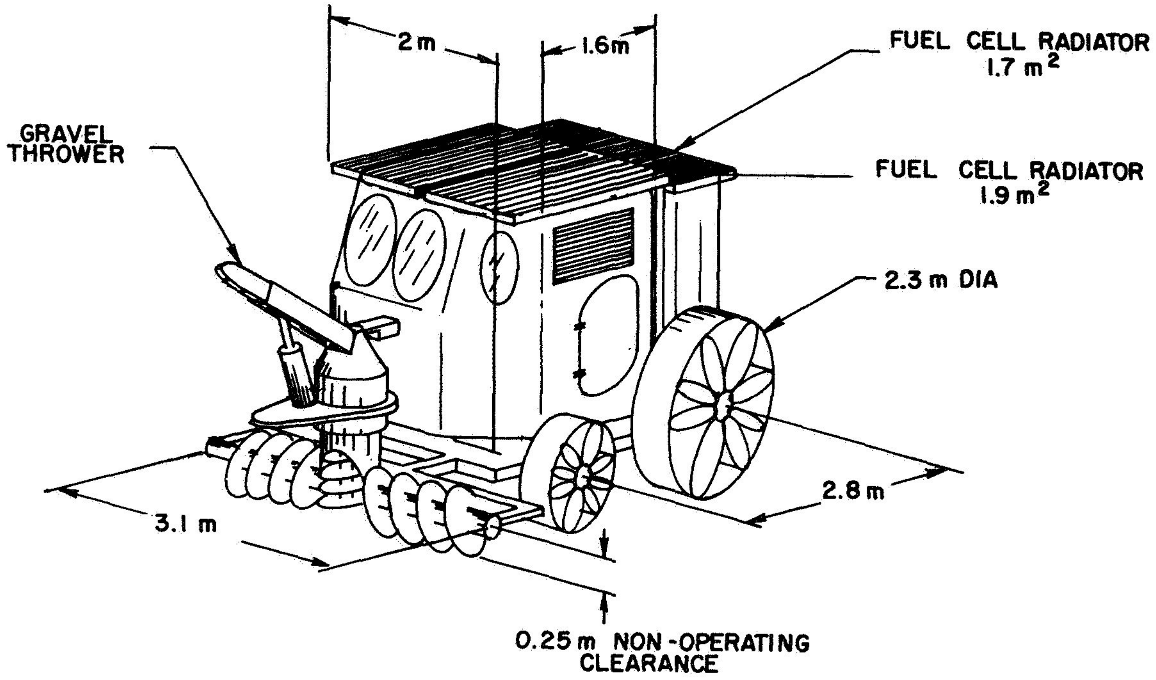


Fig. 12-4. Specialized Construction Vehicle [1].

Continuous operation of the helical cutter, collector, and dirt-thrower combination offers time-saving features and ease of operation not possible with equipment designed for intermittent operation or the use of an auxiliary vehicle. The cutter pictured has two helical blades that move the dirt to a central helix. The vertically pointed central helix lifts the dirt gathered by the horizontal cutters and collects it in the central region between the two horizontal cutters. The vertical helix is equipped with a hardened cutting edge on the bottom flute and performs like a straight end mill.

After rising on the central helix the soil drops onto a conveyor belt where it is accelerated and thrown ballistically as directed by the operator. A belt speed of 8 m/s and an inclination angle of 55 deg from horizontal provides the maximum required trajectory. The vehicle has a mass of 2,700 kg and is equipped with an independent electric power system, generating 20 kW maximum power. At this rate the vehicle will collect 3 m^3/min of soil and can throw it a height of 13 m at an efficiency of 50 percent. A shelter 6 m in diameter and 6 m high can be covered with soil in 2 hours. The specialized construction vehicle concept could also be used for providing soil to the MOONLAB farm.

12.1.4 Unloading Payloads

For packaged payload of comparatively light weight, a crane or short gin pole mounted on the LLV platform as part of each logistic payload can be used. It can be operated by on-board winches or by using an LRV. Figure 12-5 shows one such concept. The use of a restraining bar to extend the base support and prevent toppling is suggested when a single heavy load is handled.

The principal advantages of the gin pole are

(1) Some multipurpose use for later operations as a load tranfer base,

(2) Flexibility in placing the load on the lunar surface within a small area, and

(3) Unloading directly onto a flatbed truck or roving vehicle.

Transportation from the crane can be by means of an LRV or a specialized, but unmanned, multipurpose trailer which has its own crane for unloading at a desired site. A typical trailer is shown in Fig. 12-6. It is self-propelled but has no personnel cabin.

In addition to its function as transporter for equipment, the trailer in Fig. 12-6 [Ref. 2] is equipped with a back-hoe, a bulldozer blade, and a drill-rig. These components will be used in various construction operations. If the construction site is a considerable distance from the main base, then a pressurized personnel capsule may be placed on the trailer with additional power supply for operations of longer duration. A trailer such as this will be fully utilized for transportation and construction during MOONLAB evolution, and will not be available for other tasks.

12.1.5 Material-Handling Vehicle

A high lift or skip loader is best suited for efficient loading and lifting of packaged components. Not only can it handle the

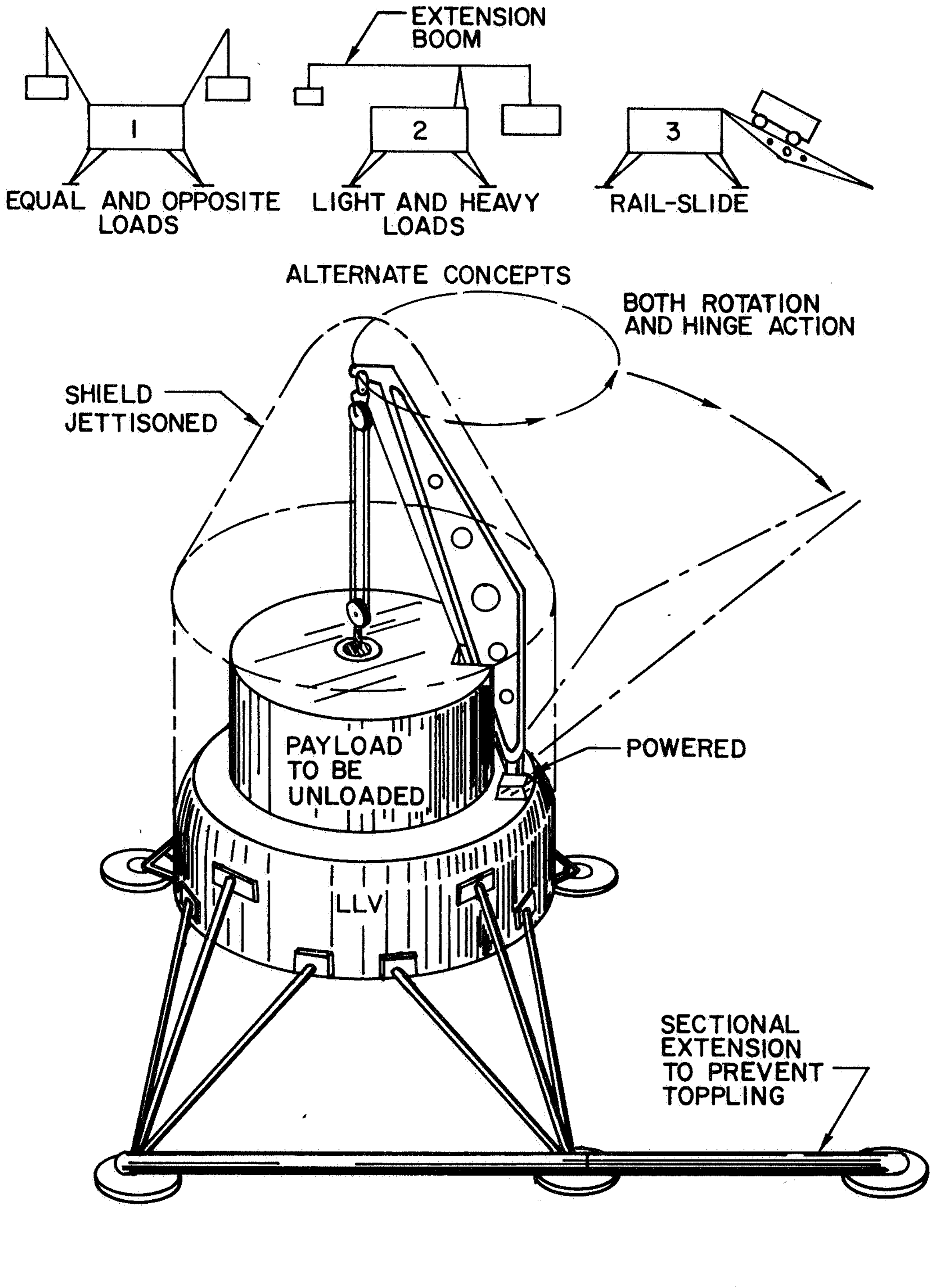


Fig. 12-5. Unloading (Up to 10,000 Pounds)[1].

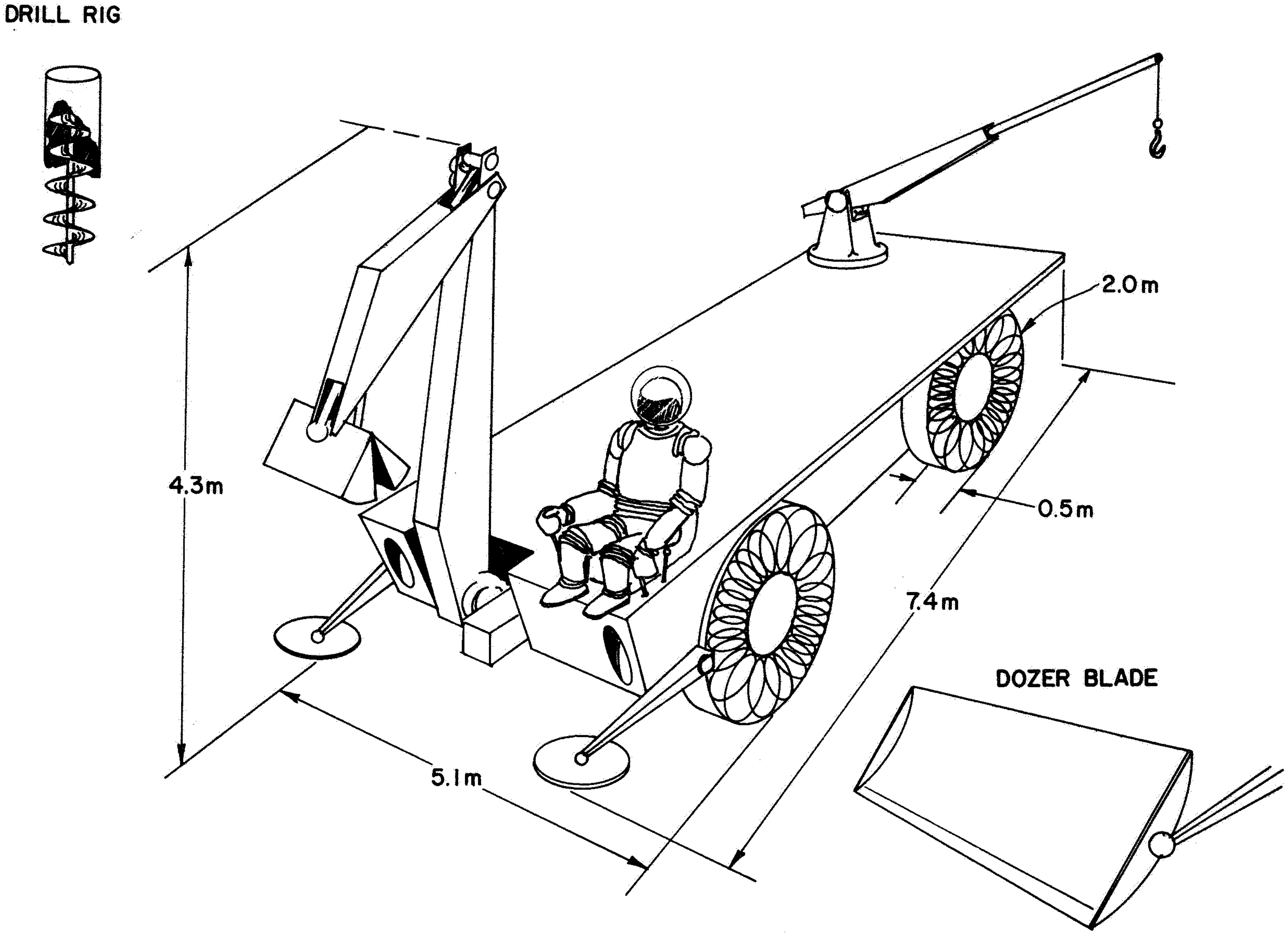


Fig. 12-6. Trailer - Multipurpose [2].

unloading of palleted payloads directly from the LLV and transportation from the unloading area serviced by the crane, but it can also serve as a personnel elevator from ground to access locks.

A material-handling vehicle is shown in Fig. 12-7. This is a specialized design in which the center of the forklift load is located between the wheels. The front wheels are mounted on a U-shaped framework which allows the load to be lowered to the ground. A feature of the design is a one-man cab that rides up and down the guide rails with the cargo so that the operator can see the handling operations.

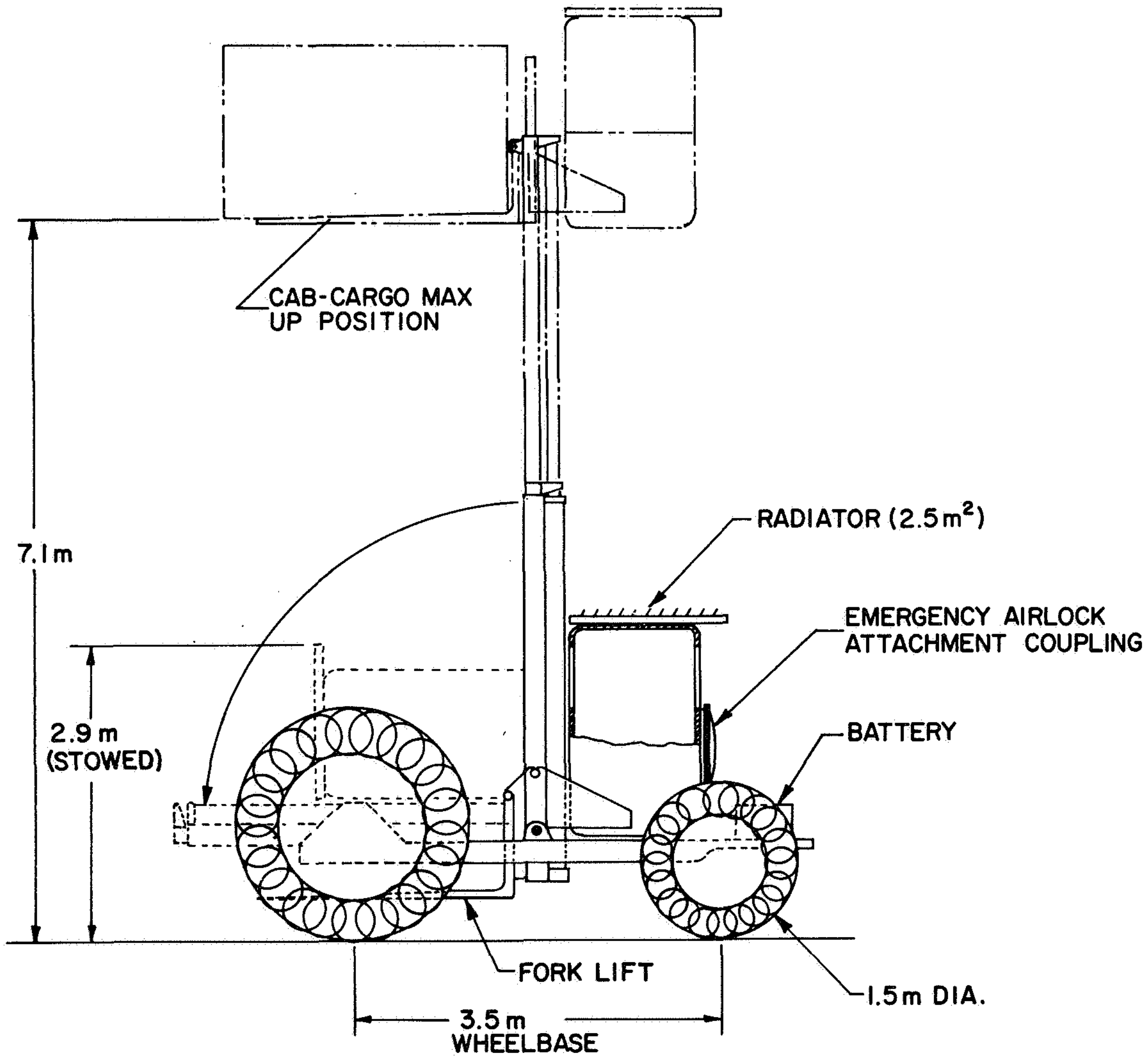


Fig. 12-7. Material-Handling Vehicle [3].

Although there is no air lock on the crew compartment, an adapter coupling is provided where a portable air lock can be connected to the crew compartment in case of an emergency.

This vehicle is designed primarily to unload the logistic payload from a platform 4.75 m above the lunar surface, to transport it to the crew shelter, and to raise the supplies 7 m to the shelter air lock where they are unloaded. It has a mass of 1,640 kg and a maximum lift capability of 2,150 kg. The power requirement for its operation is 2 kW (an additional 1 kW is necessary when the personnel cab is used).

Conventional forklift concepts are employed except that the length of lift exceeds that normally encountered. The single actuator extension provides the first 3.5 m. A roller chain, attached to the forklift slide, provides the remaining 3.5 m in conventional fashion.

The Material-Handling Vehicle utilizes electrical steering with servo control so that the operator can maneuver the vehicle while he is at the highest extended elevation. Maneuvering at the extended elevation, however, is kept to a minimum; driving or transporting is done only at the lowest elevation. The cab has two driving positions. While loading and unloading the operator maneuvers the vehicle from one station facing toward the forklift. At this time he has rear-wheel steering, which is conventional for that operation. After the fork and cab are lowered the operator takes the other station where he faces the opposite direction while driving to the shelter; this gives him conventional front-wheel steering for driving, and the cargo does not obstruct his view of the terrain.

12.2 Site Preparation

No matter what theory of formation of the lunar soil is correct, it is certain that it is non-homogeneous with respect to its mechanical properties. Consequently, any structure placed on (or in) the soil will be subjected to differential settlements. It is clear that if the base configuration adopted in this report were to be supported on an inadequately prepared site, the shelters would be subject to differential settlements and rotations relative to one another.

Such movements would threaten the integrity of the airtight connections between the connecting tunnels and the shelters. If the tunnels are flexible they will also experience differential settlements between the ends. Obviously, the airtight integrity of the system must be maintained. This can be accomplished by adjustments in the positions of the various system components or by simply not allowing movements from the very beginning.

Consideration of the cost of labor on the lunar surface demonstrates that site preparation, base construction, and maintenance labor should be minimized.

With the preceding constraints in mind, an optimum site will be one with a maximum overburden depth of 3 m and a minimum depth of 1 m. Under these conditions the following foundation configuration may be used:

(1) Each shelter will be supported by adjustable jacks which rest on rock,

(2) Each connecting tunnel may be supported by a lightweight truss which in turn rests on jacks to rock.

Using the suggested shallow depth of overburden has the advantages that,

(1) No rock removal or treatment should be necessary,

(2) Soil is available for covering structures and for the farm, and

(3) Any excavation that is needed can be done by the buckets on the two multipurpose trailers.

If the base should be situated on deep soils, the foundation problem becomes more complex. However, the foundation criterion remain--the same minimum differential settlement. Possible solutions to the foundation problem with deep soils might be

(1) Spread footings which support adjustable jacks that in turn support the structures,

(2) Pile foundations to rock, or

(3) Chemical grouting to rock.

Of these alternatives, the first is probably the most reasonable but would require that the structures be monitored regularly for settlement and rotation. If piles are used, they would be either bored-in or driven. The latter requires that a new pile driving technology be developed. This is probably the most expensive and difficult of the alternatives. Chemical grouting would require the development of special techniques for lunar soils and the lunar environment and would have to be carried through the entire soil depth.

Since the lunar soils probably have low cohesive strength and water content, compaction can be produced by simply running the construction vehicles over the surface. The bulldozer blade provided with the construction vehicles can be used for smoothing the surface. Finally, a wearing surface, probably plastic or aluminum, can be applied. One area where such surface treatment might be needed is at the connecting tunnel from Module M-6 to the LRV because of the hatch alignment requirement.

Since the farm structures are quite flexible the only soil treatment required for them should be a small amount of excavation and boulder removal, which can easily be handled by the construction equipment.

12.3 Off-Site Activities

The rationale for lunar exploration can be divided into two parts; scientific and technological. Actually, this division is arbitrary since most information concerning the one is useful to the other. For example, a model which postulates the mode of lunar formation is useful in estimating the mode and frequency of mineral deposits as well as in shedding light on the formation of our solar system. On the other hand, the mode and frequency of mineral deposits can disprove one formation theory while supporting another.

12.3.1 Scientific Objectives

Any theory concerning the origin of the Moon necessarily considers the origin of the entire solar system. Many such theories exist but the following currently have the most support [3]:

(1) Common existence with the Earth: the Moon formed as part of the Earth and was separated by tidal action during the solidification of the Earth's crust.

(2) Separate existence from the Earth: the Moon was formed by the accumulation of solid and gaseous particles in the vicinity of the Earth.

(3) Separate existence from the Earth: the Moon was formed outside the Earth's sphere of influence and was later captured by it.

One way in which these groups of theories may be evaluated is by logging the arrangements of lunar rocks with depth as well as the composition and characteristics of the various materials. It may even be possible to date the Moon by means of rock samples taken at depth.

Drilling and sampling along an entire diameter of the Moon is obviously the most positive method of determining its profile. This, however, is beyond the pale of foreseeable technology. Geophysical methods (primarily seismology) will have to suffice for determining the degree of differentiation of the Moon from surface to center to surface. The possibility of no differentiation exists, as well as the more probable condition of unsymmetrical differentiation about the Moon's center.

Such determinations as the foregoing require long seismological distances and very accurate instrumentation as well as deep drilling. This is the scientific reason for desiring a 300-m lunar drill, large staytimes away from the main base, and long travel distances for mobility systems.

The hypotheses concerning the agents that are primarily responsible for the topographic patterns on the Moon generally fall into one of the following categories:

(1) Internal igneous activity, vulcanism or violent release of volatiles,

(2) Impact by asteroids, meteorites or other bodies,

(3) A combination of (1) and (2).

When discussing the topological features of the Moon it is customary to use the very general division of the surface into marial areas and upland areas. The Grimaldi crater is a marial area surrounded by uplands. In fact, this mare material is the darkest on the portion of the surface that is visible from Earth. According to some hypotheses, this makes Grimaldi the youngest of the marial areas.

Not only is Grimaldi acceptable to the astronomers because of its field of view but there is also no evidence of recent tectonic activity. Quite naturally, the advocates of lunar vulcanism would prefer Alphonsus where Alter [4] has obtained some evidence for outgassing. With the exception of recent vulcanism, Grimaldi and the surrounding uplands have craters, rills, domes, faults and ridges so that careful examination of the profiles that are exposed in these features will tell much about the history of the Moon as well as the processes that formed the surface. Travelling from Grimaldi to Oceanus Procellarum by Lunar Roving Vehicle (LRV) will allow the determination of the relationships between the two and should be an important scientific objective. The LRV mode allows on-the-spot mapping, identification, and sampling, which is very important in working out geological relationships. A major drawback in taking samples in a small area of a mare and nowhere else is that the rocks may come from a meteor or asteroid impact rather than be indigenous to the Moon. Furthermore, the existence of different rocks at the rim and in the interior of the crater are not evidence of impact. The entire profile across the crater is needed.

Since Grimaldi is 150 km in diameter, long staytimes and ranges of travel are needed to gather the information needed to determine the detailed relationships between the various geological features. Obviously, an LRV with life support and payload capability is required to evaluate these important scientific hypotheses.

12.3.2 Technological Objectives

12.3.2.1 Water Sources

Free Water. The probability of the occurrence of free water is a function of the mode of lunar formation but in any case it would not exist on the surface since the vapor temperature of ice is in the range of 133°K to 173°K at pressures from 10^{-10} torr to 10^{-5} torr (approximately) [Ref. 5]. If free water exists it is as ice in deep crevasses, caves, or at the poles.

Subsurface unfrozen free water could come no closer to the continually cold surface than about 500 m or at depths where the only heat to reach it would be outflow from the depths of the Moon.

Water of Hydration. If the Moon is highly differentiated (as is Earth) then free water (at great depths) will exist as will hydrated minerals in the near subsurface. If the Moon is only partially differentiated, hydrated minerals commonly occurring in terrestrial igneous rocks (Table 12-2) hold the best hope for finding water supplies on the Moon.

12.3.2.2 Other Minerals

The probability that most of the elements and minerals present on Earth also exist on the Moon is quite high no matter what the mode of formation. In addition, new minerals may exist because of differences in the formation environments.

No matter what the scientific conditions, the operation of a permanently manned lunar base becomes much more attractive if water in any form can be found. Since the probability of finding water in hydrated rocks is good, prospecting configurations are required and a mobile manned laboratory is mandatory for this purpose.

In order to perform the scientific and technological missions described in the preceding discussion the following mobility systems are recommended:

(1) One 3-man mobile laboratory (Fig. 12-8) with a large multipurpose trailer (Fig. 12-6).

This system has a nominal staytime of 84 days, nominal range of 2,250 km. As a base support system it can provide 1,675 kW-h from its H_2-O_2 fuel cells and carry a payload of 4,500 kg. In the role of emergency shelter, it will support three men for 168 days

Table 12-2

HYDRATED SILICATES COMMONLY OCCURRING IN TERRESTRIAL IGNEOUS ROCKS [3]

Mineral name	Theoretical formula	Molecular weight	Theoretical % H_2O	Decomposition temperature	Mode of occurrence
Serpentine (including Garnierite)	$Mg_6 Si_4 O_{10} (OH)_8$	554.3	13.00	500°C	Formed by alteration, olivine and enstatite; low and medium grade metamorphic rocks.
Talc	$Mg_3Si_4O_{10}(OH)_2$	379.3	4.75	780°C	Derived, ultra-basic rocks like olivine; low and medium grade metamorphic rocks; foliated.
Chlorite	$(Mg, Fe, Al)_6 (Al, Si)_4 O_{10} (OH)_8$	620.5[b]	11.62		Alteration products, biotite and other magnesian minerals. Hydrothermal alteration, igneous rocks.
Anthophyllite or cummingtonite	$(Fe, Mg)_7 Si_8 O_{22} (OH)_2$	891.3[e]	2.02		In Mg-rich metamorphic rocks, medium grade metamorphic; often associated, talc.
Tremolite or actinolite	$Ca(Mg, Fe)_5 Si_8 O_{22} (OH)_2$	891.3[e]	2.02		Common minerals, low or medium grade metamorphic rocks. Actinolite, Fe.
Hornblende	$NaCa_2(Mg, Fe, Al)_5(Si, Al)_8 O_{22} (OH)_2$	891.6[b]	2.02		More common in plutonic than volcanic rock; medium grade metamorphic rocks.
Glaucophane-reibeckite	$Na_2(Mg, Fe, Al)_5 Si_8 O_{22} (OH)_2$	838.9[b]	2.15		Low and medium grade metamorphic rocks; reibeckite in soda-rich granite and pegmatites.
Axinite	$(Ca, Mn, Fe)_3 Al_2(BO_3) Si_4 O_{12} (OH)$	585.0[d]	1.54		Formed by metasomatic reaction at high temperature.
Tourmaline	$Na(Mg, Fe)_3 Al_6 (BO_3)_3 (Si_6 O_{13})(OH)_4$	1006.2[e]	3.58		Granite pegmatites; metamorphic rocks; high-temperature metalliferous veins.
Epidote	$Ca_2(Al, Fe)_3 Si_3 O_{12} (OH)$	497.7[e]	1.81		Low and medium grade metamorphic rocks.
Topaz	$Al_2 SiO_4 (OH, F)_2$	182.1[f]	4.95		Regular and high-temperature quartz veins.
Muscovite	$KAl_2(AlSi_3 O_{10})(OH)_2$	398.4	4.52		Granites and pegmatites; low and medium grade metamorphic rocks.
Biotite or phlogopite	$K(Mg, Fe)_3 (AlSi_3 O_{10})(OH)_2$	464.7[c]	3.88		Phlogopite in ultra-basic igneous rocks; biotite in intermediate and acid rocks.
Zeolites					
Heulandite	$CaAl_2 Si_7 O_{18} 6H_2O$	686.8	15.73		Cavities in basaltic rocks from alteration products, intermediate acid volcanic glass.
Stilbite	$CaAl_2 Si_7 O_{18} 7H_2O$	704.8	17.88		Cavities in basalts, associated with heulandite.
Laumontite	$CaAl_2 Si_4 O_{12} 4H_2O$	470.5	15.32		Veins and cavities, igneous rocks.
Chabazite	$CaAl_2 Si_4 O_{12} 6H_2O$	506.5	21.32		Lining cavities, basalts, and andesites; tuffaceous rocks from alteration products of Ca plagioclase.
Analcime	$NaAlSi_2 O_6 H_2O$	220.2	8.17		Cavities and veins, igneous rocks; Na-rich basic igneous rocks, ground mass.
Natrolite	$Na_2 Al_2 Si_3 O_{10} 2H_2O$	380.3	9.47		Cavities in basalts, alteration products of nephelene.

[b] Assume Mg = Fe = Al = Si.

[c] Assume Fe = Mg.

[d] Assume Ca = Mg = Fe.

[e] Assume Al = Fe.

[f] OH = F.

SYSTEM LAYOUT (Dimensions in Meters)

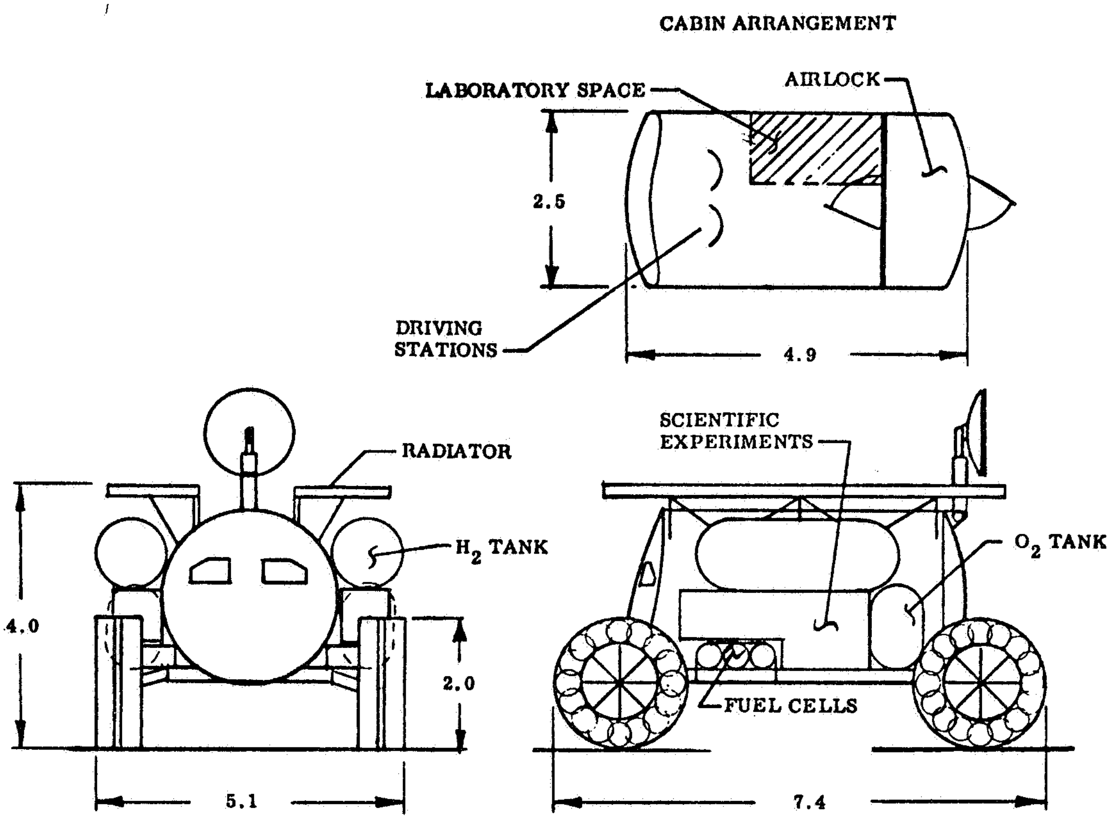


Fig. 12-8. Manned Roving Vehicle - Cabin - Three Man [2].

at 6 km travel distance. The trailer is equipped with a 650 kg capacity hoist and a 0.3 m^3 capacity backhoe [2].

This system has the capacity to perform a complete investigation of the Grimaldi crater in a single trip as well as aid in base support and construction capability.

The mass of the total system is 11,600 kg of which 6,145 kg is due to the roving laboratory and 5,455 kg is due to the trailer. Total expandable weight for the system amounts to 3,715 kg.

Development cost for the rover totals 389 million dollars with a lead time of five and one-half years. Cost for the trailer will be 48.3 million dollars and development will require a lead time of two and one-half years.

(2) Two three-man flying vehicles as described in MIMOSA [2] are needed for exploration of the highlands surrounding Grimaldi. A particularly rich area in terms of geology is the upland at the immediate southwest of the crater. It appears that this can be reached in a reasonable amount of time only by a flying vehicle. Two vehicles are needed in case of emergencies. One of them can also be carried with the roving system for emergency return to base. The MIMOSA study [2] calls for hydrazine to be used as propellant. This would be suitable for a single mission but for repeated missions the system should be propelled by cryogenics.

The maximum non-stop, one-way range of this vehicle is 800 km. It has a zero payload but two of the passengers may be replaced by a cargo of 284 kg. That would be sufficient for explosives and shallow depth exploration tools.

Total delivered mass is 5,000 kg per vehicle of which 4,000 kg are expendables.

Development of the first vehicle will cost 108 million dollars and will require a lead time of three and one-half years. The second vehicle will cost 6.5 million dollars and require one and one-half years of lead time.

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Chapter 13

EMERGENCY PROCEDURES AND BACKUP

13.1 General

In designing and specifying emergency procedures and backup an attempt has been made to consider the problems in an interrelated manner. Before describing the procedure and design of the emergency system, it may be well to list the major emergency supplies which will be on hand. This is done in Table 13-1. All space suits are listed here for consistency, even though they cannot all be considered as emergency equipment. The water and the roving vehicles listed in Table 13-1, although available for emergency use, have other functions in MOONLAB:

Table 13-1

MOONLAB EMERGENCY SUPPLIES IN THE POST-1985 PERIOD

A.	Food - one-year's supply		3,624 kg
B.	Water - two-month's supply		
	ingestion - 2,520 × 2 =	5,040 kg	
	sanitation - 1,080 × 2 =	2,160 kg	
	fire protection and drinking backup (immersion facility)	20,000 kg	
	+ 150 gal × 7 modules for 1st min. emergency	4,000 kg	
	Total Fire Protection	24,000 kg	
	Total Backup Water		31,200 kg
C.	Oxygen and Li_2O_2		
	60-day supply - whole base	1,240 kg	
	fail-safe supply (protection from sudden decompression) - 20 kg/8 modules and 3 long tunnels	330 kg	
	one-day supply with CO_2 absorption (12 kg/8 modules and 3 long tunnels)	132 kg	
	Li_2 for CO_2 absorption and O_2 generation (one day), 30 kg/8 modules and 3 long tunnels	330 kg	

Table 13-1 (Cont)

	backpack backup O_2	35 kg	
	Total oxygen and Li_2O_2		1,957 kg
D.	Spacesuits		
	hardsuits - 36	800 kg	
	hardsuit backpacks - 36, 12-hour	240 kg	
	extra-lab soft suits - 48 sets 1 suit + helmet = 4.53 kg 48 sets =	218 kg	
	softsuit backpacks - 48 sets. 30 min. - 2 hrs: 1-3 kg each = 144 kg max	144 kg	
	emergency suits and retractable helmets (sudden decompression, toxicity, etc.) max 7 kg each = 168 × 7 =	1,176 kg	
	Total		2,578 kg
E.	Emergency Lighting - Batteries - NaS rechargeable		
	11 modules - 11 kg/module for 1200 kW-hr/module	121 kg	
	11 passageways - 5.5 kg/passageway for 600 kW-hr per passageway	61 kg	
	Total		182 kg
F.	Tools - Mechanical and Plumbing (mostly in M-6)		
	handtools Torches - helion and H_2-O_2 patch material laser cutting tools (possible) electron beam welding (possible)		
	Total		~500 kg
G.	Electrical and Electronic Parts and Tools		
	spare parts	500 kg	
	oscilloscope	20 kg	
	tools	50 kg	
	Total		570 kg

Table 13-1 (Cont)

H.	Search and Rescue Vehicles	
	2 flying vehicles - 250 km and back, 1-stop range	
	1 roving vehicle (mobile lab) and trailer - 3000 km range	
I.	Central Computers - Emergency Monitoring and Control	
	2 each - one located at the command module and the other at the medical module	
J.	Power	30 kW
K.	Heat - 2 kW/module	16 kW

Table 13-2 lists the locations of emergency supplies within the lunar base.

Table 13-2

LOCATIONS OF EMERGENCY SUPPLIES WITHIN THE LUNAR BASE

Farm Modules 1, 2, and 3

Water and Firefighting - High-pressure lines from the immersion facility will be provided to these 3 modules for firefighting purposes.

Electroluminescent Emergency Display Panels.

Emergency Lighting - 1200 kW-h, battery-powered lights will be provided for each module. Batteries will weigh 11 kg in each module and will be of the rechargeable, NaS type.

Oxygen - 1,240 kg of emergency backup oxygen will be provided for the whole base, and would probably go first to the other 8 modules of the lunar base in the event of need.

First Aid Kits - One for each module.

Eight Remaining Modules

Oxygen - 20 kg in each of the 8 modules for release in the event of sudden decompression. Also 12 kg in each module plus 30 kg Li_2O_2 for oxygen supply and absorption of CO_2 (one day's supply for 24 men).

Table 13-2 (Cont)

Water - 571 kg per module, except for the personal hygiene module, of fire extinguishers (under pressure) for the first minute of firefighting. Also 900 kg per module for ingestion and sanitation (60 days supply for 24 men).

Food - 453 kg per module (one year's supply for 24 men).

Suits - 12 emergency suits with retractable helmets in six of the eight modules, 24 in the sleeping module, and 36 in the personal hygiene module.

Light - 12 kg per module. This will provide 100 W per module for 12 hours. Rechargeable NaS batteries.

Electroluminescent Emergency Panel Display - One per module.

First Aid Kits - One per module.

Additional Command Module Supplies - Emergency monitoring and control computer and maintenance parts and tools.

Additional Personal Hygiene Module Supplies - 20,000 kg water for firefighting, drinking and sanitation backup. Also 24 extra-lab soft suits, helmets, and backpacks.

Additional Hospital Module Supplies - Emergency monitoring and control computer (parallel with computer in command module) and maintenance parts and tools.

Additional Off-Site Activity Module Supplies - 36 hard suits, helmets, 12-hour backpacks, some asbestos firefighting suits.

Most tools--mechanical and plumbing, electrical and electronics, torches, patch material, epoxy.

All 11 Tunnels

Firefighting - Nozzles present under pressure connecting with the immersion facility.

Lighting - 60.5 kg of batteries, 5.5 kg per passageway, to provide 600 kW-h of lighting per passageway as emergency backup.

First Aid Kits - Present in all 11 tunnels.

Electroluminescent Emergency Display Panel - One per tunnel.

Additional Supplies for the 3 Long Tunnels - 12 kg oxygen per long tunnel, plus 30 kg of Li_2O_2 for oxygen supply and absorption of CO_2 (24 men for one day). Also 36 emergency suits and retractable helmets (12 per long tunnel).

60-day Supply of Oxygen

This is for 24 men, weighs 1,240 kg, is centrally located on the base, and is available for any or all parts of the base.

13.2 Emergency Procedures

13.2.1 Location of Personnel and Physical Diagnosis

Sensing devices to monitor crucial physical parameters such as oxygen and carbon dioxide partial pressures, temperatures, humidity, level of contaminants, and internal cabin radiation levels will be maintained in each module and passageway. In addition, sensing devices continuously monitoring important physical parameters should be attached to each person. Experts in the field of radiation have recommended radiation monitoring at different parts of the body. Receiving antennas will be placed in each module and passageway to receive the physical information from each person. The information will be fed to a central computer in the command module and also a backup computer in the medical module. A continuous record will be kept on each person. The computers will be programmed to display this information only during emergency situations and to diagnose for quick display the meaning of certain obvious combinations of aberrant physical conditions. For instance, heart attack, shock, and heat exposure might be instantly diagnosed. The computer would also continuously record the location of each person. Information from the computer during an emergency situation will be displayed at emergency control posts.

Figure 11-3 shows the Emergency Monitoring and Control Panel combined with the Communications Control Console. On the right side of the panel are location indicator lights and alarms for room pressure level, O_2 level, power failure, and light failure. The Condition and Electroluminescent Emergency Display Panel shows the emergency condition and its location for any portion of the MOONLAB. A column is also provided on this display to indicate a code letter or number for any astronaut who happens to be at the scene of the emergency. In the upper left-hand corner of the Emergency Control Panel is shown the "Personnel Diagnostic Electroluminescent Display." This gives the code name of any personnel involved in either a base or a personal emergency, his location, and a first-order physical diagnosis. If the emergency should be general enough the computer would display the location and physical condition of all personnel. Or if the Emergency Control Operator should desire assistance, he can determine the location of needed personnel and vocally instruct them in rescue or repair procedures. He can also use a typewriter nearby to type instructions for display on an electroluminescent communication panel throughout the MOONLAB. It is planned to place these panels in every passageway and module. They may be used for ordinary communications and for the broadcast of emergency conditions and instructions. The computer will be programmed to automatically display certain emergency conditions, personnel diagnoses, and emergency instructions, however, the program can be overridden by the operator.

One display screen will receive input from television cameras located throughout MOONLAB and will display any or all of the areas covered by TV cameras. Below the television display is a section labeled "Computer Action and Manual Controls." For each parameter shown (e.g., O_2H_2O fire) there is one row of lights and a row of lighted push buttons. The lights and the lighted push buttons will go on whenever the computer has taken, or is about to initiate, emergency action. The row of lights will remain lit during an emergency to indicate what the computer has done or has recommended; and will remain lit only as long as the operator has not pushed one, thereby overriding computer action. The operator may also initiate other emergency action by pressing unlighted push buttons. In this case, unless the computer concurs, the indicator lights above the buttons pushed will not go on. The operator will have a running account of computer recommended action and actual action taken. The primary control will normally be located in the Command Module. An identical Backup Monitoring and Control Computer will keep a record of the emergency conditions and actions, but will assume control only in the event of malfunction of the first computer, or in the event of operator absence from the Command Control.

There is also a Printout Backup which will give a running account of overall emergency conditions and actions taken. The entire proceeding will also be recorded on magnetic tape for future reference.

13.2.2 Sudden Decompression

Consciousness may be lost in seconds and body organs badly damaged if pressure is suddenly reduced. For this reason each module and passageway of the MOONLAB will be made fail-safe. In the event of sudden decompression of a cabin or passageway the emergency monitor computer will flood the area with gas for several minutes--long enough for persons present to effect an emergency exit. A siren and flashing light will be actuated as warning in the area concerned. If the atmospheric pressure is too low to effectively transmit sound, the computer will actuate a small local warning device (perhaps an electric shock) on each person concerned. Connecting passageways will be used as escape ways from damaged module and vice versa. When all personnel are safe, the computer or an operator will close locking doors and turn off the gas supply. This gas supply consists of the ordinary atmosphere system plus 20 kg of stored oxygen per area.

13.2.3 Fire and Explosion Protection

Prevention, of course, is the best fire protection. All materials used in clothing, furnishing, wiring, and construction will be as non-combustible as possible. Motor lubricants must be flame and explosion proof. No oil will be used in meal cooking. Flammable materials, if any, will be kept in explosion proof, insulated containers. The medical module will be the only area using volatile organic products. Should a fire occur in spite of all precautions, it is felt that water is the best material for use for firefighting in a space colony environment.

High-pressure water spray is a very effective tool against most kinds of fires. Electrical conduction in water is its greatest drawback as a firefighting agent, but its advantages (e.g., absence of toxic byproducts) overshadow this difficulty. Selective de-energizing of electrical equipment will be part of the firefighting procedure and can be computer-actuated. Standby insulated batteries will be provided as lighting power backup. For each of the seven modules, 571 kg of water is provided in fire extinguishers for the first minute of firefighting. The water in the immersion facility is also backup fire protection. The first minute will allow actuation of pumping from the immersion facility to the fire locale. Automatic nozzels and a sprinkler system will be provided in each module and passageway. The computer will control the sprinkler system until overridden. If it is possible to evacuate personnel from the area atmospheric supply to the fire area will be cut off, and the remaining atmosphere in the fire area evacuated to vacuum. Insulating blanket will be handy for fire smothering as a first effort. A few well-insulated firefighting suits will be available throughout MOONLAB.

In the event of an explosion in or near MOONLAB, both decompression and fire could be involved. The procedures already described would be initiated. Additional steps will be taken to minimize any possible explosion hazards from the H_2-O_2 fuel cell power plant and from delivery vehicles. If an explosion occurs in either of these two areas flying projectiles might penetrate MOONLAB shelters and tunnels causing decompression. Since projectiles produced by a lunar explosion will not be slowed by an atmosphere and the reduced gravity alone will increase projectile range by a factor of six, the primary damage mechanism is expected to be projectiles rather than overpressure. Therefore, the landing areas and the power plant should be sheltered, or placed away from the MOONLAB shelters and tunnels.

13.2.4 Radiation Protection

It has been mentioned that radiation monitoring devices should be placed throughout the building structures of the MOONLAB and in several places on the body of each astronaut. The latter procedure is for the monitoring of local radiation exposure to the body, since the body parts vary in sensitivity to radiation. By 1985 such monitoring devices should be available. This information will be telemetered to the computer(s) previously described.

The Hospital Module will be placed under lunar soil as protection against solar flares. Using very conservative calculations, it is estimated that should such protection against solar flares be provided and used, a maximum of 75 days of life shortening per one year spent on the Moon will occur due to galactic and solar radiation (see Chapter 8). This allows for 1 m of lunar material piled on top and around the module. Enough warning will usually be available so that all astronauts can reach the safety of this module before the harmful portion of a solar flare reaches the Moon.

It should be mentioned that all windows and space-suit helmets should protect the eyes of personnel from ultraviolet light and other harmful radiation.

13.2.5 Search and Rescue

For purposes of search and rescue, the two three-man flying vehicles and one-wheeled roving mobile laboratory provided for scientific purposes will be used. The flying vehicles have a range of 500 km (250 km one-way, including one stop). The wheeled lab has a range of 6,000 km (3,000 km one-way). These will be stocked with emergency oxygen, water, food, medical supplies, space suits, and backpacks. Small way-station blocks containing water, oxygen, first aid kits, and food will also be placed near the MOONLAB's space vehicle landing pad.

A 75 percent escape capability will be maintained on the Moon. This may be increased to 100 percent by developing personnel vehicles with longer lunar staytimes. The return capability can be used with discretion if medical emergencies arise which cannot be handled with facilities on the Moon, which threaten incapacitation of the base through an epidemic, or if the base is partially destroyed and thereby incapable of supporting the full complement of personnel.

Part III - MOONLAB POST-1985 OPERATIONS

14. Logistics and Resupply - A. Kleinschmidt
15. Resource Exploitation - J. Zickel
16. Post-1985 MOONLAB - H. Parker

Chapter 14

POST-1985 LOGISTICS AND RESUPPLY

This chapter is concerned with the operation of MOONLAB in the post-evolutionary phase, and the logistics and resupply necessary to support the lunar base. Personnel and resupply are discussed, and the chapter is concluded with a short section on costs.

14.1 Personnel

The MOONLAB is to be a science-oriented operation with about 87 percent of the available man-hours being expended on science. The distribution of personnel given in Table 5-1 reflects the emphasis on science.

If the personnel delivery vehicle capacity remains at six men and the lunar staytime is fixed at one year, the rotation of personnel will occur at the rate of six men per quarter. This crew rotation gives each group overlap ranging from 3 to 9 months and is desirable from the standpoint of program continuity. Also a manned launch and crew return scheduled each quarter will distribute the launch facility and test programs evenly over the year.

MOONLAB starts the post-1985 period with construction completed and the farm fully operational in a nearly closed ecological system. The emphasis in operations after 1985 is expected to shift from construction and preliminary scientific experiments (see Appendix A).

(1) Completion of experiments scheduled to begin in 1982 (Phase 1),

(2) Undertaking and completing scientific activities which are planned to start in 1986 and continue at least into 1987 (Phase E),

(3) Initiation of lunar exploitation activities, including the following:

   (a) Development of lunar water supplies,

   (b) Development of solar power facilities,

   (c) Development of lunar metals sources,

   (d) Applications of vacuum technology, and

   (e) Application of cryogenics technology.

14.2 Resupply

To ensure an effective operating MOONLAB requires that all material be supplied as needed, not too early and certainly not too late. In order to accomplish this certain characteristics must be considered to assure adequate logistics planning. The following considerations are of special interest:

(1) Those items essential to life support,
(2) Single items not duplicated in other parts of MOONLAB,
(3) Items having a long lead time to delivery,
(4) Parts or subassemblies essential to the functional operation of major facilities,
(5) Improvement or expansion of existing facilities,
(6) Whether items are repairable or non-repairable,
(7) Whether items are expendable or recoverable,
(8) Whether parts are for immediate use or for maintenance of inventory,
(9) Physical characteristics such as weight and volume,
(10) Interdependency of items.

In operation, such considerations will result in an effective priority system and facilitate checks on the adequacy of resupply. Expendables will be stocked between supply missions with suitable minimums for safety. Resupply will take place automatically with consideration of future usage and current stock.

Because of the high cost of shipping freight between the Earth and Moon, all items of the scientific packages from Phases B and C (described in Chapter 5) will remain on the Moon (see Appendix A). They will be protected for substitute and emergency use and for use as a source of spare parts to repair currently used equipment. This will help keep resupply weights and costs to a minimum.

The specifics of resupply are particularly difficult in those cases concerning items which have not yet been designed. Because the "first units" are years into the future, prediction of the quantities required to be resupplied has, in many cases, been based on some simplifying ground rules. In the absence of better information it has been assumed that 20 percent of each multiple item classification will require replacement each year, and that single items will be replaced every five years. In the conditions actually prevailing in the post-1985 period 20 percent per year may prove to be generous, because the tradeoff of improved design versus extra weight favors additional design effort while transportation costs remain high. To the extent that longer life appears to be feasible during intervening years before the items are needed, appropriate adjustments may be made. In any case, resupply should always be adequate but not excessive.

Table 14-1 shows the main classes of activities and overall estimates for logistics and resupply in the post-1985 period of the evolved MOONLAB.

Table 14-1

ACTIVITIES AND ESTIMATES FOR POST-1985 LOGISTICS AND RESUPPLY

Resupply - Large Units (Annual Requirements)	Mass (kg)
Shelters and Life Support	
Power	3,800
Farm Unit - 10 m diameter	100
Farm Unit - 18 m diameter	600
Life Support replacement and repair	3,000
Canopy Module Repairs	125
Air Locks at 300 kg	240
Hard Suits	250
Soft Suits	100
Backpacks	623
	8,840
Mobility Systems Repair and Replacement	
Rover	1,400
Medium Trailer	600
Large Trailer	1,200
Flying Vehicles (2)	1,500
Spare Wheels	500
	5,200
Resupply - Expendables and Small Units (Annual Requirements)	
Food	1,500
Atmosphere	400
Farm Supplies	200
Miscellaneous Personal Items	125

Table 14-1 (Cont)

Communications - Maintenance	175
New Communications Equipment	300
Tools and Equipment	100
Photographic Film and Supplies	70
Pumps	100
Hydrogen and Oxygen as fuel for lunar vehicles	11,600*
Medical	30
	3,000 to 14,600
Lunar Water-Producing Equipment**	
Solar Units (12)	32,150
Electrolysis Units (6)	3,450
Drill	3,000
Loader	1,000
Dump Truck	3,000
Rock Crusher	8,000
Processing Equipment (4)	10,000
	60,600

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*If lunar water is not available.

**The figures given are based on 1 percent water recovery from lunar rock.

In addition, there will be further shipments involved with lunar exploitation in the post-1985 period. The activities and their required delivery of masses is shown in Table A-4 (Appendix A).

Assuming continuation of the process of supplying hydrogen and oxygen to power lunar roving vehicles, renewal and replacement of the equipment as listed in Appendix A is anticipated. Assuming a 20 percent replacement and repair rate on the solar cells, each set of which has a mass of 422 kg, 20 percent on the electrolysis units, and 10 percent on the remaining equipment, a resupply rate of approximately 420 kg per annum is determined.

The year 1986 may be exceptional if both of the above major units of equipment are transported to the lunar base. The Phase E Scientific (see Chapter 5) Equipment constitutes more than one payload. The 100-in. telescope with associated equipment and packaging can well go as one unit. The 300-m drill and the submillimeter radiometric system can go as part of the cargo associated with the lunar water producing equipment. Thus, five launches will be required in this year for new equipment.

If the lunar water production process proves to be unfeasible, every year, including 1986, the resupply of expendables and repair and maintenance of existing equipment will require shipment of appreciably more than one full launch vehicle. Considerably less than one launch, approximately 18,500 kg plus packaging, is required if hydrogen and oxygen supplies can be renewed from lunar water.

14.3 Costs of Post-1985 Operations

The annual cost for MOONLAB rises in 1986 due to the delivery of extra equipment. Cost estimates for post-1985 operations, including and excluding the extraction of lunar water, are given in Table 14-2. These figures do not include development or acquisition costs for equipment delivered to MOONLAB, and thus represent only a lower bound.

Table 14-2

COST ESTIMATES FOR POST-1985 OPERATIONS

Year	Item	Cost (Millions)
	Without Lunar Water	
1985	Launch operations	300
	Vehicle sustaining cost	240
	4 personnel vehicles	1,052
	Cargo capacity for 30,100 kg	262
		$1,854
1986	Launch operations	300
	Vehicle sustaining costs	240
	4 personnel vehicles	1,052
	Cargo capacity for 62,000 kg	526
		$2,218
1987	(Same as 1985)	$1,854
	With Lunar Water	
1985	---	1,854
1986	Launch operations	300
	Vehicle sustaining cost	240
	4 personnel vehicles	1,052
	Cargo capacity for 123,500 kg	1,050
		$2,642
1987	Launch operations	300
	Vehicle sustaining cost	240
	4 personnel vehicles	1,052
	Cargo capacity for 18,500 kg	158
		$1,750

Chapter 15

RESOURCE EXPLOITATION

15.1 General

The three most abundant elements found on the Moon by Surveyor V are the same as those found on the surface of the Earth, oxygen, silicon, and aluminum. The relative amounts of these elements in the lunar sample are similar to those in a silicate rock of basaltic type. Results from Surveyor V are shown in Table 15-1.

Table 15-1

CHEMICAL COMPOSITION OF LUNAR SURFACE AT SURVEYOR V SITE

Element	Atomic percent*
Carbon	< 3
Oxygen	58.0 ± 5
Sodium	< 2
Magnesium	3.0 ± 3
Aluminum	6.5 ± 2
Silicon	18.5 ± 3
$28 < A < 65$†	13.0 ± 3

---

*Excluding hygrogen, lithium and helium.

†This group includes S, K, Ca, and Fe.

The similarity of the Surveyor V sample to Earth basalts raises the possibility of obtaining useful minerals, gases, and water from the lunar surface.

The lunar environment is also of interest from an exploitation standpoint. During the lunar day of approximately 350 h the sun shines onto the surface with strength undiminished by an atmosphere and its constancy is unbroken by cloud cover. The lunar vacuum is not only extremely significant for astronomical investigations, but also may make it possible to produce pure metals of high strength and improved quality. Temperatures during the lunar night lend themselves to the development of cryogenic techniques which may also be useful during the day if proper shielding from the Sun can be provided.

15.2 Solar Energy

Solar energy, the most directly usable lunar resource, can be harnessed in a number of ways.

15.2.1 Solar Panels

The photovoltaic process for the generation of electric power utilizes the Sun's rays impinging on single crystal siliconcells or cadmium sulfide thin films. Arrays of such cells are usually used for the generation of secondary power. A typical advanced configuration is 14 m long and 8.5 m wide and produces 2.5 kW of electric energy (Fig. 11-1). In its stored condition it occupies 1.5 m^3 and weighs 105 kg. Losses from meteoroids and radiation are to be less than 10 percent per year.

Solar panels can furnish electric power during 95 percent of the lunar day for the operation of shelters, mining, water extraction, and perhaps most importantly, the production of electrolytic reactant. The latter is used in individual fuel cells on vehicles or other equipment, for night-time operation of specific laboratories, the life support of the base and the production of LOX, the fuel for return rockets and for further space explorations.

Initial costs for electric energy from solar panels are presently quite high. However, as production increases and installation know-how is developed, this figure will be reduced considerably.

15.2.2 Solar Concentrator

In certain applications direct use can be made of the Sun's rays as a heat source; but, the high energy density necessary to operate thermionic converters or solar furnaces for the extraction of water from rocks requires very precise concentration. The best concentrator is a precision paraboloidal reflector which can be inspected on the ground and stowed on a launch vehicle without folding or deflating. Other types of concentrators are:

(1) The Fresnel Reflector offers the advantage of a nominally flat surface for easier stowage. However, steps between the reflecting surfaces form large areas which do not concentrate incident solar flux; therefore, the efficiency is considerably lower than that of a parabolic surface.

(2) The Petalline Reflector can be folded for stowage in the launch vehicle to obtain low volume requirements, but the loss of precision associated with the folding mechanism is a serious drawback.

(3) The Fresnel Lens is not as sensitive to distortion as the reflector, but it has a step loss similar to Fresnel Reflectors. Glass lenses are subject to breakage and plastic lenses are susceptible to ultra-violet damage.

Low concentration systems which do not approach thermionic requirements include the hemispherical concentrator, the "umbrella" type concentrator and the parabolic cylinder concentrator. These systems may be adequate for the extraction of water because temperatures on the order of only 1100°K are required. The optimum temperature for a thermionic converter is 3000°K, with a practical temperature of 2000°K.

15.3 Water Extraction

Ice or ice-soil mixtures may exist in permanently shadowed surface zones where the temperature does not rise above 120°K. In the equatorial belt, where the subsurface temperature is about 240°K, any ice near the surface will have been lost by sublimination. However, subsurface ice protected by an impermeable rock may have remained since its formation.

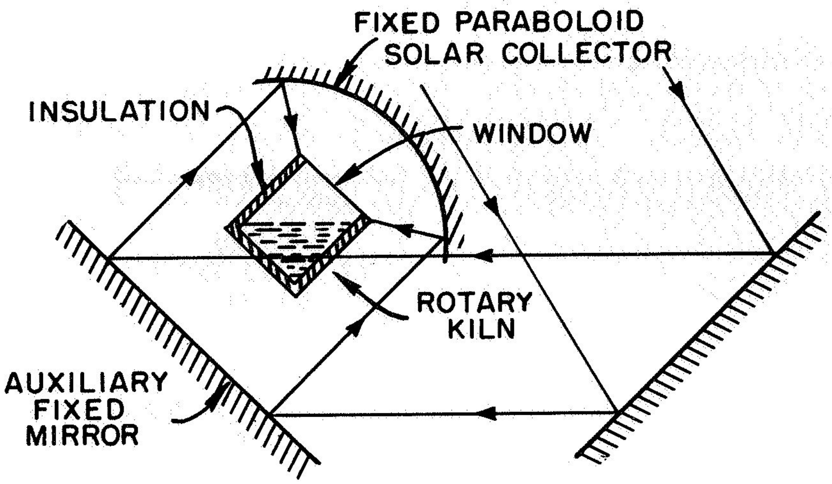
Water of hydration is considered the most likely form to be expected on the Moon. The moisture content may range from a few percent to as low as 0.01 percent. Two relatively simple methods for extracting water of hydration are kiln or furnace processes and fluid bed processes. Each of these is used in many commercial applications which are similar to the dehydration of rock.

15.3.1 Kiln or Furnace Processes

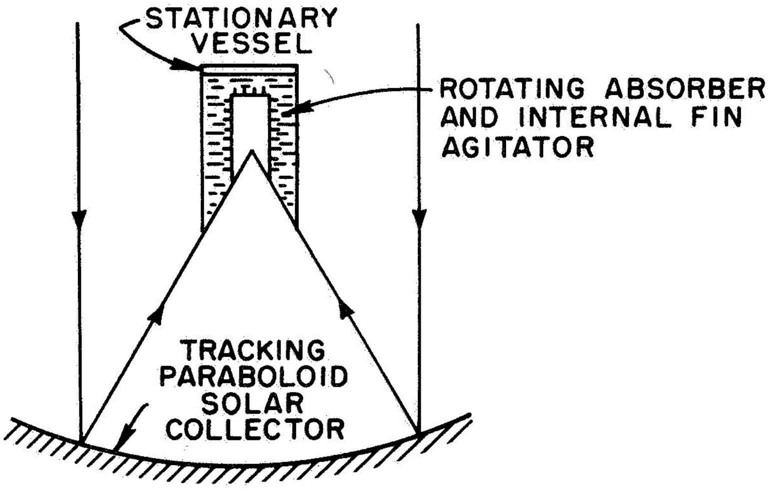
The rotary kiln is a versatile device for drying, calcining, and dehydrating. Several types of kilns can be used for extracting water on the lunar surface. Figure 15-1(a) illustrates a rotary kiln with a window across the aperture so that all the radiation falls upon the rock particles. Figure 15-1(b) shows a system in which the rock is heated between the absorber and the outer vessel wall. Figure 15-1(c) shows a system in which the rock is heated in an absorber which forms the outer vessel wall. Each of the latter two systems have a multiple array of cavities by which the concentrated solar radiation is absorbed.

Kilns can also be heated by electrical energy. A semi-continuous dehydrating system is shown in Fig. 15-2. It is divided into three sections, the loading hopper, the dehydrator, and the discharge compartment. The loading hopper is an air-lock capable of holding about 800 kg of crushed rock. It prevents the escape of water vapor from the dehydrator section during loading. An electrically operated gate opens at the top to permit loading. During this operation the lower end of the hopper is sealed from the dehydrator by a remotely controlled gate. The upper gate is then closed during the transfer of the rocks into the dehydrator. Each gate has a metal seal to keep vapor leakage at a minimum. The dehydrating compartment contains the condenser, the preheater, the dehydrator heat exchanger, and two flow control gates to discharge the rock with a minimum loss of water vapor.

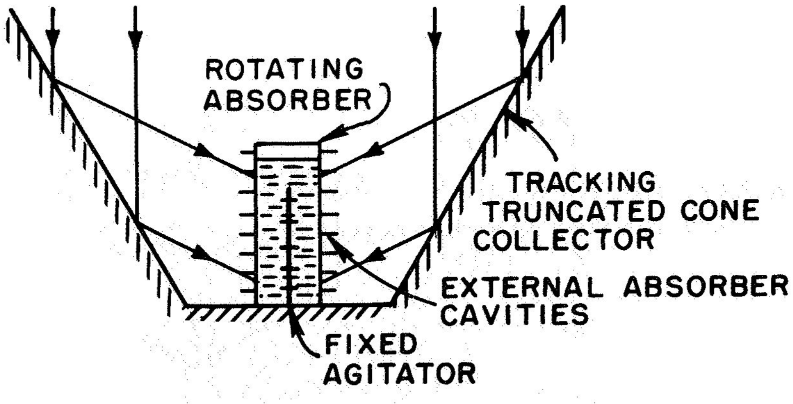
The numbers shown in Fig. 15-2 represent a design which will produce 4 kg of water per hour from altered "rhyolite." This requires the processing of about 280 kg of rock per hour. The temperature of the rock is raised to 900°K. It then falls to the bottom of the dehydrator and is removed in batches into the discharge compartment. To keep the system as simple as possible heat of the spent rock is not recovered. The steam that is given off travels through filters to the condenser contained in the preheat bed. Cold rock at the top of this bed acts as the heat sink for the condenser. Flow through the condenser is regulated to control the vapor pressure within the dehydrator. The condensed water is then drained into a reservoir.



a. Rotary kiln with window.



b. Vessel with internally heated absorber.



c. Vessel with externally heated absorber.

Fig. 15-1. Kilns for Direct Heating Processes.

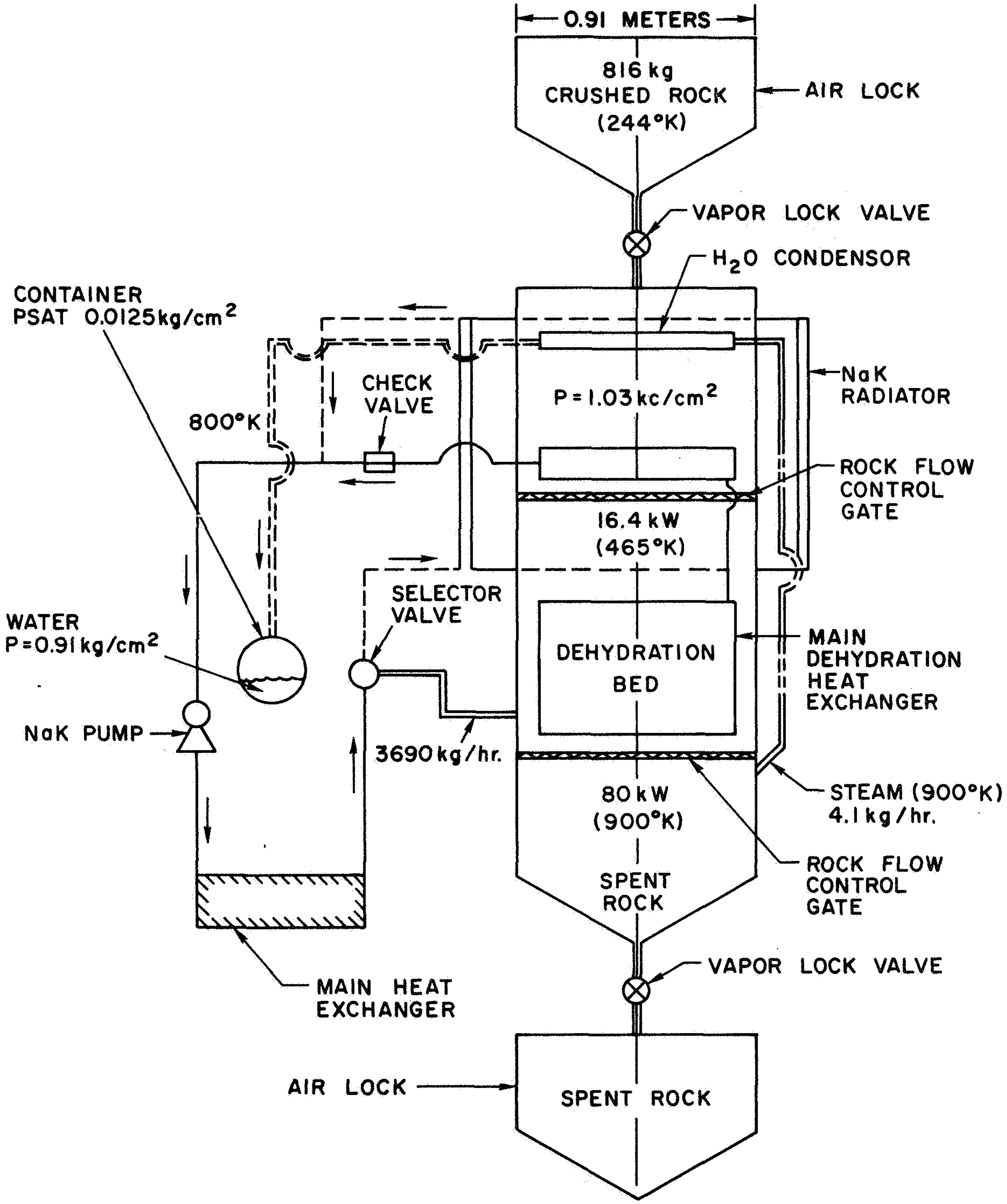


Fig. 15-2. Schematic of Semicontinuous Water Extraction System.

15.3.2 Fluidized Bed Processes

Fluidized bed reactors can also be used to dehydrate rocks containing water of hydration. They are similar to the rotary kiln; however, higher heat transfer rates can be achieved and more direct advantage is taken of rock preheat.

Figure 15-3 shows a design for radiant-heated fluidized bed processing. Crushed rock is ground to between 50 and 100 mesh and introduced into the upper bed where it is preheated by steam rising from the calcining zone. From the upper bed the rock overflows into the calcining zone which is maintained at 980°K by a circulating stream that passes through tubes located within the radiant heater. Before it is discharged, the rock leaving the calcining zone is cooled by incoming steam. The steam produced must be condensed in a radiation cooler.

15.3.3 Mining

The suggested methods of water extraction depend on a large quantity of crushed rock which will be obtained by blasting and strip-mining techniques. Four specialized pieces of equipment are needed for this operation, a multiple drill rig, a loader, a dump truck, and a rock crusher.

Figure 15-4 shows a concept for a multiple drill rig. It is sized to be able to turn around in underground tunnels. During drilling operations, which can be conducted at varying entry angles, the machine can be braced against the tunnel floor or walls by means of self-contained jacks. An attachment provides the means for automatic loading and tamping of explosive charges. Because high speed is not essential, the machine travels at a rate of up to 3 km/hr. Each drill can penetrate 3 m of hard rock per hour.

The other mining equipment is similar to conventional equipment except that power will be provided by fuel cells or thermionic devices, consequently, all drives will be electrical. The launch vehicle requires that all components must fit into a cylinder of 6 m diameter and that a minimum assembly time be required on the Moon.

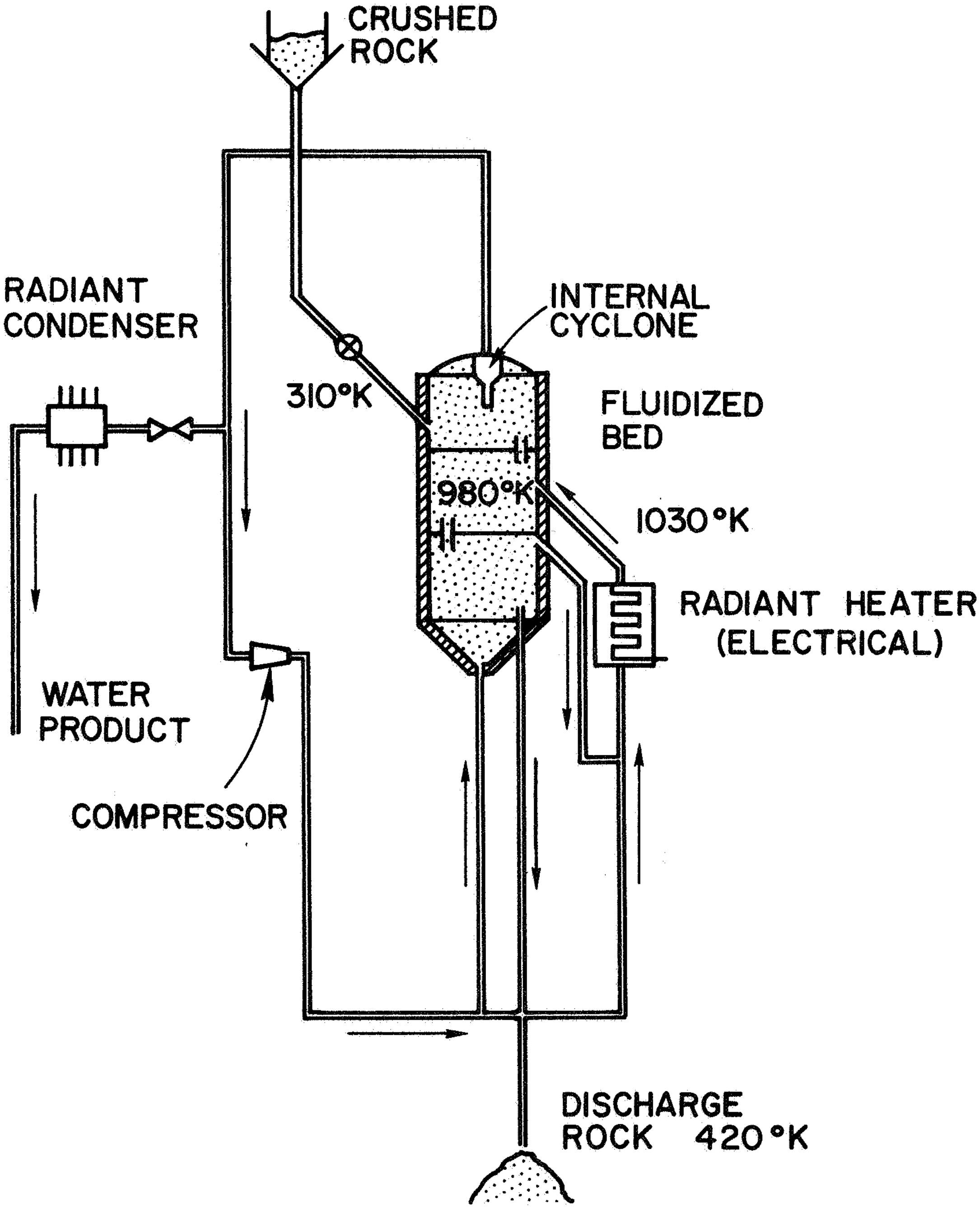
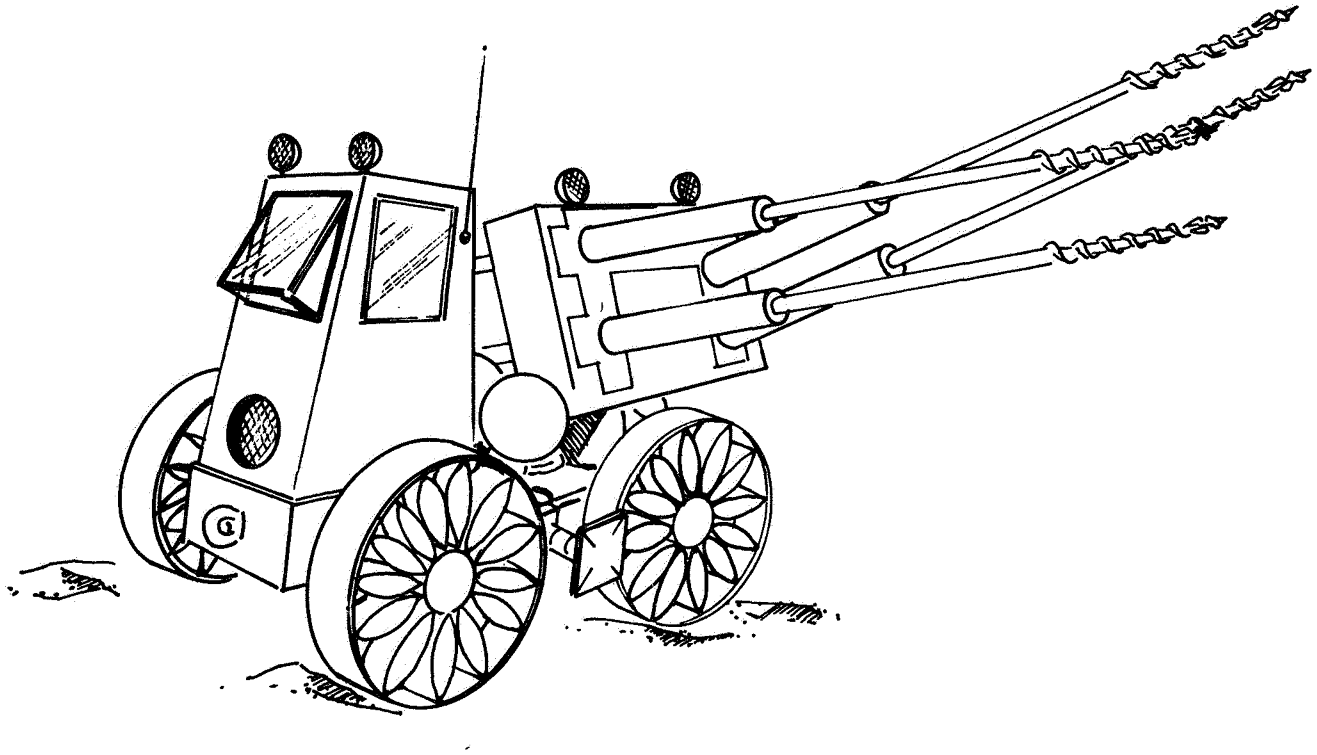


Fig. 15-3. Fluidized Bed Process for Water Extraction.



Source: North American Aviation, Inc. Space and Information Systems Division.

Fig. 15-4. Multiple Drill Rig.

15.3.4 Cost of Water Extraction

For purposes of estimating the cost of obtaining water on the Moon, it is assumed that the process involves dehydration by electric energy. If the rock contains 1 percent of moisture then 10 kW of energy will be required per kilogram of water. When the moisture content is reduced to 0.1 percent, the required energy is increased by a factor of 7, while for 10 percent moisture content the factor is decreased to about one third.

If 10^4 kg of water is extracted from material having a moisture content of 1 percent, a quantity of 10^6 kg of surface material must be mined by blasting or other means and made ready for pickup. For a rock weighing 1900 kg/m^3, 530 m^3 of rock must be picked up and transported an assumed distance of 150 m to the water extractor. The total energy required to pickup and transport 10^6 kg of surface material is approximately 1750 kW-h, or 0.175 kW-h/kg of water.

Figure 15-5 shows the energy requirement and cost of water extraction plotted against moisture content in the rock. It is estimated that electrical energy on the Moon will be available at 400 dollars/kW-h. The cost of extracting water by other means is assumed to be competitive or perhaps cheaper because of direct use of solar energy.

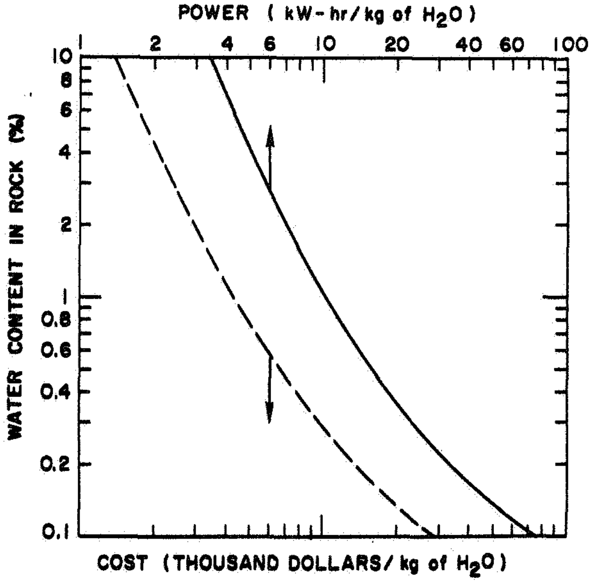


Fig. 15-5. Water Extraction.

15.4 Vacuum Technology

The Moon is superior in almost every way to Earth-orbiting vehicles as an astronomical observatory. The Moon environment eliminates the difficulties which astronomers find with the Earth's atmosphere, i.e., distortion and filtering of much of the radiant frequency spectrum. The establishment of a lunar astronomical observatory may provide some answers to such everyday problems as the origin of the universe and the existence of intelligent life in space. Some thought indicates that the answers to these questions may allow economic and social benefits to mankind of truly astronomical proportions. The vacuum of the lunar enrivonment may offer other yet unknown technological advantages.

In both analysis and synthesis, control is crucial. The vacuum on the lunar surface removes one variable and may allow many surprising breakthroughs, both in knowledge and technology of chemical processing and metallurgy. Utilizing vacuum and the temperature cycles on the Moon's surface and the minerals found on the Moon, it may be possible to produce known metals and ceramics and many new ones as well. Perhaps stronger, more efficient, and more reliable space vehicles could be built on the Moon than on the Earth.

A process for the production of magnesium and calcium is reported in which the reaction occurs at 1500°K and results in magnesium which is purer than ordinary electrolytic magnesium. The process occurs in two major steps:

(1) Calcination of dolomite ($CaCO_3$ - $MgCO_3$), and
(2) Reduction of calcine in small, batch vacuum retorts.

A second example of the use of ultra-high vacuum is in the production of thin films having precisely reproducible magnetic and electrical properties. Large quantities of solar cells will be used to generate the electric energy for the operation of the MOONLAB. These arrays require replacement at the rate of 10 percent per year. In the dehydration process of rocks, which are basically silicates, silicon is a byproduct that can be processed into a thin film by dendritic growth.

Single crystals of silicon could be formed into a ribbon 0.3 mm thick and 30 mm wide in a continuous process. Strips of this ribbon could then be assembled into panels to form the MOONLAB solar arrays.

The vacuum and the extreme surface temperatures on the Moon offer excellent opportunities for development and use of new electric and electronic technology. Transmission of electric energy over long distances can be performed efficiently in a vacuum. Electric motors, used for all motive power on the Moon, can be designed considerably lighter for operation in a vacuum and the absence of windage losses increases their efficiency to nearly 100 percent. Repair of metallic components is simplified by use of electron-beam welding which requires a vacuum environment. Metals which form oxide layers in the Earth's atmosphere may be readily joined in vacuum with joints as strong as the parent material.

15.5 Cryogenics

The development and application of cryogenic technology will be aided by the 120°K temperature on the lunar surface during the lunar night. The absence of convective heat transfer makes cryogenic techniques feasible even during the lunar day because shaded radiators can dissipate heat to outer space which is close to absolute zero temperature. Most significant among the uses of cryogenics on the Moon is the production of liquid hydrogen and oxygen from the electrolysis of water. Although the required temperatures are lower than the natural temperatures on the Moon, advantage will be taken of the lunar temperatures in reducing the energy necessary to liquify these gases.

Another application of cryogenics might be the generation of a magnetic field of high flux and high density. Such fields could be used as a deflecting shield against high energy protons and ions in galactic radiation.

REFERENCES

1. North American Aviation, "Study of Scientific Mission Support for Extended Lunar Exploration," December 1966.

Chapter 16

POST-1985 MOONLAB

In this chapter some estimates of MOONLAB activity and efforts in the post-1985 period will be made. It is assumed that the preceding program, or its approximate equivalent, has been accomplished.

It is estimated that one of two alternative situations, together with the possibility of conversion from one to the other, will prevail in 1985. These alternatives will be discussed in the last section of this chapter. Before this discussion, however, six points in the argument leading to the conclusions will be presented. After this, a dilemma concerning space science and a possible solution will be summarized.

16.1 The Six Points

(1) It seems reasonable to guess that by 1985, and with the accomplishments of the MOONLAB program, the popular glamor associated with a "man on the Moon" will have decreased to either zero or a very small fraction of what it currently is. The story of public reaction to nuclear weapons and the coolation of public opinion about the United States space program seem to be good examples. There seems to be no reason to think that public reaction to a lunar program will be qualitatively different.

(2) Rather obviously the military powers in this country have decided that there is little or no military advantage to be acquired from lunar operations. It is assumed that the military aspects of a lunar program will never be significant.

(3) It can be shown (Appendix F) that the use of a lunar base as a way-station for an Earth-planet mission is not advantageous unless (a) lunar water is available to manufacture rocket fuels and (b) the mission velocity requirement is in excess of the Earth-to-Moon transfer velocity. These "ifs" place the possible use of MOONLAB as an interplanetary base beyond the 1985-1990 period and perhaps into the 21st century.

(4) It is estimated that no one will be able to establish a direct lunar payoff to the Earth economy by 1985. In other words, no commercial profit-making lunar enterprise will have been discovered by 1985. Discoveries such as

inexpensive lunar water may be extremely beneficial to the lunar economy; however, the Earth economy will benefit from the lunar program only in indirect ways such as discussed in Chapter 4.

(5) In 1985 there will be plenty of science remaining on the Moon. For example, the single area of high resolution astronomical observation, for which a lunar base is extremely attractive, could extend a MOONLAB program indefinitely.

(6) It is estimated that the already established trend to evaluate and judge large national expenditures on a benefits/cost basis rather than a more superficial or emotional basis will continue and grow. The general effectiveness of appeals to national prestige will have decreased somewhat. The MOONLAB program as well as most of the space programs will have lost most of their ability to appeal to the public desire for national prestige. A national emotional surge, either for or against an ongoing MOONLAB program in 1985, is not likely to occur. Consequently, an even stronger than current necessity to justify a post-1985 MOONLAB program by cold hard numbers will probably exist in 1985.

16.2 The Dilemma

If point four above is a correct prediction and the others are even approximately correct, then a dilemma will exist in 1985, quite similar but perhaps somewhat more acute than the one existing now in the lunar program.

The dilemma is: no direct return to the Earth economy can be seen; advances in science can be seen with certainty; there is general acceptance of the proposition that science often eventually results in economic returns; a quantitative economic return due to advances in science ratio cannot be established; and, a favorable, quantitative benefits/cost ratio is highly desirable, if not necessary, to justify a large expenditure. The crux of the dilemma is that while science is valuable, it is impossible to be quantitative about how valuable.

One of the difficulties is that even scientists tend to arrive at judgments or conclusions which their colleagues consider (and believe demonstrably) unjustified. A very good example is the astronomy of deep space. It is very difficult to foresee that an advance in our understanding of the state, history, etc. of the far universe will give rise to an economic return to humanity. Nonetheless, it seems completely unscientific to conclude that it could not happen. Do you imagine that Galvani on observing the frog's leg twitch (assuming that the story is true) could have foreseen the present day electricity and electronics industry? Hardly, though one suspects a few current scientists secretly feel that they would have if they had been looking over Galvani's shoulder. Let's look the other way--ahead for a bit. Imagine that 10 years from now, an Earth-based laser and Moon emplaced corner reflector system will have detected gravitational waves absorbed by the Moon. Further, imagine that careful data and analysis have shown conclusively that these gravational waves must have had communications of intelligence coded into them. The conclusion that there is a lot for us to learn about gravitational phenomena would be forced on us. How many could foresee the technological and economic impact of these advances in understanding gravitation, i.e., if we make these advances? The inability to foresee an economic return from a given advance in science does not justify an assertion that there will be no economic return.

16.3 A Proposed Solution

A possible solution to the dilemma, and one which seems reasonable, requires that human society make the decision (through its governments) that a certain, small fraction of its productivity will be devoted to the pursuit of pure science, i.e., science for which no technological application or economic return can be foreseen. One could imagine, for example, this country investing 1/2 percent of its GNP into this kind of science. An integral part of such a policy would correspond to a recognition that ALL areas of science should, if possible, be advanced.

It seems obvious there would be many problems to be worked out. Hopefully the most efficient methods of buying the scientific advances would be found. In no circumstances is it reasonable to perform a scientific investigation on the Moon when it is possible to do that investigation on the Earth at 1/1000 the cost, or in an Earth orbit at 1/10 the cost. Hopefully, the governmental and scientific communities could construct, monitor, and maintain reasonable total programs with the only concern being that of obtaining advances-in-science returns.

16.4 The Two Alternatives for Post-1985 MOONLAB

16.4.1 No Exploitation Valuable to the Earth Economy is Found.

The primary MOONLAB activity is science--the lunar sciences, appropriate subareas within astronomy, astrophysics, and probably to a much smaller degree biological and behavioral sciences, physics, and chemistry. The word "appropriate" indicates that it must be shown, for each specific information bit or experiment, that the Moon is the only place or the most efficient place to acquire that information. There is little doubt that this alternative could extend the life of MOONLAB indefinitely, e.g., high resolution study of deep space could occupy man for a very long time. The major question is "what level of operation?" Science on the Moon is costly and there is a threshold cost. It is predicted that the wealth of scientific information to be acquired will ensure an ongoing MOONLAB program. However, depending upon the details of the station in 1985 and the accumulated experience, it is possible that MOONLAB after 1985 might be reduced to a 12-man, or even a 6-man operation.

16.4.2 Exploitation Valuable to Earth Economy is Found

This alternative is, of course, by far the more attractive one as well as being the least predictable. If some lunar product or service is established as a mechanism of profit in the Earth economy, then clearly the total lunar program will grow to a size determined by the specific details of the situation. It would seem likely that a single product becoming profitable to the Earth economy would initiate a chain reaction, by virtue of system improvements and increased efficiencies, of additional profitable products or services. In this alternative it would seem likely that more science, at a greater rate, and at a much reduced cost would result.

It is predicted that in 1985, alternative one will prevail; i.e., that no profitable to Earth economy exploitation will have been found. If and/or when a conversion to alternative two might occur appears to be completely speculative.

As a final bit of crystal-ball gazing, Appendix F, Section 2 contains a rough estimate of possible future transportation costs between Earth and Moon. MOONLAB is heavily constrained by transportation costs. The analysis in Section 2 of Appendix F shows that this constraint may soften.

APPENDICES

A – Personnel, Scientific Activities and Equipment

B – Human Engineering Information

C – Thermal Load Calculations

D – Comparisons of Power Systems

E – Communication System Calculations

F – Studies of Utopian Transportation System and Use of a <u>MOONLAB</u> as a Lunar Way-Station

Appendix A

PERSONNEL SCIENTIFIC ACTIVITIES AND EQUIPMENT

Table A-1

EVOLUTION OF MOONLAB PERSONNEL (1976-1985)

Three Men (1976-1978)

1	Geophysicist (competent in other physical sciences and in agriculture)
1	Engineer (capabilities in construction, life support, communications)
1	Physicist (with MD degree)

Six Men (1978-1981)

1	Geophysicist (agriculture)
1	Engineer (life support, communications, construction)
1	Physicist (Md, biology)
1	Engineering and Research Support Personnel
2	Astronomers (with competancy in other physical sciences)

Twelve Men (1981-1983)

1	Geophysicist
1	Engineer
1	Physicist
2	Engineering and Research Support Personnel
1	MD-biologist-physiologist
1	Biologist
1	Microbiologist (exobiology)
1	Agriscientist
2	Astronomers
1	Communications expert

Table A-1 (Cont)

Eighteen Men (1983-1984)

1	Geophysicist
1	Engineer
1	Physicist
1	Geologist
4	Engineering and Research Support Personnel
1	MD-biologist-physiologist
1	Biologist
1	Microbiologist
1	Agriscientist
1	Agronomist (life support)
1	Communications expert
4	Astronomers

Table A-2

ACTIVITIES AT MOONLAB (Measured in Man-Years)

Year	Construction	Life Support	Communi- cations	Physical Sciences and Technology	Biological and Behavioral Sciences	Astronomy	Total
1976	1.0	0.2	0.3	0.0	0.0	0.0	1.5
1977	0.0	0.2	0.3	1.5	0.5	0.5	3.0
1978	0.5	0.2	0.3	1.5	0.5	0.75	3.75
1979	0.2	0.3	0.5	2.0	1.0	2.0	6.0
1980	0.2	0.3	0.5	2.0	1.0	2.0	6.0
1981	1.0	0.5	1.0	4.0	2.0	2.0	10.5
1982	0.0	0.5	1.0	2.35	5.2	2.95	12.0
1983	1.0	0.5	1.0	3.0	5.0	3.0	13.5
1984	4.7	0.8	1.5	1.95	6.0	3.05	18.0
1985	0.0	1.0	2.0	5.0	5.0	11.0	24.0
1986	0.0	1.0	2.0	5.1	5.25	10.65	24.0
etc.							

Table A-3

SCIENTIFIC EXPERIMENTS AT MOONLAB

Phase A (completed prior to 1976)

I. Physical Sciences and Engineering

  A. Lunar Atmosphere

    Lunar atmospheric pressure at landing sites

    Charged atmospheric dust analyses with a charged dust spectrometer

  B. Geology

    Surface photogeology

    Visual subsurface logging for fine structure

    Sample collection from all sites and traverses

  C. Geochemistry

    Distillation of solids and differential thermal analysis

    Density measurements by flotation

    Chemical analysis using X-ray fluorescence at lunar base

    Chemical analyses using neutron activation at lunar bases

  D. Geophysics

    Measure spectral reflectance of lunar-surface materials

    Gravity, absolute, and its variations

    Heat flow, thermal blanket

    Seismic recording, passive

    Seismic velocity, surface

    Temperature gradient in borehole

    Temperature, shallow probe

    Meteorite measurements

    Thermal diffusivity, surface

    Thermal emissivity, surface

    Magnetic field, determine existence of permanent lunar magnetic field

    Magnetic field, total

  E. Particles and Fields

    Solar wind particles at lunar surface

    Magnetic field time variation at lunar surface

  F. Mission Support

    Dust removal technique

    Lunar geological-geochemical sample cassets

    Engineering properties of the lunar surface

II. Biological and Behavioral Sciences

  A. Biology

    Genetic effects of lunar conditions and Earth-lunar trips on microorganisms

    Soil bank, establish lunar sample depots at various locations on the Moon

III. Astronomy - none

Phase B (begun in 1977)

I. Physical Sciences and Engineering

A. Lunar Atmosphere

Electric field magnitude and direction at and near lunar surface

Time variations of lunar atmosphere pressure

B. Geology

Age dating of lunar rocks and formations

Detailed mapping of lunar surface geologic fine structure

Geologic mapping, general, including on-site verification of features identified from orbital experiments

Shallow drilling for subsurface structure and sampling

Sample collection

Paleomagnetism of the Moon

C. Geochemistry

Chemical analysis using X-ray fluorescence

Chemical analysis using IR spectrometer

Gamma-ray spectrometry on traverse

Chemical analysis of solids using mass spectrometer

Chemical analyses using neutron activation

Mass spectrometry near emission sources

Mass spectrometric analysis of gases on lunar surface

Mineralogical and petrographic studies by use of microscope

IR reflectance and emissivity in situ

UV and visible reflectance spectra in situ

Chemical analysis at base laboratory using chemical reagents, etc.

Chemical analysis using a nuclear magnetic resonance spectrometer

Mineralogical study with X-ray diffractometer in situ

Mineralogical study using an X-ray diffractometer

Density measurements by gamma scattering in situ

D. Geophysics

Earth ocean heat balance study

Sequential multiband ocean photography

Study of Earth atmosphere heat balance from lunar site

Study of Earth reflectivity and albedo

Study of Earth auroral and airglow emission

Ultraviolet scattering in earth atmosphere

Earth atmosphere sounding by passive infrared scanning

Subsurface hardness

Meteorite measurements, velocities, and momentums

Alpha particle mass spectrometer

Electrical permittivity, subsurface

Neutron flux and energy spectrum

Natural radioactivity at different lunar locations

Electrical permittivity, surface

Electrical surveying, earth current

Magnetic susceptibility, subsurface

Self potential, subsurface

Gravity survey on traverses

Plasma potential variations versus height and time

Magnetic field, total field surveying

Seismic profiling, shallow refraction

Resistivity, subsurface

Magnetic susceptibility, surface in situ

Magnetism, remnant

Magnetic field, total, ESS

Electrical surveying, subsurface

Temperature profile in deep borehole

Surface and subsurface gamma ray spectroscopy

Seismic recording, passive, (long period, short period)

Thermal diffusivity, borehole

Seismic profiling, shallow reflection

Magnetic field components

Temperature, borehole logging

Electrical survey, surface

Resistivity of lunar surface materials in situ

Seismic recording, large array

Seismic profiling, deep refraction

Neutron activation experiment

Electrical surveying, deep formations

Gravity, absolute

E. Particles and Fields

Solar-charged particle enviornment at surface, 0.01-0.5 MEV, later activity

Solar-charged particle environment at surface, 0.01-0.5 MEV, later phase

Solar-charged particle environment at surface, 0.01-0.5 MEV

I.D. (continued)

Observe spectrum of outer solar corona

Solar and galactic radiation environment at lunar surface

Electrons escaping Earth auroral zones during geomagnetic storms

Galactic particle scattering and reactions

Vertical components of electrostatic field at and above lunar surface

Measure UV spectrum of solar flares

Monitor magnetic field strength and direction at lunar surface

Solar wind interaction with Moon and geomagnetosphere

Steady and slowly varying electrostatic field near lunar surface

F. Selenodesy

Selenodetic surveying to establish ground control for satellite mapping

Selenodetic astronomy observations for improving map accuracy

Gravity measurements at lunar surface to supplement surveying observations

G. Mission Support

RF ground wave propagation

Lunar optical astronomy test program

Solid state materials, effect of lunar environment

RF forward scatter techniques

Radiation shielding effectiveness of lunar soil

Shelter shielding and construction support properties of lunar soil

Lunar surface transmission line interactions

Damage to lunar equipment

Thermal radiation intensities and surface temperature gradients

Lunar environment effects on antenna systems

Retrodirective optical system techniques

Lunar strata electromagnetic propagation parameters

Temperature/density stratification of cryogenic liquids

Simulated personnel shielding from solar event protons

Electrical systems grounding

Electrode electrical coupling properties in lunar surface

Calibration of remote sensing techniques

Mechanical efficiency of man at reduced gravity

Work capability determinations on lunar surface

Repair techniques for major structural damage

Vision studies

Lunar drill bit technology

Gas requirements for lunar core drilling

Explosive energy coupling in lunar materials

Explosive techniques for surface modification

Detection of hydrogen in lunar materials using infrared spectrometer

Detection of hydrogen in lunar materials using neutron activation

Lunar RF noise, Part 1, low-frequencies

Lunar RF noise, Part 2

Antenna dust accumulation

Elastomer and polymer behavior

Static exposure effects on materials

Exposure effects on radiator materials

Corrosive action of lunar surface material

Effects of leakage from vehicles, shelters and space suits

Lunar atmosphere contamination effects of rocket exhaust

Early materials dynamic tests - machine elements

Early materials dynamic tests - thin film bearings

Early materials dynamic test - electrical components

Static and dynamic seals

Visual techniques in land navigation - astronaut vision

Visual techniques in land navigation - land recognition

Dangerous terrain warning techniques

Soil value variations in lunar terrain

Quantitative analysis of hydrogen in lunar material

Detection of hydrogen with a phosphorus pentoxide conductance cell

Lunar surface and subsurface electrical parameters

Dynamics and surface environment effects on long antenna structures

Biological contamination of lunar soil

Clinical monitoring

Lunar surface dust environment

RF subsurface propagation

H. Miscellaneous Basic and Applied Research

Corner reflectors for laser beams

Heat convection and flow of gases in enclosed spaces

II. Biological and Behavioral Sciences

A. Biology

Induced prebiotic chemistry

Evidence of existing life

III. Astronomy

Test the influence of lunar environment on optical telescope installation

High-resolution astronomical photos with 12-inch telescope

Cislunar wave propagation, study of medium

Lunar ambient vector magnetic field measurements

Cislunar wave propagation advanced central station

Cislunar wave propagation, advanced outliving Section A

Cislunar wave propagation, advanced outliving Section B

Einstein eclipse problem

Investigation of variable brightness extended surface phenomena

Medium and low-dispersion spectroscopy of stars, plantes, galaxies, etc.

Photo survey of sky, 1000-3000 angstroms, with 12-inch wide field telescope

Phase C

I. Physical Sciences and Engineering

A. Lunar Atmosphere

Electric field magnitude and direction at different lunar positions

Gas chromatography for identification of heavy gases

B. Geology

Formation stratigraphic correlation over large distances by coring, etc.

Subsurface sampling

C. Geophysics

Electrical permittivity, subsurface

Electrical permittivity, surface

Resistivity of near-surface materials in boreholes

Meteorite measurements on traverse

Gravity survey, regional anomalies

Magnetic susceptibility surface

Electrical surveying, surface

Resistivity of lunar-surface materials on traverses

Temperature, surface profile

Magnetic susceptibility, suface

Self potential, subsurface

Alpha particle mass spectrometer on traverse

Natural radioactivity on traverse

Magnetic field survey for determining models of lunar structure

Determine hardness of subsurface lunar material

Seismic profiling, deep reflection

Surface and subsurface gamma-ray spectroscopy

Magnetism, remnant, late exploration

Temperature and emissivity of borehole walls

Thermal diffusivity, borehole

Neutron activation experiment on traverse

Seismic velocity, subsurface logging

D. Particles and Fields

Galactic particle scattering and reactions, advanced

Galactic nuclei environment at surface, 100 MEV - 100+ BEV, later solar activity

Galactic electron environment at surface, 100 - 1000 MEV, later solar activity

Interplanetary magnetic field and distance geomagnetic field, including lunar limb measurements

Galactic electron environment at surface, 100 - 1000 MEV

Solar-charged particle environment at surface, 0.04-1000 MEV, later activity

Solar wind interaction with moon and geomagnetosphere including lunar limb measurements

Interplanetary magnetic field and distant geomagnetic field

Electrons escaping Earth auroral zones during geomagnetic storms, later solar activity

Galactic nuclei environment at surface, 100 MEV - 100+ BEV

Solar-charged particle environment at surface, 0.04-1000 MEV

E. Selenodesy

Seismic measurements to supplement gravity observations

Earth-Moon distance observations for determining liberations, etc.

F. Mission Support

Effects of breathing various gas mixtures

Use of lunar soil for microrganisms and higher plants

Earth reference gravimeter

Psychological studies

Bioassays of body fluids

Cardiovascular phenomena

Heat transfer in liquids through natural convection

Heat transfer in film and drop condensation processes

Characteristics of lunar ores - self welding

Particle adhesion in mechanical processing

Lunar dry cement and concrete applications

Chemical and differential thermal analysis for oxygen and CO_2 sources

Differential thermal analysis of potentially castable materials

Long-term static exposure effects on materials

Lunar impact sferics

Remote occulting disk as solar coronograph

Laser scatter propagation

Bone demineralization studies

Metals joining techniques in lunar surface construction and repair

Materials dynamic test program

II. Biological and Behavioral Sciences

A. Biology

Behavior and rhythms of planets under the lunar day-night cycle

Behavior and rhythms of animals under the lunar light/dark cycle

II.A. (continued)

Genetic effects of lunar conditions and Earth-lunar trips on plantes

B. Exobiology

Effects of low g on plants and animals

III. Astronomy

Investigation of the X-ray radiation from Sun, stars, galaxies and X-ray sources

High resolution study of X-ray sources

Interstellar medium distribution investigation

Lyman-alpha survey of the sky

Nondirectional radio astronomy

Photoelectric scanning data on extended objects

Photoelectric observations with the 12-inch telescope

I. Physical Sciences and Engineering

A. Geophysics

- Earth atmosphere density measurements by stellar refraction
- Study of nonterrestrial planetary atmosphere circulations
- Sea surface height measurements by use of lunar-based sensor
- Ocean heat balance study, layer phase
- Determination of planetary albedoes and reflectivities
- Study of earth atmosphere during terrestrial eclipse of sun
- Passive probe of earth atmosphere by microwave scan
- Observations analyses of earth atmosphere circulation

B. Particles and Fields

- Solar energetic electrons associated with solar flares
- Measure UV spectrum over solar disk
- Observe motion of solar chromospheric and coronal material in and above solar flares
- Galactic nuclei environment at surface, 100 MEV - 100+ BEV, later solar activity
- Galactic electron environment at lunar surface, 100-1000 MEV, later solar activity
- Galactic particle scattering and reactions, detailed studies
- Observe structure and sudden disappearances of quiescent solar prominences
- Measure UV and visible spectrum from point to point over solar disk; determine chemical composition
- Measure UV spectrum of solar flares, advanced
- Measure velocity of photospheric material in granulations
- Solar wind interaction with Moon and geomagnetosphere, several stations and solar eclipse event
- Interplanetary magnetic field and distant geomagnetic field, several stations
- Solar energetic electrons associated with solar flares, lunar limb stations
- Observe size and magnetic field of sunspots versus time
- Solar-charged particle environment at surface, 0.04-1000 MEV, later activity
- Measure size distribution versus time of solar photospheric granulations

C. Mission Support

- Lunar seismic environment
- Evaluation of algae strains
- Evaluation of hydrogenomonas strains
- Evaluation of hydrocarbon utilizing organisms
- Biological monitor and eco-system prototype
- Nuclear reactor emplacement assessment
- Electrical transmission line routes
- Effects of lunar conditions on plants
- Growth, development, reproduction and survival of plants
- Genetic effects of lunar conditions and earth-lunar trips on animals
- Growth, development, reproduction and survival of animals

D. Miscellaneous Basic and Applied Research

- Generation of high-intensity electron beams
- Solar furnace with controllable focal energy flux
- High-intensity arc generation in lunar environment
- Radiation cryostat
- Field emission optics
- Lorentzian plasma environmental physics

II. Biological and Behavioral Sciences

A. Biology

- Influence of lunar environment on circadian rhythms
- Threshold studies of physiologic deviation
- Tolerance studies to explore the mechanisms by which an organism or tissue reacts, defends itself, or ultimately breaks down
- Radiation studies
- Physiologic effects of confinement
- Cardiovascular effects of lunar environment
- Cross contamination during confinement
- Effect of lunar environment in intracellular enzyme systems
- Atmosphere control and revitalization effects on micro-organisms
- Dietary effects on bacterial flora
- Germ free ecological studies
- Outgassing of materials in closed environment over long times
- Physiologic deconditioning

B. Behavioral Science

Study of man's response to sensory and social improverishment

Personality adjustments during confinement

Group organizations

Study of interpersonal relationships

Evaluation of techniques of arbitration

Motivation during extended confinement

General psychological impairment during confinement

Authority relationships during long confinement

Group relations in multi-sized groups

Performance decrement in lunar environment

Sex-related tensions in a mono-sexual group during confinement

Study of effects to satisfy normal emotional needs

Use of post-hypnotic suggestion to reduce emotional stress

Evaluation of psychic and personality factors effecting adjustment to confinement

Study of relationship of IQ and cultural background to successful mission performance

Determination of sensory inputs important on long-term space flights

Psychiatric study of station personnel

Evaluation of adaptability indicators of station personnel

Investigate means for adding sensory variety to space station

Influence of variation of tasks on performance during confinement

Study of group dynamics during confinement

III. Astronomy

Photographic studies of faint and bright objects at high resolution, 40-inch telescope

Wide-band photographic photometry at very faint limits

Photoelectric photometry of selected objects

Medium- and low-dispersion spectroscopy of faint stars

High-dispersion spectroscopy of bright stars, nebulae, etc.

Spectral scans of various objects

Directional radio astronomy using interferometer

Detection of high-energy gamma rays

Lunar wave propagation experiment

Phase E

I. Physical Sciences and Engineering

A. Geology

Deep-drilling for subsurface structure and sampling

B. Geophysics

Measurements of temperature and composition of planetary atmospheres

Sequential multiband ocean photography, later phase

C. Particles and Fields

Interplanetary magnetic field and distant geomagnetic field with added measurements from lunar orbiter

Solar and galactic neutrino sources

Magnetohydrodynamics of solar wind flow past Earth and Moon

D. Miscellaneous Basic and Applied Research

Lifetimes of atomic species

II. Biological and Behavioral Sciences

A. Agricultural Science

Investigation of lunar farm soils

Optimization of lunar crops

New crops for the lunar diet

Lunar processing of crops

Plant adaptability studies

Study of intensely lighted greenhouses

Moon soil organisms

III. Astronomy

Submillimeter radio astronomy experiments

High-resolution photographic studies with diffraction-limited 100-inch telescope

High-dispersion spectroscopy of stars, planets, nebulae, comets, etc.

Systematic observations of high-energy stellar phenomena

Determination of nature and extent of stellar outer envelope

Photo survey for planet-like companions of stars

Photoelectric magnitude and color index measurements of stars

Lunar Orbiting Phase

I. Physical Sciences and Engineering

A. Geology

Geologic base maps from unmanned lunar orbiters

Photogeologic mapping from lunar orbit

B. Selenodesy

Selenodetic mapping to establish detailed topographic lunar maps

Gravity observations from lunar orbit to supplement surface observations

C. Geochemistry

IR reflectance and emissivity from orbit

UV and visible reflectance spectra from orbit

Mass spectrometric analyses from lunar orbit

Gamma-ray spectrometry from lunar orbit

D. Geophysics

Determination of surface and subsurface structure and formations by use of high resolution radar

Passive microwave determination of surface temperature and formations

Gravity gradient from orbit

Orbital gravity gradient for moment-of-inertia calculations

Magnetic field mapping from orbit

Temperature probes emplaced from lunar orbit

Meteorite counter in orbit

Orbital gamma-ray spectroscopy

Remote seismic station

Spectrazonal photography to determine lunar-surface temperature and geologic formations

E. Particles and Fields

Anistropy versus charge and energy of solar and galactic particles

Solar wind particles in shock front near Moon

Magnetic field in solar wind shock front near Moon

F. Mission Support

Sterophotogrammetry

Earth RFI and background radio noise

Dielectric properties of the lunar sphere

Topography of proposed AAP LEM landing sites

Soil bearing strength of proposed LEM landing sites

Critical plasma frequencies of orbit-to-moon transmissions

II. Biological and Behavioral Sciences - none

III. Astronomy

Electric field measurement from lunar orbit

Magnetic field measurement from lunar orbit

Particle flux measurements from lunar orbit

Table A-4

EQUIPMENT REQUIREMENTS

Equipment Needed for Phase A Activities

Redhead Pressure Gauge
Charged Dust Spectrometer
Pulse Height Analyzer
Scaler
Pulse Length Analyzer
LEM TV Monitor
Set of Liquids for flotation density measurements
Differential Thermal Analysis Apparatus
Glassware for collecting vapors
Thermobalance
Geophone
Seismic Amplifier
Time Base Generator
Tape Recorder
Interferometer Spectrometer
Reflection Grating Spectrometer
Pulse Height Analyzer
Meteoroid Detector
Temperature Probe (Thermocouple) (6)
Thermocouple Amplifier
Surface Thermal Blanket
Total Radiation Pyrometer
Heat Source, Shield
Temperature Probe
Gravimeter
Magnetometer
Astronaut Surveying Staff
Periscope
X-ray Fluorescence Activated by Gamma rays
DC Supply
Electrostatic Ballistic Pendulum
Interval Timer
Lamont 4 Component Seismometer
Thermocouple (8)
Borehole TV
Curved Plate Electrostatic Plasma Spectrometer
Triaxial Fluxgate Magnetometer

Equipment Needed for Phase B Activities

Electric Field Meter
Photographic Astronomical Transit
Chronograph
Television Unit
Phototheodolite
Surveying Tape
Surface Pendulum
Lunar Geological Tool Kit
Mapping Kit
Thin Sectioning Equipment
Petrographic Microscope
Geologic Sampler
Containers
Core Containers
Drill, 1-3 meters
Drill, 3-10 meters
Fluxgale Magnetometer
Neutron Activation Analysis Equipment
IR Spectrophotometer
Attenuated Total Reflectance Attachment
Nuclear Magnetic Resonance Spectrometer

Equipment Needed for Phase B Activities (Continued)

Inorganic Chemical Reagents
Standard Solutions of Chemical Reagents
Chemical Lab Equipment
X-ray Diffractometer and Accessories
Petrographic Microscope
Sectioning Equipment
Mass Spectrometer for solids
Gamma Source and Detector
UV and Visible Recording Spectrophotometer
Gamma-ray Spectrometer
Quadruple Mass Spectrometer for Gas Analysis
fitted with a pump
Seismic Amplifier
Magnetic Susceptibility Bridge
Geologic Hand Tool
Resistivity Probe
Inductance Bridge
Subsurface Resistivity Probe
Contact Electrode
Meteorite Detector
Preamplifier/Amplifier
Neutron Phaswich Detector
Scintillation Detector
Amplifier
Alpha Particle Source
Solid State Detector for gamma particles and protons
Geiger-Muller Counter
Neutron Generator
Geophone
Time Standard
Ranger Seismometer
Geodimeter
Magnetic Variometer
Electromagnetic Antenna
Electromagnetic Surveying Transmitter
Electromagnetic Surveying Receiver
Hand Tool for Rock Samples
Subsurface Penetrometer
Bolometer
Amplifier-Preamplifier
Subsurface Heat Source
Variable Potential Plasma Probe
10-meter Pole, insulated
Magnetometers
Telescope, 6" reflecting
Bolometer
Photomultiplier
Spectrograph - Astronomical
Plate Holder - Cassegrain Focus (5)
Astronomical Chronometer
Interference Filters (6)
Rollfilm
Telescope - 6" plus accessories
Bolometer - Scanning Device
Film and Processing Chemical Package
Charged Particle Spectrometer
Total Radiation Dosimeter
Cosmic Ray Charged Particle Solid State Spectrometer
Telescope
Faraday Cup Plasma Spectrometer

Equipment Needed for Phase B Activities (Continued)

Plasma Probes
Collapsible Pole, 10 meters
Faraday Cup Plasma Spectrometer
Electrostatic Field Meter (3)
Electric Field Meter
Pole, 10-meter
Liquid Hydrogen Bubble Chamber
Telescope, 8"
UV Scanning Photometer
UV Spectrograph
Lab Equipment for Prebiotic Chemistry
Gas Chromatograph
Compressed Gases for Prebiotic Chemistry
Chemicals for Prebiotic Chemistry
Optical Filters for Prebiotic Chemistry
Biological Autoclave
Miscellaneous Lab Equipment
Photomicrographic Cameras with Microscope
General-purpose Incubators (5)
Culture Media
Recording IR Spectrophotometer
Bacteriological Culture (20)
Telescope, 12"
Microscope
Photographic Film Holder (2)
Photographic Film Development Equipment
Photoelectric Photometer for 12" Telescope
Stellar Spectrograph for 12" Telescope
Telescope, 12" Wide-Field
5" Photographic Refractor
Metastable Helium Magnetometer (2)
Two-frequency Transponder and Antennas
Three-frequency Transponder and Antennas (3)
Oscillator
Capacitor Bridge
Scintillation Detector
Solid State Electron Spectrometer (2)
Pulse Height Analyzer - 100 channel

Equipment Needed for Phase C Activities

Gas Chromatograph
Radar Unit
Explosive Charge
Seismometer
Subsurface Sampler
Drill, 30 meter
Magnetic Susceptibility Bridge
Meteoroid Detector
Pulse Analyzer
Pressure Recorder
Drill Rate Meter
Electromagnetic Subsurface Probe Antenna
Electromagnetic Pulse Transmitter
Focused Heat Source
Microwave Radiometer
Preamplifier, Amplifier
Solid State Counter Telescope System
Cerenkov Detector Telescope System
Pulse Height Analyzer
Nuclear Emulsion, Stack (4)
Scintillation Particle Spectrometer Telescope
Pulse Height Analyzer
Faraday Cup Plasma Spectrometer
Collapsible Pole - 100 meter (2)
Rubidium Vapor/Magnetometer
Metastable Helium Magnetometer
Liquid Hydrogen Bubble Chamber

Equipment Needed for Phase C Activities (Continued)

33 mm Camera
Balances, Recording Analytical (2)
Plastic Bottles (50)
Plastic Cylinders, Graduated (20)
Plant Growth Chamber - 500 ft^2
Plants
Animal Cells for Genetic Effects Experiment
Plant Containers
Plant Nutrients
Soil
Synthetic Soil
Photoelectric Field Scanner
Lyman Alpha Camera
Variable Resolution Telescope
Photointerpretation Display
Mapping Computer
Spectrometer
IR Detector
Data Recording System
Chemical and Biological Laboratories
Remote Life Detection Device (Gulliver, Wolftrap)
Meteorological Network
Sample Collection Kit
Theodolite Equivalent
Markers
Glove Box
Microbiological Culture Equipment
Respirometer
pH Meter
Centrifuge
Atmosphere Samplers
Shaker
Staining Kits
Terrestrial Simulator
Accelerograph
Dye Injectors
CO_2 Rebreathing Equipment
Ultrasonic Equipment
ECG
Stethescope
Phonocardiograph
Cuff and Sphygmomanometer
Transparent Cuff
Ergometer and Ancillary Equipment
Biological Laboratory
Pneumotachygraph and Integrator
Electronic Integrator
Microelectrodes
EEG
Signal Conditioner Modulator to Oscillograph
Orthorater
Audiometer
Mystagmograph (with Leads and Electrodes)
Ear Syringe
Thermisters
EEG Implants
X-Ray
Gravity Independent Device for Body Mass
Dynamometer
Tape Measure
Electromyograph
Dye Injection Kit
Counter Chamber
Recorder
Refractometer
pO_2 Sensor
pCO_2 Sensor

Equipment Needed for Phase C Activities (Continued)

Geiger Counter Module Telescope Assembly
36" Grazing Incidence Reflector
Radiometer
Rapid Burst Radiometer
Phase Detector

Equipment Needed for Phase D Activities

Telescope, 40" Reflecting
Field Correcting Lens
Astronomical Spectrograph
Radiotelescope, 20' dish
Millimeter Wave Detector
Laser Ranging Device
Film and Processing Chemical Package
Cerenkov Electron Spectrometer (2)
Liquid Hydrogen Bubble Chamber
Telescope, 40", UV Optics
UV-IR Scanning Photometer
UV-IR Spectrograph
Motion Picture Camera
Photographic Plates (100)
UV Spectrograph
Photoelectric Photometer - 40" Telescope
Astronomical Spectrograph
Astronomical Coude Spectrograph
Spectral Scanner - 40" Telescope
Solid State Gamma Ray Telescope
Remote Dipole Array Antenna
Central Dipole Array Antenna
RF Transmitter
RF Receiver
Transmitter and Matched Antennas
VHF Control and Data Transmission Unit
Field Strength Meter

Equipment Needed for Phase E Activities

300 m Drill
Telescope - 100"
Millimeter Wave Detector
Film plus Processing Chemical Package
Meson Spectrometer System
Faraday Cup Plasma Spectrometer
Metastable Helium Magnetometer
Spectrograph - 100" Telescope
Photoelectric Photometer - 100" Telescope
Submillimeter Radiometric System

Equipment Needed for Orbit Activities

Photogrammetric Camera
Pendulum
Orbital TV
Orbital IR Scanner (2)
Orbital Mapping Radar
Radiometer
9" Camera
70 mm Camera (2)
4.5" Camera
UV and Visible Recording Spectrophotometer
Quadrupole Mass Spectrometer with Pressure Intensifier
High Resolution, Orbital, Mapping Radar
Spectrazonal Camera
Acoustic Transducer

Equipment Needed for Orbital Activities (Continued)

Orbital Microwave Radiometer
Temperature Probe
Orbital Gravimeter
Total Field Airborne Magnetometer
Charged Particle Spectrometer
Electric Field Meter
Electrostatic Analyzer
Faraday Cup

Appendix B

HUMAN ENGINEERING INFORMATION

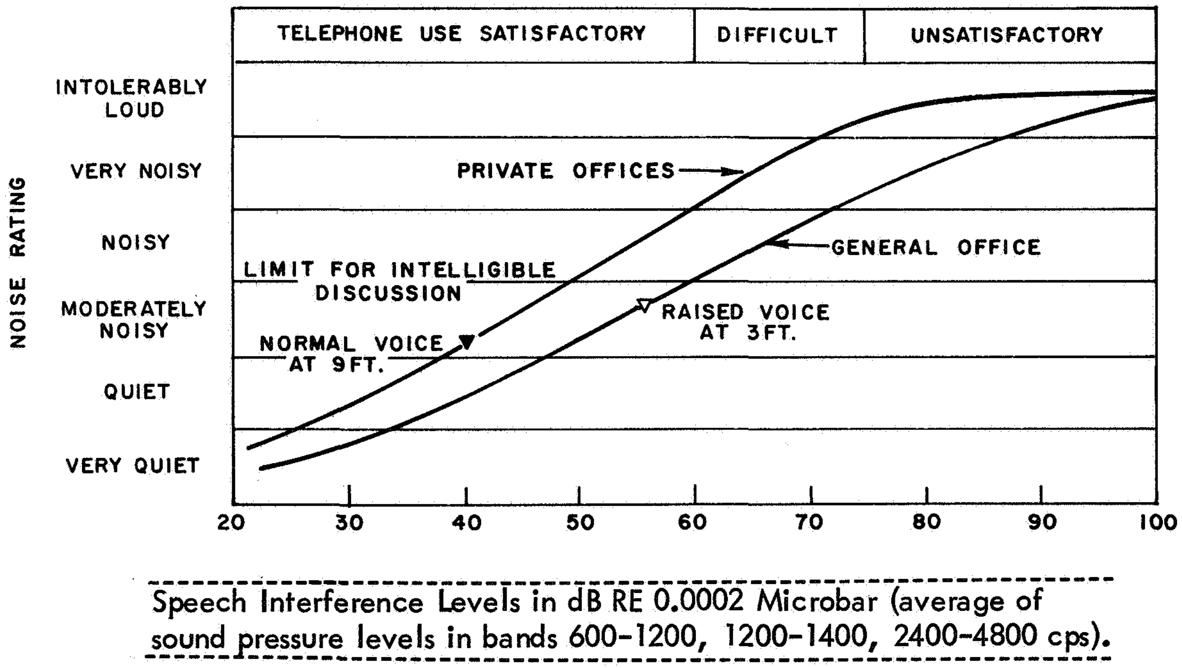


Fig. B-1. Acceptable Noise Levels.

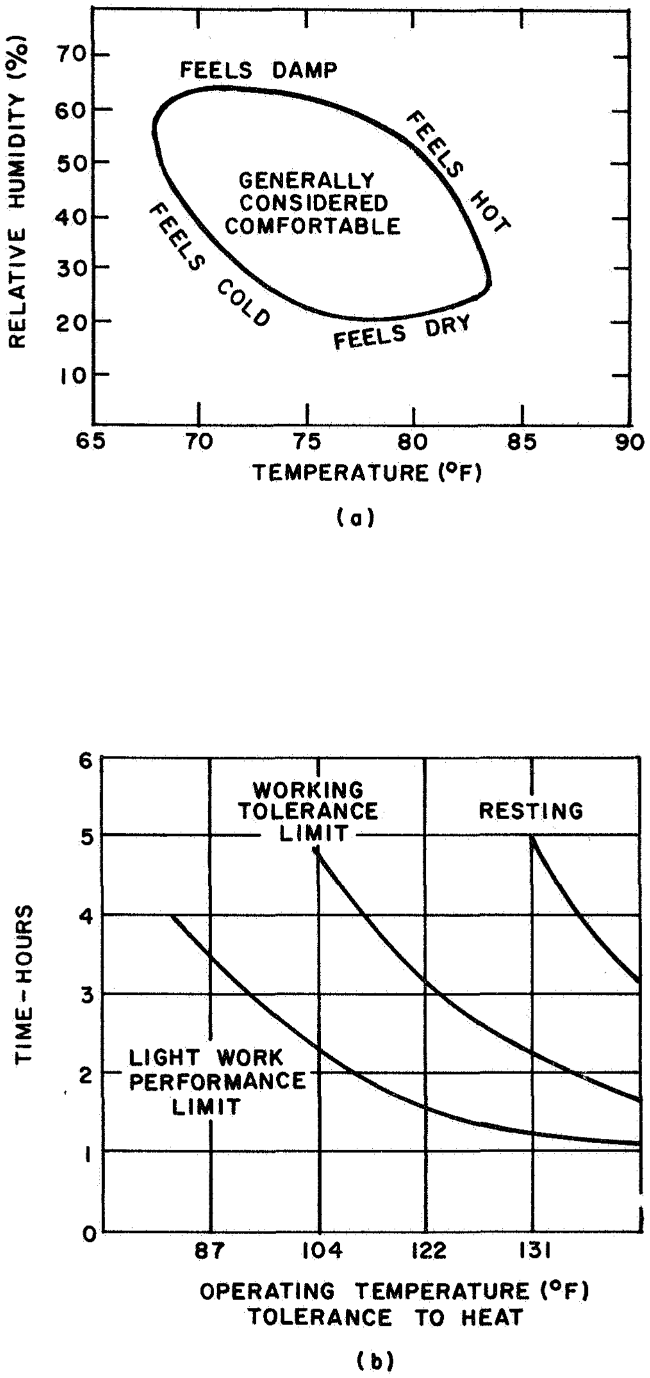


Fig. B-2. Temperature and Heat Tolerance.

Table B-1

GENERAL ILLUMINATION LEVELS

Task Condition	Level (foot candles)	Type of Illumination
Small detail, low contrast, prolonged periods, high speed, extreme accuracy	100	Supplementary type of lighting. Special fixture such as desk lamp.
Small detail, fair contrast, close work, speed essential	50-100	Supplementary type of lighting.
Normal desk and office-type work	20-50	Local lighting. Ceiling fixture directly overhead.
Recreational tasks that are not prolonged	10-20	General lighting. Random room light, either natural or artificial.
Seeing not confined, contrast good, object fairly large	5-10	General lighting.
Visibility for moving about, handling large objects	2-5	General or supplementary lighting.

Table B-2

SPECIFIC RECOMMENDATIONS, ILLUMINATION LEVELS

Activity	Level (foot candles)
Reading	40
Writing	40
Kitchen	50
Mirror (shaving)	50
Laundry	40
Workbench	50
Typing	50
Transcribing	40
General Correspondence	30
Examination Room	100
Dental-surgical	200
Operating Table	1800

Table B-3

MAN VS MACHINE

Man Excels in	Machines Excel in
Detection of certain forms of very low energy levels	Monitoring (both men and machines)
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Detecting signals in high noise levels	Exerting great force, smoothly and with precision
Ability to store large amounts of information for long periods - and recalling relevant facts at appropriate moments	Storing and recalling large amounts of information in short time-periods
Ability to exercise judgment where events cannot be completely defined	Performing complex and rapid computation with high accuracy
Improvising and adopting flexible procedures	Sensitivity to stimuli beyond the range of human sensitivity (infrared, radio waves, etc.)
Ability to react to unexpected low-probability events	Doing many different things at one time
Applying originality in solving problems; i.e., alternate solutions	Deductive processes
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to perform fine manipulations especially where misalignment appears unexpectedly	Ability to repeat operations very rapidly, continuously, and precisely the same way over a long period
Ability to continue to perform even when overloaded	Operating in environments which are hostile to man or beyond human tolerance
Ability to reason inductively	

The properties of the atmosphere considered for the lunar base and for air are given in Fig. B-4 for the purpose of making the comfort zone extrapolation.

Table B-4

ATMOSPHERIC PROPERTIES [1]

	Atmosphere	
	14.7 psia air	5 psia O_2N_2
Mol. Wt.	29	31
bTU/^{k}ft-h-°R	0.0151	0.0153
ρ #/ft^3	0.076	0.268
Cp bTU/#-°R	0.24	0.23
μ#/ft-th	0.0421	0.0465
d, ft^2/sec steam × 10^{-3}	0.264	0.756
α, ft^2/sec × 10^{-3}	0.238	0.707
N_{Le}, α/d	0.902	0.035
Nρr, Cpμ/k	0.67	0.70

B.1 General Population Stereotype Reaction (Woodson)

Handles used for controlling liquids are expected to turn clockwise for off and counter-clockwise for on.

Knobs on electrical equipment are expected to turn clock-wise for on, to increase current, and counter-clockwise for off or decrease in current. (Note: This is opposite to the stereotype for liquid.)

Certain colors are associated with traffic operation of vehicles, and safety.

For control of vehicles in which the operator is riding, the operator expects a control motion to the right or clock-wise to result in a similar motion of his vehicle, and vice-versa.

Sky-earth impressions carry over into colors and shadings: light shades and bluish colors are related to the sky or up, whereas dark shades and greenish or brownish colors are related to the ground or down.

Things which are further away are expected to look smaller.

Coolness is associated with blue and blue-green colors, warmness with yellows and reds.

Very loud sounds or sounds repeated in rapid succession, and visual displays which move rapidly or are very bright, imply urgency and excitement.

Very large objects or dark objects imply "heaviness." Small objects or light-colored ones appear light in weight. Large, heavy objects are expected to be "at the bottom." Small light objects are expected to be "at the top."

People expect normal speech sounds to be in front of them at approximately head height.

Seat heights are expected to be at a certain level when a person sits down.

Safety - Design environmental system (including backup) to maintain normal Earth-bound environment. Provide instantaneous warning of failure or any element.

Provide continuous biomonitoring of all occupants.

Provide adequate seating and restraints for attentuation of access accelerations during launch, re-entry, landing, tumbling, etc.

To overcome problems of weightlessness, provide "assist" devices (handholds and footholds), eliminate sharp corners and edges, imbed protruding controls, etc.

Consider Coriolis effects on human locomotion and dexterity (in case of a rotating, artificial g station).

Provide adequate protection from solar flare radiation.

Provide quick and simple detection and location system for meteoroid punctures.

Provide eye protection at all windows from direct sunlight.

Provide adequate escape and survival system for all conditions to be encountered: space, airborne, water, land, etc.

Provide safety lines for all personnel performing outside the space vehicle or station.

Provide compartmental isolation in the event of fire, explosion, pressure loss, etc.

Provide independent power systems to maintain uninterrupted operation of any part of the vehicle or station left intact in the event of a partial accident or station damage.

Safety Hazard Check List

Stumbling or Tripping - This type of hazard is caused by allowing objects to be placed in the direct path of people. It is amplified when illumination is poor, or people have to traverse the pathway with their arms loaded with equipment, or they have to hurry throughout the area.

Slipping - Surfaces which are highly polished or become very slick when wet, and areas subject to oil drippings, etc., invite disaster!

Bumping the Head - Can be caused by low overhead or objects which have been placed too low. If low overheads or equipment cannot be avoided, these should be well marked, padded, and illuminated. Personnel should wear protective head gear. Another type of head injury comes from things being dropped from above. Screens should be provided to catch falling objects--or in the case where construction is underway, hard hats should be worn by all personnel in the area.

Bumping Sharp Corners or Edges - All projecting corners or edges should be eliminated from equipment if there is any chance of a person's body coming in contact with the equipment. If the projections cannot be removed or the corners smoothed, these should be padded to reduce the possibility of injury.

Snagging - Catching the body or clothing on parts of equipment or metal trim may cause injury directly or even indirectly if the person is momentarily thrown off balance and into some even more dangerous situation.

Electricity - Burns or even death may result from the human body shorting across uncovered electrical leads. One must consider not only the insulation of wiring and electrical parts, but also other metal surfaces and floor. Special care should be taken to anticipate the possibility of liquids falling on wiring, thus causing shorts. Even a light electrical shock could cause a person to react in such a way as to injure himself in jumping back from the shock point and striking other equipment, or falling off a work stand.

Burns - From hot metal, glass, liquid, steam, air, or acid should be anticipated in the design of all equipment and work stations.

Pinching or Mashing - Anticipate the possibilities of the worker or user catching his hand in a door, or between a chassis and cabinet, or letting a heavy component down on fingers because of lack of adequate handles. Even tools and the location of tool attachments must be considered in their potential for pinching fingers, cracking knuckles, etc.

Falling - When there is a possibility of causing a worker or operator to lose his balance because of equipment motion, it is the responsibility of the designer to provide security against this--guard rails, safety belts, handholds, non-slip flooring, etc.

Acceleration - Acceleration, deceleration, impact shock, and oscillation are all considerations which the designer must face. These should be limited to the ranges which can be withstood by human beings. Seats should be provided to attenuate the transmitted energy.

Noise - Deafness-avoidance criteria must be adhered to in all cases. In addition, noise may lead to a worker not hearing another safety signal, or the eventual fatigue produced by continuous noise may lead to increased carelessness.

Bright Light - Flash blindness is a consideration in certain military operations. In addition, temporary blindness from a bright light may cause the operator to miss other important signals which lead to even more hazardous conditions. The nuclear age has also introduced the problem of retinal burns from rockets, nuclear explosions, etc.

Toxic Substances - Materials or substances which are toxic to the skin or through chemical reaction create fumes which may be poisonous must be avoided.

Atmosphere and Pressure - Not only should these environmental conditions be maintained within normal human tolerance ranges, but due consideration must be given to the potential hazard of such conditions being borderline--causing a reduction in human efficiency and leading to the man endangering his own life because of poor reaction to operating conditions.

Temperature - Hot or cold environments as well as hot or cold materials are hazards which must be anticipated and guarded against in design. Sweat on the hand may lead to an accident. Stiffness in the fingers may cause a man to drop a tool or component.

Physical Strain - Lifting a component which is too heavy can cause a rupture, or cause the operator to drop the item on his fingers or foot.

Radiation - Protection from electromagnetic and particulate ionizing radiation is important not only in space, but also in design and location of radar equipment.

Explosion and Fire - Although these hazards are among the most common, too many designers give too little thought to the cause and prevention of such hazards.

Note: All designers should perform a complete hazard analysis of each design problem to determine all safety hazard possibilities--and then take steps to design these hazards out of their hardware.

Appendix C

THERMAL LOAD CALCULATIONS

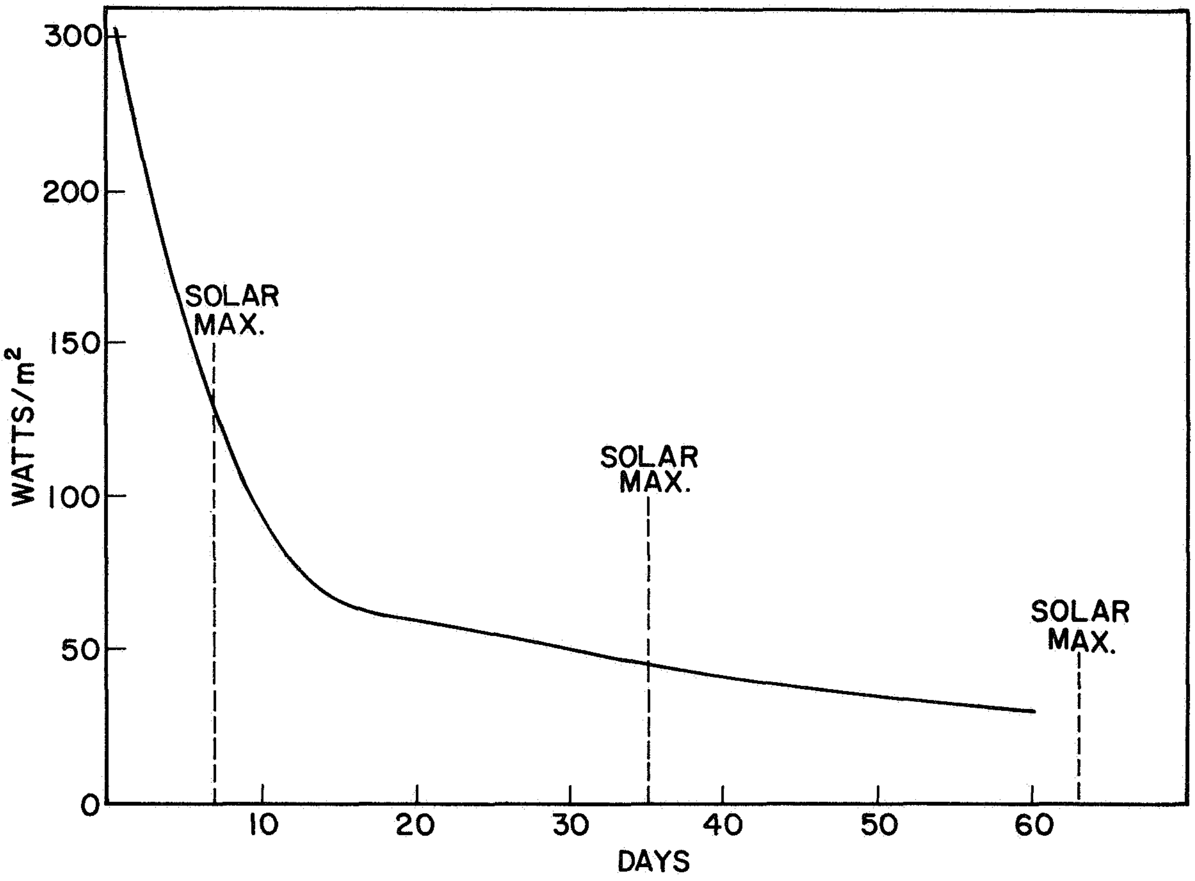
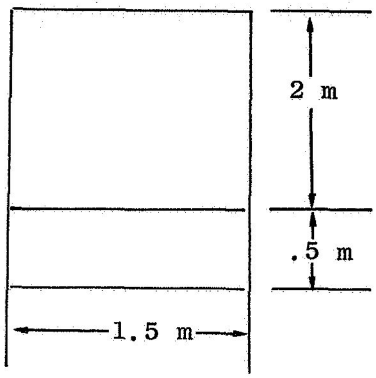


Fig. C-1. Heat Flux From A Buried Structure Maintained at 22°C to Lunar Subsoil.

Curve adapted from ASD-TR-61-119, Part II, September 1962, "Radiation Heat Transfer Analysis for Space Vehicles."

2 m tunnels except for astronomy



Shield 38 × 18 m

Tunnel weight ~ 100 lb/ft

8 tunnels - 2 m

3 airlocks - 2 m

2 tunnels - 5 m

2 tunnels - 8 m

Tunnels:

(1) Buried area = .5(2)2 + 1.5 × 2 = 5 m^2/2m = 2.5 m^2/m

(2) Total buried = 8(2 × 2.5) + 3(2 × 2.5) + 2(5 × 2.5) + 2(8 × 2.5)

= 55 + 25 + 40

= $\underline{120\ m^2}$

(3) Exposed area = 2(2 × 2) + 1.5 × 2 = 11 m^2/2m = 5.5 m^2/m

Total exposed = 11(11) + 2(5.5 × 5) + 2(5.5 × 8)

= 121 + 55 + 88 = $\underline{264\ m^2}$

(4) Shelter area exposed = 150 × 7 = 1050 m^2

(5) Shelter area buried = 8(29.4) + 150 = 235.2 + 150 = 385 m^2

(6) Total exposed area for radiation = 1050 + 264 = 1314 m^2

(7) Total area for conduction = 385.2 + 120 = 505.2 m^2

(8) Heat loss from inhabitated areas $= q_T = [.114(1314)(297-T_{sink})$

$+ (10 \times 3.154)(505.2)]\ 10^{-3}$

$= .150(297-T_{sink}) + 15.9$

T_{sink} °K	Δt	q_{rad}	q_{cond}	q_{total}
10	287	43.0	15.9	58.9
50	247	37.1	15.9	53.0
100	197	29.6	15.9	45.5
150	147	22.1	15.9	38.0
200	97	14.6	15.9	30.5
250	47	7.1	15.9	23.0

(9) Shield area $= 38 \times 18 + 10 \times 11 = 684 + 110 = 794\ m^2$

(10) Thermal energy received by shield = 1.4(794) = 1110 kW

(11) From earlier work a reasonable shield with an absorptivity of 0.08 and emissivity of 0.9 would transmit about 100 Btu/h ft^2 at solar maximum

$$q_{Trans} = 100(3.154)\ 10^{-3}(794) = \underline{250\ kW}$$

(12) Percent of transmitted radiation absorbed by shelter complex

(a) Roof area $= 7(\pi[2.1^2]) + 11(1.5 \times 2) + 2(1.5 \times 5)$

$+ 2(1.5 \times 8)$

$= 97 + 33 + 15 + 24 = 169\ m^2$

(b) $\frac{169}{794} = .213$

Assume another 40 percent of reflected radiation is absorbed by walls

Total = 61.3 percent

(13) $Q_{abs} = .613(250) = 153.2$ kW

Design for 175 kW

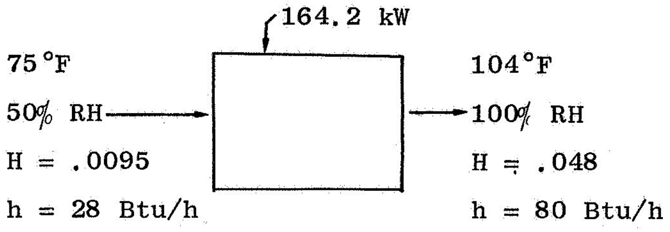
(14) Farm absorption assuming window passes about 20 percent of incident radiation [1] is

$$\text{Area: } 2\,\frac{\pi}{4}\,(18)^2 + \frac{\pi}{4}\,(10)^2 = 162\pi + 25\pi = 1872 = \underline{586 \text{ m}^2}$$

$$Q = .2(1.4 \times 586)$$

$$= \underline{164.2 \text{ kW}} \equiv 560{,}000 \text{ Btu/h}$$

(15) Dry air rate to maintain farm conditions



$\Delta h = 80-28 = 52$

$\Delta H = .048-.0095 = .0385$

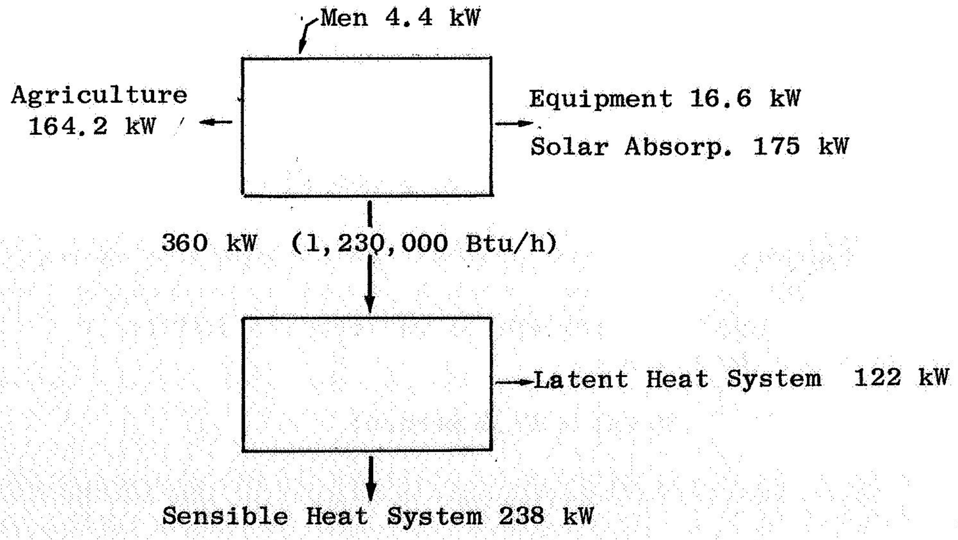
$$\text{cfm} = \frac{560{,}000}{52 \times 60} \times \frac{1}{30.42} \times \frac{535}{492} \times \frac{14.7}{5.} \times \frac{1}{.982}$$

$$= 6900 \text{ cfm}$$

Water to be removed = 180(.0385) = 6.93 lb/min

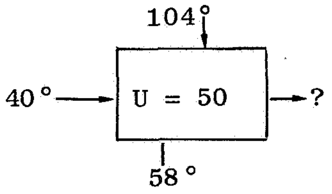
416 lb/h ≡ 189 kg/h

(16) Cooling System Load



Latent Heat (@ 1000 Btu/lb) = 416(1000) = 416,000 Btu/h = 122 kW

(17) Latent Heat Cooling System will have to operate with a 40°F inlet temperature. Assume worst condition is for radiator facing sun, and that some sensible heat can be accepted



$$50(A)\left[\frac{(104-40)\ -\ (58-50)}{\ln\frac{64}{8}}\right] = \frac{50A(56)}{\ln 8} = 416{,}000$$

$$A = \frac{416{,}000(2.08)}{50 \times 56} = 309\ \text{ft}^2 \quad \text{dehumidifier}$$

$$\underline{28.7\ \text{m}^2} \quad \text{area}$$

Because of low allowable temperature rise radiator must be designed in order to always view cold space, i.e., swiveled. If this is done then radiator size can be approximated.

Total load = 1,230,000 Btu/h; t of coolant leaving dehumidifier = 50°F (This allows a 5°F approach to the dew point of ~ 55°F). Then

$$q = wc\Delta t = 41{,}600(t - 50) = 812{,}000\ \text{Btu/h}$$

$$t = 50 + \frac{812}{41.6} = 69.5 \sim 70°\text{F}.$$

For radiator facing cold space A ~ 50 ft^2/kW

Total area = 50(360) = 18,000 ft^2

(18) Tubing requirements

(a) 1/4 in. Aluminum tube with fins has area of 0.3 ft^2/ft and w = .16 lb/ft

(b) $\frac{18{,}000}{.3} = \underline{60{,}000\ \text{ft}}$

(c) w = .16(60,000) = 9,600 lb ≡ $\underline{4{,}360\ \text{kg}}$

(d) Dehumidifier = $\frac{309}{.3}$ = 1,030 ft

w = .160(1030) = 165 lb ≡ 74.8 kg

(e) Assuming a coefficient of 10 Btu/h/ft^2/°F for thermal absorbers

$$812{,}000 = 10A\left[\frac{(75-50)\ -\ (75-50)}{\ln\frac{25}{5}}\right]$$

$$A = \frac{812{,}000(1.61)}{200} = 6{,}540 \text{ ft}^2$$

$$\frac{6{,}540}{.3} = 21{,}800 \text{ ft} \quad w = 3{,}480 \text{ lb} \equiv \underline{1{,}580 \text{ kg}}$$

$$\text{Total} = 4{,}360 + 75 + 1{,}580 = \underline{\underline{5{,}915 \text{ kg}}}$$

(19) Total Thermal Control System = $\underline{\underline{12{,}000 \text{ kg}}}$

Heater weight/module $\sim \frac{1{,}580}{8} = \underline{396 \text{ kg}}$

Recalculation of Volumes

$$\text{Form} = 2\left[\frac{\pi}{4}(18)^2 \times 2\right] + \frac{\pi}{4}(10)^2 \times 2 = 324\pi + 50\pi = 1{,}172$$

$$+ \text{ top of one shelter } (90) = 1{,}262 \text{ m}^3$$

Tunnels (cross section 1.5 × 2.5)

$$11(1.5 \times 2.5)2 + 2(1.5 \times 2.5)5 + 2(1.5 \times 2.5)8$$

$$(1.5 \times 2.5)(22 + 10 + 16) = 48(2.75) = \underline{180 \text{ m}^3}$$

$$\text{Shelters } 7(209) + 1(121) = 1463 + 121 = 1{,}584 \text{ m}^3$$

Total Shelter (all tunnels charged to shelter) = $1{,}584 + 180 = \underline{1{,}764}$

REFERENCE

1. "Radiation Heat Transfer Analysis for Space Vehicles," ASD-TR-61-119, Part II, 1962.

Appendix D

COMPARISONS OF POWER SYSTEMS

The following comparisons are made on the basis of the lunar base requiring 50 kW (electrical) during the lunar day and 40 kW during the lunar night. The proposed landing vehicles [1] have two fuel cells, each of 2 kW capacity, in the navigational system package. These landing vehicles also are an ample source of cryogenic tankage for liquid hydrogen and liquid oxygen. At any point in the discussion where fuel cells are pertinent to a given power system, it is assumed that the fuel cells and tankage are available.

D.1 Radioisotopic Thermoelectric Generators (RTG)

Radioisotopic generators of power are compact, lightweight, rugged, and reliable since they have no moving parts. Little shielding is required if the isotopic source is an alpha-emitter. Such a power generator cannot be turned on or off at will. Thermal power is produced continuously although the electrical energy can be diverted or controlled as desired.

All radioisotopic thermoelectric generators built to date have had relatively low power ratings [2]. Some typical Pu^{238} (86 year half-life) fueled RTG's are shown in Table D-1. The specific mass ratings of

Table D-1

RTG COMPARISON

Generator Designation	Power (watts)	Mass† (kg)	Specific Mass (kg/kW)	Design Life (year)
SNAP-3B (modified)	2.7	02.1	780	5
SNAP-9A	25	12.3	495	5
SNAP-19	25	21.0	840	1-3

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† Includes shielding.

these alpha-emitter fueled RTG's are quite attractive. For example, they are in strong contrast with the SNAP-7 series (B, D - 30,800 kg/kW; A, C - 73,300 kg/kW; E - 157,000 kg/kW), fueled with Sr^{90} (beta emission), with design lives of 10 years.

While the RTG's are most appealing, they cannot be seriously considered for other than standby purposes, power sources for small roving vehicles, power sources for remote unmanned monitoring stations, power sources for maintaining no-freeze conditions, and other such uses. The reason for such limitation lies in problems of availability, cost, and safety. Thus isotopic power will generally be limited to applications of a few kW or less [3]. Approximately 1 kW (thermal) of Pu^{238} can be obtained from every 1000 MW of installed thermal power provided that proper steps are taken. It is estimated that in the late 1970's there will be an annual potential of about 100 kW (thermal) available at about 500 dollars per watt. In the early 1980's, provided proper steps are taken, 500 to 800 kW (thermal) might be available for all NASA uses.

D.2 Thermionic Conversion of Solar Energy to Electrical Energy with Storage in Batteries

A suitable system has been designed [4,5] to produce 1.5 kW of electrical energy on a continuous basis. This was designed for a satellite with a 500 minute sun - 35 minute shade cycle with a total mass of 300 kg or a specific mass of 200 kg/kW. This power system was available with 1962 technology. Under the design conditions, the Ag-Cd battery stored 0.9 kWh. Under the conditions of the lunar day-night cycle, the same batteries would have to store 560 kWh. Under such conditions, the specific mass is about 20,800 kg/kW. Recent development of a liquid plate--solid electrolyte (Na-S) battery [6] would reduce the battery mass by a factor of six. This reduces the spcific mass to about 3610 kg/kW, but this is still far too much for serious consideration until specific storage capacities (kW/kg) are further improved.

D.3 Nuclear Reactor combined with Rankine Cycle Power Conversion (Nuc-Ran)

The SNAP-8 has been designed [3,7] to provide 33 kW (electrical) on a continuous basis for a 10,000 hour design life. This is an Earth-constructed system of an integral configuration which can be landed on the Moon and operated at a distance of 760 m from the nearest shelter. This is based on a total exposure to each individual of 70 rem. This includes 24 rem permitted during a total potentially required period of seven hours of repair and maintenance effort. The system includes two complete power conversion systems (Hg loop) but only one reactor. A power backup system for at least 14 days is necessary. The separation distance requires appreciable time for laying transmission cables as well as setting up the electrical control system. It has been estimated [8] that a development cost of 250-500 million dollars would be necessary. This includes the cost of the first unit. Obviously, more than one such unit would be necessary for the requirements of the proposed base.

It may be possible to uprate the SNAP-8 to 71 kW by adding 1950 kg to the original mass of 14,900 kg [7]. This additional mass is 680 kg in the power conversion system and 1270 kg in shielding (keeping the system at 760 m from the shelter). If the distance is increased by 310 m, the increased shielding is not necessary. This system can also be an integral system constructed on Earth and operationally tested before launching.

A reactor of the SNAP-8 configuration intended to produce 600 kW (thermal) has been built and operated [3]. It operated a total of 11,990 h with 8800 h at design temperature (1300°F) with power between 400 and 600 kW. The longest run was for 500 h with 2400 h at design temperature and 600 kW. While the test was considered successful, the cladding on a large majority of the fuel elements was cracked. Obviously, further work is required to solve this problem. Operation of a similar reactor to provide 50 kW (electrical) appears feasible. Since this would be partial power for this specific reactor configuration, an operational life of something greater than 10,000 h might be expected.

It is conceivable that a similar power system could be built around the LAMPRE I [9,10] which is a proven reactor design. LAMPRE I operated at one megawatt thermal power, which would provide ample opportunity to produce 50 kW (electrical) or more. In the original concept of the LAMPRE series, LAMPRE II was to be a larger and more advanced prototype, and LAMPRE III was intended to generate electrical power. It was expected that the actual power generation would be a "conventional" steam system with steam being obtained from a water-sodium heat exchanger, sodium being the coolant of the reactor.

In this context it is reasonable to adopt a research, development, and first unit cost of 300 million dollars. This does not include a backup system. It has been indicated [8] that replenishment should be by replacement of the entire system rather than seeking to change the fuel loading under the lunar conditions. This would be an annual operation with an estimated cost of the complete system of 50 million dollars. It is estimated that 200 man-hours will be required for deployment of the first unit and 180 man-hours for each subsequent unit.

A backup power system for emergency situations in the event of failure of the reactor can be provided at no expense by using the fuel cells from the landing vehicles. Forty kW will be sufficient to maintain full life support. This will require 16.4 kg of reactants per hour. For 14 days this means 5,500 kg of water in the form of liquid hydrogen and liquid oxygen. Ample cryogenic tankage from launch vehicles will be available. Excess LH_2 and LO_0 (from landing safety margin) will provide the necessary fuel.

D.4 Solar Cell Conversion of Solar Energy to Electrical Energy for Direct Use During Lunar Day and Electrolysis of Water for Use in Fuel Cells During Lunar Night (SC/FC/REG)

With 20 landing vehicles there will be 40 fuel cells available with a total capacity of 80 kW. Cryogenic tankage for storage purposes will be available by salvage from the landing vehicles. The fuel cells, tanks, and vehicles should be designed with this use in mind. The fuel consumption rate of these fuel cells is estimated at 0.41 kg H_2O/kW/h.

An electrolytic cell has been developed [11] for space (or lunar base) usage. This will produce 3.43 kg H_2O/h. The basic envelope of this subsystem is 0.51 m × 0.41 m × 0.30 m (0.063 m^3) with a mass of 93 kg. The hydrogen liquefier has a mass of 340 kg and the oxygen liquefier has a mass of 141 kg. Development and cost of first unit is 100 million dollars. Each additional unit will cost 5 million dollars.

Each unit will electrolyze 1150 kg of H_2O/lunar cycle (336 h of operation). For 40 kW (electrical) during the lunar night, reactants will be needed at the rate of 16.4 kg/h. For a fuel cell operating time of 372 h, 6100 kg of reactants will be required.

A solar cell array has been designed to match the above electrolytic cell [12] and must produce 33 kW. This can be done in a variety of solar cell configurations on the lunar surface. The one selected for this study was the 51 deg leanto arrangement.

The development and first unit cost (for a 2.4 kW array) is 10 million dollars, including foldable structure with packaging and deployment details. The Si cell array will cost 16,200 thousand dollars per m^2 although it is anticipated that quantity production might decrease this by 20-30 percent.

The 51 deg leanto arrangement will require 1070 m^2 of cell array. This will have a mass of 422 kg. The other hardware will have a mass of 2260 kg (structure - 2050 kg, power conditioning and cable - 210 kg) giving a total mass of 2680 kg. The solar array will cost 17.5 million dollars and the other hardware 1.5 million dollars, giving a total of 18.8 million dollars. Deployment time will be 20 man-hours per unit.

In other terms, the hardware for producing electricity directly from the solar cell array will cost 0.57 million dollars per kW with a specific mass of 82 kg/kW. It will require 32.4 m^2 of solar cells per kW. The hardware for electrolyzing water with liquefaction of hydrogen and oxygen for use in fuel cells will cost 3.6 million dollars per kW, with a specific mass of 435 kg/kW. It will require 142 m^2 of solar cells per kW. This is equivalent to electrolyzing 150 kg H_2O per lunar cycle or 2000 kg H_2O per year.

In terms of the proposed lunar base requirement, the development cost is 110 million dollars, the hardware cost is 155 million dollars and the mass is 21,500 kg.

D.5 Thermionic Conversion of Solar Energy to Electricity for Direct Use During Lunar Day and Electrolysis of Water for Use in Fuel Cells During Lunar Night (TH/RC/REG)

This system is similar to the previous one (SC/FC/REG) in that fuel cells and cryogenic tankage are salvaged from the landing vehicles and the same electroysis units are used. The difference is in the use of solar concentrators and thermionic converters [4,5] rather than solar cell conversion to electrical energy.

The thermionic units discussed earlier generated 1.5 kW on a continuous basis including the storage of electricity in batteries. If the batteries are eliminated from the system, the concentrators and converters can generate 3 kW each. This is from an array of 18 concentrators and converter modules. The mass of this array is 250 kg. Each of these arrays will cost 1.8 million dollars.

The hardware for producing electrical energy from the concentrator-converter arrays will cost 0.60 million dollars per kW with a specific mass of 84 kg/kW. It will require 10.9 m^2 of concentrator area per kW. (These concentrators will be about 1.5 m in diameter.) The hardware for electrolyzing water with liquefaction of hydrogen and oxygen for use in fuel cells will cost 3.29 million dollars per kW with a specific mass of 441 kg/kW. It will require 47.6 m^2 of concentrator area per kW. This is equivalent to electrolyzing 150 kg H_20 per lunar cycle or 2000 kg H_20 per year.

In terms of the proposed lunar base requirement, the development cost is 100 million dollars (not including the thermionic devices since they are based on 1962 hardware), the hardware cost is 162 million dollars and the mass is 21,800 kg. It is estimated that 500 man-hours would be required for first deployment.

D.6 Summary

In calculating the cost of maintaining the base on continuous operation, it was assumed that the replacement rate for both solar-oriented systems was 20 percent per year. This includes a cryogenic leakage rate of 10 percent per year.

It should be noted that an initial charge of 6100 kg of water, presumably in the form of liquid hydrogen and liquid oxygen, is required with both solar-oriented systems.

Tables D-2 and D-3 present a summary of these systems.

Table D-2

SUMMARY OF PRINCIPAL FACTORS*

		Cost (Million Dollars)		Deployment	Man-Hour
	Number of Launches	R & D, + 1st Item	Replacement	First Deploy	Re-deploy
Nuc-Ran	6	300	250	200	900
SC/FC/REG	1.82	265	155	200	150
TH/FC/REG	1.85	262	162	500	250

*Based on 6-year operation, 50 kW (electrical) lunar day, 40 kW lunar night.

Table D-3

SUMMARY OF COST
(Millions of Dollars, 6-year Operation)*

	Launch	Equipment	Man-hour	Total
Nuc-Ran	1650	550	55	2255
SC/FC/REG	500	420	18	938
TH/FC/REG	510	424	38	972

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*Based on 275 million dollars per launch, 0.05 million dollars per man-hour.

On the basis of the figures in Tables D-2 and D-3 it is obvious that the choice is the SC/FC/REG system. It is equally obvious that there appears to be little choice between the SC/FC/REG and TH/FC/REG systems. In addition, if it were not necessary to replace the entire Nuc-Ran system rather than replace the fuel loading, this system might also be competitive with the other two solar-oriented systems. It should be noted, however, that it is no simple or inexpensive matter to change the fuel loading in any nuclear reactor, especially on the lunar surface.

If all three systems are truly competitive on a specific mass and cost basis, then either the SC/FC/REG or TH/FC/REG system has certain inherent advantages over the Nuc-Ran system. These are:

(1) Either solar-oriented system is highly modular and can be supplied in units of essentially any size desired.

(2) Redundancy in either solar-oriented system is easily achieved by adding units or by accepting a lower availability of power in event of failure of part of the system. Earth-based testing to establish reliability and performance data is feasible. Nuc-Ran is a system with 100 percent redundancy of the power conversion subsystem but only one reactor. This requires a standby system for emergency power. In the context of this proposed design, the standby system can be supplied by fuel cells and cryogenic fluids salvaged from launch vehicles.

(3) Either solar-oriented system can be expanded easily to provide additional liquid hydrogen and oxygen for fueling vehicles for mobility on the lunar surface or for fueling vehicles for return to Earth.

(4) Buildup of a power system on the Moon with either solar-oriented system is much easier than with Nuc-Ran since components can be packaged in almost any size desired. They can be carried on any launch and do not require a separate launch for each new unit.

(5) Either solar-oriented system presents no problem of radiation of personnel. Units can be located in as close proximity to shelters as desired rather than a minimum of 3/4 km away as is the case with Nuc-Ran. This simplifies the maintenance problem of time required to travel in the lunar environment.

(6) Either solar-oriented system can supply a peak power of 225 kW (by shutting off all electrolysis) during the lunar day and 40 kW during the lunar night. The Nuc-Ran system is constrained to little over the design power at all times.

The state of current techology strongly favors the SC/FC/REG system over the TH/FC/REG system. Work is currently being considered to further develop generation of electricity by thermionic conversion.

In terms of serious future consideration of power systems for lunar bases, none of the five systems considered should be overlooked as future developments will undoubtedly alter the picture.

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Appendix E

CALCULATIONS OF THE POWER REQUIRED FOR THE VARIOUS COMMUNICATION LINKS

The several factors that must be considered when designing a communications link are the required signal-to-noise ratio at the receiver, the gains of the transmitting and receiving antennas, the noise temperature of the receiver, and the bandwidth of the modulation.

The Earth-based antennas were chosen to have a beamwidth that covers just the entire Moon (approximately 1/2 deg). The Moon-to-Earth antennas were chosen to have a beamwidth large enough to cover the Earth (approximately 2 deg). The antennas for intra-Moon communications were chosen to be a convenient size.

On the Earth-to-Moon link it will be assumed that plenty of power is available and therefore the uplink is no problem for any bandwidth or data rate.

The downlinks from the main lunar base to Earth will consist of 220 kHz wide channels operating around 2.2 GHz. Each channel will use a travelling wavetube (TWT) amplifier and be independent of the other channels except possibly several could share the same antenna. Four of the channels will carry one channel of TV each, one can be used for 24 multiplexed voice channels and one can be used for telemetry data. With this arrangement the system would be flexible. When it would be desirable to send more telemetry data in place of a TV channel it would be possible to just switch information sources to a 220 kHz channel.

The signal-to-noise ratio for a 220-kHz bandwidth channel at 2.2 GHz from the Moon to the Earth is found as follows:

(1)	Transmitter power (20 W)	+ 13 dBw
(2)	Transmitting antenna gain (3 m diameter parabola)	34 dB
(3)	Path loss at lunar distance	- 211 dB
(4)	Receiving antenna gain (18 m diameter parabola)	50 dB
(5)	Signal level at the receiver	- 114 dBw

(6)	Noise level at the Earth receiver (with 240°K equivalent noise temperature)	- 145.4 dBw
(7)	Signal-to-noise ratio	31.4 dB

This signal-to-noise ratio is sufficient to transmit high quality TV pictures at a 1 sec frame rate. Also voice transmission with this signal-to-noise ratio is relatively quiet. The error rate of the data depends on the coding scheme and data rate, both of which will be variable depending on the needs of the mission. The coding will be done by the communication computer.

For communications from a man walking or a moving vehicle on the lunar surface to the main base or a repeater a 40 MHz carrier frequency will be used. The line of sight distance to the horizon on the Moon is

$$d = 1.867 \times 10^{3}\sqrt{h_1}\ \text{m} ,$$

where h_1 is the height of the antenna in meters. For example, if a station is placed on a hill with a 1 km altitude, which is probably a maximum value, then

$$d = 1.867 \times 10^{3}\sqrt{1000} = 59\ \text{km} .$$

So it will be assumed that the maximum distance for communication, without a repeater, will be 50 km. For this distance at a frequency of 40 MHz and with a 0.1 W transmitter

(1)	Transmitter power (0.1 W)	- 10 dBw
(2)	Transmitter antenna gain	0 dB
(3)	Receiver antenna gain	0 dB
(4)	Path loss (40 MHz @ 50 km)	- 134 dB
(5)	Received power	- 144 dBw
(6)	Receiver noise (390°K - 10 kHz bandwidth)	- 157 dBw
(7)	Signal-to-noise ratio	13 dB

A signal-to-noise ratio of 13 dB is somewhat noisy, but still not difficult to understand. If the distance is reduced to one half the

50 km the signal-to-noise ratio is increased 6 dB which would result in a ratio of 19 dB which is quite good. Reflection from features of the lunar surface could cause large changes in the signal-to-noise ratio. After some experience is gained on the lunar surface it will be possible to plan a communication link to go with a particular traverse.

For communication between two repeaters, or a repeater and the main base, a 2.2 GHz system will be used. On each end of the path a 0.7 m diameter parabolic antenna will be used. Than for a 50 km path length and a 10 kHz bandwidth the signal-to-noise ratio is found as follows:

(1)	Transmitter power (0.1 W)	- 10 dBw
(2)	Transmitter antenna gain	20 dB
(3)	Receiver antenna gain	20 dB
(4)	Path loss (2.2 GHz @ 50 km)	- 134 dB
(5)	Received power	- 104 dBw
(6)	Receiver noise (390°K - 10 kHz bandwidth)	- 157 dBw
(7)	Signal-to-noise ratio	53 dB

This is a very good signal-to-noise ratio and many repeaters could be used without degrading the system. Several voice channels will be accommodated with one repeater. Each time the number of channels is doubled the signal-to-noise ratio will drop by 3 dB.

If a 2.2 GHz transmitting antenna were pointed directly at the Earth and a 18 m diameter antenna were used on Earth to receive, a voice link could be established. The signal-to-noise ratio is as follows:

(1)	Transmitter power (0.1 W)	- 10 dBw
(2)	Transmitter antenna gain	30 dB
(3)	Path loss (2.2 GHz @ lunar distance)	- 211 dB
(4)	Receiver antenna gain	50 dB
(5)	Signal level at the receiver	- 151 dBw
(6)	Noise level (240°K @ 10 kHz bandwidth)	- 159 dBw
(7)	Signal-to-noise ratio	8 dBw

This signal-to-noise ratio is sufficient to allow noisy voice communications. This mode will be useful in case of an emergency or for some special circumstance. If the transmitter power level were raised to 1 W, good voice communications would be possible since the signal-to-noise ratio would then be 18 dB.

For transmission of TV from a location on the lunar surface back to the main base a repeater station will be necessary. All repeaters will have a plug on the side of the electronics box where a TV camera may be plugged in. Then the repeater becomes a TV transmitter instead of a repeater, and the 2.2 GHz parabolic antenna on the repeater will be pointed at the main base or the next repeater. For this type of operation, with a 1 sec frame rate, the signal-to-noise ratio is

(1)	Transmitter power (0.1 W)	- 10 dBw
(2)	Transmitter antenna gain	30 dB
(3)	Receiver antenna gain	20 dB
(4)	Path loss (2.2 GHz @ 50 km)	- 134 dB
(5)	Received power	- 104 dBw
(6)	Receiver noise (390°K @ 220 kHz bandwidth)	- 147 dBw
(7)	Signal-to-noise ratio	40 dB

This signal-to-noise ratio is sufficient for good quality TV. The Apollo mission is going to use a 1-sec frame rate which has been found sufficient for exploration.

If an attempt was made to use a repeater to transmit TV directly to Earth the signal-to-noise ratio would be approximately -6 dB, which would give no picture. To receive passable TV a signal-to-noise ratio of approximately +20 dB is needed.

Appendix F

STUDIES OF UTOPIAN TRANSPORTATION SYSTEM AND USE OF A MOONLAB AS A LUNAR WAY-STATION

PART I: USE OF LUNAR BASE FOR INTERPLANETARY FLIGHT

Looking beyond the 1980s, the question arises on the role of the Moon in space travel. One possible use of the MOONLAB involves the Moon as an intermediate station for interplanetary flight. A simple method of investigating the feasibility of using the Moon as a base consists of comparing the velocity budgets required for a typical flight using a direct flight, Earth-to-planet, with an indirect flight Earth-to-Moon-to planet. For purposes of illustration Mars will be used as the target planet.

In the case of the indirect flight, a possible advantage of using the Moon arises in the case that lunar water is found. The availability of water on the Moon would permit the manufacturing of rocket fuels such as LOX-H_2, both of which are important for chemical rockets, or H_2 which could be used for a nuclear rocket.

The Moon thus would be a refueling station with the potential advantage of reducing the total mass launched from Earth. The required Earth-launched mass in turn may be used to infer the relative costs of the direct and indirect interplanetary flight modes.

Mission Profile. Both the Earth-to-Moon and the Earth-to-Mars is assumed to occur via a Hohmann transfer ellipse. For the case of lunar refueling, the trajectory goes from Earth orbit to lunar orbit where refueling occurs and then via Hohmann transfer to Mars.

Table F-1

VELOCITY BUDGET

Phase	ΔV, m/sec
Direct	
Earth orbit to Mars transfer ellipse (total)	3,690
Lunar Refueling	
Earth orbit to lunar orbit	4,360
Lunar orbit to Mars transfer ellipse	1,460
Total	5,820

The velocity budget (Table F-1) indicates that lunar refueling will not pay for itself in the above case since the velocity required to go to the Moon is greater than the mission requirements. Unless the direct mission requires a ΔV significantly greater that the 4,360 m/sec required to go from Earth orbit to lunar orbit, rocket fuels, even if free, offer no advantage for interplanetary travel. The use of the Moon as a refueling station therefore depends upon the following factors:

(1) The scope of the mission, and

(2) The cheap manufacture and delivery of rocket fuels from lunar water.

PART II: A VERY APPROXIMATE UTOPIAN TRANSPORTATION POINT

An Interesting Statistic:

Lunar escape veloc. ≅ 7750 ft/sec

Earth escape veloc. ≅ 36,600 ft/sec

Total energy change per unit mass $= \frac{\Delta E}{m} = \frac{1}{2}[(36{,}600)^2 + (7750)^2]$

$$= 6.71 \times 10^8 + 3.0 \times 10^7$$

$$= 7.0 \times 10^8 \frac{\text{ft-lb}}{\text{slug}} = 8.2 \frac{\text{kWh}}{\text{lb}}$$

at 0.004 \$/kWh we obtain 0.033 \$/lb as the energy cost.

Therefore, at the price of electrical energy, it would cost 3-1/3 cents for the energy to put a pound on the moon! Obviously, the appropriate energy conversion is expensive!

General Description:

Link 1

(1) Taxi from Earth surface to Earth orbit station (about 100 mi).

(2) Essentially all hardware reusable.

(3) Chemical fuels, $I_{sp} \sim 400$ sec (one could foresee nuclear system [with H_2] and $I_{sp} \sim 80$ sec).

(4) Re-entry from Earth orbit could use aerodynamic deceleration.

Link 2

(1) Shuttle from Earth orbit to lunar orbit.

(2) Specific thrust need not be greater than unity. Therefore, exotic large specific impulse system could be used.

(3) Transit time, for small specific thrust system, becomes the prime trade-off parameter.

(4) Power, life support, etc. crucially involved in optimization.

Link 3

(1) Lunar taxi, from lunar orbit station to lunar surface.

(2) Similar to Earth taxi, but easier to estimate and less expensive.

(3) Chemical system for larger specific thrust.

(4) Nuclear system ($I_{sp} \doteq 800$ sec) more feasible than Earth taxi.

Fuel Costs:

Link 1

(Saturn V: $W_{initial} \approx 6{,}000{,}000$ lb : $W_{orbit} \approx 300{,}000$ lb.)
Assume development of reusable system which can put payload into Earth orbit for 20 lb fuel (LOX-H_2) for each pound of payload. At liquid air cost (20 cents per pound), we get

$4 \frac{\$}{\text{lb}}$ fuel cost to put cargo in Earth orbit from Earth surface.

Link 2

ΔV required is about 13,000 ft/sec.
Even for effective ΔV of several times this, due to continuous thrusting in gravitational field, an exotic system (e.g., ion propulsion with exhaust velocity of 0.1 the speed of light) the fraction of mass to be ejected is a very small fraction (10^{-3} to 10^{-4}) of the total mass. The most important requirement is the power required. One envisions the energy source to be nuclear,

which even today is competitive in the electrical power field. Thus fuel cost comes close to ordinary energy (electrical) cost and is negligible within uncertainty.

Link 3

$\Delta V \sim 5500$ ft/sec

Chemical fuel $\doteq$ 10,000 ft/sec yields a mass ratio $\simeq 1.7$

$$\frac{\text{mass fuel}}{\text{initial mass}} = .42 \; ; \qquad \frac{\text{cargo mass}}{\text{initial mass}} \sim .21$$

this gives

$$\frac{\text{lb fuel}}{\text{lb cargo}} \approx \frac{.42}{.21} = 2.0$$

Liquid air price = >.04 \$/lb cargo.

Thus,

$$\frac{\text{Total fuel cost}}{\text{lb cargo}} \text{ is about } 4.4 \text{ \$/lb cargo}$$

Replacement Costs:

Link 1

Cost Saturn V Launch Vehicle = \$131,000,000

Let N = average useful life, in number of trips. We would imagine various lifetimes for various components, so this is an average with respect to cost.

$$\text{Replacement cost} = \frac{131,000,000}{300,000\ N} = \frac{436}{N} \text{ \$/lb cargo}$$

Assume N = 21.8

Replacement cost = 20 \$/lb cargo

Link 2

Much more speculative. Both cost and lifetime should be considerably larger. Crystal-ball as follows:

Initial weight (loaded shuttle)) $= 10^7$ lb

Fuel for Link 3 $= 2 \times 10^6$ lb

Cargo weight $= 10^6$ lb

Unit cost (in orbit) $= 10^{10}$ \$

Life (trips) $= 10^2$

Replacement cost $= \frac{10^{10}}{10^6 N} = \frac{10^4}{N}$ $= 100$ \$/lb cargo

Link 3

Probably could do a good estimation again, since similar to Link 1. This one is sensitive to availability of material on Moon, but is the least job to do.

Assume Replacement Cost ≈ 20 \$/lb cargo,

Total Replacement Cost $\approx (20 + 100 + 20)$ \$/lb cargo,

$\cong 140$ \$/lb cargo.

Operation Cost

People and their support. Even more speculative. Assume:

lb cargo/yr $= 6 \times 10^6$, six round trips of shuttle

operations $= 10^9$ \$/yr

$$\text{operations cost} = \frac{10^9}{6 \times 10^6} \cong 160 \text{ \$/lb.}$$

Finally (omitting any initial investment)

Fuel Cost + Replacement Cost + Operations Cost $\cong (4 + 140 + 160)$ \$/lb cargo

$\cong 300$ \$/lb cargo

Note: The above estimates are, admittedly, very rough and undoubtedly could be done better--at least some better though the uncertainty remaining after a best effort would likely be discouraging.

Thoughts:

(1) Nothing really far-out--any kind of breakthrough--has been assumed.

(2) A final cost situation depends primarily on engineering developments, as opposed to progress in the more fundamental aspects (e.g., specific impulse). This is a good and pleasant situation--the rewards for good engineering can be large.

(3) The entire idea is based on the tacit assumption that a large scale Earth-lunar transportation system will develop.

(4) Personally, would like to see some theoretical, numerical studies of the shuttle (Link 2).