1972 NASA/ASEE SYSTEMS DESIGN INSTITUTE

DESIGN OF A LUNAR COLONY

UNIVERSITY OF HOUSTON
MSC
RICE UNIVERSITY

NASA GRANT
NGT 44-005-114

CONCEPTUAL DESIGN

of a

LUNAR COLONY

September, 1972

Approved by:

J. R. Howell, Associate Director
University of Houston

C. J. Huang, Co-Director
University of Houston

Barbara Eandi, Co-Director
NASA MSC

R. F. Baillie, Technical Director
NASA MSC

Edited by:

Charles Dalton
University of Houston

Edward Hohmann
California State
Polytechnic College

AUTHORS

CHARLES DALTON, Ph. D., STUDY MANAGER

LARRY O. DEGELMAN, M.S., STUDY MANAGER

JOHN R. BIDDLE, Ph. D.

DONALD A. CAREY, M.S.

ATTRU M. CHOWDIAH, Ph. D.

JON A. COLE, Ph. D.

CARLOS W. COON, Ph. D.

RAMON E. GOFORTH, M.S.

STEPHEN J. GOLD, Ph. D.

WILLIAM A. HEENAN, D. Ch. E.

DEAN R. HEERWAGEN, S.M.

RODNEY HEISLER, Ph. D.

EDWARD C. HOHMANN, Ph. D.

WALTER KONON, M.C.E.

JAMES G. SECKLER, Sc. D.

FOREWORD

This report contains the results of eleven weeks of concentrated effort by the participants of the 1972 NASA/ASEE Engineering Systems Design Institute. The Institute was jointly sponsored by the University of Houston, NASA-MSC and Rice University. This was the sixth consecutive summer in which this type of program has been held.

The purpose of the Institute was twofold: We were to learn to use systems engineering so that it might fill a place in our own thinking and encourage us to incorporate the concept in our programs at our own schools. We also were to accomplish a systems-engineering design of a complete engineering facility during the program.

The systems-design study undertaken as our project was the development and growth to a colony of a 12-man lunar surface base. The lunar colony was to utilize lunar resources wherever economically feasible and was to become as independent of earth as was possible.

The effort was beneficial from several points of view:

(1) The participants learned to work together in a project-type situation. This was easy for some and more difficult for others of us who were accustomed to working by ourselves.

(2) We experienced group interactions and realized that the success of the group depends on cooperation and communication.

(3) We learned enough about NASA so that we now better understand its goals and attitudes.

(4) We feel that we made a significant contribution to the NASA-MSC Program Planning Office for the further study of a lunar colony.

ACKNOWLEDGMENTS

We, as participants in the 1972 NASA/ASEE Engineering Systems Design Institute at NASA-MSC, acknowledge the aid, assistance, and encouragement of numerous persons connected with our effort. Dick Baillie of the Program Planning Office at NASA-MSC provided direct technical liaison between our group and MSC. Dick was a great help on occasions when our thinking was cloudy. Barbara Eandi of the University Affairs Office at MSC provided some administrative aid for us. Pat Elliot, Barbara's assistant, always had answers for our questions on where (or how) do we get this (or do that).

Dennis Fielder, head of the Program Planning Office at MSC, encouraged us with his insight and vision for things to come. Pat Miller served as our secretary and provided us with several humorous experiences. Inez Law from the Chemical Engineering Department at the University of Houston handled many of our administrative matters and provided us with paychecks.

Kent Russel and Jane White typed portions of this final report. Pam Dahlstrom typed the bulk of the report and to Pam goes the credit for making this job easier for the editors.

ABSTRACT

This report contains a systems-engineering study of a proposed lunar colony. The lunar colony was to grow from an existent, 12-man, earth-dependent lunar surface base. The colony was to utilize lunar resources and was to become as earth independent as possible.

This study was an in-depth treatment of some of the aspects of the lunar colony. We have found that the use of lunar resources is feasible for oxygen production (both for breathing and for space-tug fuel), food production, and building materials. We have outlined a program for recycling of the waste materials developed at the colony. In connection with this point, we envision full usage and reusage of all available materials. We have outlined a full program for growth and research activity of the colony to a level of 180 colonists. We have raised several important questions pertaining to habitability which need to be answered prior to the colony beginning.

Our recommendations for the lunar colony include the following: An earth-dependent lunar surface base which is growth and research oriented should be established. If the base proves feasible, then the base should be expanded at a rate which would allow use of lunar materials to be included in the development. Personnel at the growing base should be those people who can contribute both to the growth and to the research effort. The base is envisioned to grow from the original twelve people to 180 people in units of twelve. Kopff Crater was chosen as the site for the lunar colony mainly because its limb location was more conducive to some of the research effort envisioned for a colony away from the influence of the earth.

CONTENTS

Appendices

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

The concept of a lunar colony is intriguing. The existence of such a colony would enable man to conduct studies which he presently does not have the capability to make. For example, a lunar colony would offer man the chance to determine what degree of independence from earth he may achieve. Man would be able to determine his capability to exist for a long period of time in a hostile environment while having to provide his own food and life-support needs from local resources. The moon presently offers the unique opportunity to conduct such a study. In addition, there are certain scientific investigations which require isolation from earth's atmosphere and from the radio frequency noise generated on earth. The moon also offers the unique opportunity to conduct these scientific studies. Furthermore, the moon provides the base or way station from which deep-space probes may be launched. The availability of this capability away from earth is important to extensive space travel.

The Apollo program of NASA laid an excellent foundation for further lunar study. The Apollo missions have shown that man can successfully travel to and from the lunar surface. The Apollo astronauts were able to stay on the moon's surface for short periods of time. They were able to undergo limited physical activity wearing their cumbersome space suits. The Apollo findings can be extrapolated to indicate that man's lunar stay time may be extended while his physical coordination would be improved with reduced-gravity familiarity and with advanced suit technology. Within the confines of a lunar shelter, complete with atmosphere, man should be able to function quite well.

The Skylab program will provide additional data on man's ability to function away from earth. The combination of the Apollo findings and the Skylab results will give meaningful input toward the development of a lunar colony. However, for a lunar colony to develop successfully, much additional information beyond

Apollo and Skylab is necessary.

One of the most important preliminary tasks to the establishment of an earth-independent lunar colony will be the construction of a Lunar Surface Base. The LSB will be completely earth-dependent. All of the supplies, including food, water and atmosphere, would be delivered from earth. There would be no self-sustaining capability present in the LSB. The activities of the LSB would be science and growth oriented. Thus, if the LSB were considered to be a forerunner to the lunar colony, two purposes would be served: Scientific study could begin during the earth-dependent phase. The growth potential of the LSB would also be examined during this phase to determine to what extent lunar materials could be used in achieving a measure of independence from earth. The degree of success of the conversion of lunar resources to useful life-support and building materials would indicate whether or not a semi-independent lunar colony could evolve.

Thus, the subject of the evolution of a lunar colony, using lunar resources as much as possible, is the topic of this study. The first part of the report deals with systems concepts of the lunar colony and a colony configuration is presented. The design requirements, using the systems engineering approach, are treated in the second part. The third part of the report deals with analysis of the various subsystems and their selection.

PART I

LUNAR COLONY
SYSTEM CONCEPTS

CHAPTER 2 THE LUNAR COLONY: A FRONTIER COMMUNITY IN SPACE

In the design of this lunar colony, one of the major assumptions has been that it will exist as a permanent colony. A colony is defined in terms of a community where people are willing to live for long periods, even a lifetime, as opposed to a base which supplies people's needs for a year or two. The nature of the envisioned colony makes it efficient to interweave colony development with the scientific and support goals of previously conceived short-term space efforts. This chapter describes the colony goals and methods for their accomplishment.

2.1 GOALS AND IMPORTANCE OF LUNAR COLONIZATION

The major goals of lunar colonization include the following:

1. Utilization of the unique lunar environment for research and technological development.
2. Advancement of our understanding of the solar systems and its origin.
3. Evaluation and extension of man's capability in space.
4. Expansion of our understanding of man's ecology.
5. Expansion of our understanding of human interactions and psychological processes.
6. Stimulation of creativity in all forms.
7. Provision for the opportunity to develop new forms of social, political and economic structures.
8. Enrichment of our lives.

The design team has considered the growth plan for a permanent lunar community from an initial lunar base to the point where a colony threshold is reached. We believe the growth pattern will establish the basis for the continued existence and further growth beyond the threshold point. As such, it should represent the life needs of the colony and permit further expansion. The stated goals reflect this growth concern and in this sense depart from goals for previous endeavors in space.

Prior efforts have tended to stress scientific exploration and research. The lunar colony concept will not diminish efforts in astronomy, cosmology and selenology but rather extend these and broaden the base for capabilities in research. An indication of the spectrum over which the efforts will reach is given in Figure 2.1-1. Chapter 3 gives a more detailed description of these activities and the personnel anticipated for the colony threshold configuration.

The broad nature of the colony goals makes it difficult to indicate some specific point in time when they will have been accomplished. Rather, the colony threshold configuration is one which will find a serious on-going effort directed toward satisfying the intent of these objectives.

The complexity of the lunar colony effort and its commitment to utilize the unique features of the moon's landscape are goals which should not be considered mutually exclusive. Primarily this means each area of research must be designed in a way which does not cause other activities to be jeopardized. Secondarily, early activities should carry a potential toward colony development.

The efforts of the United States in space have been built around extending man's capabilities in the belief that direct manned observation is a more flexible approach than indirect or unmanned missions. This approach has proven useful in test pilot developments as well as scientific exploration. An apparent corollary to the direct observation approach is to have those people make the observations who are best able to collect and interpret the data. As the research information and subsequent specificity increase, more people will be needed as the "best" observers. One solution to this problem would be to provide a series of temporary bases on the lunar surface to meet the needs of a variety of research efforts. Earth orbital research will likely follow an equivalent development through use of the shuttle

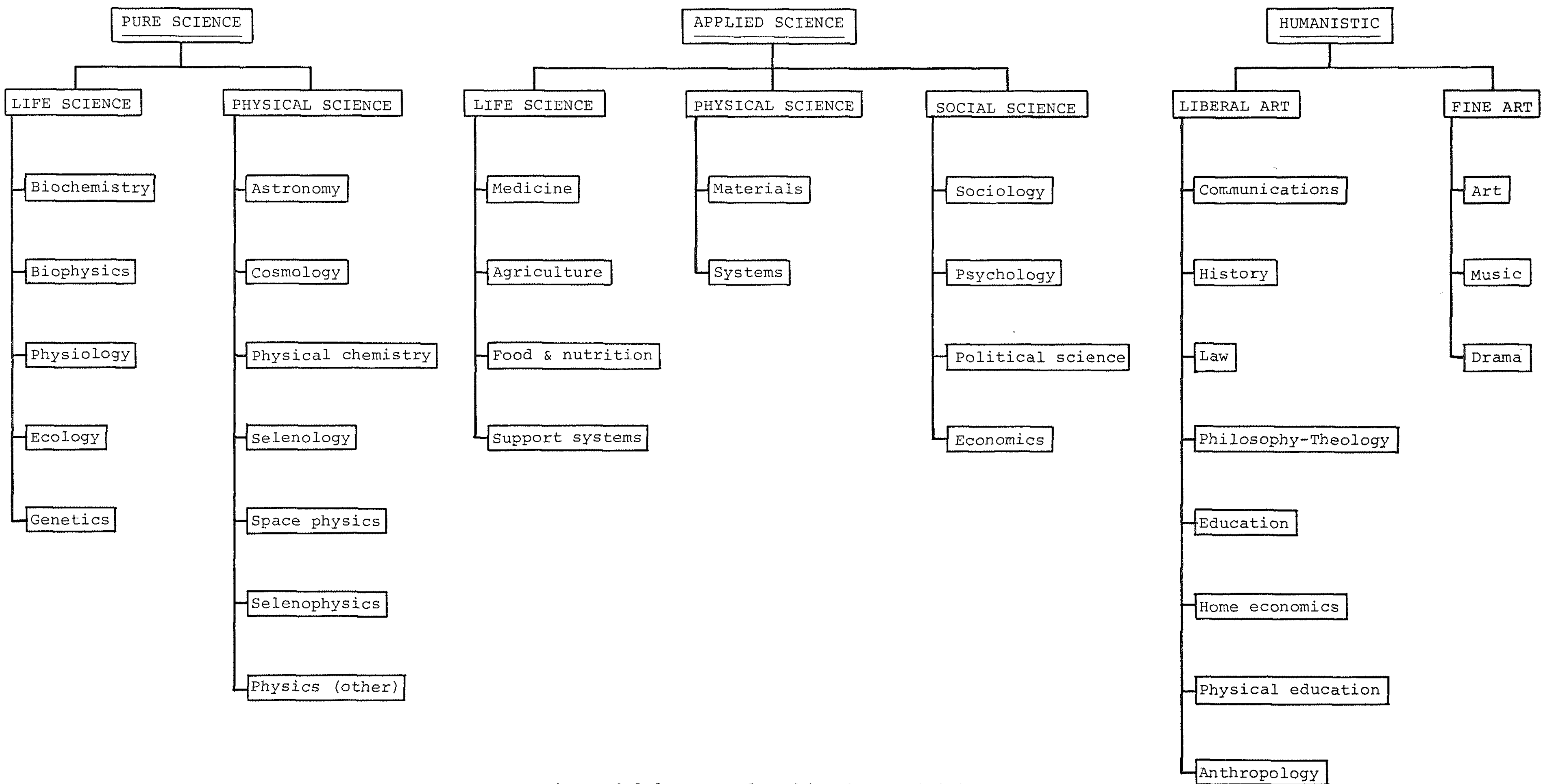


Figure 2.1-1 Areas for Objective Activities

and sortie laboratories [1]. However, the requirements of some lunar research projects for long time periods in developmental or sequential experiments will severely limit the value of a series of bases. Likewise, the base concept restricts the collection of data to discrete time intervals. Intuitively, the semi-independent colony concept seems to be less costly than a series of temporary bases. The wider variety of research support and the possible contribution to man's understanding of himself gives further impetus to the colony concept and its goals.

2.2 PUBLIC ACCEPTANCE OF THE LUNAR COLONY*

Advancement of our understanding of the earth and solar system are obvious topics for scientific study in the lunar environment. However, these alone will not be sufficient justification for such a costly endeavor as a lunar colony. Nor is utilization of the knowledge gained to support man's physical needs in space likely to evoke sufficient public enthusiasm and cause the colonization of the moon to become a reality. However, if a broader spectrum of our population could be presented with personally identifiable reasons for such an effort, the likelihood of implementation would be greatly increased.

Public acceptance of the effort to place a man on the moon came as a result of a variety of factors. (The factor which undoubtedly produced the greatest motivation was the time-dependent national goal set by President Kennedy). In order to achieve broad public support for the lunar colony, an even wider variety of individually motivating factors will be necessary, but again "the goal" will play an important part.

Fulfillment of the American dream of exciting new frontiers will mean different things to different people. Some will consider the

*The basis for much of the material in this section is a half-day conference at the University of Houston with representatives from the Departments of Communications, Music, Sociology, Health and Physical Education, Drama, Religion, Psychology and Art. See Appendix G for the names of the participants.

task merely as something to be accomplished because the possibility exists. This approach might be likened to that of a mountaineer who believes that mountains were created to be conquered.

The colony will be viewed by some as a utopia where new political-economical-ethical ideas can be implemented or, at least, tested. While this view could be considered dangerous to the growth or even the existence of the colony, the desires of the inhabitants to carry out such an experiment must be reflected in its implementation. Closely related to such experiments is the consideration of international cooperation in establishment and growth of the colony. Not only would this cooperation extend similar goodwill efforts on earth, but international pride in a lunar colony might also have the effect of waylaying military conflicts.

In addition, the distinct economic advantages which could result from an international sharing of the costs for development and growth of a lunar colony are worth pursuing. Regarding limited-purpose international organizations for the development of space, Cleveland [2] observed, "National independence is not infringed when a nation voluntarily accepts in its own interest the restraints imposed by cooperation with others".

Other members of the public will see the establishment of a lunar colony as a method for relieving the overpopulation of the earth. This would be especially true if the colony were to be the basis for establishment of other colonies. Perhaps more realistic at this point in time is the satisfaction that comes to the pioneer who avoids overcrowding by becoming a member of the colony.

In order to decrease the public tax-support level of such a project, it is conceivable that corporations or individuals would be encouraged to privately develop components for inclusion in the colony system. With private development, subsequent proprietary rights could lead to long-term financial gain for the investors through terrestrial and extraterrestrial applications and developmental spin-off. Interest in the space effort is widespread and the concept of a lunar colony is likely to evoke additional attention. Corporations made up of stockholders who are motivated toward reaching the lunar-colony goal would be more likely to assume the long-term, high-risk financial responsibility than large existing firms which strongly favor a high rate of return on short-term investments. Another method of tax-support level reduction could be through tax-deductible gifts to the space program. Consideration should also be given to selling small quantities of lunar material to rare-item collectors.

The extent to which financial advantage will accrue to the colonists or governmental entities on earth is dependent upon the political structure adopted for the program as well as the technological developments which utilize lunar resources. Developments may make use of the physical lunar resources or take advantage of the lunar environment in some way. For example, a lunar-manufacturing process will depend upon finding earth applications which are sufficiently attractive to overcome costs of transporting the goods to earth.

Another form of economic advantage can result if the information obtained in the research and development of one project is used to develop a separate, although related, concept or product. Commonly termed spin-off, this process may utilize basic research knowledge or technological utilization information. Economic advantages appear greatest when little additional research and development are required prior to manufacturing the product or marketing the concept. Not all technological spin-off should be expected to result in an obvious economic advantage.

Technically educated citizens tend to recognize the potential advantages of space efforts most quickly. However, even this cognizance is discipline oriented. The hardware-related engineer has identified most closely with the space effort and other small groups of applied and physical scientists have been able to identify a panorama of important discoveries and applications. But a more common attitude among pure and applied scientists is the acceptance of a portion of NASA's program as it relates to their specific discipline, with skepticism regarding the justification of the program in general. As a broader spectrum of educated tax payers is considered, attitudes tend toward a feeling that someone really ought to be assigned the task of reaping the results of these very large expenditures. The public seems to be developing the general attitude that "We have been told that the spin-offs alone can be justification for the spending and while we may believe it, our increasing anxiety level is strongly related to the question, when?"

Another attitude which can be isolated among the general United States citizenry concerns the lack of communication about real feelings which the astronauts experience. The feeling also seems to exist that "The only thing of value that is returned from the moon is a box of rocks carrying with them deep dark secrets and who cares?" When fast moving, leisure-time entertainment is so available and people are so accustomed to continuous emotional highs, the moon is too abstract and too far away to receive much attention, especially without a description in language that has meaning on a feeling level. To the general public, the excitement and purpose of placing a man on the moon has been lost, hopefully not irretrievably.

When public acceptance of the lunar colony is considered, some of the justification of what can be done in the future is identified with what has been done in the past. In its Technology Utilization Series (NASA SP-5000 series), NASA has made a great deal of information available to the technical community. Examples of such information include Air-Pollution-Monitoring Instrumentation [3], Clean Room Technology [4], and Flat-Conductor Cable Technology [5]. In today's world of environmental concern, the first has obvious applications. Clean Room Technology gives information which is useful to the pharmaceutical, electronic, cosmetic and other industries concerned with control of chemical and microbial contamination. With the advent of modern circuitry design and construction, unit-connecting cables have increased in importance. Traditionally used round cables are space consuming and often incompatible with miniaturization concepts. Flat-cable technology produced for space components is often directly applicable to industrial and domestic situations.

While the industry takes advantage of this technical information in miniaturization, increased product quality, reduced production costs and, sometimes, feasibility of product construction, this is only rarely apparent to the public. A clandestine approach to lunar colonization is inconceivable. Government-fund utilization for short-term, emergency efforts such as rescue of archeological treasures from potential reservoirs prior to flooding may require consistently decisive action, but for the colony concept, long-term public support is a necessity. In order to build an attitude of public acceptance or, better still, public desire for the lunar colony, there must be continuing communication with the general public. No single medium will satisfy this requirement.

Some have suggested articles in the daily press as well as a range of magazines from Scientific American to Reader's Digest to True Story. Because this range indicates a spectrum of interest, intellect and style, the article and stories will provide the vehicle for attitude development. Perhaps an even more powerful educational tool is the medium of television. Use can be made of newscasts, documentaries, specials, serials, and movies as direct and subtle ways of informing the public of what the space effort has done for the people of the world: A track record, if you please. A lot more support for the lunar colony will be forthcoming when concrete examples of space spin-off are provided for the public through communication with them at the variety of levels which they have already chosen. And a little bit of believable crystal-ball gazing can be helpful as well.

Another of the obvious methods for conveying information to the public is through the use of the radio. While the character of this medium has changed considerably, there is no doubt concerning the number of people it reaches. An outlet which describes itself as a music, sports and information station is probably describing most of what radio is about. The informational aspect may include news reporting or commentary, individual and panel interviews, and audience-participation talk shows. Continued and improved information flow through these instruments is likely. It is even conceivable that music, in the variety of forms it takes, could be composed and performed in a manner which causes increased public awareness and promotes acceptance of space endeavors. While it is more difficult to imagine ways in which sports can assist the effort, one might consider employing the fertile human imagination to devise games for the inhabitants of a lunar colony. These might have the advantage of providing a basis for maintaining earth-required muscle tone in order to return after long stays on the moon.

A more direct way of indicating the influence of space agency development of materials and concepts used in daily life would be through the placement of an artistically designed seal or signature on devices produced as a result of NASA funding. Great advertising advantage can be gained from that small electronic calculator that fits in the palm of your hand and sells for only $119.95, or from a central computer for the utilities in your home to control the dishwasher, stove, clothes drier and more. While miniaturized medical instrumentation does not generally come in knowing contact with the public, awareness on the part of medical doctors can make the information flow indirectly. Although a law could be required in order to obtain widespread usage of the signature, some industries might find voluntary implementation advantageous.

As a note of caution, it should be recognized that the difference between acceptance and rejection of a program which contains emotionally volatile issues is not great. The question of acceptance is one of degrees, too much or too little advertising, too soon or too late. Any such program should be conceived and carried out by those best trained for the job.

REFERENCES

1. Convair Aerospace Division of General Dynamics "Research and Applications Modules Phase B Study, Preliminary Design Review Brochure", Report No. GDCA-DDA72-013, Convair Aerospace Division of General Dynamics, San Diego, California.

2. Cleveland, Harlan, "The Politics of Outer Space", Proceedings of the Fifth National Conference on the Peaceful Uses of Space. Held in St. Louis, Missouri, May 26-28, 1965, NASA Publication SP-82, pp. 129-133.

3. Lieberman, Alvin and Schipma, Peter, "Air-Pollution-Monitoring Instrumentation", NASA SP-5072, 1969.

4. Useller, James W., "Clean Room Technology", NASA SP-5074, 1969.

5. "Flat Conductor Cable Technology", Marshall Space Flight Center, NASA SP-5043, 1968.

CHAPTER 3 ACTIVITIES OF THE LUNAR COLONY

Much has been said of the research potential afforded by manned space exploration. To this time, however, science and humanistic interests have taken a backseat in the manned space effort to the development of technology and flight skills. This has for the most part been a necessary consequence of the need to establish man's capability in space. As larger, more habitable, multi-manned vehicles become available, it is anticipated that more payload will be devoted to science equipment and science personnel who can implement experiments and/or make observations firsthand This should at some point in time also include persons not necessarily in the "hard" sciences.

In looking forward to the possibility of a lunar base and still further to its growth to a lunar colony, one sees, perhaps, the greatest opportunity in terms of a truly heterogeneous staff with many varied professional and vocational interests. We are particularly interested in the colony at the time it has achieved substantial independence and is supporting an ongoing, though somewhat constrained, program of serious research and development. This chapter examines the anticipated activities of the lunar colony at this "threshold" point in time in terms of the skills and activities of the residents.

3.1 RESEARCH ACTIVITIES

3.1.1 RESEARCH PHILOSOPHY

The long duration characteristic of a lunar colony will afford flexibility in research activities (this is not true during the early stages of base growth). The actual experiments which might be performed cannot be accurately defined at present and will depend to a great extent on the experimental results of earth-orbital and lunar-orbital missions. For this reason, it is advisable to avoid a list of individual experiments with necessary equipment items. Rather, it would be more reasonable to strive towards a research "facility" which would permit flexibility in program planning and be capable of research activities in as yet unknown specifics. In general, it is anticipated that the lunar colony should be capable of scientific and humanistic efforts of varying degrees, in the general areas designated in Figure 2.1-1.

Previous reports have approached space-laboratory missions from the point of view of research "facilities" and have defined these facilities in detail. Specifically, "Reference Earth Orbital Research and Applications Investigations (Blue Book)" [1] defines research functions and laboratory facilities from this point of view for flight with either the initial Space Station or Research and Applications Modules (RAM) supported by the Space Shuttle. The list of equipment is long and is added to and updated periodically. "Life Science Payload Definitions and Integration Study" [2] defines specific biological research functions and facilities for earth-orbit missions generally supported by RAM payload modules attached to a space station. Scaled-down versions with decreased capability were suggested to operate in a shuttle-sortie mode.

Both of these projects are long-range programs (beyond 1980) and as such, any planning as to specific research equipment items is destined to suffer through numerous revisions and additions and in the end to be obsolete by the time the mission is flown. But, such detailed planning is necessary, for without it no mission would ever be flown. Some obsolescence at flight time in this case is inevitable since laboratory equipment is constantly being improved or replaced. The intent here is not to discourage but to caution the reader when examining long and detailed lists of laboratory equipment items for space research application in the far future.

3.1.2 RESEARCH AREAS

The lunar colony should be capable of scientific and humanistic efforts in the general areas designated in Figure 2.1-1. During the growth of the lunar base, those areas which contribute explicitly to the viability of the base and growth towards earth-independence will receive emphasis. At the colony threshold time, it is expected that the colony would also support serious effort in nonsupport and implicit support areas.

Tables 3.1-1 through 3.1-6 present a compilation of likely research activities for a number of the disciplines represented in Figure 2.1-1. This list is an adaptation from several sources [1, 2, 3] with some original contributions from this study. It is not an exhaustive list and it lacks specificity in places (e.g., the Life Sciences are much less specific than Selenology), but it does serve to demonstrate the large number of likely research activities, anyone of which could employ much time and personnel if these were available.

Table 3.1-1

Anticipated Research Activities - Astronomy

Extend the spectral and/or spatial range and greatly
improve the resolution of observations in

Solar Astronomy
Radio Astronomy
Stellar Astronomy (X-ray, gamma-ray optical, ultraviolet, infrared)

Table 3.1-2

Anticipated Research Activities - Physics

Pursue investigations in the following areas:

- Atmospheric Magnetospheric and Solar Wind Science
- Cometary Physics
- Meteoroid Science
- Plasma Physics
- Charged-Particle Motion
- Particle Physics
- Electromagnetic Wave Propagation
- Heat Transfer
- Biophysics
- Vacuum Deposition
- Physical Electronics

Table 3.1-3

Anticipated Research Activities - Physical Chemistry

Perform experiments in the following areas of investigation:

- Critical-Point Phenomena
- Gas-Surface Interactions
- Operational Characteristics of Chemical Lasers
- Flame Chemistry and Reaction Chemistry
- Quantum Effects
- Gaseous Reaction Kinetics in High Vacuum
- Low Vapor-Pressure Chemistry
- Crystal Growth

Table 3.1-4

Anticipated Research Activities - Selenophysics

Pursue investigations in the following areas:

- Physical State and Composition of the Lunar Interior
- Internal Dynamics of the Moon
- Mass Distribution and Figure of the Moon
- Earth-Moon Mechanical Interactions
- Magnetic History of the Moon

Table 3.1-5

Anticipated Research Activities - Selenology

Pursue investigations in the following areas:

- Physical, Mineralogical, and Chemical Properties of Lunar Materials
- Type, Form, Structure, Distribution, Relative Age of Lunar Features
- Ongoing and Extinct Selenological Processes
- Selenochronology
- Selenologic Mapping (Surface and Subsurface)
- Morphologic Differences Between Far and Near Side of the Moon
- Locate Geologically Favorable Sites for Future Investigation and/or Colonization

Table 3.1-6

Anticipated Research Activities - Life Sciences

Investigate environmentally induced changes and adaptations of functions in the following areas:

Cardiovascular	Parasitology	Botany
Cardiopulmonary	Biochemistry	Horticulture
Psychology	Arcadian Rhythm	Microbiology
Neurology	Denistry	Genetics
Physiology	Pharmacology	Orthopedics
Nutrition	Optometry	Pediatrics
Pathology	Behavioral Science	Ecology

Clearly, not all of these activities will be pursued concurrently or with the same emphasis. Rather, time-sequencing and allotment priorities will have to be established and then possibly revised on the basis of the experimental results.

The lunar colony candidate endeavors must be weighed according to a list of criteria to establish their compatibility with the colony goals. On these bases, the candidate would be accepted or rejected as colony activities. The following is a list of criteria, grouped according to their relative importance, which reflect the colony goals:

1. Nonjeopardy of lunar colony.
   Degree of reliance on unique lunar environment.
   Utility in establishment, maintenance and enhancement of lunar colony.
   Contribution toward mans' understanding of himself and the universe.

2. Utility toward enhancement of quality of life on earth.
   Contribution to overall space program.
   Degree of interest to humanistic and/or scientific community.
   High probability of obtaining meaningful results.
   Diversity of spectrum of all experiments.
   Relative cost.

3. Diversity of subject areas served by a given experiment.
   Availability of physical resources at lunar site.
   Manpower requirements.
   Time-scheduling and duration.

3.1.3 RESEARCH PERSONNEL

For previously cited reasons and lack of time and facilities, an exhaustive listing of laboratory equipment items is not given in this report. Such a description is important and should be assembled along with specific functions. The approach that is taken here is to identify the specific research and support personnel required for a continuous, though constrained, serious research effort in the many areas described in this chapter.

A number of individuals in developmental, design, and support positions will also be involved in research activities or the support of research activities (e.g., material science, food technology, and physical electronics). In many cases, it is not possible to state with certainty which person and how much of his time will be involved in research. Personnel responsibilities have not been defined adequately enough to allow this. For this reason and for the sake of completeness, the list of research and direct research support personnel is not presented separately but included in the list of all colony personnel in Table 3.1-7. (Note that our colony population totals 178 individuals, which is a number of no unique significance.)

It is expected that this definition or research personnel will also undergo many revisions. In spite of the fact that science personnel are somewhat more prominent than the specific equipment items they employ, significant changes in personnel would result from changes in national priorities. It would certainly be unreasonable to assume that there would not be significant changes in national objectives and priorities over the next 20 years or more.

Table 3.1-7 Proposed Lunar Colony Personnel at the Colony Threshold Time

(R) Indicates possible research activity

1 Commander
1 Systems Manager
1 Technical Director
1 Personnel Services Director
1 Administrative Secretary
3 Secretaries (Secretarial Pool)
4 Systems Monitors
2 Communications Technicians
1 Head Cook
3 Cook's Assistants
1 Baker
(R) 1 Nutritionist/Dietitian
(R) 1 Chemical Food Processing Engineer
2 Food Processing Technicians
4 Housekeepers and Laundry Attendants
1 Barber/Beautician
1 Chaplain/Counselor
(R) 1 Clinical Psychologist
(R) 1 Physical Therapist/Recreation Specialist
(R) 1 Pharmacist
(R) 1 M.D. Surgeon
(R) 1 Dental Surgeon
(R) 1 Journalist/Photographer
1 Architect/Artist in Residence

(R-1) 2 Electronics Engineers
(R) 1 Electromechanical Engineer
(R) 1 Electronics Communications Engineer
3 Electronics Technicians
(R-1) 2 Mechanical Engineers
2 Mechanical Technicians
1 Mechanical Draftsman
2 Chemists (Operational)
1 Microbiologist (Operational)
1 EVA Technician
(R) 1 Reactor Engineer
(R) 1 Power Systems Engineer
2 Electricians
(R) 1 Waste Renovation Manager
1 Waste Renovation Plant Technician
2 Vehicle Mechanics
2 Physical Plant Maintenance Technicians
6 Plant Operators-Oxygen and Metals (Day)
2 Mining Technicians (Night)
2 Physical Plant Maintenance (Night)
1 Materials Technician (Night)
1 Foundry Assistant (Night)

Full Time Research and Support

1 Field Selenologist
2 Field Selenologic Technicians
2 Petrographers
2 Petrographic Technicians
1 Selenochemist
2 Chemistry Technicians
1 Secretary (Selenology, Selenophysics)
2 Selenophysicists
1 Selenophysical Technician
1 Electronics Technician (1/2 Selenophysics, 1/2 Physics)
2 Physicists
1 Electrical Engineer (research)
1 Electronic Engineer (support) (1/4 Physics, 3/4 Astronomy)
1 Astronomer (Radio)
2 Astronomers (X-Ray)
2 Astronomers (Solar)
2 Astronomers (Stellar)
2 Electro-Optics Technicians
1 Secretary (Astronomy, Physics)
2 Physical Chemists
1 Physical Chemistry Technician
1 Biophysicist
1 Biophysics Technician
1 Geneticist
1 Microbiologist
1 Plant Physiologist
1 Botanist
1 Biochemist

1 Poet in Residence
(R) 1 Historian/Philosopher
1 Drama Director
1 Musician (Director)
1 Storekeeper
1 Supply Technician
1 Loadmaster
1 Computer Software Specialist
1 Computer Hardware Specialist
1 Electronics Technician
1 Librarian
1 Glassmaker/Blower
1 Photographer/ Photoprocessor
1 Photo Lab Technician
1 Lawyer

(R) 1 Chemical Process Engineer
1 Mechanical Engineer
(R) 1 Metallurgist
1 Metallurgical Technician
(R-1) 2 Materials Engineers
3 Foundry Technicians
2 Machinists
4 Materials Producers and Fabricators
6 Construction Technicians
1 Heavy Equipment Operator
(R) 1 Civil Engineer (Soils)
(R) 1 Civil Engineer (Structures and Transportation)
1 Civil Engineering Draftsman
2 1/2 Surveying Crew
1/2 Civil Engineering Technicians
(R) 1 Greenhouse Operator (Horticulturist/ Agronomist)
3 Greenhouse Assistants
1 Chemist (Farm Support)
(R) 1 Animal Technologist

1 Pathologist
3 Biotechnicians
1 Secretary (Plant Research)
1 Sociologist/Anthropologist
1 Political Scientist/ Economist
1 Secretary (Social Science Group)
1 Research Psychologist
1 Psychoneurophysiologist
1 Physiologist (to be specified)
1 Cardiac M.D.
1 M.D. (to be specified)
1 Biomedical Engineer
1 Biochemist
1 Electrical Engineer (research)
1 Electrical Engineer (support)
2 Medical Technicians
2 Electronics Technicians
1 Secretary (Medical Team)

3.1.4 COMPUTER SUPPORT SYSTEMS

Many functions of the lunar colony will require large amounts of computer support. Table 3.1-8 presents a list of colony functions which would be expected to rely quite heavily on computer support.

Table 3.1-8

Anticipated Colony Functions Which Rely on Computer Support

Life-Support Control	Library Acquisition
Environmental Monitoring	Monetary Exchange
Experiment Control and Data Acquisition	Drafting and Mapping
Analysis	Information Storage and Processing
Simulation	Scheduling
Process Control and Monitoring	Supply Inventory
Communication Media (Personal and General)	Education
Vehicle Control	Testing
	Entertainment

These many needs will require a configuration of several types of computing systems. These can be categorized as

Special purpose, lunar-based minicomputers (local);
General purpose, lunar-based minicomputers;
General purpose, earth-based computing centers;
Special development, lunar-based control systems (local).

This configuration is assembled on the basis that real-time control and monitoring must be done at the lunar colony. In addition, many jobs not requiring large facilities will also be run locally. Large computational needs, as well as some smaller ones, will be served by earth-based computing centers. This will require a number of up and down telemetry links between computers and/or storage facilities.

We believe the above configuration represents the best system at the present time in terms of cost-effectiveness and computer needs. However, computer hardware is changing at such a phenomenal rate that in twenty years or more the best choice may well be an all moon-based facility.

3.2 LUNAR COLONY SUPPORT ACTIVITIES

A community is more than an assemblage of people living in proximity. It is an interdependent structure of workers, consumers, services, and goods. No community and, for that matter, no nation, is totally self-sufficient in all of these. However, a community does contain many diverse talents and abilities such that all four of these aspects are represented to greater or lesser degrees. Communities which are separated from each other and from larger urban areas by relatively large distances must be even more independent than others.

A lunar colony is a community with a high degree of self-sufficiency. It must be a heterogeneous community representing a wide range of talents and abilities. To be truly a colony, it must be more than a scientific instrument. It must offer services to enhance the quality of life and the fine arts to stimulate its soul. A spirit of pioneering and adventure will draw its citizens together and instill a strong identification with the colony. The capability must be present to support the many complex systems involved in life support and manufacturing. Research and research-support personnel must be present to carry on the complex program of research experimentation and observation in situ.

At the colony threshold time, all of the above functions will be present in a limited way. It is expected that the research and development and basic life-support programs will be best developed, but still constrained. A complete listing of all colony personnel was given in Table 3.1-7 of the previous section. The functions of the many personnel are mostly self-explanatory from their occupational titles. However, there are some assumptions and functional relationships not expressed by the table that should be made clear.

The personnel are listed in a logical pattern with related function placed in proximity as far as possible. Colony administrators are listed first, followed by food-service personnel, then personal services, systems support, and research and research-support personnel. A strictly logical pattern is not claimed because some personnel function in several areas and some functions are not so closely related to any others.

It is expected that there will be a number of family units among the colony personnel. However, at the colony-threshold time, it will be necessary to require that both adult members of the family fill positions indicated in the list of colony personnel. It is not anticipated that there will be a significant number of children in the colony at this time (no child or educational service is provided), but this does not rule out the possibility that there may be a few. Children are important to the health of the community, and, if the colony continues to grow in number, some growth may come about by childbirth.

No attempt will be made here to identify a political system which should govern the lunar colony, except to state that it should not be assumed to be a military type of structure. The type of government will be critical to success and consequently should be chosen by the colony itself. Further impetus is given to this point by the strong hopes of many that the lunar colony will be an international effort. At the lunar-base stage, the administration should be chosen by the earth sponsors but, as the base grows, the government should shift into the hands of the colony itself, reflecting its degree of self-sufficiency.

Secretarial services will be minimal partially because of number constraints but primarily because it is anticipated that a new technique for personal communications, memos, reports, filing, etc., will be developed independent of the use of paper. This will likely be a semiautomated procedure with computer assistance.

The system's monitors are control console operators. The reactor power systems will be monitored here as will all the life-support systems and, where appropriate, some of the manufacturing operations. Tug launching and landing will also be controlled from these consoles. At this time, all colony systems will be nominally monitored and controlled internally to the colony with little earth backup ability. The communications system will be housed in this same location so that the systems' monitors can work closely with the communications technicians and give backup support during low activity time periods when the communications technicians are off duty.

The lunar colony will be independent in food supplies. Personnel are indicated for food production, processing, preparation and serving. In addition, limited housekeeping (individuals will be responsible for the cleanliness of their own living units and immediate work areas) and laundry facilities will be available. The laundry is expected to be semiautomated with garments of the type that require little personal attention. A barber/beautician is in residence providing professional grooming services.

Professional medical, therapeutic and counseling services will be available and responsible for maintaining the mental and physical health of the colony residents. In addition, the presence of individuals from the fine arts and social sciences will do much to enhance the quality of life and help maintain the morale of the colony. They should contribute directly to colony habitability planning as well as offering performances and/or classes and/or private lessons to interested individuals. Their efforts should be therapeutic in relaxing tensions and fear and constructive in building team interaction.

A relatively large number of skilled and professional personnel are designated in Table 3.1-7 for the support of the many colony systems and activities. Their abilities cover a wide range, starting in the list at storekeeper and continuing down to physical plant maintenance. Examples of occupations included are glassblower, librarian, electrical and mechanical engineers and technicians, chemists, and EVA technicians. Many of these personnel are expected to be involved in the support of research and development work to some degree.

An important activity contributing to colony independence will be the production of oxygen and some of the few metals available in the lunar fines. Nonmetalic materials will also be fabricated and used in colony construction applications. These latter materials can be used as structural elements and in lunar fabricated furniture. Personnel are identified for these activities.

The colony must have the ability to grow. The decision as to the extent of this growth will probably be made sometime after the colony has reached the threshold point. However, it is thought that the growth from this point will initially be slow--one structure at a time at a relatively slow pace. Design and construction personnel will be available for these expansion activities. In addition, these personnel can be used for renovating older facilities.

There are a total of 178 personnel listed in Table 3.1-7. Of these, 61 are directly involved in research or research support on a full-time basis. In addition to these, there are 23 persons at the professional level who are expected to be involved in research and/or development on a part-time basis. There are numerous others at the technical level who will be supporting the research and development programs to some degree.

It must be recognized that this is a first attempt at defining the personnel contingent for a semi-independent lunar colony. As such, it will undoubtedly be revised many times. Perhaps its greatest contribution will be to serve as a guide to future efforts.

REFERENCES

1. National Aeronautics and Space Administration, "Reference Earth Orbital Research and Applications Investigations", Vol. I-VIII, NASA Report NHB 7150.1 (1-VIII), National Aeronautics and Space Administration, Washington, D. C., January 1971.

2. Convair Aerospace Division of General Dynamics, "Life Science Payload Definition and Integration Study", Vol. I-III, Report No. GDC-DBD72-002, Convair Aerospace Division of General Dynamics, San Diego, California, March 1972.

3. Space Division of North American Rockwell, "Lunar Base Synthesis Study--Final Report", Vol. I-IV, NAR Report SD71-477-1(2,3), Space Division of North American Rockwell, Downey, California, May 1971.

4. Robbins, D. E., "Scientific Programs in Astronomy for a Lunar Base", NASA-MSC Memorandum to R. V. Battey, Manned Spacecraft Center, Houston, Texas, March 29, 1972.

5. National Aeronautics and Space Administration, "1967 Summer Study of Lunar Science and Exploration", NASA Report NASA SP-157, National Aeronautics and Space Administration, Washington, D. C., 1967.

6. Jet Propulsion Laboratory, "A Program Analysis for Lunar Exploration", Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, July 25, 1967.

7. Convair Aerospace Division of General Dynamics, "Research and Applications Modules Phase B Study, Preliminary Design Review Brochure", Report No. GDCA-DDA72-013, Convair Aerospace Division of General Dynamics, San Diego, California.

8. Convair Aerospace Division of General Dynamics, "Research and Applications Modules Phase B Study, Executive Briefing Brochure", Report No. GDCA-DDA72-012, Convair Aerospace Division of General Dynamics, San Diego, California.

9. NASA Science and Technology Advisory Committee for Manned Space Flight, "Proceedings of the Winter Study on Uses of Manned Space Flight, 1975-1985", Vol.I, II, NASA Report NASA SP-196, National Aeronautics and Space Administration, Washington, D. C., December 1968.

10. National Aeronautics and Space Administration, "Architectural and Environmental Considerations for Space Station Design", NASA-MSC Internal Note 71-EW-3, Manned Spacecraft Center, Houston, Texas, June, 1971.

11. Hodges, Carl N., and Carle O. Hodge, "An Integrated System for Providing Power, Water and Food for Desert Coasts", Hortscience, Vol. VI, pp. 10-76, February 1971.

CHAPTER 4 THE LUNAR SURFACE BASE - A BEGINNING

Evolution of growth and functional requirements of the lunar colony (LC) are predicated on an initial base concept. It is the purpose of this chapter to describe the Lunar Surface Base (LSB) from which the colony will grow. Section 4.1 considers the present NASA concept of the LSB while Section 4.2 redefines the LSB to provide a logical baseline for growth.

4.1 THE LSB

Previous work sponsored by NASA was oriented towards a lunar surface base which would support a two- to five-year program of scientific and exploration activities in the 1980's by a crew of up to 12 men at any location on the moon which might be selected [1]. The principle program option involved considering the operation of the LSB with or without an operational Orbiting Lunar Station (OLS). A LSB configuration which included a main shelter, major science elements and surface mobility system elements was conceptually defined.

The scientific mission requirements fall into two main categories of surface activities: main base activities, which include astronomy, deep drilling and nonsite-dependent experiments which may be performed at the base, and the selenological explorations at multiple sites in an expanded region around the base site. The drilling concept would require equipment for stratigraphic investigations to depths of 10, 100, and 1,000 feet; the astronomical measurements would utilize X-ray, optical (50 and 100 inch), infrared and radio (0.3-1 and 1-15 MHz) telescopes.

The remote sorties (i.e., those surface mobility missions to satisfy the selenological explorations described above) involve both travel to a site and travel at the site. Main shelter activities also require multiple trips to the outlying elements of the base. A mobility concept was derived to satisfy these requirements. For local trips the mobility equipment should provide a shirt-sleeve environment and habitability provisions to permit an overnight working trip for two men. For the longer trips of up to 90 days for four men on a sortie to a remote site, much larger living quarters are desired. The mobility concept which was selected to satisfy these requirements, as well as base construction and logistics requirements, is shown conceptually in Figure 4.1-1. The concept involves a prime mover with a shirt-sleeve habitability provision for two men, capable of autonomous operations for up to 48 hours away from a shelter, and providing attachments to accomplish the construction and logistics tasks. For the long sorties, two prime movers are utilized to provide redundancy, "back-out" control, and two 2-man vehicles for local exploration when the remote site is reached. A mobile shelter is included in the train which provides the additional habitable volume and subsystems to support the 4-man sortie crew for the sortie duration.

Power for the sortie equipment is provided by a mobile power supply unit. This power concept is a radioisotope-powered organic rankine system which also supplies the power for the widely dispersed elements of the LSB. It was determined that power tended to follow men, i.e., when the sortie crew left the main base, the base power decreased by essentially the same amount as the sortie crew needed to take with them. Therefore, the base power is provided from a J-box (bus) which is energized from a number of mobile, modular power units, any one of which can be unplugged and taken along for the sortie. This concept is shown in Figure 4.1-2.

In order to minimize the expenditure of consumables on the lunar surface, a life-support mass-conservation system is utilized as shown in Figure 4.1-3. The basic approach is that the main base and the sortie mobile shelter utilize the same water recovery and carbon dioxide reduction processes but that in order to minimize the power constraints on the mobile equipment, all electrolysis

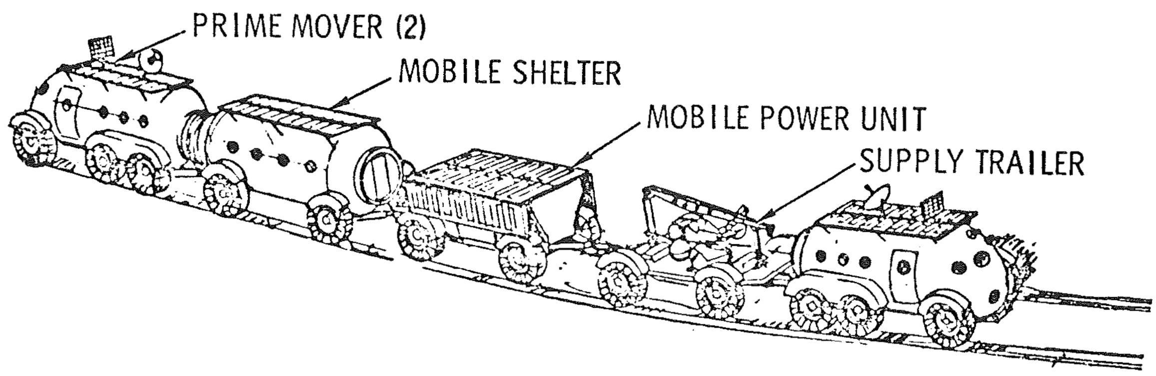


Figure 4.1-1 Mobility system concept

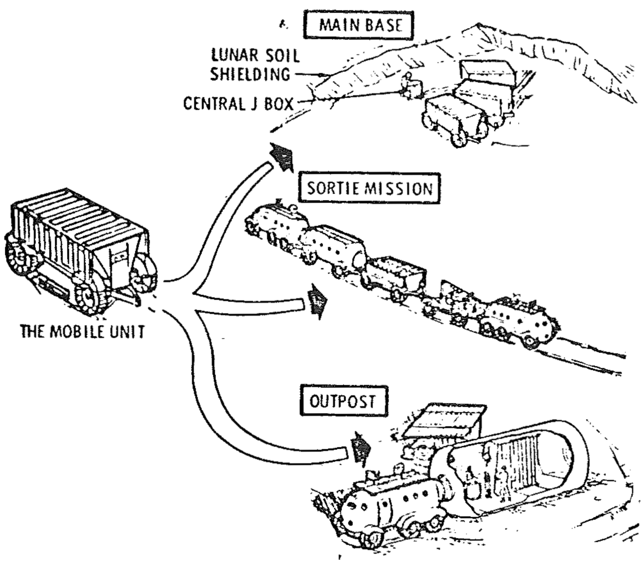


Figure 4.1-2 Mobile power module concept

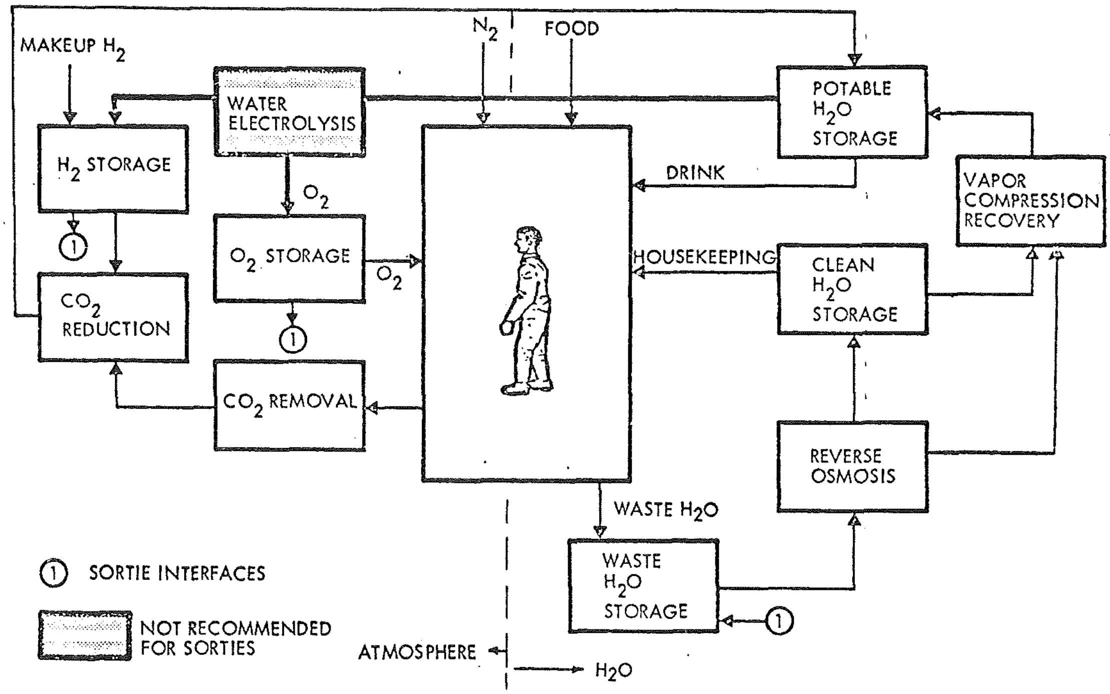


Figure 4.1-3 Mass conservation concept

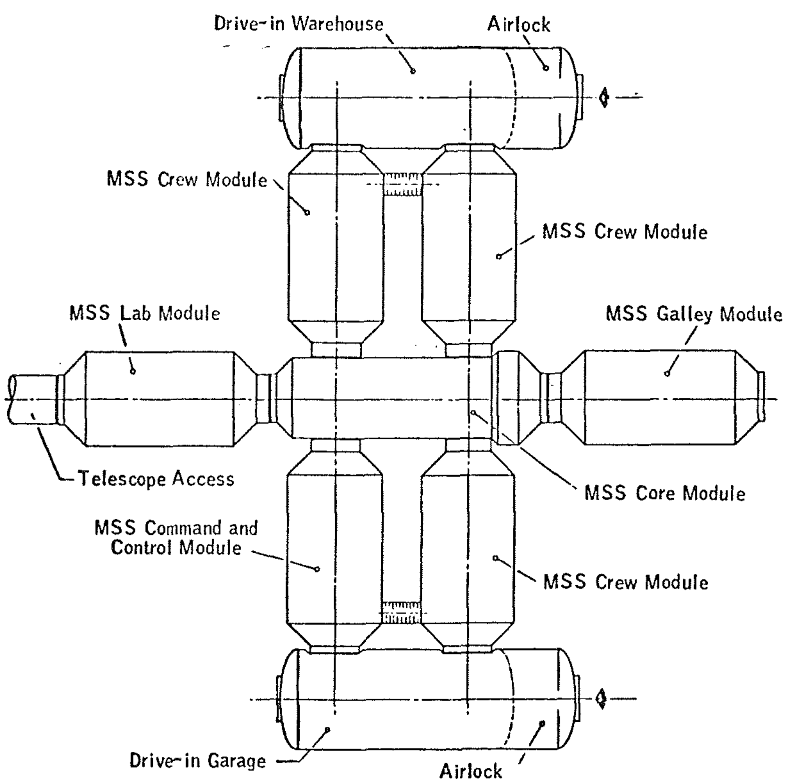


Figure 4.1-4 MSS derivative LSB shelter

to recover oxygen and hydrogen is done at the main base only.

The main base shelter design consisted of two possible configurations. One was designed to optimize the shelter configuration for the spectrum of lunar surface missions. The definition of the optimized LSB shelter produced a conceptual design of a lunar shelter from the specified OLS module. This latter concept envisions a base configuration as shown in Figure 4.1-4. Seven modular space-station (MSS) derived modules are shown along with their proposed functions, such as crew module, lab module, etc. The modules are 15 feet in diameter and 30 feet long. Two other modules are modified to 45 feet long and serve warehousing and garaging functions. The overall LSB concept as it might appear on the lunar surface is shown in Figure 4.1-5. The logistics vehicle landing site is removed from the other base elements to minimize potential damage. The drilling site is separated from vibration-sensitive base elements and the astronomical site must be located away from both the tug landing site and the drilling site. The main shelter is covered by not less than 6 inches of lunar soil which provides thermal, meteoroid and radiation protection for short lunar surface crew stay-times (less than 200 earth days). The arrangement of the modules provides two exits from each module for safety considerations. The MSS derived modules, when coupled with the OLS concept, are expected to yield a saving in program development costs over the optimum baseline shelter.

4.2 REDEFINITION OF THE LSB

The NASA Lunar Surface Base as described in Section 4.1 is science-mission oriented with major efforts in geology and astronomy. In contrast, the LSB we envision is growth oriented with the basic objective of growing to earth independence and achieving the status of a colony. Therefore, the science objectives of the NASA LSB will be somewhat altered. The requirements of a 100-inch optical telescope will be initially relaxed. After the colony

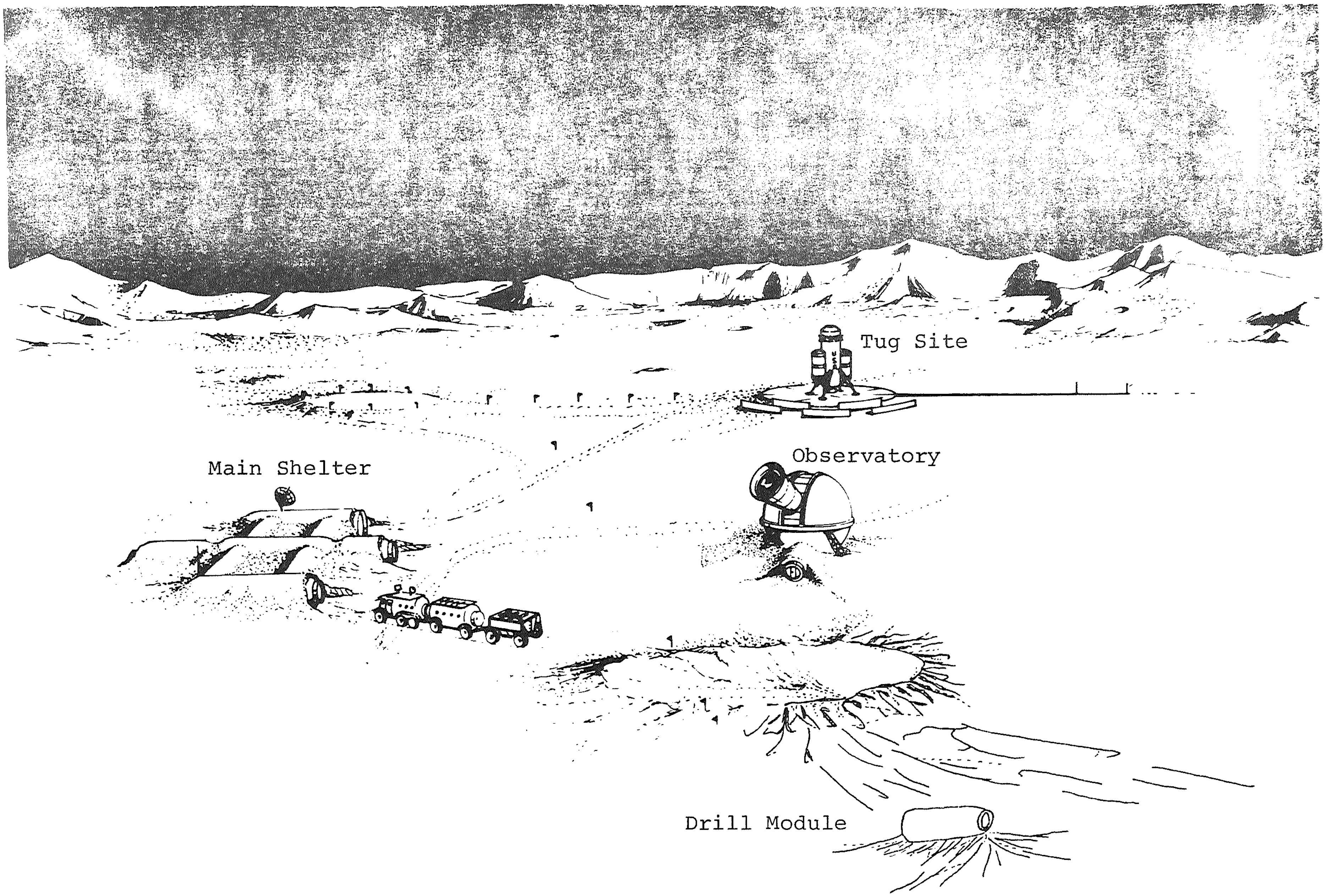


Figure 4.1-5 NASA 12-Man Lunar Base

becomes established and attains a large degree of independence, the need for this large telescope can be considered. The 50-inch optical telescope will be retained. The X-ray telescope and the 0.3-1 MHz radio telescope are to be omitted initially with possible inclusion later. The initial need for the 1000-foot drill is also relaxed along with the long-range sortie mobility concept. The LSB will, however, have the capability for 10- and 100-foot drilling. Drilling ability should include horizontal as well as vertical drilling. To place the redefinition of the LSB into perspective, the science equipment to be initially relaxed comprises 72% by weight (52.3 Klb.) of the NASA LSB science-equipment weight and 63% of the major scientific-equipment costs ($521M). Relaxation of these science requirements permits the inclusion of some scientific and technological experimental equipment/development pertinent to base expansion. This equipment/development would be used in initial plant life-study for future lunar-food production, mining-technique studies for a source of raw materials and an initial study for developing building materials from lunar sources. Also, many of the main-base science-equipment items are replaced by other equipment items capable of performing the redefined experimental and developmental goals of the LSB.

In the redefinition of the LSB, it is assumed that the OLS is operable and will be available for LSB support along with a lunar orbit-to-surface logistics vehicle (tug). The MSS derived LSB shelter configuration is accepted as defined. However, for personnel safety to long-term exposure (unlimited) from radiation, the LSB main shelter will be partially beneath the lunar surface and covered with 5 meters of lunar soil. The garage and warehouse modules will be on the lunar surface and covered with 3 meters of soil. Possibly, this soil protection will not be needed, see Section 6.3.

The mobile radioisotope-powered organic rankine system (6 power carts rated at 3.5 KWE each) for LSB power supply is accepted, as is the mass-conservation life-support system. Both are capable of being expanded modularly. The mobility concept as described in the NASA LSB will be accepted with some modification. As mentioned before, the long-range sortie concept is to be deleted, but adequate equipment must be available for burying the LSB main shelter as previously described. The prime-mover vehicle can adequately perform construction tasks with equipment attachments of a front-end loader and a 30-foot boom crane with a clamshell bucket. These attachments will be available at the LSB. Due to the relaxation of the long-range sortie, all four prime movers specified in the NASA LSB study are no longer needed, so one of them will be deleted, leaving three at the redefined LSB. Also deleted will be the mobile shelter and the supply trailer since their specific functions are concerned with long-range sorties.

In order to accomplish the redefined objectives of the LSB, the skills of the 12-man crew would have to be altered somewhat. The personnel at the LSB will be as follows:

1. M.D. (internist)/physiologist
2. Power systems engineer
3. Chemical process engineer
4. Mechanical/materials engineer
5. Heavy equipment operator
6. Chemist
7. Construction technician (mechanical)
8. Construction technician (electrical)
9. Geologist/petrographer
10. Horticulturiest/minerla nutritionist
11. Plant pathologist/microbiologist
12. Astronomer

The personnel and the facilities of the redefined LSB as described above are assumed to exist at "time zero" of lunar colony growth. "Time zero" is defined as that point in time at which the redefined 12-man LSB has produced significantly promising research/development results to achieve the go-ahead decision for growth to the earth independent LC concept.

REFERENCES

1. Lunar Base Synthesis Study - Final Report, Vol. I, II, III, and IV, Space Division of North American Rockwell Corporation, Downey, California, Contract No. NAS8-26145, May 1971.

CHAPTER 5 GROWTH TO A COLONY

The semi-independent lunar colony is envisioned as growing in some well-defined way from the twelve-man lunar base described in Chapter 4. The purpose of this chapter is to outline the growth from this base to the colony threshold. The base is said to have reached the colony threshold when it has achieved a high degree of independence and is supporting a serious, on-going research and development program as described in Chapter 3. A possible colony configuration and its status at various periods in the growth sequence outlined here is presented in the next chapter.

5.1 PHILOSOPHY OF GROWTH

Initially, the Lunar Surface Base will be totally earth dependent. It will be configured for growth, with research and development programs in those areas which will contribute to growth. In addition, it will have some pure physical science capability in nonsupport areas. Growth from this point will strongly emphasize those skills which will contribute most directly to the goal of independence. However, at all stages of growth, pure science research should not be neglected as this also contributes directly to the goals of the colony. The growth should be a reasonable balance of all areas contributing to the colony goals with initial emphasis on those areas which contribute most directly to realizing independence.

It is thought that there should also be a balance in terms of time and growth so as to avoid surges and lags in growth and, consequently, funding. Avoiding large surges in growth is a necessity because of the need for experimentation, verification, and development between the small discrete steps in growth. Lags should also be avoided as they tend to cause lapses in interest and frequently have the potential for being more expensive in the long run.

Figure 5.1-1 demonstrates graphically the anticipated time form of colony growth in terms of population and earth dependence. The population growth will be slow at first and then increase as the colony increases in capability and independence. The level of earth dependence will drop dramatically at points where breakthroughs occur in the lunar manufacturing of necessary support items. These "kilometerstones" (milestones) are described and put in proper time frame in subsequent sections of this chapter. Note that at the colony threshold point (about 180 personnel), there is still some degree of earth-supply dependence.

The sequencing of growth of colony functions has been defined on the bases of colony objectives, functional independence, hardware availability, and on-site development time. The first two points are more easily treated, whereas, the last two are much more difficult to predict. Because of the finely tuned nature of the growth sequence, it is sensitive to any variability in these four bases. It is, therefore, subject to revision up to the start of the colonization program and even more so after it has begun.

5.2 INCENTIVES FOR GROWTH

With present transportation systems, the intitial growth of any lunar colony will be limited primarily by the weight of material that can be delivered from earth to the lunar surface. If, as a colony grows, it develops the ability to utilize lunar resources, this dependence on weight of materials sent from earth can be drastically reduced. This section discusses the four areas that we feel are most important in reducing the effect of the weight constraint on growth.

5.2.1 OXYGEN PRODUCTION

The production of oxygen from lunar fines for life-support needs will eliminate the necessity of transporting this critical consumable from earth. Plentiful oxygen will also place less

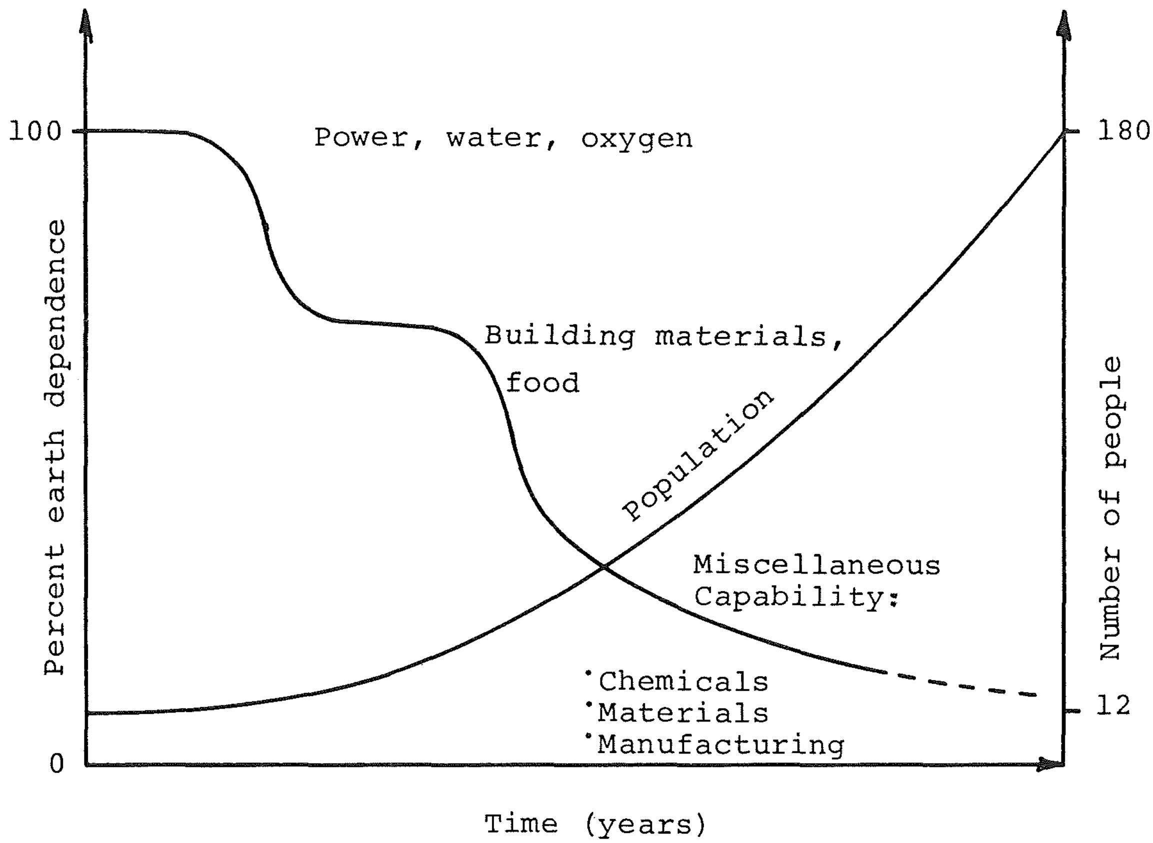


Figure 5.1-1 Anticipated Time Form of Lunar Colony Growth

stringent demands on the life-support system.

However, the largest effect of oxygen production on the moon will be when sufficient quantities are available for tug fuel. This will greatly increase the payload that can be delivered to the lunar surface and hasten growth.

Our basis for calculation is a constant 500,000 pound per year payload in lunar orbit. This payload is composed of three parts: (1) men to be delivered to the base, (2) materials for the colony, and (3) fuel (oxygen and hydrogen) for the tugs that travel from lunar orbit to lunar surface and back. The tugs require 11,000 lbs of hydrogen and 53,000 lbs of oxygen for a round trip. Figure 5.2-1 shows combinations of flights for delivering part or all of this payload to the lunar surface. Tug trips can be unmanned or manned. A manned flight is composed of six or more people who are delivered to the lunar colony for crew rotation or augmentation purposes. Manned flights require the use of a 10,000 lb crew module which in turn reduces the material portion of the payload when compared with unmanned flights. The two types of flights considered are shown diagrammatically on the figure. The solid square symbol at the top of each line shows the most payload that can be delivered in a year for the given number of manned flights. Fewer total flights will not deliver all the payload available in orbit. For the 0 and 3 manned-trip cases, a somewhat unrealistic situation is portrayed. The slope of the payload line is less at the last segment, indicating that not enough payload was available in orbit for a full trip. In practice, this would not occur since the flight spacing would be increased slightly and not necessarily correspond with a calendar year.

Now we will consider the greatly improved payload delivery that can occur when lunar oxygen is supplied in sufficient quantity to fuel the tug. Figure 5.2-2 (same scale as Figure 5.2-1) shows the more favorable situation. Again, the combination of manned and unmanned trips have been shown. The number of flights are

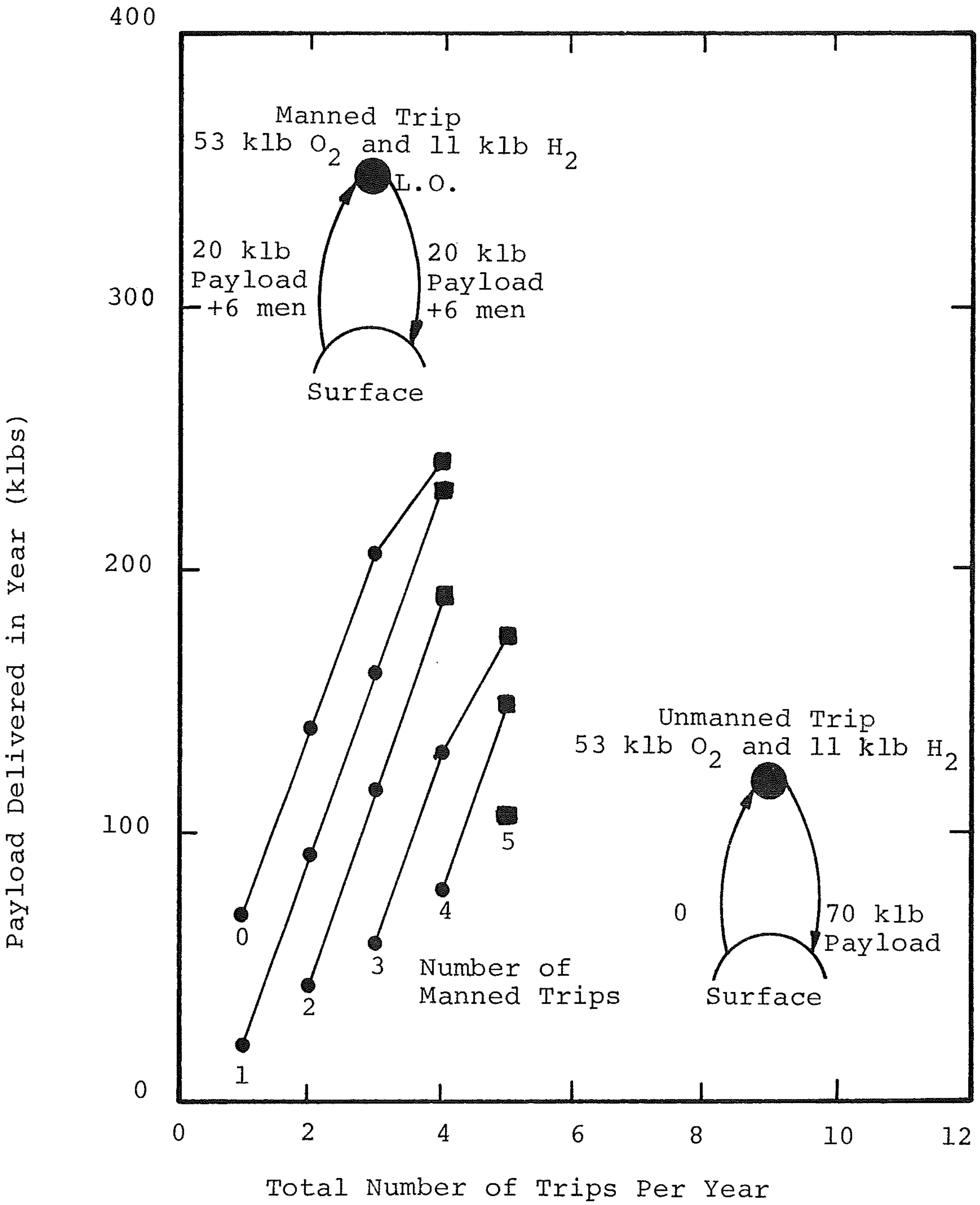


Figure 5.2-1 Payload Delivery With Earth-Supplied Oxygen

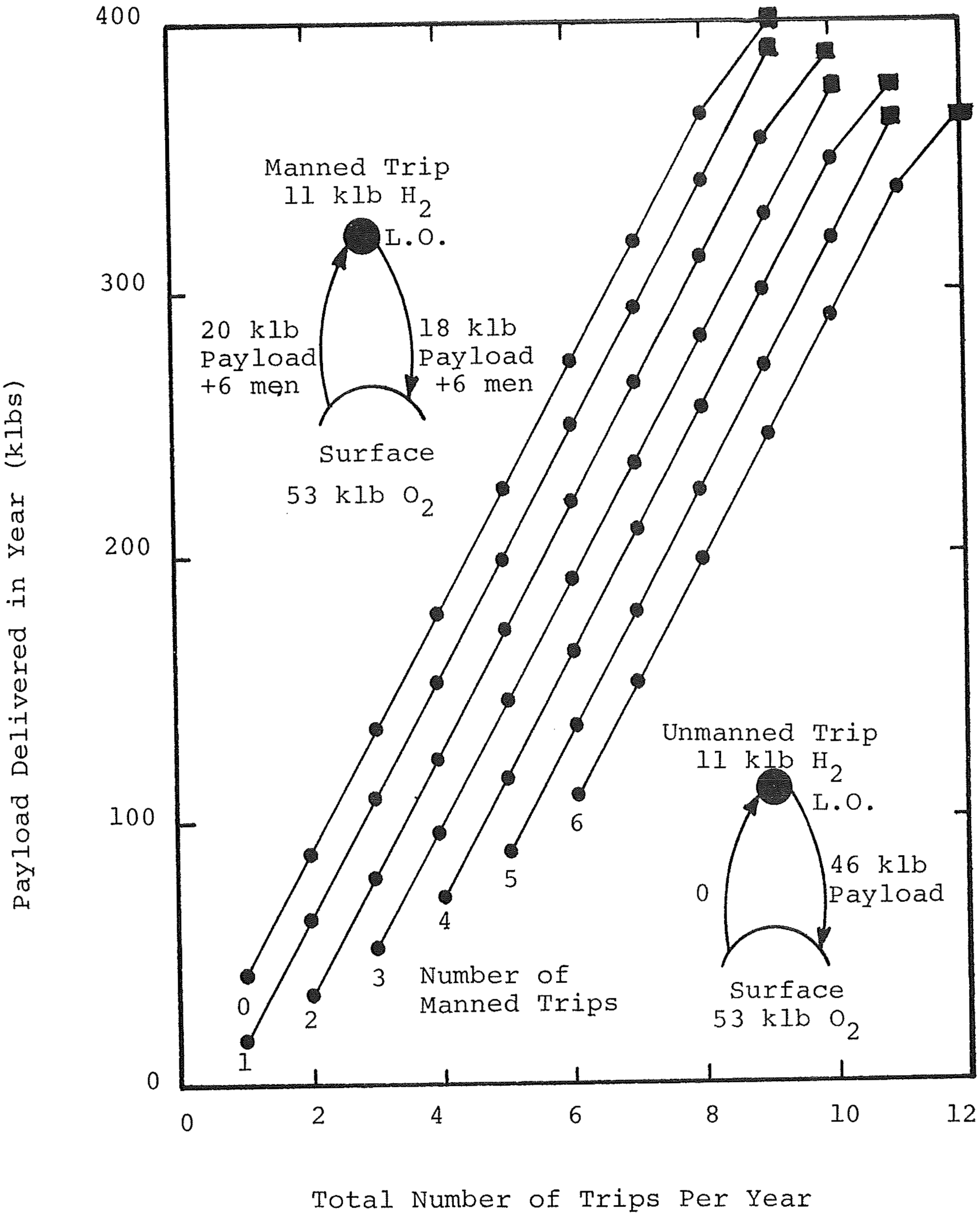


Figure 5.2-2 Payload Delivery With Lunar-Supplied Oxygen

increased, but payloads are more than doubled in most cases. Also the number of manned flights does not affect the payload delivered to the surface as much as in the earth-supplied oxygen case. The slight changes in slope at the top of some payload lines again represent the artificial limiting of the delivery time to one year.

Other payload combinations for the tug system may be desired and the two discussed above are for purposes of illustration only. Figure 5.2-3 shows the range of tug payload capabilities, including lunar-surface/lunar-orbit return capabilities, for both earth-supplied oxygen and lunar-produced oxygen. In practice, the types of trips may be varied considerably over the course of any year to suit the colony's supply requirements.

We believe the above explanations indicate the need for an oxygen-production plant at the earliest possible date in the colony's development.

5.2.2 FOOD PRODUCTION

It has always been recognized that for a colony to be viable and permanent, a food-production process must be included. However, in space missions to date, no attempt has been made to produce food. The volume required for such a project is one obvious reason. In a lunar colony, conditions for food production will be more favorable.

The magnitude of the long-duration food-supply problem can become enormous. Information compiled for manned space missions [1] show the rise of life-support weight with mission duration (Figure 5.2-4). The stored-food portion of life-support needs increase rapidly while the remaining part of the life-support system increases only moderately. Although the graph shown in Figure 5.2-4 is for a 50 man crew, the relative proportions are thought to hold for a 5 to 100 man system.

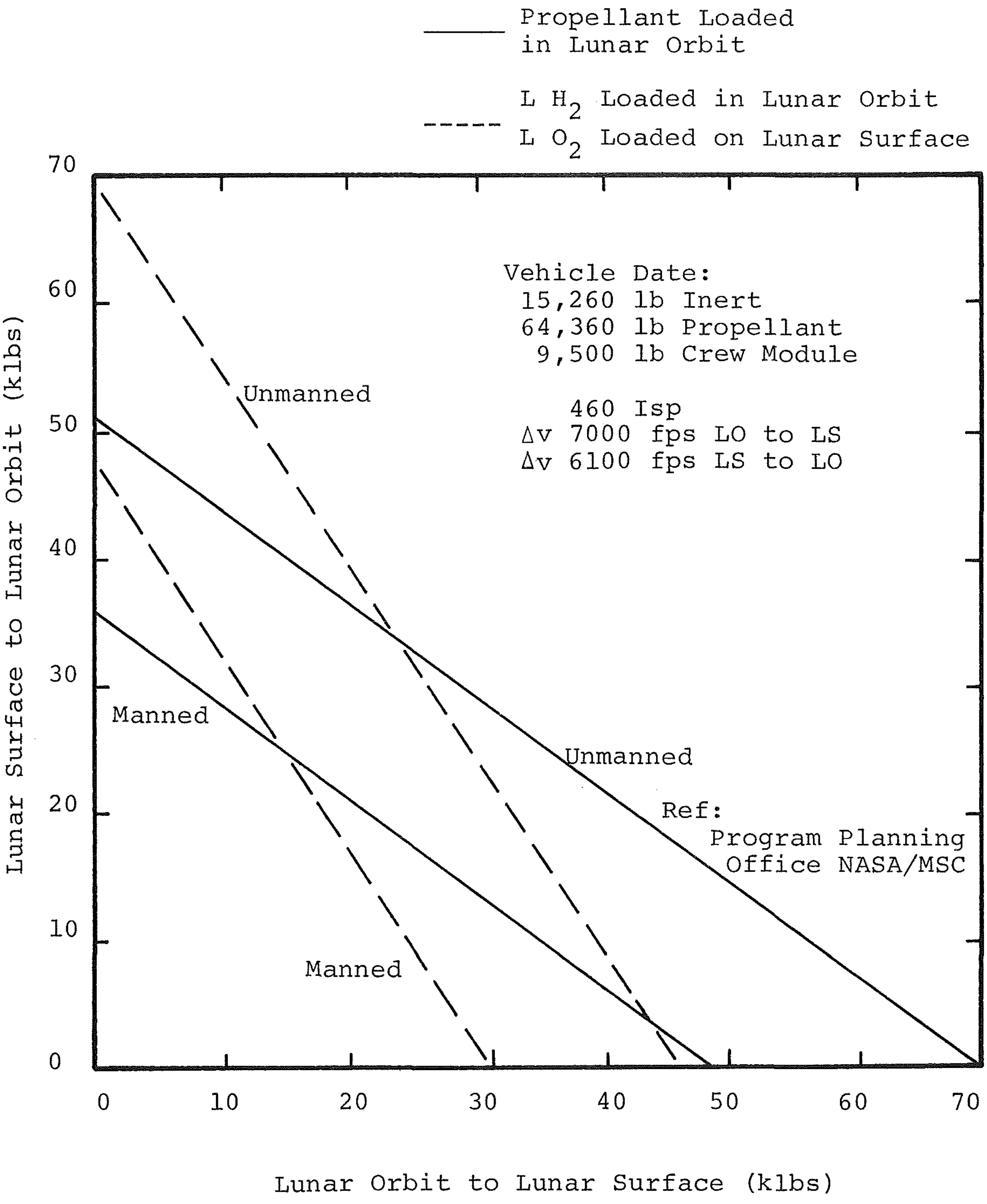


Figure 5.2-3 Payload Tradeoffs

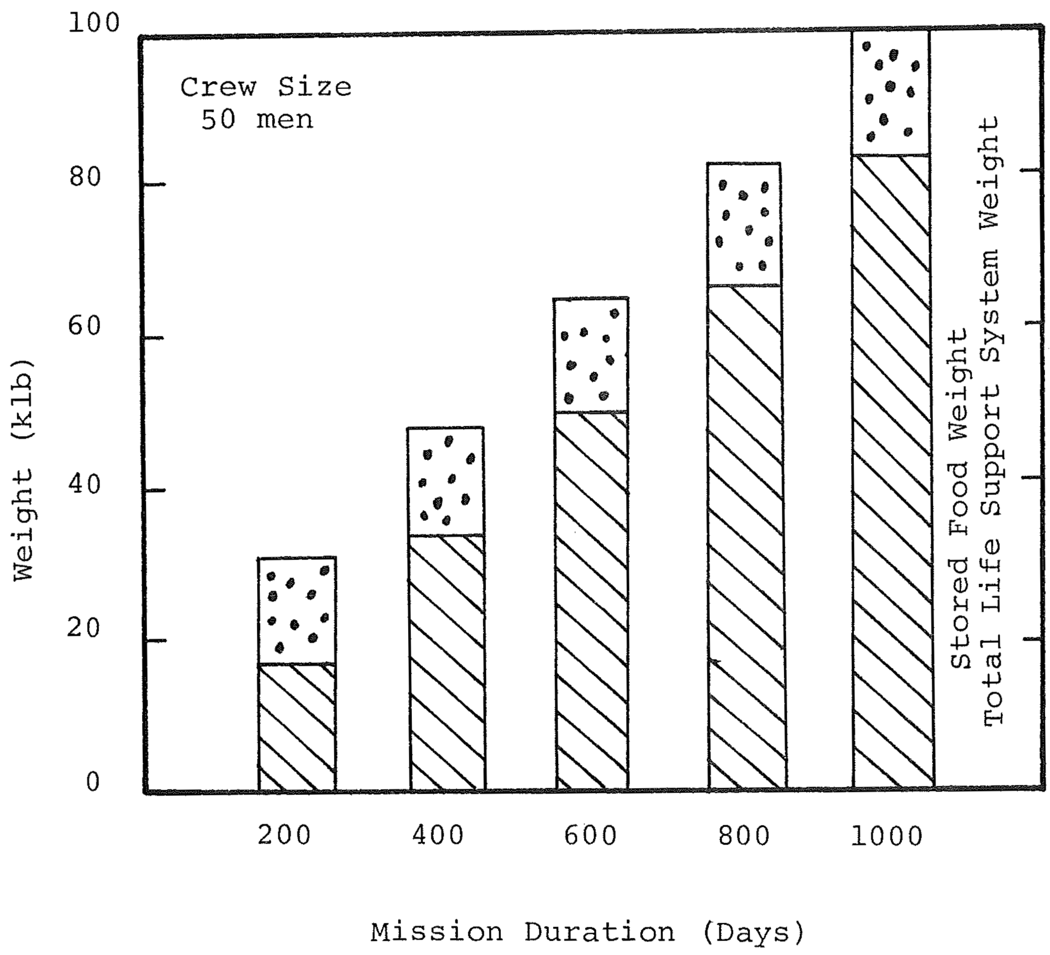


Figure 5.2-4 Relative Weights in a Life Support System

The need for a farm or food-growth facility in the development of a lunar colony seems second only to oxygen production in terms of cost effectiveness. Unfortunately, our preliminary study (Chapter 13) shows that much research and development work needs to be done in this area before a total food-growth system could be developed. However, it may be possible to relieve the food-supply problem partly through the production of diet supplements from lunar-colony waste materials.

5.2.3 MATERIALS AND MANUFACTURING

Initially, structures for the lunar colony will be delivered from earth. As the capabilities of the colony increase, lunar materials will be used in construction (Chapter 15) of new facilities. This utilization of materials is necessary for cost effectiveness in expanding the colony and it also reduces colony dependence on the earth. It is apparent that additional facilities will be needed as colony population increases. However, other factors require that a colony needs increased living and work facilities above what might be provided initially even for a constant population. Studies [2] show that habitability considerations have an influence on effective work in a mission. Figure 5.2-5 shows a representation of this effect that we might consider as relating at least partly to inhabitable volume provided in a colony. Additionally, permanence and the large number of personnel in the colony will require larger facilities than would be determined by scaling-up space-mission habitat. Figure 5.2-6 gives an indication of the effect that mission duration and crew size have on volumetric requirements. The cross-hatched area on the figure represents an additional volumetric requirement due to specialization in a long mission. Specialization [2] refers "to the physical separation of activities which may have formerly occupied a 'Dual Room Usage' area."

5.2.4 POWER PRODUCTION

The electric power system is mentioned at this point simply to

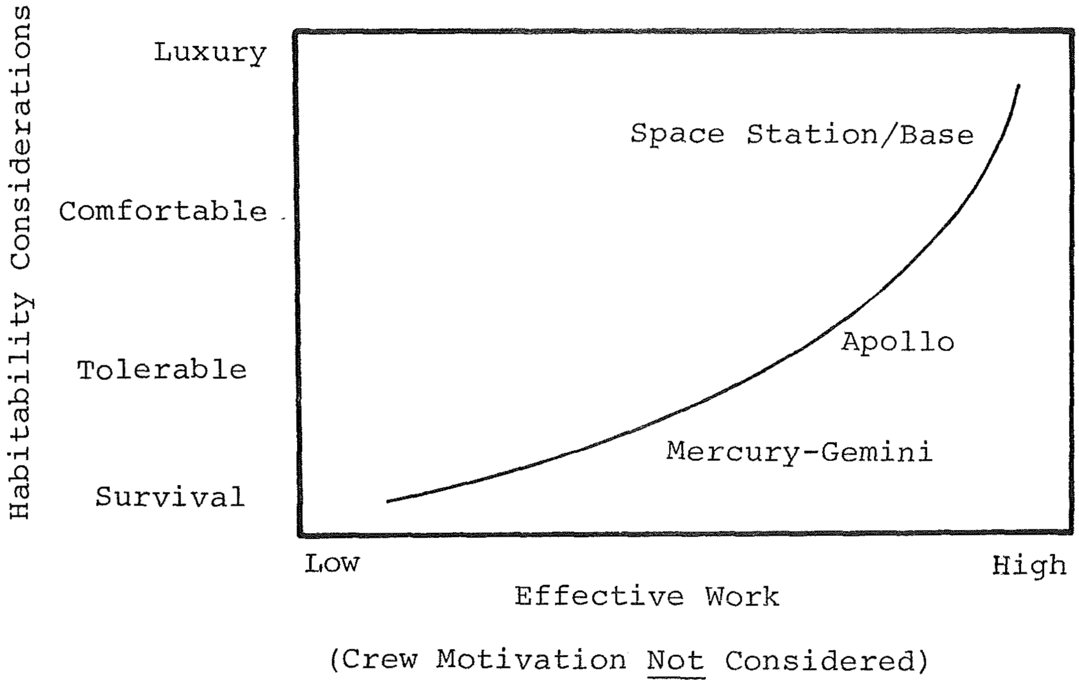


Figure 5.2-5 Effective Work Output

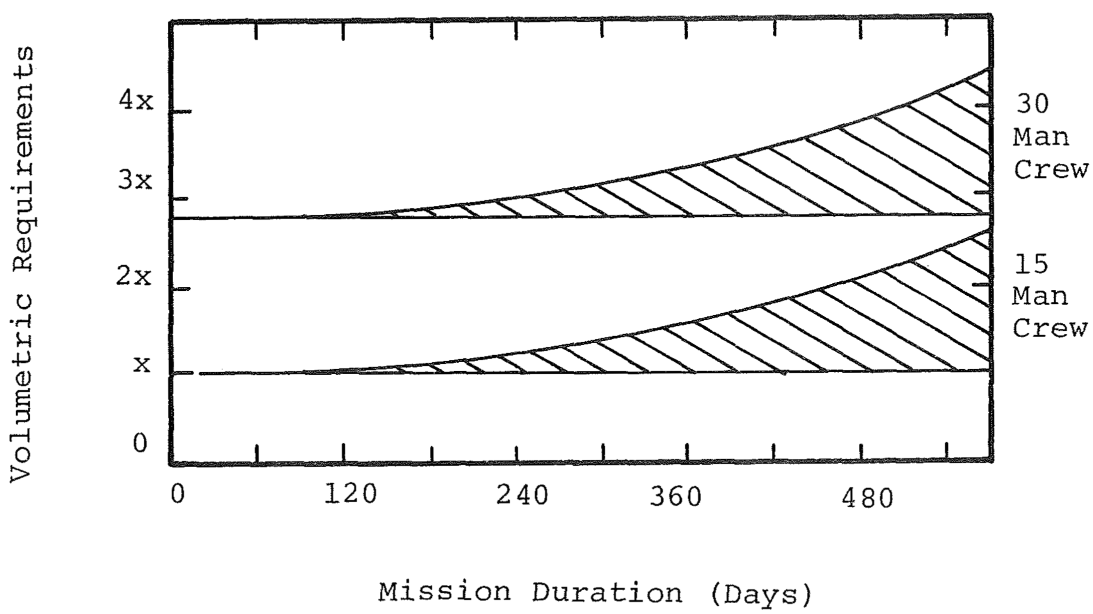


Figure 5.2-6 Increasing Volumetric Requirements

indicate that all of the above activities depend on the availability of large amounts of power. Thus, the power system is really the precursor to all of the colony-independence steps described. A large and reliable longlife power supply should be the first item delivered when the initial step from a base to a colony is taken.

5.3 FUNCTIONAL GROWTH PATTERN

The reorientation of the NASA LSB (twelve-man) base for growth potential was described in Chapter 4. A low manpower effort of this type presupposes thorough advanced planning for accomplishment of reasonable productivity. To increase the likelihood of a productive effort at the twelve-man base level and during later growth, a number of stages are presented for the development of subsystems:

1. Earth-based development of technology using simulated lunar materials.
2. Earth-based verification and development using small quantities of lunar materials.
3. Lunar-based verification and technological development using compact earth-built equipment.
4. Lunar-based production using lunar-produced equipment, probably with some earth-manufactured components.

Economics will form the broad basis for progression from one stage to the next. While there are some subsystems for which the progression is not directly applicable, it indicates the general growth philosophy.

At time zero, when the twelve-man base is occupied, the functions which this contingent will perform are as follows:

1. Install and start the power generation system and gain experience in operation of the nuclear reactors. (Five

3.5 kwe organic rankine radioisotope sources are still available from the buildup of the twelve-man base.)

2. Develop and initiate thermal power generation using a solar furnace; the specific thermal subsystem integrates with the oxygen-production facility.
3. Initiate oxygen-production pilot plant operation and gain data in operation for utilization in scale-up to full oxygen production plant. Install full-scale oxygen production plant.
4. Locate lunar materials in concentrations higher than found on the average in the lunar countryside. Begin development of methods for mining these materials in the required quantities.
5. Test to determine the properties of metals from earth sources which have been exposed to the lunar environment with or without protective coatings. Determine the properties of lunar materials which might be used in construction with minimal processing (brick, block, glass).
6. Obtain initial information on connecting lunar blocks or bricks and testing the properties of the connected materials.
7. Test the viability of plants in the lunar environment (low gravity, diurnal cycle, negligible magnetic field, etc.) and obtain information regarding the effects of their pathogens in this environment. Determine initial information regarding reproduction capabilities. Determine the effect plants have on soil composition and characteristics.
8. Maintain life through foods supplied from earth. Maintain physical and mental health through monitored, regular exercise. Determine performance and capability degradation through periodic physical and psychological examinations. Predict effect of reentry into earth environment as a function of natural and synthetic lunar environmental conditions and the length of lunar stay. Initiate experimentation with mammals to determine

genetic mutation effects resulting from radiation dosage.

9. Supply earth materials for life support and continued expansion of the base.
10. Connect new earth-supplied modules for use by expanded 24-man base in next stage of growth. Provide radiation protection for combined base configuration. Initiate inflatable structure technology through use of a 2-meter diameter farm module, perhaps using external manipulation (glove box system).
11. Initiate astronomical observations. Visual galactic and solar observations will be made utilizing the 50-inch telescope. Radio observations will be carried on in a semiautomated mode by a two-element interferometer (1-15 MHz) and a three-frequency transponder. Other minor operations such as determining the effects of the lunar environment on optical surfaces will be performed.
12. Initiate selenological research. One man effort in the areas of field selenology, petrography, and selenochemistry; would oversee some preplanned, semiautomated solid-earth selenophysical observation equipment.
13. Monitor life-support systems with alarm system basis. Data collected and stored as well as telemetered to earth.

The philosophy of functional activities selection at this time and in future growth can be described by development and balance. These are consistent with a growth-to-colony concept as well as the philosophy of getting some information (contingency sample equivalency) in case a mission abort is necessary.

It should be apparent at this point that the personnel of the twelve-man base will need to be very flexible. A large number of functions, some highly technical, some physically demanding, must be accomplished by a relatively small group. The personnel must be willing and able to give physical and semitechnical assistance under the direction of the person responsible for accomplishment of a given task. A list of the responsibilities for each person follows:

1. Power Systems Engineer
   Serves as base commander also. Responsible for the electrical power generation system and the thermal power generation system. Depending upon the critical nature of his function at any point in time, he will monitor the life-support systems (backup provided on earth) or delegate this responsibility. Responsible for communication systems operations.
2. M.D. (Internist/Physiologist)
   Serves also as assistant base commander (personnel). Acts as physiological and psychological monitor for base personnel. Prescribes physiological and psychological changes in personnel living patterns. Determines the advisability of modifying individual stay times. Provides medical, surgical and limited dental support.
3. Chemical Process Engineer
   Responsible for production of oxygen from lunar materials and storage subject to use. He will also be responsible for base control systems operation and will assist in materials development.
4. Selenologist/Petrographer
   Responsible for characterization of minerals in the area of base and selection of mining areas in conjunction with materials engineer. Combined responsibility with materials engineer for best use of drilling equipment. He will, as is available, carry out a one-man research effort in field selenology and petrography. Additionally, he will deploy and oversee earth-remote instruments for selenophysical experiments.
5. Mechanical Engineer/Materials Engineer
   Responsible for developing mining and quarrying procedures, methods for connecting quarried materials, and properties testing for proposed structural materials. He will assist chemical process engineer in start up and

data collection for oxygen-process development. Combined responsibility with power systems engineer for development of solar furnace. Combined responsibility with selenologist for best use of drilling equipment.

6. Horticulturist/Mineral Nutritionist
   Responsibility for experimental verification of viability of plants in lunar environment. Verification of capability for plant production of man's nutrient requirements. Direct experiments toward determination of plant reproducibility.

7. Plant Pathologist/Microbiologist
   Responsible for determination of susceptibility of plants to disease and institution of control procedures. Joint responsibility with botanist for development of resistant strains. He will assess changes in microbial populations associated with man, plants and soil.

8. Heavy Equipment Operator
   Responsible for operating equipment in support of mining, quarrying, installation of large equipment and modules, and trenching operations. Vehicle operator for complex, remote operations. Assists construction technicians as necessary.

9, 10. Construction Technicians-Electrical and Mechanical
   Install electrical power-generation system, thermal power-generation system, oxygen-production system and second stage habitability modules. Responsible for physical plant maintenance. Generally assist in physical support of base-systems expansion. Mechanical technician helps in operations of oxygen-production plant. Electrical technician does electrical (and electronics) repair.

11. Chemist
   Support of chemical process engineer, materials engineer, selenologist, M.D. (internist/physiologist, horticulturist/mineral nutritionist, and plant pathologist/microbiologist by chemical analysis and other laboratory techniques.

12. Astronomer
He will carry on a one-man research program in astronomy. Combined responsibility with earth-based astronomers for alerting base of occurrence and magnitude of solar flares.

Arrival and departure from the base will be in crews of six. Each crew will be expected to include a trained pilot/navigator as a secondary capability. He will be responsible for delivering the crew from lunar orbit to the surface and delivering them back to lunar orbit at time of crew rotation. An inherent delivery redundancy is hereby provided within the base personnel.

No specific mix of males and females is prescribed. Rather, the ability of the individual to perform not only his assigned task but to fit flexibly into the entire colony evolution is the basis for personnel choice. One observation is that the low gravity situation somewhat reduces physical limitations and may encourage balance of male and female personnel. Social-psychological testing procedures yet to be developed will help select personnel that can effectively carry out their individual functions as part of a team. Food preparation and general housekeeping will be shared by the entire group.

As the base is expanded to the twenty-four man level, more specificity of tasks is possible. However, base personnel must still be willing and able to give physical and semitechnical assistance under the direction of the person responsible for the accomplishment of a specific task. General housekeeping duties will continue to be shared by all. The activities related to colony development, research and support are listed with corresponding responsibility and assistance:

1. Administration and Life-Support Monitoring
Life-support systems will be monitored semiautomatically. The commander will schedule and have local responsibility for all activities of the lunar base and act as local

civil authority.

-----Commander/Control Monitor/Communications Controller, M.D./Physiologist

2. Food-Production Development

Determine plant-growth requirements in planning for the farm. Consider plant-nutrient sources in terms of available metabolic wastes. Determine changes in soil physiochemistry as a result of plant growth. Continue monitoring plant pathogenicity and development of resistant strains. Start herb garden as food supplement. Begin more basic biochemical mechanism research comparing earth-bound with lunar-growing systems. Broaden study of biological organisms to include lower plants as possible food-cycle members. Extend reproduction, physiological changes and adaptations research.

-----Horticulturist/Mineral Nutritionist, Microbiologist/Plant Pathologist, Applied Biochemist/Botanist, Biotechnician, Chemist, Food Technologist/Dietitian, M.D.

3. Materials Development

Conduct laboratory experiments in materials fabrication and determine the physical properties of such, comparing them with earth-fabricated lunar materials where possible. Develop methods for construction utilizing lunar nonmetallic materials. Construct small test structures and evaluate their performance in the lunar environment. Test for degradation of nonmetallic materials. Reprocess broken glassware and develop impure glass production techniques.

-----Materials Engineer, Mechanical/Materials Engineer, Selenologist, Chemist, Construction Personnel

4. Health/Physical Maintenance

Maintain life through foods supplied from earth. Maintain physical and mental health through regular exercise and periodic physical and psychological examinations. Provide medical, surgical and limited dental support.

-----M.D./Physiologist, Social Psychologist, Food Technologist/Dietitian, Microbiologist, Chemist

5. Social Psychological Investigations and Contributions
Observation of social interactions and individual behavior in a small, closed society whose members have been purposefully selected. Provide counseling service. Investigate possible degradation in psychomotor and perceptual skills, intellectual functions and team interactions. Evaluate the effectiveness of team selection methods.
-----Social Psychologist, M.D./Physiologist

6. Metals Development
Conduct laboratory batch verification experiments in the separation and casting of metals. It is possible that this will be done utilizing the slag from the oxygen-production plant but more likely that a separate process will be required. Compare atomic structures and metallic properties of lunar and/or earth-produced, lunar-exposed, and unexposed samples.
-----Metallurgist, Materials Engineer, Mechanical/ Materials Engineer

7. Process Operations
Operate, service, repair, and evaluate the performance of the electrical and thermal power generation systems, and the oxygen-production plant. Modify these systems where advisable. Install, start and operate the large scale oxygen-production plant. Monitor the nuclear reactor and develop backup power supplies.
-----Power Systems Engineer, Oxygen Plant Operator, Chemical Process Engineer, Mechanical/Materials Engineer, Heavy Equipment Operator, Electronics Engineer, Construction Personnel

8. Communication and Computing
Maintain and operate the communications and computing facility. Schedule telemetry of data to earth and provide computational consulting support.
-----Electronics Engineer/Computer Specialist, Commander

9. Construction-Maintenance
Install first farm-module canister and an experimental,

inflatable farm module fifteen meters in diameter. Attach earth-manufactured canister modules for expansion to thirty-six man base. Cover prescribed sections of base with lunar fines to provide radiation protection. Perform physical plant maintenance. Complete installation of large scale oxygen-production plant and initiate production. Construct small test structures of lunar materials. Maintain power and processing systems. Provide maintenance for surface and space mobility vehicles.

-----2 Construction Technicians, 2 Construction-Maintenance Technicians, Heavy Equipment Operator, Vehicle Maintenance Technician, Chemical Process Engineer, Power Systems Engineer, Mechanical Engineer, Electronics Engineer

10. Mining

Mining will continue in surface stripping form. Drilling to a depth of 100 feet will be performed to attempt to locate subsurface concentrations of ores. Quarrying procedures will be developed. Mining techniques and ore transportation systems will be examined.

-----Heavy Equipment Operator, Mechanical/Materials Engineer, Selenologist, Vehicle Maintenance and Operator

11. Space and Surface Transportation

Coordinate supply of earth-manufactured materials as needed to continue expansion and development. Transport materials on the lunar surface.

-----Commander, Vehicle Operator, Heavy Equipment Operator

12. Medical Research

Initiate limited medical-research program, investigating human physiological and psychological changes and adaptations. Continue radiation experiments.

-----M.D./Physiologist, Social Psychologist

13. Astronomical Research

Continue astronomical observations. Begin investigations of particles and fields.

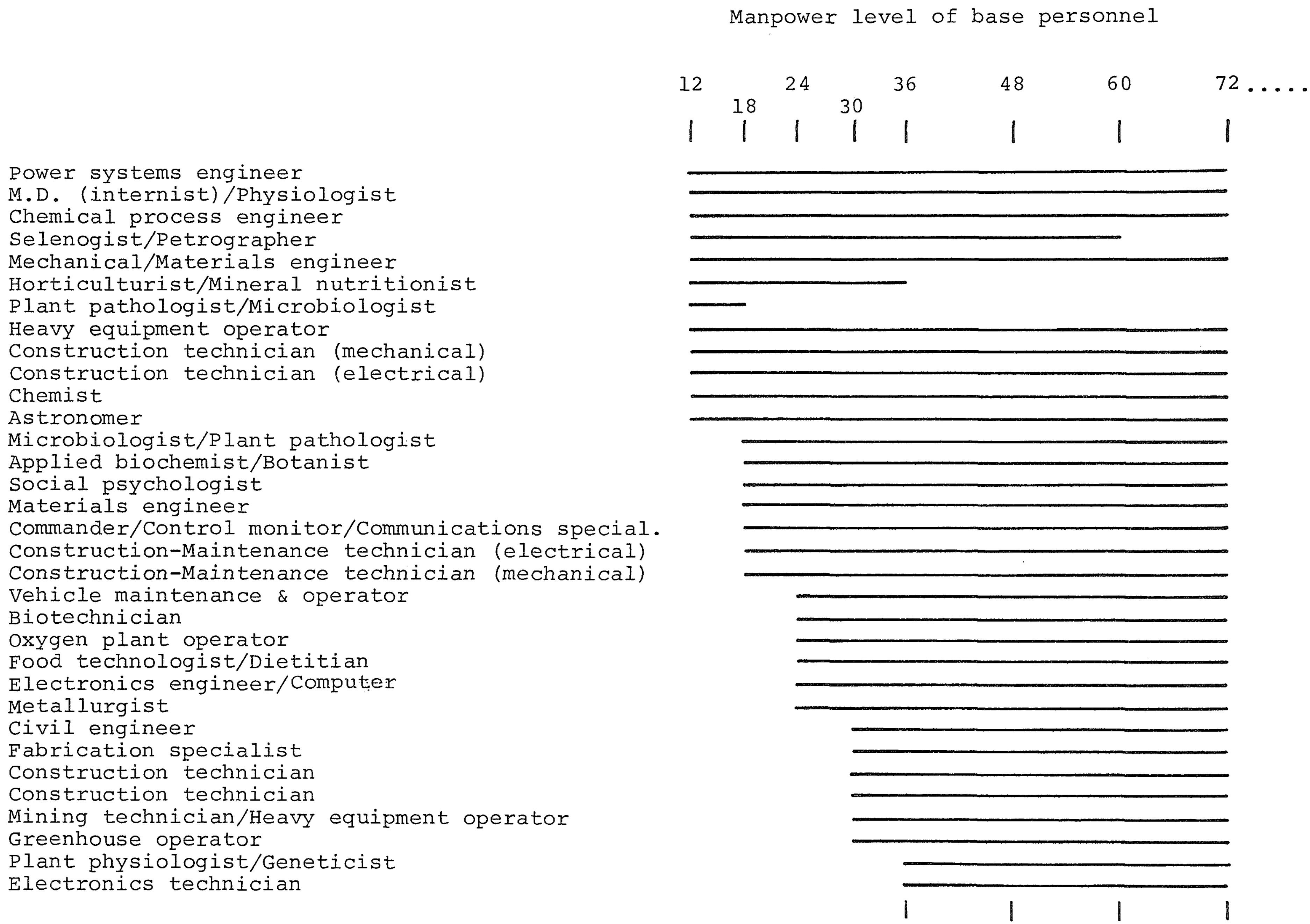
-----Astronomer, Electronics Engineer

14. Selenological Research
Continue selenological research started in twelve-man contingent.
-----Selenologist, Mechanical/Materials Engineer

If it is found that any area critical to the development of the colony lags drastically behind, reshuffling of personnel may be necessary to bring the area up to schedule.

A list of the personnel occupying the base at any point up to 72 people can be obtained by examining Figure 5.3-1. Purposely, the chart shows no direct time dependence. The personnel present at any point in growth are indicated by the solid lines below a given manpower level. A base growth unit is twelve people, while the tug system has the capability of transporting six people in any given landing. The selection of a first and second six-man group for the initial twelve-man contingent was not considered since the necessary personnel are assumed to be living at the existing twelve-man base at time zero. However, with six-month projected landing intervals for growth personnel, it appears desirable to distinguish the order of arrival for each six-man crew. Accordingly, the functional positions at levels of 12, 18, 24, 30 and 36 people were specified. The relative uncertainty of task completion times makes such a fine distinction impractical beyond this point.

During the cycle of growth that reaches a level of thirty-six people, there will be a further significant decrease of instances where individuals will need to provide physical and semitechnical assistance outside of their areas of major responsibility. Such occasions, however, will still be expected to be considered through the commander. Likewise, a portion of the housekeeping tasks will be done by an appointed individual, but all will be responsible for their own living and working areas. Although the functions for this cycle are more generally defined than previous cycles, this is in keeping with the needs of a larger group and its inherent


Manpower level of base personnel
12
18
24
30
36
48
60
72.....
Power systems engineer
M.D. (internist)/Physiologist
Chemical process engineer
Selenogist/Petrographer
Mechanical/Materials engineer
Horticulturist/Mineral nutritionist
Plant pathologist/Microbiologist
Heavy equipment operator
Construction technician (mechanical)
Construction technician (electrical)
Chemist
Astronomer
Microbiologist/Plant pathologist
Applied biochemist/Botanist
Social psychologist
Materials engineer
Commander/Control monitor/Communications special.
Construction-Maintenance technician (electrical)
Construction-Maintenance technician (mechanical)
Vehicle maintenance & operator
Biotechnician
Oxygen plant operator
Food technologist/Dietitian
Electronics engineer/Computer
Metallurgist
Civil engineer
Fabrication specialist
Construction technician
Construction technician
Mining technician/Heavy equipment operator
Greenhouse operator
Plant physiologist/Geneticist
Electronics technician

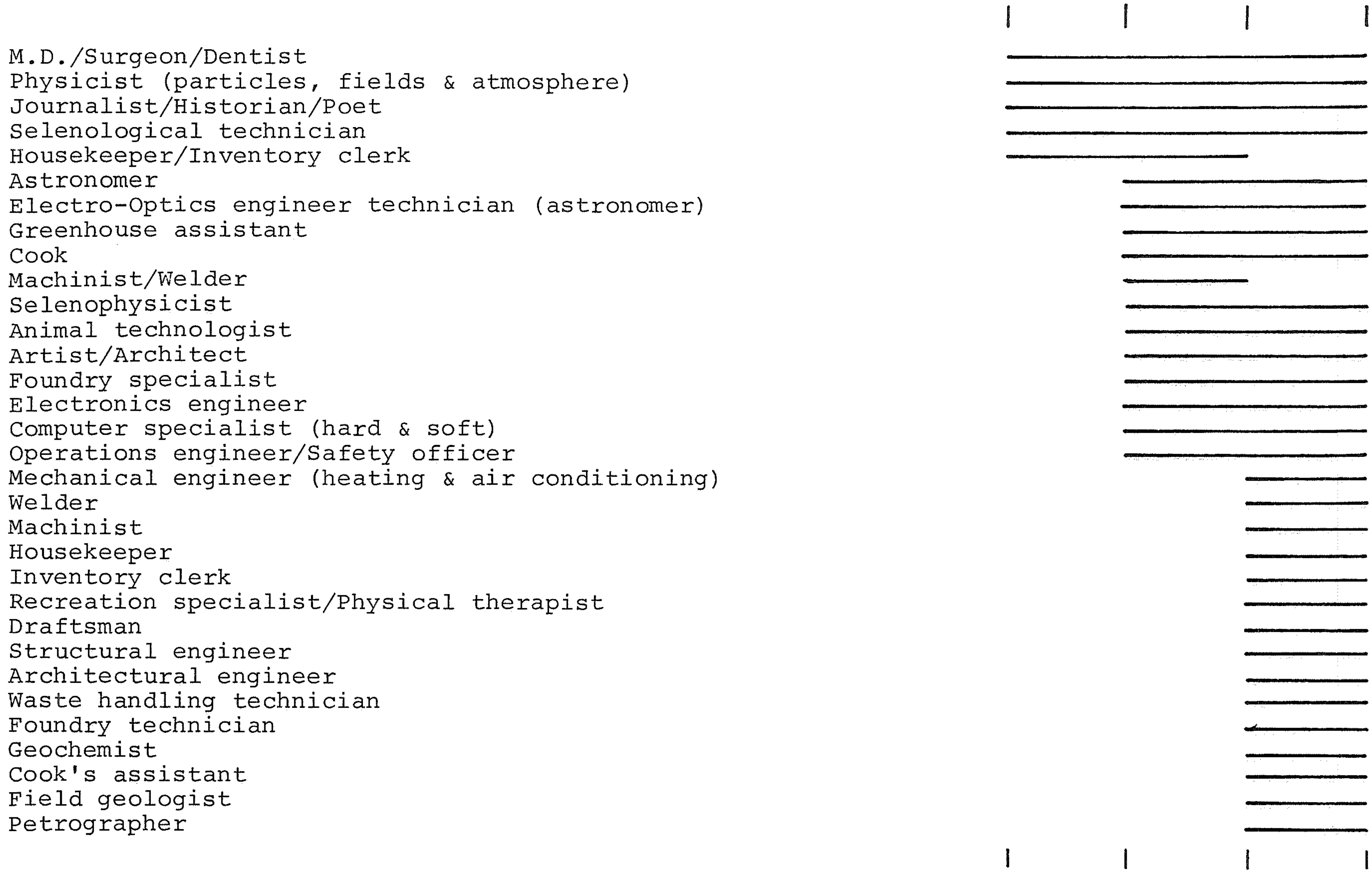


Figure 5.3-1 Personnel Growth Sequence

flexibility. A list of the functions and the responsible individuals follows:

1. Administration and Life-Support Monitoring
   Continue as in twenty-four man contingent.
   -----Commander/Control Monitor/Communications Controller, M.D./Surgeon/Dentist
2. Food-Production Development
   Continue work of second growth cycle. Plan farm areas conceptually and design early buildings in detail. As a result of investigation of lower plants, consider alternative food-source needs and possibly develop them. Initiate food-processing studies.
   -----Greenhouse Operator, Plant Physiologist/Geneticist, Microbiologist/Plant Pathologist, Biochemist/Botanist, Biotechnician, Chemist, Civil Engineer, Food Technologist/Dietitian, Chemical Process Engineer.
3. Physical and Mental Health Maintenance
   Continue as in second growth cycle with expanded services.
   -----M.D./Surgeon/Dentist, M.D./Physiologist, Social Psychologist, Food Technologist/Dietitian, Chemist
4. Construction and Maintenance
   Major construction projects in this stage will take place in the following order:
   Install second farm-module canister.
   Install second of three nuclear reactors.
   Install nonmetallic lunar-construction material production facility, including earth-configured canister below the lunar surface containing control facilities.
   Install metals-producing pilot plant.
   Configure earth-manufactured canister modules for 48-man base.
   Construct first building of nonmetallic lunar materials to serve as farming module.
   Perform physical plant, systems and vehicle maintenance.
   -----4 Construction Technicians, 2 Construction-Maintenance

Technicians, 2 Heavy Equipment Operators, Vehicle Maintenance and Operator, Civil Engineer, Power Systems Engineer, Mechanical Engineer, Electronics Engineer/Computer Scientist

5. Materials

   Mass-produce lunar nonmetallic construction materials following installation of facility. Install and operate pilot plant for producing metals from lunar materials. The small quantities of metals produced will be used for testing, reinforcing for nonmetallic construction materials and small cast parts. Supply lunar materials for processing.

   -----Fabrication Specialist, Materials Engineer, Metallurgist, Mechanical/Materials Engineer, Chemical Process Engineer, Geologist, Chemist, Mining Technician/Heavy Equipment Operator.

6. Physical Plant

   Maintain existing facilities. Provide parts inventory service on a part-time basis. Supply housekeeping for joint-use facilities and where possible for joint-work facilities.

   -----2 Construction Maintenance Technicians,Housekeeper/Inventory Clerk

7. Process Operations

   Operate and evaluate performance of electrical power-generation system, thermal power-generation system, oxygen-production plant, nonmetal production facility and metals-production pilot plant.

   -----Power Systems Engineer, Oxygen Plant Operator, Fabrication Specialist, Chemical Process Engineer, Mechanical/Materials Engineer, Electronics Engineer/Computer Scientist, Materials Engineer, Metallurgist, Mining Technician/Heavy Equipment Operator, Electronics Technician, Construction Personnel

8. Mining

   Surface strip mining will continue. Limited subsurface

mining will begin if information from previous growth cycle indicates its feasibility and desirability.
-----Mining Technician/Heavy Equipment Operator, Mechanical/Materials Engineer, Selenologist/Petrographer, Selenological Technician

9. Communications and Computing
Continue services of previous cycle and increase effectiveness of interpretation and communication events.
-----Electronics Engineer/Computer Specialist, Commander/Control Monitor/Communications Controller, Journalist/Historian/Poet in Residence

10. Research Programs
Continue as in second growth cycle with expansion as indicated by increase in personnel.
-----Astronomer, Selenologist/Petrographer, Selenological Technician, Physicist (particles, fields and atmosphere), Biochemist/Botanist, Microbiologist/Plant Pathologist, Plant Physiologist/Geneticist, M.D.(Internist)/Physiologist, Social Psychologist, Biotechnician, Chemist, Electronics Technician

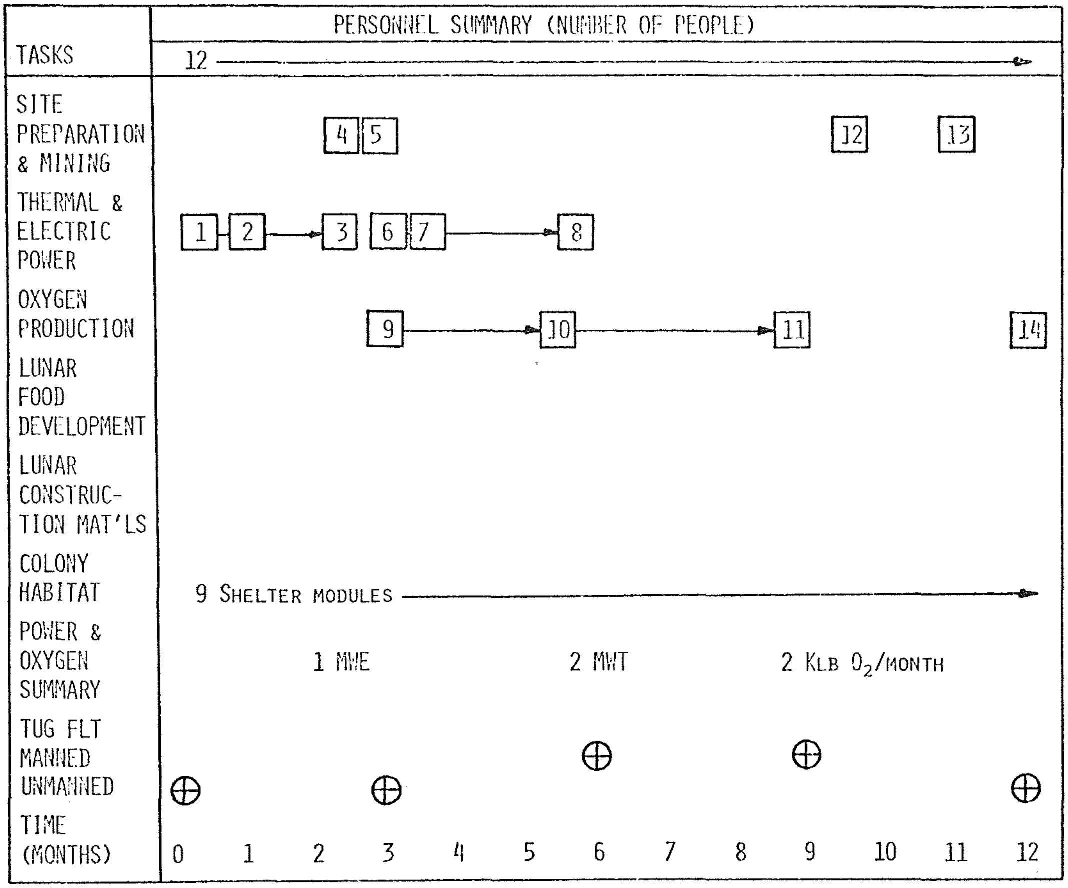
Functional personnel positions have been given in Figure 5.3-1 for units of twelve to seventy-two. These positions reflect needed growth functions and a continued increase in research and support. As the colony grows, its independence will depend upon the flexibility and creativity of the people making up the community. While decisions pertaining to growth during this interval must be made on earth, the basis for those decisions in sequencing require continual innovative planning by those in the colony. This can not be over emphasized, as sterile planning from a distance will likely destroy the colony. Consistently, additional fine planning of functions beyond the thirty-six man level and selection of base personnel beyond the seventy-two man level is delayed until better estimates of early growth-time requirements are established. Chapter 19 defines many of the research and development efforts which will help in the formation of a stronger basis on which to build later sequencing.

5.4 PHYSICAL GROWTH PATTERN

The functional growth pattern as described in Section 5.3 must be accompanied by a physical growth pattern for realization of a viable colony concept. The physical growth pattern is best described by a sequencing of tasks to be performed.

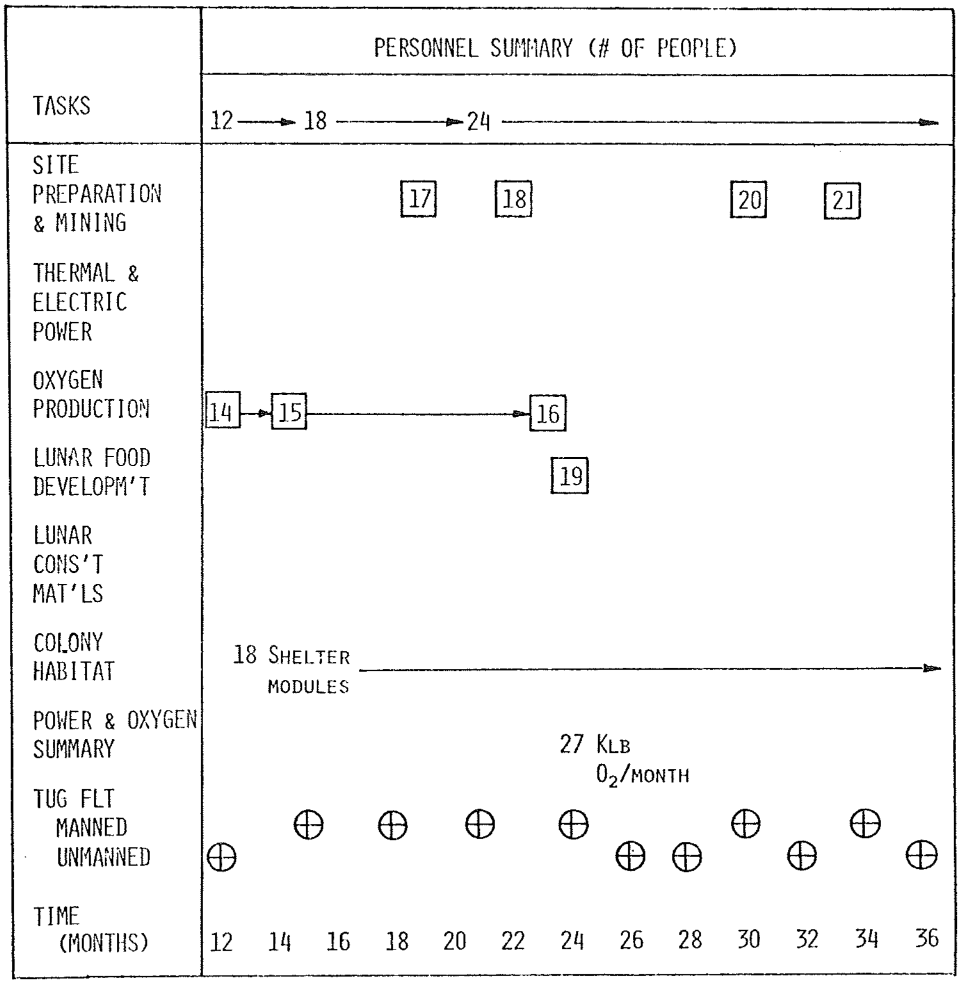
The colony physical growth sequence is shown graphically in Figures 5.4-1, 5.4-2 and 5.4-3. The sequencing as indicated on these graphs is primarily dependent on the colony personnel. The number of personnel and their functions must be sufficient to perform the proposed tasks. The colony growth sequence during the first year after "time zero" is shown on Figure 5.4-1. The number of personnel remains stable at 12 and the major tasks performed include installation of the initial nuclear electric-power system, solar furnace and oxygen pilot plant. These tasks are indicated by numbered boxes on Figure 5.4-1 and those connected by arrows are related tasks. The numbers in the boxes correspond to specific tasks which are listed below the graph.

The time scale shown is subject to change by a number of factors, all of which are not clear at this time. For example, man's ability to perform heavy construction tasks in the lunar environment for long periods of time awaits further actual data. Also, lunar-installation times depend on prior earth development and assembly of colony subsystems (i.e., it may be possible to deliver a package nuclear reactor and thus have a minimum of lunar-installation time). The tug (lunar-orbit lunar-surface logistics vehicle) flights shown are sufficient for the growth pattern indicated. It would be unwise at this time to indicate exact tug payloads, however, the subsystem equipment weights used for payload calculations were conservative. The frequency of tug flights shown allow for a crew lunar stay-time of 12 months during the 12-man operation period. Each manned tug flight can be used



TASK NO.	DESCRIPTION
1	DELIVER ELECTRICAL POWER SYSTEM
2	ASSEMBLE ELECTRICAL POWER SYSTEM
3	COMPLETE ELECTRICAL POWER SYSTEM
4	PREPARE SOLAR FURNACE SITE
5	PREPARE PILOT O_2 PLANT
6	DELIVER SOLAR FURNACE
7	ASSEMBLE SOLAR FURNACE
8	COMPLETE SOLAR FURNACE
9	DELIVER PILOT O_2 PLANT
10	ASSEMBLE PILOT O_2 PLANT
11	COMPLETE PILOT O_2 PLANT
12	PREPARE NEW 12-MAN SHELTER SITE
13	PREPARE O_2 PLANT SITE
14	DELIVER O_2 PLANT

Figure 5.4-1 Task Sequencing For Year One



TASK NO.	DESCRIPTION
14	DELIVER O_2 PLANT
15	ASSEMBLE O_2 PLANT
16	COMPLETE O_2 PLANT
17	INITIATE MINING FOR O_2 PLANT (CONT.)
18	PREPARE LUNAR FARM MODULE SITE
19	DELIVER & ASSEMBLE FARM MODULE
20	PREPARE NEW 12-MAN SHELTER SITE
21	PREPARE 2ND REACTOR SITE

Figure 5.4-2 Task Sequencing For Years Two and Three

TASKS	NO. OF PERSONNEL 36 → 48 → 60 → 72 → 84 → 96 → 108 → 120 → 132 → 144 → 150
SITE PREP & MINING	[22] [28]
THERMAL & ELECTRIC POWER	[25]
OXYGEN PRODUCTION	[29]
LUNAR FOOD DEVELOPM'T	[23] [26]
LUNAR CONS'T MAT'LS	[24] [27] [30]
POWER & OXYGEN SUMMARY	2 MWE 52 KLBO$_2$/MONTH
COLONY HABITAT	27 SHELTER MODULES → 36 SHELTER MODULES

TASK NO.	DESCRIPTION
22	PREPARE SITE FOR SECOND FARM MODULE CANISTER, SECOND NUCLEAR REACTOR, NONMETALLIC LUNAR CONSTRUCTION MATERIAL PRODUCTION FACILITY, METALS PRODUCING PILOT PLANT, EXPANSION OF COLONY TO 48 MEN USING MODULES, FARM BUILDING USING LUNAR NONMETALLIC MATERIALS.
23	INSTALL SECOND FARM MODULE CANISTER
24	INSTALL NONMETALLIC LUNAR CONSTRUCTION MATERIAL PRODUCTION FACILITY (CANISTER)
25	INSTALL SECOND NUCLEAR POWER REACTOR
26	CONSTRUCT FARM FACILITY USING NONMETALLIC LUNAR MATERIALS
27	INSTALL METALS PRODUCING PILOT PLANT
28	PREPARE SITE FOR SECOND OXYGEN PRODUCTION FACILITY, FULL SCALE METALS PRODUCING PLANT AND SHELTER FACILITY USING NON-METALLIC LUNAR MATERIALS FOR EXPANSION OF COLONY TO 60 MEN
29	INSTALL SECOND OXYGEN PRODUCTION FACILITY
30	INSTALL FULL SCALE METALS PRODUCTION PLANT

Figure 5.4-3 Task Sequencing to Colony Threshold

for a 6-man crew rotation.

The tasks accomplished and their sequence during the colony growth from 12 to 24 personnel is illustrated in Figure 5.4-2 which is similar in format to Figure 5.4-1. The major tasks performed in this period are the installation of the full-scale oxygen plant and an experimental farm module. This time-based sequence is dependent on the success of the oxygen pilot plant. Note that only the major sequencing tasks are shown on the sequencing graphs; however, it should be remembered that concurrent studies are being carried out in the pure and applied science, areas of life sciences, physical sciences, social sciences and humanities by colony personnel. At the 24-man level, the frequency of tug flights is increased due to the availability of lunar-produced oxygen for tug propellant. As the amount of lunar-produced oxygen propellant is increased, more useable payload can be brought from lunar orbit to lunar surface and this will require more tug flights. The tug-flight frequency shown allows for crew stay-time on the lunar surface of 16 months during the 24-man interval. On a time scale, Figure 5.4-2 covers the second and third years of colony growth.

The physical growth sequence shown in Figure 5.4-3 covers the colony development from 24 personnel to 60 personnel. The time line for sequence of growth is not shown at this stage of development, since it would be highly speculative. For similar reasons, tug flight frequency is not specified. The important point is the sequencing of tasks to allow for logical colony growth. Although broad tasks consistent with colony goals can be specified, a detailed specification of personnel-dependent task sequencing beyond the 60-man level is not realistic at this time. This must await actual lunar experience appropriate in colony growth.

In summary, a physical growth sequence has been presented. It is primarily a major-task sequence listing which is personnel dependent. This sequence of colony buildup is founded on current tug-logistics information and present concepts of colony subsystems hardware. Although the physical growth pattern has been shown in detail through a colony size of 24 personnel, details of further sequencing await actual lunar experience appropriate to colony growth.

REFERENCES

1. Jagon, R. B. and Thomas, R. S., "The Closed Life-Support System", NASA SP-134, Ames Research Center, April 14-15, 1966, pp. 75-78.

2. Rysavy, G. and Council, C., "Architectural and Environmental Considerations for Space Station Design", NASA-MSC Internal Note 71-EW-3, June, 1971.

CHAPTER 6 POSSIBLE CONFIGURATIONS

This chapter outlines the complete colony concept. The selected subsystems are integrated into an overall configuration that satisfies colony requirements. The configuration and growth of a possible physical layout encompassing the subsystems design is also presented. Finally, alternate concepts that might change the configuration described are presented.

6.1 A SYSTEMS CONFIGURATION

The integrated flow chart of all required subsystems for lunar colonization is shown in Figure 6.1-1. Only the inputs to the system and subsystem interactions are depicted. Detailed flow paths within each subsystem are provided in Part III of this report. Complete analysis of all candidate subsystems is also presented. The systems configuration shows the selected subsystems required for a colony of approximately 180 men developed to our best estimate of earth independence.

We recognize that not all provisions for colonization can be derived from known lunar resources. Complete earth independence is, therefore, viewed with pessimism. Unless future discoveries provide locations of concentrated elements and deposits of additional minerals, some items must be imported from earth to sustain the colony. Among these are liquid hydrogen, liquid nitrogen, carbon, disenfectants, waste and water treatment chemicals, medical supplies and medicines, other miscellaneous chemicals, and some foods. It is possible that future developments may eliminate the requirement for some or all of these earth-derived supplies. The principal subsystems analyzed will be briefly described here insofar as they interact and support colony functions.

6.1.1 THE MAIN COLONY COMPLEX

The central portion of Figure 6.1-1 represents the central colony

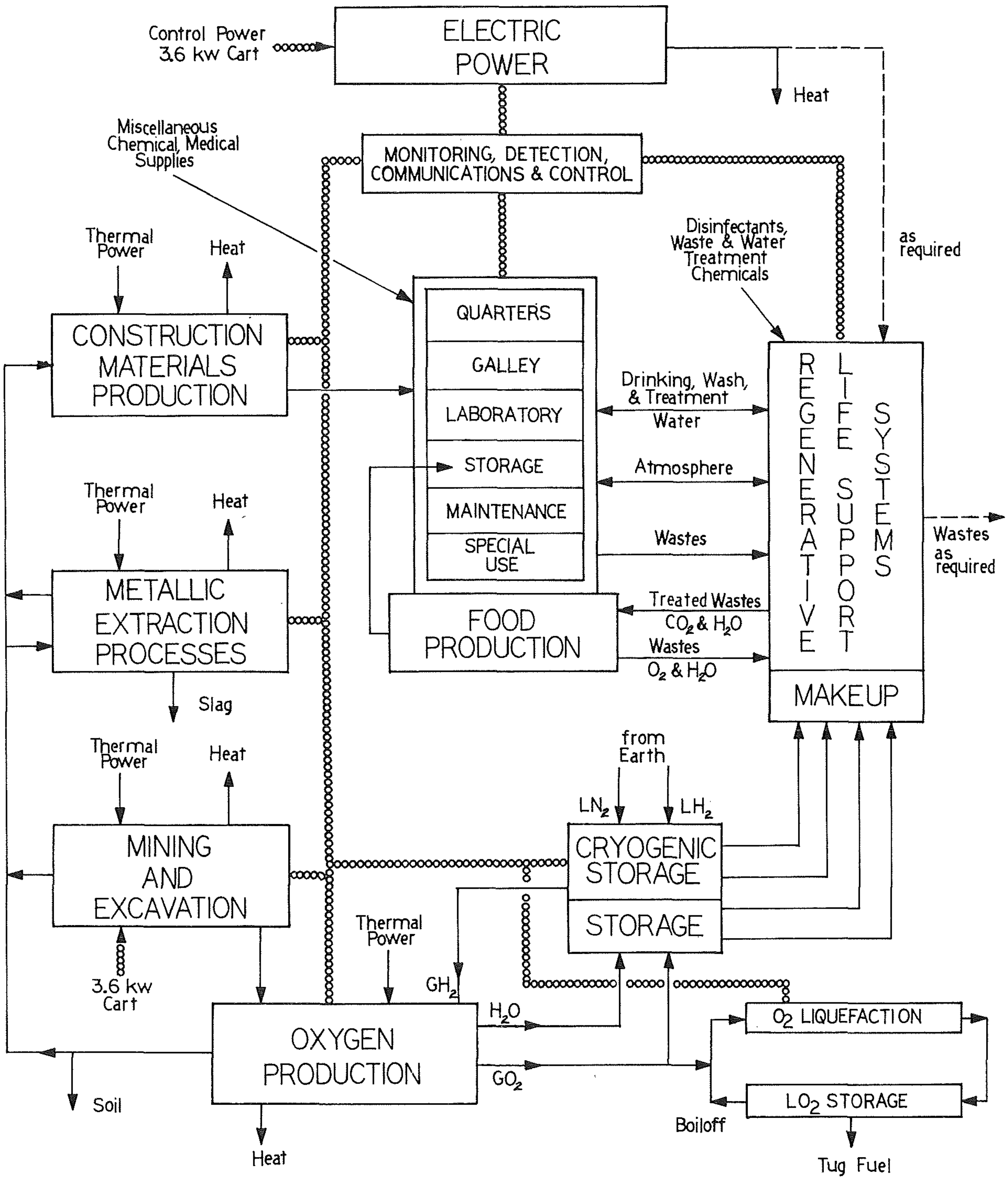


FIGURE 6.1-1 SYSTEMS CONFIGURATION

complex which encompasses the living quarters, maintenance functions, laboratories, dining, recreation, storage, and special use areas. The double border around these functions emphasizes the interdependent relationship of these facilities. Input arrows indicate total distribution within the main complex. For example, the atmosphere input from the life-support system is distributed to all areas within the complex and returned to the regeneration units. The food-production facilities are physically contained within the main complex, but have somewhat more specialized support requirements such as carbon-dioxide enriched atmospheres for plant growth. Food output is stored for consumption. Remote facilities, such as astronomical observatories, are assumed to have self-contained life-support systems. Many earth-supplied materials, such as film-developing chemicals and medicines, will be consumed within this area.

6 .1.2 ELECTRIC POWER GENERATION

Primary electrical power will be provided by three one-megawatt U235-fueled fission reactors. Multiple reactors will provide redundancy and contingency backup. Each reactor will be buried so that six meters of lunar soil act as shielding material. The reactors are liquid-metal cooled with heat rejection provided by 230 square meters (2500 $ft.^2$) of radiator. Control power is provided by one 3.6 kilowatt power cart. These carts are also available for powering mobile exploration trains and charging vehicle batteries for short-term intracolony surface travel.

6.1.3 REGENERATIVE LIFE SUPPORT SYSTEM

The life-support system is designed to make the maximum utilization of foreseen recycling processes. The system is designed to facilitate lunar plant growth with closure of the food-waste cycle. A wide variety of earth-supplied chemicals and gases must be input. Makeup water and gaseous oxygen are supplied from the oxygen-production process. Thermal power can be supplied from the output of the nuclear reactors. Drinking, wash and treatment water, and atmosphere is continually recycled through the main colony complex. Wastes from the complex are converted to plant and animal nutrients. Carbon dioxide and water are also provided to the food-production facilities. Output wastes, oxygen, and water are recovered by the system. Unrecoverable wastes may be converted to ash for soil enrichment or packaged for disposal.

6.1.4 OXYGEN PRODUCTION PROCESS

Production of oxygen is accomplished by a hydrogen-reduction process. Hydrogen, thermal power, and lunar soil containing ilmenite ($FeTiO_3$) are provided to a plant with a capacity to produce 20,000 pounds of oxygen per month. Multiple plants will provide larger amounts as colony requirements increase. Output products are soil, heat, water, and gaseous oxygen. The large majority of the oxygen will be liquified for eventual use as tug fuel. Processed soil may supply input to metallic extraction processes and construction-materials production.

6.1.5 MINING AND EXCAVATION

An entire spectrum of equipment from hand shovels to cable excavators should be available for mining and excavation. These functions include site preparation, transport of soil to the oxygen, metallic extraction, and construction material processes, and covering colony facilities.

6.1.6 METALLIC EXTRACTION PROCESSES

Metals production from lunar resources will be a highly desirable objective if it can be done economically. Two concepts considered are the electrlytic reduction of lunar fines and the flourine exchange processes. The former is also highly desirable as a potential oxygen-production process, if the electrode-consumption problem can be overcome. No high confidence metallic-extraction system is proposed in this study. Hopefully, future research will solve the extraction process if high metal-content lunar "ore" bodies can be located. The output of such a process would include heat, processed slag or soil, and metal ingots.

6.1.7 CONSTRUCTION MATERIALS PRODUCTION

This facility converts lunar fines to cast-basalt construction components. Input materials are provided by the mining and/or excavation operations. The components may be utilized to construct a wide variety of facilities in the colony.

6.1.8 OTHER SUBSYSTEMS

Analysis was not performed on all the subsystems shown. The requirements deserve mention here, however, due to the vital functions performed.

Monitoring, Detection, Communication and Control System: A complete monitoring system is installed throughout the main colony complex. This system will monitor the life-support functions, detect fires and leaks, and provide a central control facility for the reactor and other remote operations. Communications equipment is also assumed complete throughout the colony, including constant contact with a lunar orbiting station and earth through lunar communication satellites.

Storage Systems: Another important function is the storage of water, gaseous oxygen and cryogenic oxygen, nitrogen, and hydrogen. The oxygen liquefaction and storage facilities will be located near the tug landing and takeoff area. Other storage facilities will be located within the main colony complex since they will provide makeup supplies to the life-support system.

6.2 A POSSIBLE COLONY CONFIGURATION

Chapter 5 describes the growth and sequencing necessary for the lunar colony to develop from a twelve-man, earth-supplied base into a community of about 180 individuals.

The purpose of this section is to describe a plausible growth sequence and possible ultimate design for the colony configuration during this period. The configuration growth sequence is described in this section since the number of possible ways in which growth might occur is quite large, and many factors could change the sequence and the ultimate configuration. Therefore, it is not the purpose of this section to define a specific growth pattern either in time or geometry, but rather to describe what we expect to be a typical pattern and resulting configuration. It is instructive to follow a plausible sequence of colony growth, for such an exercise does point out areas where further work is necessary. Furthermore, an attempt to outline a possible configuration serves to draw together various individual studies into a cohesive unit.

The following discussion is related to Figure 6.2-1, a plan view of a possible colony configuration. The figure depicts the colony structures with numbers on some elements to indicate the order of construction. By way of interpretation, it should be recognized that most of the structures shown on the plan are about 5 meters (16 feet) below the lunar surface. This depth of lunar soil is required to achieve radiation levels in the dwellings that are equal to ambient values on earth; if it is decided that higher limits are acceptable, then most buildings would be located on the surface.

The array of structures resembles a portion of a hexagon and was chosen to illustrate the need for an arrangement that will allow future expansion to occur in an orderly manner. The hexagonal pattern chosen is quite flexible in this respect and expansion

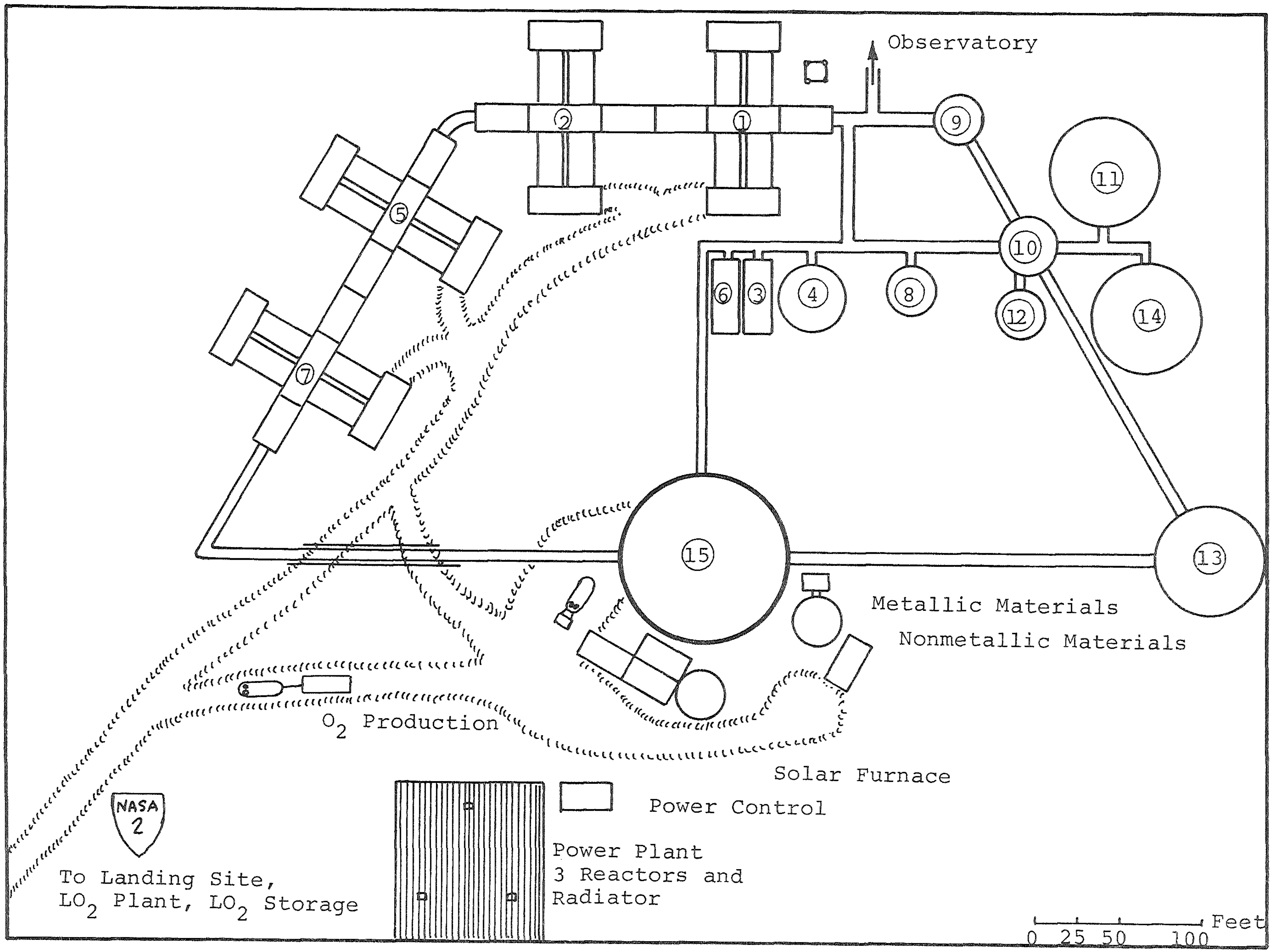


Figure 6.2-1 The Colony Configuration

could occur in a number of directions. It should be observed in this context that the location of the colony is also important; initially attractive physical features such as craters or mountains could ultimately present a barrier to colony growth.

It is assumed that the initial structure will be the twelve-man base unit, consisting of nine canister modules, labelled (1) in Figure 6.2-1. The sites for the observatory and the landing field would be located at some distance from the base, and initial construction work on those facilities would begin. During the first year of lunar-base activity, the population would remain constant at twelve individuals, and an oxygen pilot plant, one of three power reactors, and a solar furnace would be installed. During the second and third years, the population would increase to 36, and the second group of modules, labelled (2), would be installed. In addition, a farm module, labelled (3), would be integrated into the configuration. This farm module would be a canister module, supplied from earth and used primarily as a research facility.

Structure (4), also supplied from earth, is envisioned as an inflatable building. This addition would test the viability of inflatable structures; the space would probably be used for farming. If no surface structure had been constructed by this time, the inflatable farm would be a likely candidate.

Structure (5), another set of canister modules, would allow expansion of the population to 36 individuals; another canister farm module, (6), would follow shortly. Still another set of modules, (7), would permit a total population of 48 individuals. During this same period, a second power reactor and the nonmetallic materials production facility would be added.

A crucial step for the colony occurs at this juncture. Building (8), the next to be constructed, will be the first built using lunar materials. It is expected that this first effort would be confined to a single story, and that the building would be used in a relatively low risk capacity, such as a farm, until appropriate tests are completed. This structure would be followed by the pilot plant for metal production, which would of necessity be supplied from earth. Subsequently, a full-scale oxygen plant and a full-scale metal-production plant would be installed.

Following the demonstration of adequate capability for construction with lunar materials, the building labelled (9) would be added. This structure, the first made of lunar materials for human inhabitants, would probably have two main floors and, if those floors were below ground level, a surface facility. The surface facility might be either of lunar construction or a modified canister module. It is envisioned as being part laboratory and part lounge, and is considered necessary to satisfy the desire of the colony inhabitants to view their surroundings. The structure would probably have a diameter on the order of ten meters (33 feet), and it could house twelve individuals according to a plan similar to that shown in Figure 6.2-2. Shown in Figure 6.2-3 is a sketch of the lunar colony as shown in plan view Figure 6.2-1 but located near the surface.

Some comment concerning the floor plans in Figure 6.2-2 is in order. The lower floor contains twelve individual living units arrayed around a central lobby containing isolated shower and toilet facilities. Access to the floor is by means of a one-meter central hole equipped only with handholds. This constitutes a drastic departure from earth practice in architecture, but such a concept is not unreasonable in the 1/6-gravity lunar environment. The upper floor of the structure contains laboratory or work space, a galley, and circulation room for a tunnel intersection.

The next structure in the sequence, labelled (10) in Figure 6.2-1, would be somewhat larger than (9) but also built from lunar materials. Building (12) is intended as a food storage and processing plant; it would be constructed in a similar fashion and situated at the end of a tunnel.

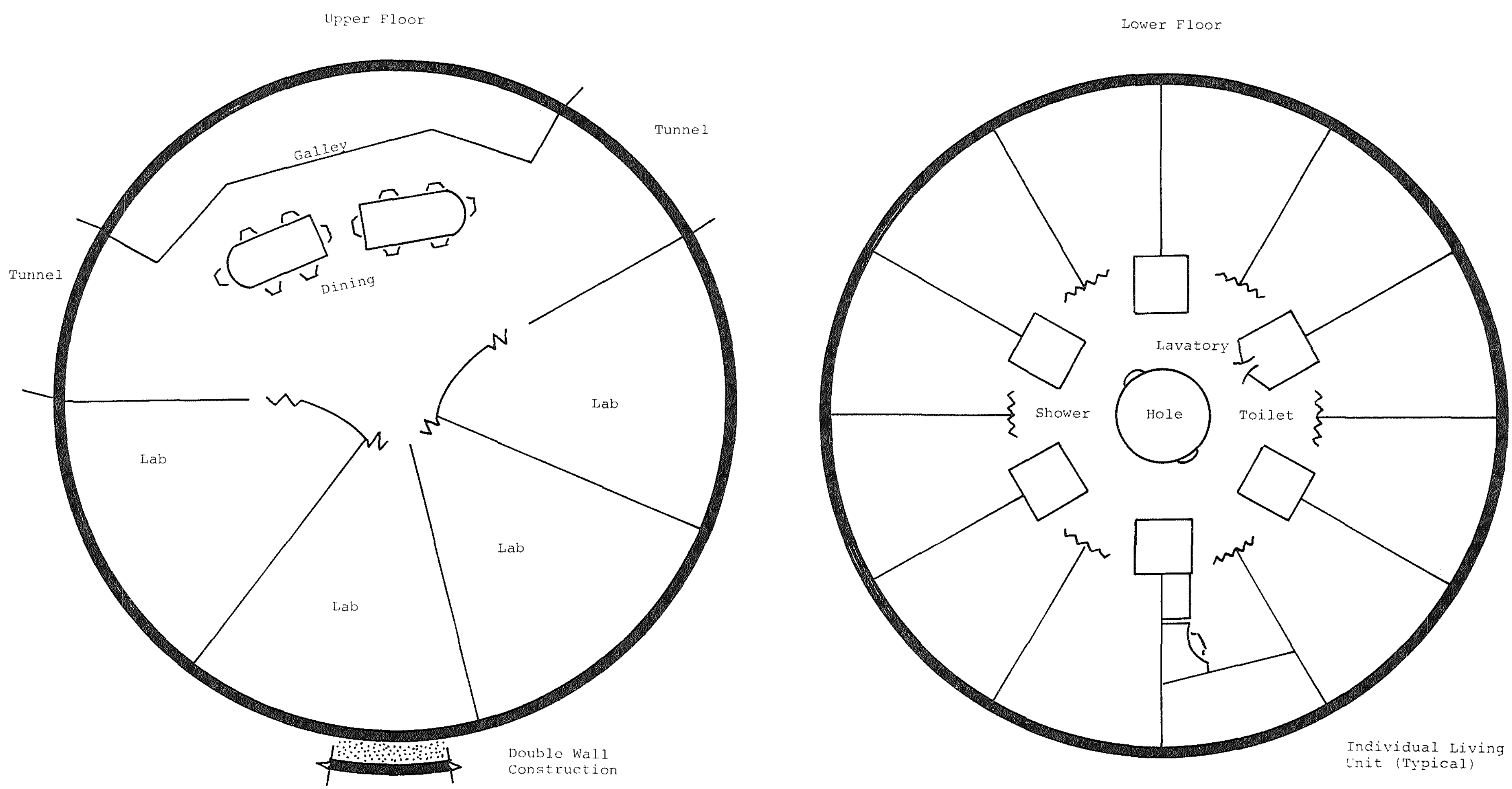


Figure 6.2-2 Living Unit - Constructed of Lunar Materials, Approximately 10 Meters (30 feet) in Diameter

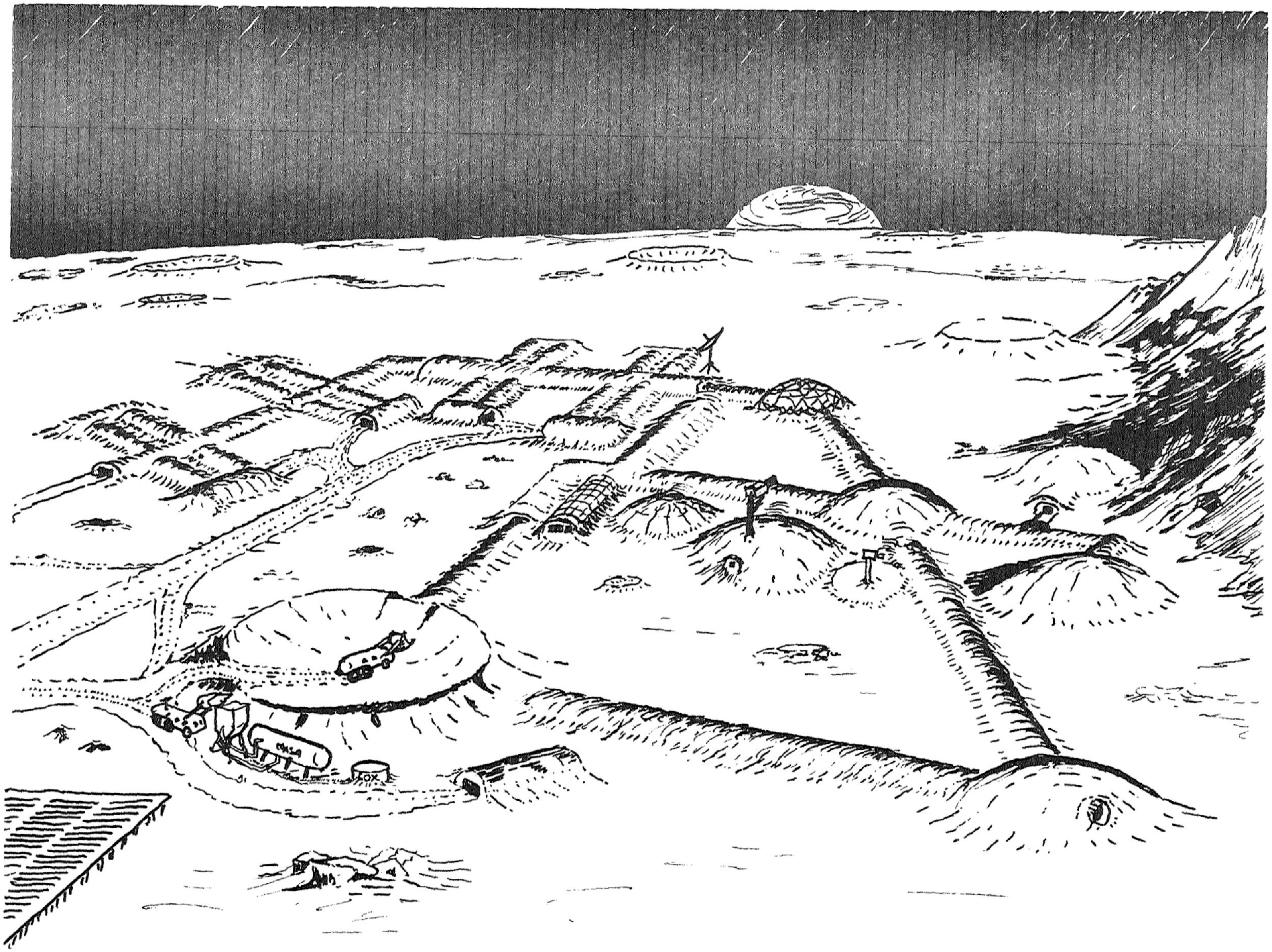


Figure 6.2-3 Surface Configuration of the Colony

Buildings (11) and (14) are intended as large farm structures. They could be either inflatable units transported from earth or hard structures made of lunar materials, depending upon the technology at the time.

Building (13) is envisioned as a large structure, having a diameter on the order of 20 meters (66 feet), and extending to perhaps five stories. It would be constructed of lunar materials, using the experience acquired from previous structures.

The structure shown as (15) on the plan is quite large, by lunar standards, having a diameter on the order of 30 meters (100 feet). The excavation for such a building could be accomplished over a period of two or three years by judicious manipulation of the oxygen-production plant supply and effluent. It is quite possible that the construction of such an edifice would enlist, or even require, methods not apparent at this time. However, the postulated backlog of experience with lunar materials and the anticipated availability of metals might well allow such a structure.

If a structure such as (15) is indeed possible, then the inhabitants of the lunar colony would have available what, to them, would be a luxurious quantity of space. This point would appear to be another critical juncture from which the population and activity of the colony could continue to expand.

6.3 ALTERNATE COLONY CONCEPTS

This section describes those areas which we feel are most likely to effect the final colony configuration. In all cases, further study is required before a definite configuration change can be proposed.

Undoubtedly, the most dramatic alternate colony concept envisioned would be to place the majority of the colony structures on the surface. The colony might be covered with a thin layer of fines (perhaps 6 inches) for thermal and meteoroid protection but the structures and their inhabitants would be exposed to a level of radiation higher than that on the earth. Appendix C of this report argues that the possibility of genetic mutations and other problems associated with this level of radiation are not sufficient to drive the colony underground. Construction of a surface colony is probably easier than building an underground installation, but in a surface installation the weight of the soil is not available to help offset the internal pressures required for life-support in the structures.

Dramatic changes might also occur in the colony configuration if any of a number of subsystems we have proposed fails to develop as indicated. Lunar farms, for example, may require a special size, shape or lighting arrangement for efficient plant growth. Additionally, the development of lunar building materials or techniques might dictate a certain type of configuration or a limited structure size.

Undoubtly, long term experience with people in the lunar environment and extended use of such items as vehicle garages and airlocks will show that some designs are much prefered to others. The total colony design should, as it evolves, change to include those design features that work well (convenient, low maintenance, etc.) in the lunar environment and eliminate the ones that are less efficient.

Long term habitibility experience, for remote structures and small populations largely closed off from their surroundings, will likely influence the final colony configuration. The interaction of various scientific disciplines in laboratory and other areas will determine the feasibility of shared facilities. Likewise, the ability of the scientists and humanists to share facilities and work in close proximity to one another requires consideration in the development of a colony configuration.

Finally, the development of a lunar-colony configuration should be perhaps even more flexible than other colony subsystems to permit the colonists themselves to take an active part in the planning and development. The additional effort and ingenuity that a team of colonists are likely to put forth for construction of "their" colony will undoubtly be an asset in the lunar environment.

PART II

GENERATION OF DESIGN REQUIREMENTS

CHAPTER 7 SYSTEMS APPROACH

This chapter describes the various aspects of systems engineering which were applied to our interdisciplinary design team problem. Specifically noted are the design-team structure, team interaction, methods of decision making, and the analysis tools employed in the systems-engineering effort.

7.1 SYSTEMS PHILOSOPHY

7.1.1 FORMAL SYSTEMS ENGINEERING CONCEPTS

The design approach employed in our design effort falls into the category of problem solving commonly referred to as "systems engineering." Actually, there are several allied terms which are frequently used to describe this area of problem solving--the most popular of which are "systems design," "systems analysis," "operations research," or simply, "the systems approach." However, all of these terms are synonymously used to describe a formal systematic method of problem analysis and problem solving. To simplify the terminology, the term "systems engineering" is used exclusively throughout the discussions in this report.

What is the systems engineering process? Basically, systems engineering is a formalized method of problem solving, wherein each step of the analysis is made explicit wherever possible. It is a process that methodically considers the total system in approaching the problem, and it employs formal logic to establish a focal point for system evolution.

What are the procedures involved which can be identified as formal methods? The formal process of systems engineering consists of (1) making a functional analysis of the system functions, (2) determining requirements for these functions, and (3) then, and only then, coming up with design requirements. The process of generating a functional analysis will be discussed in further detail in Section 7.1.4.1.

In addition to providing a framework for developing design requirements, another prominent feature of systems engineering is that its problem solving process is closely identified with decision making processes. Due to the formal nature of the problem solving process, the method provides decision traceability. This is very significant to project management and efficiency.

Systems engineering, for our design team, provided a contrast to an intuitive approach to problem solving, but we noted that it does not substitute for common sense. (As a matter of fact, we will show later that subjective inputs based on group consensus can be just as useful as objective inputs based on physical facts.) Also, it is no guarantee that we will consider all the relevant important alternatives, but it does make the alternatives examined--and the omissions--a little more open to scrutiny.

In this brief summer experience, our design team was not quite able to validate all the claims made for the systems-engineering process. This was partially due to the fact that the project did not have time to go into detailed design or engineering, so a real payoff could never be ascertained. However, there were several specific areas in which the design team was able to gain some experience. These experiences have at least revealed to our design team some of the inherent values and benefits of using the systems engineering approach. The specific areas which can be identified as being ingredients of formal systems engineering are delineated in the following sections of this chapter.

7.1.2 INTERDISCIPLINARY TEAM BUILDING

What probably best characterizes the systems-engineering problem is its overwhelming nature when it is first proposed. Usually, it is of such magnitude and breadth that a single individual cannot even hope to solve the problem alone. This means that several persons are required to solve the problem, and thus the requirement for a team approach.

Why is an interdisciplinary approach required? First, Baumann [1] states that "systems engineering is in itself an interdisciplinary activity." The problem usually is so vast that it covers many specialty fields. Solution of the systems engineering problem not only requires expert knowledge of the environment in which the system is expected to operate, but also knowledge of how the system will ultimately affect the environment into which it is introduced. Thus, experts in many fields are required to evolve a solution which is acceptable from the many different viewpoints.

Looking at the knowledge spectrum of one individual graphically, we would see a curve like that depicted in Figure 7.1.2-1 (from Dickerson [2]). This figure shows that while a person may be classified as "genius" in one specialty, his knowledge of other fields is around average or below average. By putting together the proper mix of persons in an interdisciplinary design team, we can improve our problem solving capacity as shown in Figure 7.1.2-2.

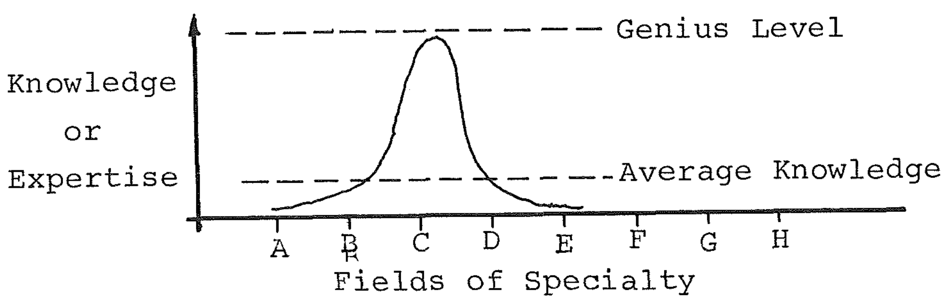


Figure 7.1.2-1 Knowledge Spectrum for an Individual

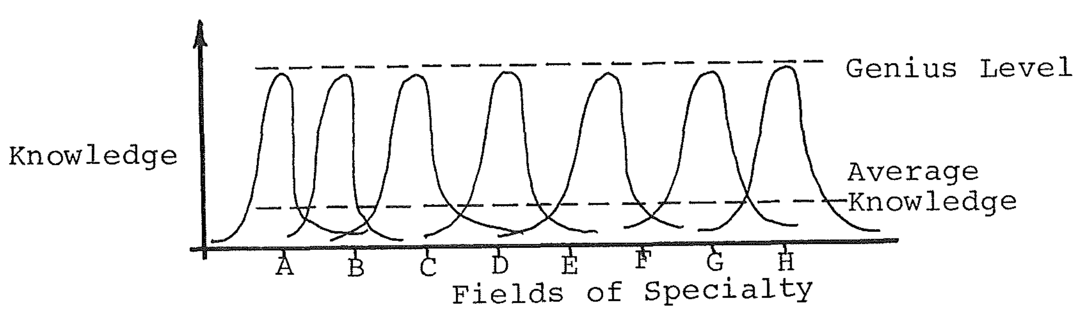


Figure 7.1.2-2. Knowledge Spectrum for Interdisciplinary Team

Because individual members of the design team have attained expert knowledge in limited areas, the design team can attain a genius status in all relevant areas. The lower level knowledge that each expert has outside his field provides for the understanding and appreciation of other interests. This is essential in order to maintain the communication link within the team.

We have seen that systems engineering is by requirement an interdisciplinary activity. But, how is an interdisciplinary design team formed? First, the objective of any interdisciplinary design team is to work together in such a manner as to fully utilize each individual's resources and to produce the best possible design product. In order to accomplish this objective, the team must have effective interaction and must be able to understand each other's abilities and shortcomings.

Several guidelines for team organization became evident to our design team and may be useful considerations for structuring of any design team. These guidelines are summarized as follows:

1. Effort should be made to ensure that there is the appropriate distribution of expertise among the team members to cover all problem areas in depth.
2. Every team member must be able to put the success of the project above his own personal objectives. He must be willing to make trade-offs to favor a choice which does not match his personal bias.
3. Every team member must be willing to express and justify his own viewpoints. This is necessary in order that all viewpoints receive democratic consideration.

A workshop was presented to our design team by a consultant, Peter Diehl [3], in order to demonstrate to the team the value of understanding each other's abilities. The basis of this phase of the workshop was to illustrate the use of a managerial grid for team building. This grid, shown in Figure 7.1.2-3, is a matrix of "Concern for Design Team" versus "Concern for Design Quality." All persons will fit some location on the grid. It is up to the project manager to determine the position of all his team members, and each team member was exposed to this grid so that he could have a better appreciation for other team members' viewpoints.

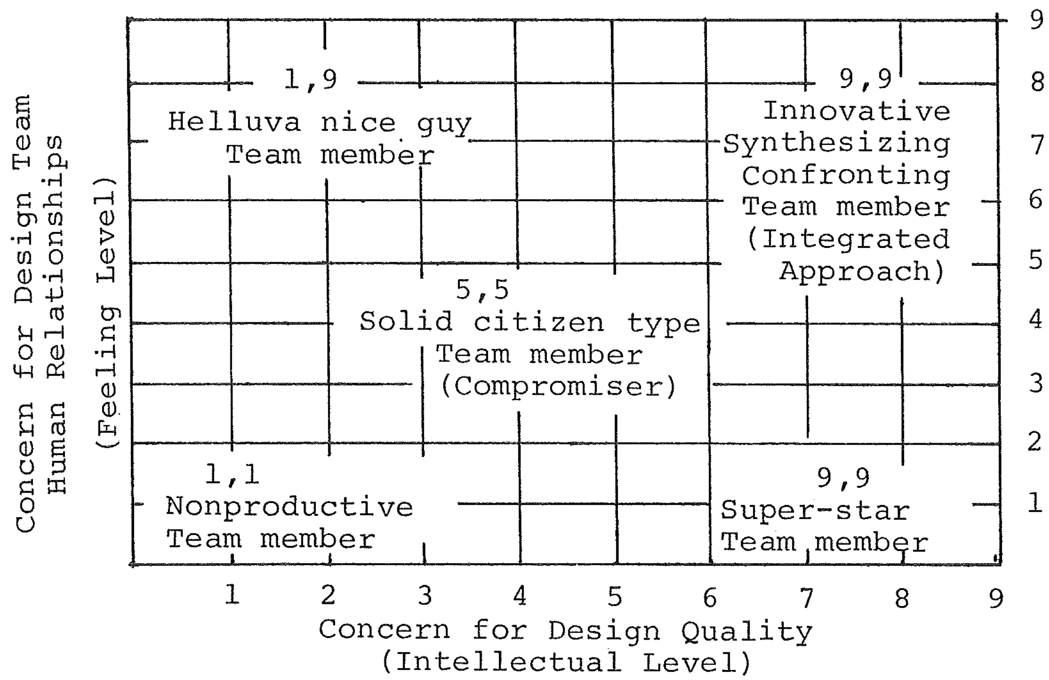


Figure 7.1.2-3 Contribution Management Grid

During the course of the project, team members frequently referred to the management grid to indicate their (or others') position on a certain topic. It became evident that this grid provided a focusing device for directing team members' attentions to team interface considerations.

7.1.3 DECISION BY CONSENSUS

The second phase of the one-day decision making workshop, presented by Peter Diehl [3], was an exercise in group decision making, the results of which indicate how group consensus on subjective parameters might be used as a consistent decision-making technique.

The workshop assignment given to our 15-man design team was to employ the method of group consensus in reaching a decision. The problem was a hypothetical emergency situation in which our team's task was to rank 15 survival items from a list in order of importance. After each individual had done his own ranking, groups of four individuals were formed. The task then was to reach a group consensus on these rankings. This meant that the prediction for each of the 15 survival items had to be agreed upon by each group member before it became a part of the group decision. Consensus is difficult to reach. Therefore, not every ranking met with everyone's complete approval. We were told to try, as a group, to make each ranking one with which all group members could at least partially agree. Here are the guides used in reaching consensus:

1. Avoid arguing for your own individual judgments. Approach the task on the basis of logic.
2. Avoid changing your mind only in order to reach agreement and avoid conflict. Support only solutions with which you are able to agree somewhat, at least.
3. Avoid "conflict-reducing" techniques such as majority vote, averaging or trading in reaching decisions.
4. View differences of opinion as helpful rather than as a hindrance in decision-making.

After the various groups had reached a consensus, each group made a summary of the new rankings on a "Group Summary Sheet." It was then discovered that a NASA group had already ranked these survival items, and we were to compare our ranking to the NASA ranking (considered the standard).

The comparison was made by listing the NASA rankings adjacent to the group rankings. The difference (or error) between the rank numbers was recorded and summed over all 15 items. The total was regarded as the overall score. The smaller this number, the more accurate was the group's rating.

The same method was employed in computing the overall score for each individual's ranking that were done before the group meetings.

The best individual score (the lowest) was then chosen from each group. This was compared to the group score. The difference was called the "creativity index." This was a measurement of the degree of improvement that was achieved by a group consensus over what was achieved by the group's "best" member. Surprisingly, the group score was typically better than the best member's score. Many design team members had anticipated that the group score would be an average of its members' scores. This was not true, indicating that a group consensus has significant value and therefore represents a credible way to weigh design factors and to establish rank values.

7.1.4 ANALYSIS TOOLS IN SYSTEMS ENGINEERING

7.1.4.1 Functional Analysis Diagramming

A "Functional Analysis" is possibly the most important item which identifies systems analysis with a formal methodology. In this process, gross functions are determined first, and then in a methodical manner increasingly lower level functions are identified.

How is a functional analysis performed? The best description of the functional analysis is the "functional analysis diagram." A complete functional analysis for the lunar colony functions is included in this report under Section 7.2.

The first step in a functional analysis is to identify gross functions of the system under study. To do this, one simply asks what functions are most descriptive (in a general sense) of the system's purpose or operation. The basic functions of a lunar colony include (1) Support Life, (2) Land and Launch Vehicles, (3) Support Base, and (4) Support Professional Activities. Note that the functions are very gross, almost to the point of being vague. This is intentional in order to keep the systems design from favoring any one solution.

This is called a "first level" functional analysis. Each succeeding level of the functional analysis is intended to describe in further detail the functions of the level above it. The process is terminated when the functions begin to reveal the actual methods that are used to perform the functions. The purpose of the functional analysis is to identify to as much detail as possible all required functions of the system without committing the design to a specific solution.

The major purpose of the functional analysis is to ensure that the total picture has been considered before design requirements are established. The analysis does not ensure a 100 percent chance of including all functions, but since these functions are documented graphically the risk of omissions is minimized to a negligible level. The risk is minimal because of the manner in which the functions are evolved. First of all, the entire design team is included in the process of identifying functions. The design team meets for the sole purpose of identifying the functions of the system. This is done by the "brainstorming" process. Usually, enough functions can be generated in a 30-minute meeting to establish the functional analysis to the first and second levels. The details of the third level and beyond are assigned to an ad-hoc committee to be performed over a much longer period of time.

The detailed functional analysis becomes, in a sense, a large check list. This analysis diagram should always be visible to the design team members for the remainder of the design study. It is the functions of this diagram that should drive all design requirements, criteria and solutions which evolve after this point.

In summary, there are several specific guidelines that were employed by our design team in doing the functional analysis. These are listed below :

1. Functions at the first and second levels should be generated by the entire design team by the process of "brainstorming."

This will guarantee the highest chance of including all functions and avoiding omissions.

2. Functions should begin by being as vague as possible at the first level. This will assure a high chance of agreement between team members and serves as an appropriate starting point for the functional analysis. Carry on the process of going to lower levels until the group as a whole becomes nonproductive in the meeting.
3. The evolution of the lower level (more detailed level) functions should be assigned to an ad-hoc committee.
4. All functions should be active verbs.
5. The number code in the function boxes should indicate both the level and the subset in which the function is included.
6. The functional analysis should be performed to a level which, if further detail is provided, would commit the design to a specific solution.
7. The functional analysis diagram should be made visible to the team members to serve as a check list throughout the entire design project.

After the functional analysis is complete, a brainstorming session should be held to generate "candidate" solutions to the problem. Each candidate must be in some way capable of serving all functions at the lowest level of the functional analysis. It is these candidates which become the object of analysis for the remainder of the design process.

7.1.4.2 Evaluation Methods

The functional analysis process provides a method of beginning at basic functions, methodically making these functions more detailed, producing design requirements, and finally providing a framework for generation of candidate solutions.

After candidate solutions are proposed for the design problem, a systematic method of evaluating them is required. The evaluation methods considered by our design team included the "Cost-Effectiveness" and "Evalumatrix" methods. However, the detailed costs and other design values required in these two methods simply were not available. Therefore, because the lunar colony study was expected to reach only a conceptual rather than a detailed level of design, another method of evaluation was favored. Furthermore, much of the state-of-the-art of certain systems developments in expected to change drastically by the time of lunar colonization. Our team did not consider it wise to eliminate candidates based on present-day technology, when near-future developments could alter the decision and make the candidate a viable consideration.

The team did propose certain evaluation procedures; these methods are described in Chapter 11 and are employed in the subsystem selections under Part III of this report.

It will be noted that some of the criteria used in judgment of a candidate are subjective. In this respect, most of the judgment technique is an art rather than a science. However, all of it is formal. The only reason that these subjective judgment schemes seem credible is that they are made by a team. The workshop experience on group-consensus decision making had already established a certain level of confidence in this type of team evaluation. The consistency of the team ratings is what established the methods as credible.

7.1.5 LUNAR COLONY STUDY APPROACH

At the beginning of the lunar colony design project, our design team met for the purpose of establishing a team structure which would be conducive to a productive study. The result of that meeting was the establishment of three basic groups whose efforts would be coordinated by two study managers. We also determined that it would be necessary to establish ad-hoc committees from time to time for the purpose of studying special problems which would be of interest to all three groups. The ad-hoc committees that were formed typically had at least one member from each group to provide the proper interfacing of ideas.

The three groups established for this study were the following: (1) Food, Water and Atmosphere, (2) Fuels, Transportation, Power and Energy, and (3) Shelter and Accommodations. The interfaces between these groups, the study managers, and ad-hoc committees are shown in Figure 7.1.5-1, along with the group responsibilities. A list of the ad-hoc committees formed during the project are given in Appendix I.

After the team structure was established a list of tasks for completion of our study was formulated, and a study logic sequence was planned. This study logic diagram (shown in Figure 7.1.5-2) was used to maintain a work production schedule for the 11-week term. Slight deviations from scheduled due dates occurred at times; however, the plan proved to be a valuable aid in keeping the entire team aware of our current progress with respect to the time remaining in the project.

REFERENCES

1. Baumann, D. M., "Interdisciplinary Systems Engineering at M.I.T.," Engineering Education, March 1968, pp. 823-825.

2. Dickerson, S., "Systems Design Orientation Lectures," Presented at the NASA-ASEE Systems Design Fellowship Program, Manned Spacecraft Center, July 1970.

3. Diehl, P., "One Day Workshop on Team Building: Consensus Decision Making," Presented at NASA-ASEE Systems Design Fellowship Program, Manned Spacecraft Center, by Peter Diehl, Staff Consultant, Miami-Dade Junior College, North Campus, 11380 N.W. 27th Avenue, Miami, Florida 33167, June 1972.

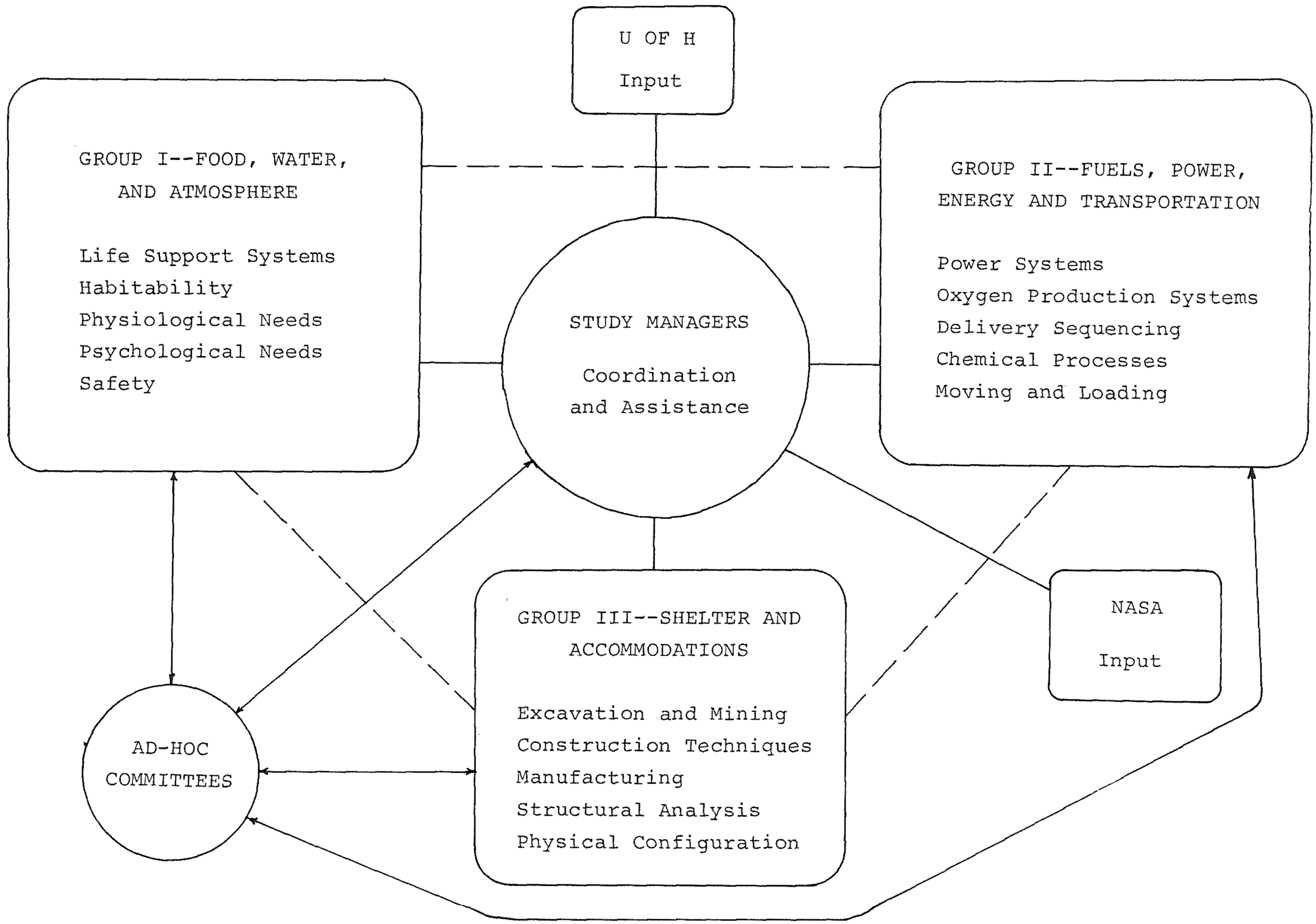


Figure 7.1.5-1 Design Team Organization

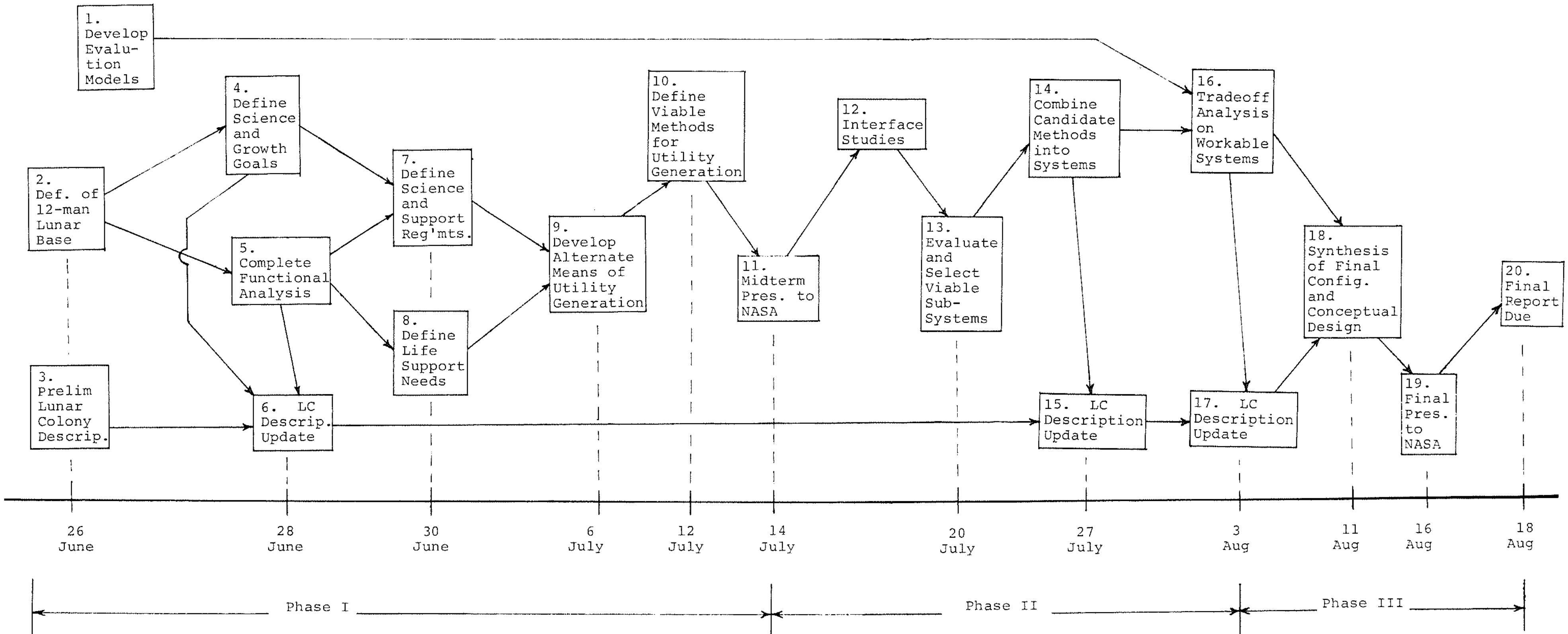


Figure 7.1.5-2 Study Task Sequencing Diagram

7.2 FUNCTIONAL ANALYSIS

7.2.1 INTRODUCTION

The functional analysis has generally been carried to the fourth level except in areas where work below the second or third level indicated simplistic differentiations. We assume that future studies on lunar colony concepts will pursue analyses below the fourth level where such work would be applicable. The functional analysis serves as a descriptor of tasks associated with the planning and subsequent growth of the colony. The analysis may be used as a catalogue of design criteria in which the research and implementation areas needed for eventual colony establishment have been delineated.

The first and third activities--support life and support base--are of prime importance reflecting go/no go situations. These activities must be provided for and their performances must be assured. They represent absolute goals. The second and fourth areas--land and launch vehicles and support professional activities--are of secondary importance relative to the first and third activities; each, however, is essential to base growth. Analysis was also performed on a fifth area--develop population sequencing and growth--and this was broken down into three sub-areas: (1) delineate required tasks for growth; (2) develop occupation/activities priorities; and (3) plan growth according to accomplishment staging. This fifth area is essentially a planning statement for the monitoring and controlling of growth, and it has been carefully developed in Chapters 3 and 5.

7.2.2 LUNAR COLONY FUNCTIONAL ANALYSIS

1. SUPPORT LIFE
    - 1.1 Feed
        - 1.1.1 Store Earth Goods
        - 1.1.2 Synthesize Food
        - 1.1.3 Farm (Plants)
            - 1.1.3.1 Germinate
            - 1.1.3.2 Grow
            - 1.1.3.3 Harvest
            - 1.1.3.4 Process
        - 1.1.4 Ranch (Animals)
            - 1.1.4.1 Breed
            - 1.1.4.2 Feed
            - 1.1.4.3 Harvest
            - 1.1.4.4 Process
    - 1.2 Provide Water
        - 1.2.1 Store
        - 1.2.2 Manufacture
        - 1.2.3 Transport
        - 1.2.4 Recycle
    - 1.3 Control Environment
        - 1.3.1 Control Temperature
            - 1.3.1.1 Heat
            - 1.3.1.2 Cool
            - 1.3.1.3 Circulate
        - 1.3.2 Control Pressure
            - 1.3.2.1 Maintain Homogeneous Pressure
            - 1.3.2.2 Maintain Layered Pressure
        - 1.3.3 Control Atmosphere Composition
            - 1.3.3.1 Control Oxygen Partial Pressure
            - 1.3.3.2 Control Carbon Dioxide Partial Pressure
            - 1.3.3.3 Control Humidity
            - 1.3.3.4 Control Inert Gasses Partial Pressures
            - 1.3.3.5 Control Contaminants
        - 1.3.4 Control Light
            - 1.3.4.1 Control Natural Light
            - 1.3.4.2 Provide Artificial Light
        - 1.3.5 Control Radiation
            - 1.3.5.1 Control Natural Radiation
            - 1.3.5.2 Control Man-Induced Radiation
        - 1.3.6 Control Noise
            - 1.3.6.1 Isolate Noise Sources
            - 1.3.6.2 Provide Sound Privacy
        - 1.3.7 Protect from Meteors
    - 1.4 Provide Waste Control
        - 1.4.1 Provide Metabolic Waste Control
            - 1.4.1.1 Provide Human Waste Control
            - 1.4.1.2 Provide Animal Waste Control
            - 1.4.1.3 Provide Plant Waste Control
        - 1.4.2 Provide Nonmetabolic Waste Control
            - 1.4.2.1 Control Solid Wastes
            - 1.4.2.2 Control Liquid Wastes
            - 1.4.2.3 Control Gas Wastes

1.5 Maintain Mind & Body
    1.5.1 Maintain Physical & Physiological Fitness
        1.5.1.1 Provide Medical Care
        1.5.1.2 Provide Physical Care
        1.5.1.3 Provide Recreation
    1.5.2 Maintain Mental Health
        1.5.2.1 Maintain Self-Presence (Psychological Well-Being)
        1.5.2.2 Encourage Group Interaction (Social Well-Being)
1.6 Procreate Life
    1.6.1 Procreate Human Life
    1.6.2 Procreate Animal Life
    1.6.3 Procreate Plant Life
1.7 Provide for Rest and Sleep
1.8 Communicate
    1.8.1 Lunar
    1.8.2 Extra-Lunar
1.9 Transport
    1.9.1 Transport Human Beings
        1.9.1.1 Rescue
        1.9.1.2 Recreate
        1.9.1.3 Travel to Work
    1.9.2 Transport Life-Dependent Supplies

2. LAND & LAUNCH VEHICLES
- 2.1 Construct Sites
  - 2.1.1 Locate Possible Sites
    - 2.1.1.1 Determine Launch Site Requirements
    - 2.1.1.2 Catalogue Potential Sites Relative to Specific Descriptors
  - 2.1.2 Determine Specific Site
    - 2.1.2.1 Set up Criteria for Selection
    - 2.1.2.2 Compare List of Sites with Criteria and Choose Site
  - 2.1.3 Plan Layout
    - 2.1.3.1 Develop Operational Program
    - 2.1.3.2 Relate Landing Site Activities to Workings of Colony
  - 2.1.4 Excavation (as Necessary)
    - 2.1.4.1 Determine Soil Mechanics
    - 2.1.4.2 Clear Site
    - 2.1.4.3 Create Foundations as Necessary
  - 2.1.5 Fabricate Parts
    - 2.1.5.1 Select Suitable Materials
    - 2.1.5.2 Develop Materials Handling Techniques
    - 2.1.5.3 Determine Materials' Behavior Under Usage During and Between Operations
    - 2.1.5.4 Develop Suitable Nondestructive Testing Procedures
  - 2.1.6 Assemble
    - 2.1.6.1 Study Joining Techniques
    - 2.1.6.2 Develop Erection Sequence
    - 2.1.6.3 Build Landing/Launching Facilities as Required
  - 2.1.7 Test for Workability
    - 2.1.7.1 Develop Performance Record Over Time
    - 2.1.7.2 Maintain and Repair as Required
- 2.2 Supply Fuel
  - 2.2.1 Store Material Brought In from Earth
    - 2.2.1.1 Above Ground
    - 2.2.1.2 Underground
  - 2.2.2 Manufacture
    - 2.2.2.1 Manufacture Oxygen
      - 2.2.2.1.1 Use Ilmenite Process
      - 2.2.2.1.2 Boil-Off from Liquified Lunar Soil
      - 2.2.2.1.3 Electrolyze Liquified Soil
      - 2.2.2.1.4 Use Carbothermic Process
      - 2.2.2.1.5 Use Fluorine Reduction
      - 2.2.2.1.6 Use Sodium Hydroxide System
    - 2.2.2.2 Manufacture Other Fuels
- 2.3 Produce Vehicle Products
  - 2.3.1 Fabricate/Manufacture
    - 2.3.1.1 Set up Machine Shop
    - 2.3.1.2 Develop Assembly Line Procedures
    - 2.3.1.3 Choose Materials
- 2.4 Maintain/Repair Vehicle
  - 2.4.1 Provide Diagnosis/Check Up
    - 2.4.1.1 Monitor Service Lifetime of Parts
    - 2.4.1.2 Do Nondestructive Testing
    - 2.4.1.3 Monitor Performance Quality

        2.4.2 Install New Parts
        2.4.3 Load Fuel
    2.5 Control Flights
        2.5.1 Provide Guidance/Assistance for Manned Landing
        2.5.2 Control Unmanned Supply Tugs During Orbiting and Landing
    2.6 Handle Materials
        2.6.1 Storage
        2.6.2 Move

3. SUPPORT BASE

- 3.1 Construct
  - 3.1.1 Locate Possible Sites
    - 3.1.1.1 Delineate Base Functions
    - 3.1.1.2 Determine Means to Perform Functions
    - 3.1.1.3 Catalogue Potential Sites Relative to Specific Descriptors
  - 3.1.2 Determine Specific Site
    - 3.1.2.1 Set up Criteria for Selection
    - 3.1.2.2 Compare Potential Sites with Criteria
  - 3.1.3 Plan Layout
    - 3.1.3.1 Develop Program Based upon Activity Profile
    - 3.1.3.2 Determine Physical Habitability Issues
    - 3.1.3.3 Develop Building Types
  - 3.1.4 Dig and Establish Foundations
    - 3.1.4.1 Determine Soil Mechanics
    - 3.1.4.2 Develop Digging Techniques
    - 3.1.4.3 Determine Foundation Types Suitable to Soil and Building Type
  - 3.1.5 Choose Materials
    - 3.1.5.1 Set Out Performance Requirements for Materials
    - 3.1.5.2 Examine Material Properties in Lunar Environment (Simulated or Real)
    - 3.1.5.3 Select Suitable Materials
  - 3.1.6 Fabricate Parts
    - 3.1.6.1 Develop Materials Handling Techniques
  - 3.1.7 Assemble
    - 3.1.7.1 Study Joining
    - 3.1.7.2 Plan Erection Sequence
  - 3.1.8 Test for Habitability
    - 3.1.8.1 Test for Survival Level
    - 3.1.8.2 Test for Safety
    - 3.1.8.3 Test for Comfort Levels
- 3.2 Transport
  - 3.2.1 Move People
    - 3.2.1.1 On Surface
    - 3.2.1.2 Under Surface
    - 3.2.1.3 Suborbit ("Flying")
  - 3.2.2 Move Machinery
    - 3.2.2.1 On Surface
    - 3.2.2.2 Under Surface
    - 3.2.2.3 Suborbit
  - 3.2.3 Move Materials
    - 3.2.3.1 On Surface
    - 3.2.3.2 Under Surface
    - 3.2.3.3 Suborbit
  - 3.2.4 Move Lunar Resources
    - 3.2.4.1 On Surface
    - 3.2.4.2 Under Surface
    - 3.2.4.3 Suborbit
    - 3.2.4.4 Into and Out of Shelter or Refinery
- 3.3 Equip
  - 3.3.1 Provide Life Support Systems
    - 3.3.1.1 Develop Chemical Forms
    - 3.3.1.2 Develop Mechanistic Forms

3.3.1.3 Develop Biological Forms
3.3.1.4 Seek Overlays or Redundancies
3.3.2 Provide Suitable Environment for Machinery
3.3.2.1 Provide Atmospheric Pressure
3.3.2.2 Provide a Thermal Environment
3.3.2.3 Provide Appropriate Humidity Levels
3.3.2.4 Provide Fuels
3.3.2.5 Provide Waste ("Combustion") Products
3.3.3 Provide Machinery for Lunar Resource Development
3.3.3.1 Develop Minerals
3.3.3.2 Develop Energy
3.3.3.3 Analyze Implications of Vacuum Environment
3.4 Maintain
3.4.1 Develop Service Capabilities
3.4.1.1 Develop Test Procedures for Performance
3.4.1.2 Monitor Performances
3.4.1.3 Compare with Performance Norms
3.4.2 Provide Repair Techniques
3.4.2.1 Isolate Nonworking Parts or Those in Need of Replacement
3.4.2.2 Develop Installation Technique
3.4.3 Generate Supplies
3.4.3.1 Fabricate and Repair Equipment as Necessary
3.5 Store Supplies
3.5.1 In Vacuum
3.5.1.1 Develop Suitable Containers
3.5.2 In Pressure
3.6 Provide Energy
3.6.1 Determine Energy Needs
3.6.2 Determine Means of Provision
3.6.2.1 Chemical
3.6.2.2 Solar
3.6.2.3 Nuclear
3.6.2.4 Gravitational
3.6.2.5 Lunar-Thermal Environment
3.6.3 Develop Energy Storage Capabilities
3.6.3.1 Mechanical Tramway
3.6.3.2 Batteries and/or Fuel Cells
3.7 Communicate
3.7.1 Maintain Intralunar Environment Contact
3.7.1.1 Establish Line-of-Sight Contact with Local Individuals
3.7.1.2 Establish Intrabase Contact
3.7.1.3 Establish Interbase Contact
3.7.2 Maintain Extralunar Environment Contact
3.7.2.1 Establish Base-to-Satellite (Lunar and Earth Orbits) Contact
3.7.2.2 Establish Base-to-Earth Contact
3.7.2.3 Establish Base-to-Other Planets Contact (for Pioneer Series)
3.8 Protect Base
3.8.1 Protect from Meteoroids
3.8.2 Protect from Solar Radiation

3.8.2.1 Protect from Ultraviolet Radiation
3.8.2.2 Protect from Flares
3.8.2.3 Protect from Winds
3.8.2.4 Protect from Heat
3.8.3 Protect from Lunar Night
3.8.3.1 Provide Warmth
3.8.3.2 Provide Light

4. SUPPORT PROFESSIONAL ACTIVITIES

- 4.1 Research
  - 4.1.1 Life Sciences
    - 4.1.1.1 Biochemistry
    - 4.1.1.2 Botany
    - 4.1.1.3 Biophysics
    - 4.1.1.4 Zoology
  - 4.1.2 Physical Sciences
    - 4.1.2.1 Geology
    - 4.1.2.2 Astronomy
    - 4.1.2.3 Geophysics
    - 4.1.2.4 Physical Chemistry
    - 4.1.2.5 Cosmology
  - 4.1.3 Medical Sciences
    - 4.1.3.1 Nutritional
    - 4.1.3.2 Cardiovascular
    - 4.1.3.3 Psychological
    - 4.1.3.4 Physiological
- 4.2 Develop Technology
  - 4.2.1 For Life Support
  - 4.2.2 For Transportation
  - 4.2.3 For Communication
  - 4.2.4 For Materials Production
  - 4.2.5 For Oxygen Production
- 4.3 Monitor Homeostasis of Base Systems
  - 4.3.1 Man
  - 4.3.2 Animals and Plants
  - 4.3.3 Machinery for Life Support Systems
  - 4.3.4 Lunar Mineral Development
- 4.4 Creative/Imaginative Expression
  - 4.4.1 Fine Arts
  - 4.4.2 Crafts
  - 4.4.3 Music
  - 4.4.4 Philosophy
  - 4.4.5 Theology
  - 4.4.6 Literature

CHAPTER 8 THE LUNAR ENVIRONMENT

In the words of W. Von Braun [22] "Space is not hostile..... Neither is it hospitable. It is neutral. Space is simply there, following the scientific principles of nature, neither assisting nor resisting the attempts of man to fathom its mysteries". The environment on the moon, and in space, generally is different from that on the earth to which the human being is accustomed. An understanding of the characteristics of the environment enables man to interact and adjust with it. Much environmental data has been published and much more needs to be developed in order to have a better understanding of the environment. In this chapter, an attempt has been made to compile and present briefly the relevent information published in the references given at the end of the chapter.

8.1 ATMOSPHERE

8.1.1 GAS PROPERTIES

The atmosphere of the moon is rarefied with an estimated density of less than 10^{-13} times the earth's atmosphere. The composition is estimated as follows [9, 10, 11, 12, 13, 14]:

Constituent	Particles/cm^3
H_2	5.30×10^3
He	3.67×10^4
H_2O	1.7×10^3
Ar	5.4×10^4
Kr	1.7×10^{-2}
Xe	1.87×10^{-3}
H^+	3.3×10
He^{++}	5.9×10^{-2}
H_2O^+	3.0×10
Ar^+	3.41×10^2
SO_2 and CO_2	Estimate not available

Minimum density is 5.5×10^4 particles/cm^3 at very small solar flux.

8.1.2 GEOMAGNETIC FIELD

Knowledge on the geomagnetic properties helps in the study of evolutionary history of the moon and the solar system. The magnetic field is useful in the determination of the electromagnetic properties of the earth's interior, solar-wind and ionospheric environments. The electrical conductivity and in turn the temperature characteristics of the moon's interior may be determined from the magnetic-field measurements. The thermal state will give additional information on the origin of the moon. The magnetometer experiments of the Apollo missions are also useful in the study of the magnetic response of the moon to the solar and terrestrial fields is a function of the lunar orbital position. The measurements at the Apollo sites show a considerable variation in the magnetic field and indicate that the field sources are local. The measured magnetic fields at the Apollo sites are given [4], and are reproduced in Table 8.1.2-1.

Table 8.1.2-1 Magnetic Fields at the Apollo Sites

Site	Coordinates Degrees	Magnetic Field, gammas	Magnetic Field Components, gammas		
			Up	East	North
Apollo 12	3.2°S, 23.4°W	38±3	-24.4±2.0	+13.0±1.8	-25.6±0.8
Apollo 14	3.7°S, 17.5°W				
-Site A	(1.1 km between	103±5	-93±4	+38±5	-24±8
-Site C'	the sites)	43±6	-15±4	-36±5	-19±5
Apollo 15	26.1°N, 3.7°E	6±4	+4±4	+1±3	+4±3

The magnetic field at the equator is approximately 35 gammas. Kopff Crater (17.5°S latitude and 89.5°W longitude) is closer to Apollo 12 than the other Apollo sites; however, the wide variation in the magnetic field at the different sites would make any estimate of the field at Kopff Crater purely speculative except in general terms. The magnetic field of the moon is weak and is less than

0.001 of the earth's field which means the metallic core in the moon is small and is probably less than 2% of its total mass [20].

8.1.3 RADIATION

8.1.3.1 Galactic Cosmic Rays

These rays have origin outside the solar system. Particles with energies up to 10^{20} electron volts have been observed [9,22]. The flux range of the rays is from about 2 protons/cm^2-sec at sunspot maximum to about 4 protons/cm^2-sec at sunspot minimum. The integrated yearly rate ranges from about 1.3×10^8 protons/cm^2 to about 7×10^7 protons/cm^2. The energy range is from 40 Mev to 10^{13} Mev. The dose produced by radiation is small. Four protons/cm^2 -sec are required to produce about 0.01 rad/day. Integrated dose (without shielding) is about 4 to 10 rad/year. The composition and relative dose of the rays given in [23] are reproduced in Table 8.1.3.1-1.

Table 8.1.3.1-1 Galactic Cosmic Radiation Abundance and Dose

Group	Z	Relative Abundance	Relative Dose
H	1	0.86	0.86
He	2	0.12	0.48
Li	3	0.0008	0.0072
Be-B	4-5	0.002	0.032
C	6	0.004	0.144
N	7	0.002	0.098
O	8	0.003	0.192
F	9	0.0002	0.0162
Ne	10	0.0008	0.0800
Na	11	0.0005	0.0605
Mg	12	0.0008	0.1152
Al	13	0.0002	0.0338
Si	14	0.0003	0.0588
P-Sc	15-21	0.0003	0.0972
Ti-Ni	22-28	0.0008	0.5000

Table 8.1.3.2-1 Total Estimated Solar Flare Doses by Event for 10 Shielding Configurations [9]

	Shielding Configuration									
Date	1/0*	2/0	5/0	10/0	20/0	1/5	2/5	5/5	10/5	20/5
2/23/56	280.00	181.00	91.80	50.20	24.80	64.78	58.00	43.75	30.40	17.90
8/3/56	8.50	5.00	2.20	1.00	0.40	1.39	1.21	0.85	0.53	0.27
1/20/57	122.00	43.50	8.30	1.80	0.30	3.42	2.57	1.23	0.46	0.11
8/29/57	77.00	25.10	4.20	0.80	0.10	1.63	1.20	0.54	0.19	0.04
10/20/57	18.50	10.30	4.10	1.80	0.70	2.53	2.17	1.46	0.88	0.41
3/23/58	148.00	53.60	10.90	2.50	0.40	4.67	3.55	1.75	0.69	0.17
7/7/58	150.00	53.70	10.50	2.30	0.40	4.38	3.30	1.60	0.61	0.15
8/16/58	23.70	8.60	1.80	0.40	0.10	0.75	0.57	0.28	0.11	0.03
8/22/58	45.00	14.90	2.50	0.50	0.10	0.96	0.71	0.32	0.11	0.02
8/26/58	75.00	23.10	3.40	0.50	0.10	1.19	0.85	0.36	0.11	0.02
5/10/59	470.00	211.10	59.30	18.30	4.40	30.18	24.28	13.60	6.70	2.10
7/10/59	420.00	214.00	73.20	27.40	8.40	41.56	34.65	21.76	11.84	4.80
7/14/59	650.00	284.50	75.90	22.30	5.00	37.56	30.00	16.75	7.80	2.50
7/16/59	382.00	194.80	67.20	25.30	7.80	38.30	31.98	20.16	11.03	4.50
9/3/60	13.00	7.20	2.90	1.20	0.50	1.77	1.52	0.10	0.06	0.03
11/12/60	484.00	269.60	105.50	44.90	16.20	64.53	55.12	36.87	21.83	10.05
11/15/60	288.00	151.90	55.90	22.40	7.50	30.04	7.91	18.14	10.33	4.49
11/20/60	17.30	9.50	3.60	1.50	0.05	2.14	1.82	1.20	0.69	0.31
7/12/61	25.70	8.40	1.40	0.30	0.03	0.54	0.40	0.18	0.06	0.01
7/18/61	128.00	64.20	21.60	8.00	2.40	12.16	10.11	6.30	3.39	1.35

*Shielding configurations are given as X/Y where X is the shielding thickness in g/cm^2 of aluminum and Y is the shielding thickness in g/cm^2 of tissue.

8.1.3.2 Solar Cosmic Radiation

These rays originate from the disturbed regions on the sun during solar flares and are valuable in the study of solar processes and magnetic field near the sun and in interplanetary space. A solar flare is a bright eruption of the sun's chromosphere when high energy particles are ejected into space.

The composition of these rays consists primarily of protons (H^+) and alpha particles (He^{++}) [22, 23]. Integrated yearly flux at 1 AU for particles with energy greater than 30 Mev is about 8×10^9 protons/cm^2 near solar maximum and 5×10^5 protons/cm^2 near solar minimum. Integrated yearly flux at 1 AU for particles with energy greater than 100 Mev is 6×10^8 protons/cm^2 near solar maximum and 5×10^4 protons/cm^2 near solar minimum. Maximum dosage with shielding of 5 g/cm^2 (equivalent thickness) is about 200 rad/week.

The total estimated doses for 20 solar flares given in [9] are reproduced in Table 8.1.3.2-1.

8.1.3.3 Thermal Radiation

The thermal radiation from the lunar surface varies from 565 watts/m^2 at 200 km to about 5 watts/m^2 at 20000 km [9, 22, 23].

8.1.3.4 Albedo Radiation

Albedo radiation varies from 151 watts/m^2 at 200 km to 1 watt/m^2 at 20000 km.

8.1.4 METEOROIDS

Meteoroids are solid objects moving in space. A meteorite is a meteoroid which reaches earth. Meteor is the light phenomenon associated with the passage of a meteoroid through the earth's atmosphere. The meteoroids have their origin in comets and

Table 8.1.4-1 Meteoroid Craters and Related Information [4]

	Window Exposure m^2-sec	Number of Impacts	Meteoroid Flux, Number/m^2-sec	95 Percent Confidence Limits Number/m^2-sec	Minimum Meteoroid mass, g
Apollo 7	2.21×10^5	5	2.26×10^{-5}	5.29×10^{-5}	2.1×10^{-12}
(Earth orbital without LM)				7.23×10^{-6}	
Apollo 8	1.46×10^5	1	1.32×10^{-5}	7.41×10^{-5}	2.9×10^{-13}
(Lunar orbital without LM)				1.32×10^{-6}	
Apollo 9	1.78×10^5	1	5.57×10^{-6}	3.12×10^{-5}	8.4×10^{-12}
(Earth orbital with LM)				5.57×10^{-7}	
Apollo 10	1.49×10^5	0	----	4.86×10^{-5}	1.3×10^{-13}
(Lunar orbital with LM)				---	
Apollo 12	1.79×10^5	0	----	4.00×10^{-5}	1.3×10^{-13}
(Lunar landing)				---	
Apollo 13	1.42×10^5	1	1.37×10^{-5}	7.64×10^{-5}	1.3×10^{-10}
(Circumlunar abort with LM)				1.37×10^{-6}	
Apollo 14	1.93×10^5	2	2.00×10^{-5}	7.24×10^{-5}	1.3×10^{-13}
(Lunar landing)				2.00×10^{-6}	

asteroids. The meteorites which survive the earth's atmosphere generally have asteroidal origin and meteoroids with cometary origin generally disintegrate in the earth's atmosphere. Meteoroid impact forces depend on the mass, density and velocity of the meteoroids. Photographs which give the flux of the meteors as a function of their luminosity, and radar observations obtained from the reflection of radar beams by the ionized meteor trails furnish information on meteors with mass range greater than 10^{-6} gram. Direct measurements from acoustic-impact sensors and penetration sensors on space vehicles provide information on meteors in the mass range 10^{-13} to 10^{-6} gram [9, 24]. The meteoroid activity on the Apollo missions given in [4] is reproduced in Table 8.1.4-1.

8.1.4.1 Average Total Flux

The average annual cumulative meteoroid model based on available data is described mathematically as follows:

For $10^{-6} \leq m \leq 10^{0}$, $\log N_t = -14.597 - 1.213 \log m$, and

For $10^{-12} \leq m \leq 10^{-6}$, $\log N_t = -14.566 - 1.584 \log m - 0.063 (\log m)^2$,

where

N_t = number of particles of mass m (or greater) per square meter per second,

m = mass in grams.

The unshielded flux, N_t, is multiplied by a defocusing factor for the moon,

$$G_m = 0.966 + \frac{0.034}{r},$$

where r is the distance from the center of the moon in units of lunar radius

When the orbital tracks of spacecraft, earth or moon, and a meteoroid stream are aligned, the earth or moon blocks the meteoroid stream, and the flux N_t is multiplied by a body shielding factor,

$$\xi = \frac{1 + \cos\theta}{2} ,$$

where $\theta = \sin^{-1} (R/(R + H))$, R = radius of shielding body, and
H = altitude above surface

We feel that the shielding factor is not applicable in the case of a lunar colony since it has a permanent or semipermanent character.

8.1.4.2 Sporadic Meteoroids

Examination of asteroidal meteoroids show that about 90% are stony and of average density of 3.5 grams/cm^3. About 10% are iron-nickel and of average density of 7.8 grams/cm^3. Observations of cometary meteoroids have shown that the density range is 0.16 to 4 grams/cm^3. An average density of 0.5 gram/cm^3 has been chosen for cometary meteoroids.

The meteoroid velocity of 11 to 72 km/sec based on celestial mechanics has been verified by photographic and radar observations. An average velocity of 20 km/sec with the probability velocity distribution given in [9] and reproduced in Figure 8.1.4.2-1 is assumed.

The sporadic meteoroid flux-mass model is described as follows:

For $10^{-6} \leq m \leq 10$,

$$\text{Log } N_{sp} = 14.41 - 1.22 \log m + \log \left(1 + \frac{0.035}{r}\right) + \log \left(1 + \frac{\sqrt{1 - 1/r^2}}{2}\right) + \log F_{seasonal},$$

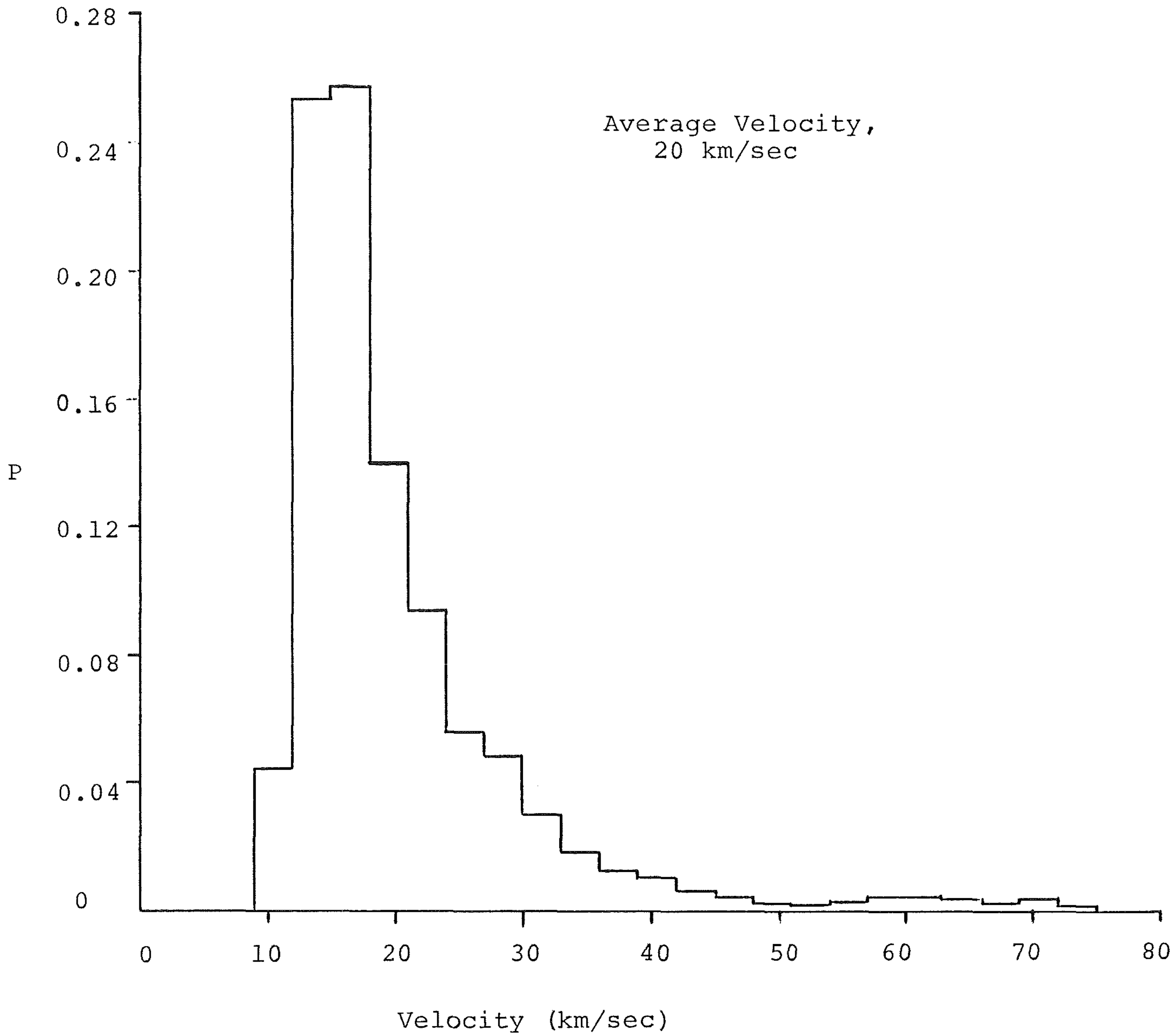


Figure 8.1.4.2-1 Probability Velocity Distribution for Sporadic Meteoroids [9]

For $10^{-12} \leq m \leq 10^{-6}$,

$$\text{Log } N_{sp} = 14.339 - 1.584 \log m - 0.063 (\log m)^2$$

$$+ \log \left(1 + \frac{0.035}{2}\right) + \log \left(\frac{1 + \sqrt{1 - 1/r^2}}{2} \right) + \log F_{seasonal},$$

where

N_{sp} = number of particles/m^2/sec or mass m or greater encountered by a randomly oriented surface,

m = mass in g,

r = distance from the center of the moon in units of lunar radius,

and $F_{seasonal}$ = seasonal factor from the table below. (The factor is obtained by taking the average of monthly factors listed for the months of the mission duration.)

Monthly Factors

January	0.6
February	0.4
March	0.5
April	0.6
May	1.1
June	1.6
July	1.8
August	1.6
September	1.1
October	1.1
November	0.9
December	0.7

The average value of $F_{seasonal}$ = 1 may be used, since the lunar colony is of a permanent or semipermanent nature.

8.1.4.3 Stream Meteoroids

Due to the interaction of the earth's orbit with the stream of particles in similar orbits in the solar system, an increase in the meteor activity during certain periods of the year has been observed. The increase has been associated with cometary meteoroids. The major meteoroid streams showing the period of activity, peak period and velocity given in [9] are reproduced in Table 8.1.4.3-1.

Table 8.1.4.3-1 Major Meteoroid Streams [9]

Period of Activity	Date of Maximum	F_{max}*	Geocentric Velocity (km/s)
Jan. 2 to 4	Jan. 3	8.0	42
Apr. 19 to 22	Apr. 21	0.85	48
May 1 to 8	May 4 to 6	2.2	64
May 14 to 23	May 14 to 23	2.0	37
May 29 to June 19	June 6	4.5	38
June 1 to 16	June 6	3.0	29
June 24 to July 5	June 28	2.0	31
July 26 to Aug. 5	July 8	1.5	40
July 15 to Aug. 18	Aug. 10 to 14	5.0	60
Oct. 15 to 25	Oct. 20 to 23	1.2	66
Oct. through Nov.	Nov. 5	1.1	28
Oct. 26 to Nov. 22	Nov. 10	0.4	29
Nov.		1.0	37
Oct. 26 to Nov. 22	Nov. 5	0.9	28
Nov. 15 to 20	Nov. 16 to 17	0.9	72
Nov. 12 to 16	Nov. 14	0.4	16
Nov. 25 to Dec. 17	Dec. 12 to 13	4.0	35
Dec. 20 to 24	Dec. 22	2.5	37

*F_{max} is the ratio of average maximum cumulative stream to average sporadic flux for a mass of 1 g and a velocity of 20 km/s.

The average particle density for all streams is assumed as $0.5\ g/cm^3$.

The cumulative flux-mass model of a stream is described as follows:

$$\text{For } 10^{-6} \leq m \leq 10^{0},$$

$$\text{Log } N_{st} = -14.41 - \log m - 4.0 \log (V_{st}/20) + \log F,$$

where

N_{st} = number of particles/m^2/sec of mass m or greater,
m = mass in g,
V_{st} = geocentric velocity of each stream in km/sec,
and F = ratio of cumulative flux of stream to the average cumulative sporadic flux. (Graphs showing the relation between F and period of activity are given in [9].)

Here again, since the lunar base is of a permanent or a semipermanent nature, the most critical activity will be of interest in the design.

8.1.4.4 Lunar Ejecta

Due to meteoroid impact on the lunar surface, particles are forced out into the atmosphere. These particles which constitute the lunar ejecta have a low velocity compared to the meteoroid velocity. The effects of the lunar ejecta are in addition to those of the meteoroids and are considered for a height 30 km from the lunar surface.

The mass density for all ejecta is $2.5\ g/cm^3$. The average velocity for all ejecta is 0.1 km/sec. The average annual total cumulative flux model for the ejecta is described as follows:

$$0 \leq V_{ej} \leq 1.0, \ \log N_{ej_t} = -10.75 - 1.2 \log m$$

where

N_{ej_t} = number of particles/m^2/sec of mass m or greater,

m = mass in g.

The average annual individual cumulative flux-model for the ejecta for three different velocity ranges is described as follows:

$$0 \leqq V_{ej} \leqq 0.1 \ (V_{ej} = 0.1 \text{ km/sec}),$$

$$\text{Log } N_{ej} = -10.79 -1.2 \log m;$$

$$0.1 \leq V_{ej} \leq 0.25 \ (V_{ej} = 0.25 \text{ km/sec}),$$

$$\text{Log } N_{ej} = -11.88 -1.2 \log m;$$

$$0.25 \leqq V_{ej} \leqq 1.0 \ (V_{ej} = 1.0 \text{ km/sec}),$$

$$\text{Log } N_{ej} = -13.41 -1.2 \log m.$$

8.1.5 CHARACTERISTIC PROPERTIES OF THE MOON

Pertinent characteristic moon properties are listed below:

Distance from center of moon to center of earth (average)	38440 km
Volume	2.2×10^{25} cm^3
Angular diameter (average)	31.09 min
Mass	7.35×10^{22} kg
Density (average)	3.34 g/cm^3
Circular velocity	1.68 km/sec
Escape velocity	2.38 km/sec
Mean gravitational acceleration on the moon's surface	162.3 cm/sec
Eccentricity of orbit (average)	0.0549
Inclination of orbital plane to ecliptic plane	5° - 9'

Inclination of lunar equator to ecliptic plane	1° - 32'
Inclination of lunar equator to orbital plane	6° - 41'
Earth/moon mass ratio	81.3010 (±0.001)
Sidereal period, true period of rotation and revolution	27.322 days
Synodic period, new moon to new moon	29.531 days
Mean lunar radius	1738.09 (±0.07) km
Inertial rotational rate of the moon	ω_m = 0.00015250437 deg/sec

The principal axes are the following:

$$A = 1738.57\ (\pm 0.07)\ \text{km},$$
$$B = 1738.21\ (\pm 0.07)\ \text{km},$$
$$C = 1737.49\ (\pm 0.07)\ \text{km},$$

where A is directed toward the mean center of the lunar disk, C is coincident with the moon's rotational axis, and B is perpendicular to A and C.

The gravitational parameter is $\mu_m = GM_m = 4902.78\ (\pm 0.06)\ \text{km}^3/\text{sec}^2$ and the gravitational potential function of the moon is

$$U\ (r,\phi,\theta) = \frac{\mu_m}{r}\left[1 - \frac{J_2}{2}\left(\frac{R_m}{r}\right)^2\left(3\sin^2\phi - 1\right) + 3C_{22}\left(\frac{R_m}{4}\right)^2\cos^2\phi\cos 2\theta\right],$$

where

R = magnitude of selenocentric radius vector, km,

ϕ = selenocentric latitude,

θ = selenocentric longitude (positive eastward),

R_m = mean lunar radius = 1738.09 (±0.07) km,

J_2 = 2.07108 (±0.05) x 10^{-4},

C_{22} = 0.20716 (±0.05) x 10^{-4}.

8.2 GEOLOGICAL AND SURFACE FEATURES

8.2.1 INTRODUCTION

The origin of the moon is a controversial subject [1, 2, 3, 4, 9, 10, 11, 27]. Some of the more well-known theories are that, due to the tidal action of the sun, the moon escaped from the earth (G. H. Darwin, 1879), that the moon formed by accretion close to earth at the time the earth was still growing (G. P. Kuiper, 1951, and E. L. Ruskol, 1962), that the moon which formed elsewhere in space was captured by the earth through tidal processes (H. Gerstenkorn, 1955, H. C. Urey, 1962, and H. Alfven, 1963) and that the present moon was formed by several small moons captured by the earth about 1.5 billion years ago (G. J. F. MacDonald, 1964). The theories of origin are of great interest in that it may throw more light on the origin of life on earth and help in the utilization of lunar resources by the human being.

The information on the composition of the interior of the moon is also controversial like its origin. The interior is under high pressure and higher temperature than the surface. According to H. C. Urey, the moon's composition is similar to chondritic (stony) meteorites and consists primarily of calcium and magnesium silicates and about 10 percent of iron (the iron content of most chondrites is 20 percent or more). The lesser density of the moon is the basis for the suggestion of lower iron content.

The temperature of the moon at the time of its formation is necessary in the study of the surface structure. One theory is that the temperature of the moon's interior was originally low for a long time and gradually increased due to the moon's gravity. According to this cold condition theory, there would be no reason to have lava on the moon. The other theory is that the temperature of the moon was originally high and lava existed in the interior. Since the temperature could not have risen much due to gravitation, large quantities of radioisotopes of relatively short half-life like aluminum-26 may have given out sufficient heat during the process of decay of these isotopes to heat and melt the interior of the moon to produce lava. The temperature of the moon's outer layer up to a thickness of about 240 km may be gradually falling from its maximum due to radiation. Fractures in the moon's crust would reduce the interior pressure and the melting point of silicates and facilitate the formation of liquid magmas.

8.2.2 TOPOGRAPHY

Galileo (1610) classified the moon's surface into two broad regions, Maria comprising the dark areas and the Terrae (uplands or highlands) comprising the light areas. The most prominent features of the moon, especially in the Uplands, are the craters ranging in size from small to as big as 227 km in diameter and 5 km in depth. There are two theories on crater origin, one which associates craters with volcanic origin and the other which states that the craters are the result of impact of meteoroids, asteroids or comets. Generally speaking, the central region of the craters are distinctly below the crater; but there are many craters with central peaks rising about the bottom of the crater and some of the peaks have smaller craters at the top. There are also ray craters which are not very deep but several hundred km long. Some of the prominent ray craters are Copernicus, Kepler and Aristarchus in the Maria and Tycho in the Uplands. There are also mountains on the moon with peaks as high as 3 to 6 km. In addition to telescopic and photographic observations which have provided a great deal of information about the moon, remote sensing techniques have been used. The divisions in the electromagnetic spectrum in the order of increasing wavelengths are cosmic rays, gamma rays, x-rays, ultraviolet, visible light (wave length of 0.4 to 0.4 micron), infrared, microwave (radar) and radio waves. Short wavelengths are associated with atomic, molecular, and mineralogical configurations; larger wavelengths are associated with larger structural features. Visible light and infrared radiation may be used for depth of 1 or 2 cm of the lunar surface whereas radar penetration is deeper (in the order of meters) and may be used to prepare topographic maps. The material underneath the regolith of the moon is basalt in the Maria and a less dense material in the Uplands. The calculated regolith thickness based on crater frequency is about 2 m. The regolith thickness at the Surveyor sites varies between 1 to 10 meters. Regolith is the result of repeated impact by meteoroids. The calculated thickness of regolith from Explorer satellite readings varies from 1 m in the Maria to 20 m in the Uplands.

The cumulative frequency of crater distribution is expressed in the form of $N_o = KD^n$, where N_o is the cumulative number of craters per unit area larger than diameter D, and K and n are constants. The log-log plot of the expression is given in [11, 27]. A relation between slope (horizontal distance between two elevations) and median slope on lunar surface has been established and plotted in [11]. The Maria has both the smoothest and roughest regions whereas the Upland although has the steepest slopes, generally falls in and in between category of roughness. The surface-roughness power-spectral density (meter^2/cycle/meter) relations for the Maria and Upland are shown in [11]. The lunar surface has blocks (protuberances) of diverse shapes and sizes which are gray and generally brighter than the surrounding soil distributed in between and around the craters. The ratio of the longest to shortest dimension of a block is considered to be 2/1. The estimated average density of a lunar block is between 2.8 to 2.9 g/cm^3 and the estimated shear strength is about 200 N/cm^2. The block distribution is shown in [9].

8.2.3 THERMAL PROPERTIES

Equatorial-brightness temperature measurements made from earth have shown that local variations of temperature differing from that of the general area of a region do occur. The differences in the surface and brightness temperatures are due to the following: The lunar surface is assumed to be black. The thermal radiation measurements are made in the 10 to 12 micron range of the infrared. The measured value is an average temperature for a circular region of 14 to 17 km in diameter. The equatorial-brightness temperature T_E over a complete lunation period can be represented by a Fourier series as given in [11]. The temperature below a depth of about 1 m is considered constant at about 230°K.

The surface thermal conductivity K is dependent on the temperature T and is given by the expression $K = K_0 + K_1 T^3$ where K_0 and K_1 are conductive and reflectivity constants, respectively. The ranges of values of K_0 and K_1 for powdered pumice stone and basalt (applicable for lunar soil) are

$$2.5 < K_0 \times 10^6 < 21 \text{ watt/cm°K, and}$$

$$0.88 < K_1 \times 10^{13} < 3.57 \text{ watt/cm°K}^4.$$

8.2.4 OPTICAL PROPERTIES

The diffuse reflectivity of the full moon is expressed by a parameter called normal albedo. Combined photographic and photoelectric techniques have been employed to obtain normal albedo data. Errors in the data may occur due to various reasons such as uncertainty in the photometric function, extrapolations to zero phase angle, luminescence and errors in recording instruments. The normal albedo values are given in Smith [9] and are reproduced in Table 8.2.4-1.

Table 8.2.4-1 Normal Albedo Values of Front and Back Faces of the Moon [9]

Regions	Normal Albedo Minimum	Normal Albedo Maximum	Average (Peak Value)
Front Side			
Mare	0.07	0.12	0.095
Upland	0.108	0.24	0.150
Entire Face	0.07	0.24	0.110
Back Side			
Entire Face			0.217

The relation between the brightness of the lunar surface and the viewing angle and solar incidence angle is given by the photometric function which varies for different areas of the surface. The luminance B of the lunar surface is given in the form

$$B = E\rho\phi/\pi \ ,$$

where E is the solar constant (1400 W/m^2 at 1 AU), ϕ is the photometric function and ρ is the normal albedo. The relations between ϕ and the phase angle and between ϕ and the surface orientation angle are given in Smith [9].

The electromagnetic vibrations of the sun's rays reflected by the lunar surface are not the same in all the planes. The polarized moonlight is given by the expression,

$$P_1 = (I_1 - I_2)/(I_1 + I_2)$$

where I_2 is the intensity of the reflected light in the phase plane (containing the incident and reflected light paths) and I_1 is the intensity in the plane at right angles. The curves representing the relations between polarization and phase angle are also given in Smith [9].

8.2.5 SEISMICITY

The network of geophysical stations established in the Apollo missions [1, 2, 3, 4] has provided much useful information on the seismic activity of the moon. There is a crust and a mantle in the moon and the thickness of the crust is between 55 to 70 km and may consist of two layers.

The moonquakes occur in monthly cycles. The depth of the focus of moonquakes is greater than that of the focus in case of earthquakes. Also, there are periods which may last several days during which quakes may occur continually at short intervals on an average of 2 hours. Most of the seismic energy from the surface sources is dissipated locally. However, the seismic waves are transmitted efficiently through the lunar interior. From the seismic signal generated by the lunar-module ascent-propulsion engine, the velocity of sound in the lunar regolith determined at the Apollo-12, Apollo-14 and Apollo-15 sites are approximately 104, 108 and 92 m/sec respectively. These results associated with locations which are far from each other indicate that the mechanical properties of the regolith are fairly uniform over the entire moon. An analysis of the seismic activity shows that most of the quakes occurred at the times of maximum (apogee) and minimum (perigee) distances between the earth and the moon during each monthly revolution of the moon. The timing of the events indicate that the quakes are a result of lunar tides. The focus of the moonquakes is at a depth of approximately 800 km from the surface. This large depth shows that the lunar interior has sufficient shear strength to be able to store the strain energy released during the quakes.

Seismic signals during the impacts of the Apollo Missions further indicate that the outer shell, to a depth of about 20 km, is highly heterogeneous. The outer shell may consist of several layers of lava each broken up by thermal stresses and meteoroid impact. It further suggests that the composition in structure occurs at a depth of between 55 to 70 km. Rock with a compressional wave velocity of approximately 6 km/sec exists at a depth of between 15 to 20 km. The changes in the velocity of the wave and the presence of secondary compression wave indicate layered structure.

The seismic activity of the moon is relatively low compared to that of the earth. The energy of the largest moonquake is in the range of 10^9 to 10^{12} ergs. Based on the activity at the Apollo-12 region, the total energy of the moonquakes is approximately in the range of 10^{11} to 10^{15} ergs/year compared to the earthquake energy of approximately 5×10^{24} ergs/year. Internal convection currents leading to significant lunar tectonism are absent. The outer shell of the moon is relatively cold, rigid and tectonically stable. However, the small quakes at frequent intervals are probably due to continuous adjustment of stresses in the crust.

REFERENCES

1. "Apollo 11 Mission Report", NASA SP-238, 1971.

2. "Apollo 12 Preliminary Science Report", NASA SP-235, 1970.

3. "Apollo 14 Preliminary Science Report", NASA SP-272, 1971.

4. "Apollo 15 Preliminary Science Report", NASA SP-289, 1972.

5. "Lunar Base Synthesis Study, Final Report", North American Rockwell, Space Division, 1971, Volume I - Executive Summary.

6. Ibid; Volume II - Mission Analysis and Lunar Base Synthesis.

7. Ibid; Volume III - Shelter Design.

8. Ibid; Volume IV - Cost and Resource Estimates.

9. Smith, R. E., editor, "Space and Planetary Environment Criteria Guidelines for use in Space Vehicle Development", NASA TM X-64627, 1971.

10. Weidner, D. K., editor, "Natural Environment Criteria for the NASA Space Station Program, NASA TM X-53865, 1969.

11. "NASA Space Vehicle Design Criteria (Environment), Lunar Surface Models, NASA SP-8023, 1969.

12. "NASA Space Vehicle Design Criteria (Environment), Models of Earth's Atmosphere (120 to 1000 km)", NASA SP-8021, 1969.

13. "NASA Space Vehicle Design Criteria (Environment), Meteoroid Environment Model-1970 (Interplanetary and Planetary)", NASA SP-8038, 1970.

14. Cour-Palais, B. G., Zook, H. A., and Flaherty, R. E., "Meteoroid Activity on the Lunar Surface from the Surveyor III Sample Examination", NASA TM X-58079, 1971.

15. "Surveyor I, A Preliminary Report", NASA SP-126, 1966.

16. "Surveyor III, A Preliminary Report", NASA SP-146, 1967.

17. "Surveyor V, A Preliminary Report", NASA SP-163, 1967.

18. "Surveyor VI, A Preliminary Report", NASA SP-166, 1968.

19. "Proceedings of the Seventh Annual Working Group on Extraterrestrial Resources, June 17-18, 1969, NASA SP-229, 1970.

20. Mason, B., and Melson, W. G., The Lunar Rocks, Wiley-Inter-Science, 1970.

21. Farley, T. A., "Space Technology, Volume VI - Space Sciences", NASA SP-114, 1966.

22. Reetz, Jr., A., editor, "Second Symposium on Protection Against Radiations in Space, October 12-14, 1964", NASA SP-71, 1965.

23. Reetz, Jr., A. and O'Brien, K., editors, "Protection Against Space Radiation", NASA SP-169, 1968.

24. "NASA Space Vehicle Design Criteria (Environment), Meteoroid Environment Model - 1969 (Near Earth to Lunar Surface)", NASA SP-8013, 1969.

25. "Surveyor Program Results", NASA SP-114, 1969.

26. Green, J., "The Geology of the Lunar Base", North American Aviation, Inc., SID 61-358, 1962.

27. Mutch, T. A., Geology of the Moon, Princeton University Press, 1970.

28. Fielder, G., Lunar Geology, Lutterworth Press, 1965.

29. Hess, W. N., Menzel, D. H., and O'Keefe, J. H., editors, The Nature of the Lunar Surface, Johns Hopkins Press, 1965.

30. Green, J., "Geological Problems in Lunar and Planetary Research", AAS Science and Technology Series, Vol. 25, AAS Publication Office, Tarzana, California, 1968.

31. Potter, G. J., Moon History's Missing Pages Imagined, Wester Lithograph Company, Los Angeles, California, 1968.

32. Fielder, G., Structure of the Moon's Surface, Pergamon Press, 1961.

33. Malina, F. J., Applied Sciences Research and Utilization of Lunar Resources, Pergamon Press, 1968.

34. Glasstone, S., Sourcebook on the Space Sciences, D. Van Nostrand, 1965.

35. Carrier, W. D., III, "Lunar Soil Grain Size Distribution, MSC-06852, NASA MSC, Houston, 1972.

36. Mitchell, J. K., et al, "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction, Third Lunar Science Conference, Proceedings, Houston, 1972.

37. Carrier, W. D., III, "Strength and Compressibility of Returned Lunar Soil", Proceedings, Third Lunar Science Conference, Houston, 1972.

38. Scipio, L. A., "Structural Design Concepts", NASA SP-5039, 1967.

39. Gatzek, L. E., "Advanced Space Structures Design: Optimization, Materials, Fabrication", U.C.L.A Short Course, 1968.

CHAPTER 9 HABITABILITY

9.1 INTRODUCTION

The study of habitability is essentially an attempt to describe the shelter requirements necessary to support an individual in a specific environment. The environment may be highly variable, effecting frequent change within itself, or it may be manifested primarily as a continuous, though extreme condition. In either instance, the individual's capability to exist in these situations may be severely constrained. To provide appropriate support, the development of a shelter is predicated upon the ability to catalogue the physiological, psychological, and social needs and behaviors that characterize the individual or group. Once understanding of these elements is established, habitability can be demonstrated by the integration of observations in these areas and the translation of such data into physical design guidelines or statements. The degree of habitability is dependent on the relative quality of the living and working spaces.

Generally, the fitness of the shelter is indicated by the intended activity, the duration of usage, and the quality of performance while in the space. At best, habitability may be determined only from a comparative basis (i.e., one space allows more effective work performance than a second.) As such, the study of habitability dwells on the isolation of the differences between these two spaces and the explanation of why performance is affected by these differences. The variation in support may well appear small, and it is likely that it will be difficult to quantify the differences. This observation is particularly true when psychological or social evaluation data are sought.

An associated problem may also be manifested in such studies. It will be difficult to correctly identify the important variables. To isolate these variables and to perform investigations on them without neglecting adjacent variables may also be tenuous.

Nevertheless, the development of habitability guidelines for a lunar colony is most important. A great difference exists between the habitability requirements of the Apollo capsule and a lunar colony. In the first, survival was the key determinant to the success of the mission, and getting there and back was the goal. Additionally, these missions were flown by individuals who were adventurers and were mission-oriented to the highest degree. The colony, with its longer stay time and with survival techniques, which will then be state-of-the-art, will allow and require fulfillment of other goals. These goals should include support for specific living and professional activities, the development of some degree of comfort, and opportunities for occupant/habitat adaptability. The lunar colony will similarly require a high amount of sociability among the crew members. The individuals who comprise the crew will be group-dependent. But opportunities for individual expression and activity must be present also. The colony crew members may be as mission-oriented as the Apollo crews, but the design of the colony should not be predicated on this factor. Rather, we must seek to offer a facility which would permit the attendance, for example, of an outstanding scientist who may not have the physiological or psychological capabilities of contemporary flight crews.

As we have indicated earlier in this section, the need for shelter, and therefore the provisions for habitability, are variable and are dependent upon the severity of the environment--both physical and emotional. The shelter can offer varying degrees of support and will markedly influence performance. Kubis [1] has indicated that there are three primary levels of habitability :

1. a basic survivability,
2. a tolerable discomfort with a possible, but acceptable, reduction in overall efficiency for individuals performing professional or work activities, and
3. a comfortable situation allowing a reasonable efficiency in work and a normalized life style.

An important consideration that will determine work performance and ability to live in nonordinary situations concerns the individual's capability to respond to changing life conditions. The individual who lives and works in the lunar colony must have a well-developed ability to adapt and to change in order to overcome situations which differ from his accustomed life practices. Though an individual may be highly mission-oriented, inflexibility may limit the success with which the crew member performs his functions. In general, the ability to adapt to different life conditions can be influenced by several features:

1. the individual's prior attitudes,
2. the amount of preconditioning experienced prior to initiation into the new environment,
3. the nature of the individual's and the group's activities, and
4. the duration and the difficulty of the task.

Thus, the ability to adapt will directly influence the means by which habitability is provided.

An example of how the crew member's adaptability will affect the development of the lunar colony can be displayed in physiological terms. There are several features of the lunar environment that differ from the earth and which may produce harmful effects on the colony inhabitants. Among these are the reduced gravity, the extended day-night cycle, the high incidence of harmful radiation, and the possibility of using lower atmospheric pressure in the colony shelter than common to sea level-earth. Exposure to the reduced gravity for a long duration may produce positive or negative changes in the physiological behavior of the colony personnel. The extended day-night cycle may cause the development of a different circadian rhythm. Either of these manifestations could influence performance and comfort. Psychological and social behavior may also change, caused by the strong influence of this extreme environment and the shelter provided.

Habitability data must be developed for the design of the lunar colony. While information on performing activities and supporting them in the lunar environment may be minimal, we may seek to design lunar shelter facilities using earth-based experiences. The act of design is essentially a predictive statement in which facilities are fabricated to meet requirements for expected activities and behaviors. The degree of success is generally higher when design is pursued as an interactive process. In such, design is evaluated following each effort and new or revised guidelines are developed for the next generation. After several generations, success rates should be higher. While we may not have sufficient data to make a completely rigorous statement about design guidelines for the Lunar Surface Base, later research groups may be able to generate these for the colony. To accomplish this goal, it will be necessary to closely observe the behavior of the crew and the use of the Base facilities. The shelter should be evaluated to determine the degree of fit between the anticipated behaviors and the quality or completeness of the performance. Using this successive approximation technique, it should be possible to identify primary design issues and to develop colony configurations.

REFERENCE

1. Kubis, J. F., "Habitability: General Principles and Applications to Space Vehicles" from Proceedings of the Second International Symposium on Man in Space, Paris, 1965; Published by Springer-Verlag, New York, 1967; pages 399-427.

9.2 PHYSIOLOGICAL ASPECTS-- LIFE-SUPPORT NEEDS AND REQUIREMENTS

We have developed a physiological model for two members of a lunar colony as they perform general tasks associated with their professions. This model describes metabolic energy expenditure, food and water requirements, waste production, and atmospheric composition and pressure. The form of the model has been generalized to allow for maximum adaptability, and its applicability should be limited only by nonspecificity.

9.2.1 METABOLIC ENERGY EXPENDITURE

Knowledge of metabolic energy expenditures for various tasks on earth is well established, and accurate predictions for work activities are not difficult. But, for the individual on the moon working in a pressure suit, the lunar environment of 1/6 G, large thermal ranges, and vacuum conditions may cause marked changes in energy expenditures. The only real-time data on living and working conditions on the moon are provided by metabolic rates measured during extra-vehicular activity (EVA) for Apollo flights 11, 12, 14, 15 and 16. Thus, an attempt to project energy consumption for an individual pursuing a series of specified tasks on the moon may at best be a speculation. A best effort approach would likely include:

1. developing an activity profile for conditions using observed earth-bound data; and
2. reducing, by a significant factor (such as 40%), the figures for all activities for which we are using earth-bound results.

Work activities simulating lunar EVA experiences have been conducted at Cape Kennedy using full suit and pack. These simulations have shown that energy costs for earth work required 38 to 95% greater consumption of energy than for similar observed activities on the lunar surface (see Michel [1]).

The measured metabolic rates for EVA on the lunar surface have been recorded to be approximately 240 kilocalories per hour for Apollo flights 11, 12, 14, and 15 (see Michel [1]). It has been said that the astronauts on Apollo 15 worked at performance levels which nearly reached the limits of their work capabilities. Because of the over-strenuous nature of these work loads on Apollo 15 and because EVA times on Apollo 16 were to be longer, activity requirements were reduced. Consequently, Waligera [2] found that metabolic work loads on Apollo 16 during EVA averaged 215 kcal per hour. This expenditure rate is thought to be a reasonable level, and future missions specifying lunar surface activities will be based on this figure.

An energy profile can be constructed from EVA and earth data for the daily activities of a member of the lunar colony. If we assume that the individual is healthy, weighs 75 kilograms, is male, and is between 25 and 35 years old, then his energy profile for completion of daily tasks including two EVA periods used for construction work will follow the form of Table 9.2-1.

To repeat, two different standards have been used in compiling this prototypical table:

1. EVA rates reflect lunar experience, whereas
2. all others are based on earth-bound conditions.

We might thus assume that, as the individual gains alacrity or adapts to the lunar environment, he will be able to reduce these second figures (the 1785 kcal per day not associated directly with the EVA work) by 20 to 40%. This would indicate a daily metabolic expenditure of 2195 to 2555 kcal (a reduction of 360 to 720 kcal per day for nonwork activities).

For an astronomer or a plant pathologist who may not be involved with the construction work which is the main activity of the EVA in the profile model, a work or energy rate for a similar seven-hour period might be closer to 850 to 900 kcal for the 7 hours.

Table 9.2-1 Daily Energy Expenditure for a Member of a Lunar Colony

Clock Time (lunar mean time)	Activity	Length (hours)	E Rate (kcal/hr/kg)	E Expend (kcal)
12:00-7:00	Sleep	7	1.00	525
7:00-7:30	Shower, shave, dress (overalls)	½	1.80	70
7:30-8:00	Breakfast	½	1.60	60
8:00-9:00	In-shelter work at desk	1	2.00	150
9:00-12:00	EVA--preparation and performance	3	2.15	485
12:00-1:00	Lunch	1	1.60	120
1:00-5:00	EVA--preparation and performance	4	2.15	645
5:00-6:00	Lab work	1	2.00	150
6:00-7:00	Relaxation	1	1.30	100
7:00-8:00	Dinner	1	1.60	120
8:00-9:30	Discussion (work-related)	1½	1.70	190
9:30-11:00	Read and study	1½	2.00	225
11:00-12:00	Sleep	1	1.00	75
				2915

These figures are appropriately less than the 1130 kcal expended to perform the construction work during the seven-hour EVA.

Therefore, a possible energy expenditure range might be 1965 kcal per day (900 kcal work related for laboratory work and 1065 kcal for other activities) for the lunar-adapted plant pathologist to 2915 kcal per day (1130 kcal work related for EVA and 1785 kcal for other activities) for the construction engineer who has yet to adapt to the lunar environment.

9.2.2 FOOD REQUIREMENTS

The human diet, observed and theoretical, has great variability. But certain products or food forms are required in specific quantities. The basic elements are protein, carbohydrate (present in a variety of digestible and nondigestible forms - e.g., sugars and cellulose, respectively), fats (saturated and unsaturated), vitamins, and minerals. A balanced or "mixed" diet that is considered to be prototypical for the average American citizen has the generalized composition of 12% protein (P), 35% fat (F), and 53% carbohydrate (C). Alternately, an Olympic champion's diet is projected as 20% P, 40% F, and 40% C. Extremes of diet compositions may be best exemplified by the very low protein, high carbohydrate diet common to many Asian peoples and the high protein diet on which the Argentinian cowboy is said to subsist. This diet consists of more than 80% protein and fat. Table 9.2-2 indicates the quantities of protein, fat and carbohydrates required to meet the metabolic energy expenditures of the two individuals described above. The table is based on the percentages of the diets already listed. For energy conversion, 1 gram of protein material (dry) when oxidized during metabolic action produces 4.32 kcal; similarly, 1 gram of fat produces 9.46 kcal and 1 gram of carbohydrate provides 4.18 kcal (see [3]).

Protein material is the primary source for amino acids. The human body requires certain quantities daily of eight specific amino acids which are used for tissue regeneration and growth. Assuming a protein source that contains the amino acids in the requisite quantities, Lappe [4] notes that the minimal protein requirement may be fulfilled by ingesting 0.28 gram of protein per pound of body weight per day. Thus, a man weighing 75 kilograms would need about 46.5 grams of protein per day.

Table 9.2-2 Diet Compositions

	1965 kcal/day			2915 kcal/day		
	P	F	C	P	F	C
	(in grams)			(in grams)		
Mixed Diet--American (12% P, 35% F, 53% C)	54	72	245	81	108	370
Olympic Champion (20% P, 40% F, 40% C)	90	82	185	135	121	280
High Carbohydrate, Low Protein Diet--Asian	48	12	384	48	12	620

Protein sources are rarely more than 80 or 85% protein (dry weight). Fatty substances normally comprise much of the rest of the dry material (fatty materials are insoluble in water). Rambaut [5] has indicated that only a small quantity of fatty material is required. The essential fatty substance is a linoleic acid, and this compound is required in quantities of only a few grams per day. It is present in most fatty materials ingested as food. For the low protein, high carbohydrate diet described in Table 9.2-2, if we assume that the foodstuff providing protein is 80% protein (dry weight) and 20% fat, then to supply 48 grams of protein, about 60 grams (dry weight) of that foodstuff are required. The other 12 grams (of fatty material) should be at least adequate for the provision of fat requirements. The balance of such a diet would be furnished by carbohydrate-based energy sources. In this diet, carbohydrates would supply 80 to 90% for the metabolic energy expenditure. A limiting factor, though, for a diet of these proportions could be general palatability. For an individual accustomed to a medium to high quantity of protein and fat in his diet, there may be some resistance to its acceptability.

The high carbohydrate, low protein diet is likely to be a prime candidate for any first-generation colony diet (for the time when the base ceases to employ a stored-food supply predicated upon freeze-drying or another storage technique). Common vegetables and fruits will be utilized to provide the majority of the largely carbohydrate diet with other plans such as soybean and peanuts grown for their ability to serve as sources of protein and fat. No single plant taken in moderate quantities appears to generate all of the required quantities of the eight amino acids. Therefore, a mixture of plants will be necessary. Another difficulty associated with this general diet form is that larger absolute quantities of food materials are required to provide the appropriate dry weight because

1. oxidized carbohydrate material does not supply as much energy as either fat or protein, and
2. carbohydrate sources tend to have more water present in the actual food material.

The actual quantity of a given plant supplying carbohydrate may be several times larger by gross weight than a selection of meat (animal protein and fat) that would provide an equal quantity of metabolic energy.

Seemingly, in early generations of the lunar colony, meat (provided by avian, fish, or mammal life forms) would likely be supplied only by stored quantities brought up from earth. Only in later generations will animal sources be included in the life systems, and these will probably be employed for their nonflesh outputs such as milk and eggs. The complexity of maintaining animal life as a source of protein and fat is similar to that required to support man. Such an inclusion will necessitate a maturity in the life systems that will be lacking in the early years of the colony.

An alternative to the reliance upon natural sources for food production may be based upon the development of various synthetic processes. Carbohydrate and protein syntheses are currently theorized and some developmental work has begun. Fats (or fatty acids, which are suitable nutritional substitutes for fats) are unable to be synthesized under current technologies which start from simple substances like water, methane, carbon dioxide, and nitrogen.

Balancing a diet around vitamins and minerals provided by plant and animal sources that will prosper in a lunar colony will require much additional work to insure a high degree of confidence. Ultimate food source choices will probably be based upon the ability of specific foods to provide the required vitamins and minerals. The capability of plants to supply minerals may well depend upon the composition of the lunar soil used for growth.

Past and present plans for vitamin and mineral supplementation on the Apollo and Skylab flights have called for capsules to be taken daily. This route is also likely for early lunar colony diets.

9.2.3 WATER CONSUMPTION AND LIQUID WASTES PRODUCTION

For any given diet and energy profile, we may assume that for each 1 kcal of food energy consumed, the individual will require 1 milliliter of water. For a diet providing 2915 kcal of food energy, the individual crew member will require 2915 ml of water.

Results for some of the Apollo flights, including EVA work experiences, indicate the conversion factor of 1 ml of water per kcal of energy may be somewhat too high; and perhaps a factor of 0.90 or 0.95 ml per kcal would be more appropriate. Alternately, if the individual works at high energy expenditure rates or exists in a microclimate that is hot or hot and dry or hot and wet, then the water intake may be higher than 1 ml per kcal. In this situation, the water intake will also be a function of the body's thermal balance.

The relationship between water intaken and water voided may be described by the generalized water balance equation:

$$(H_2O)_{net} = (H_2O_{liq\ intake} + H_2O_{food\ intake} + H_2O_{met\ oxid}) - (H_2O_{urine} + H_2O_{feces} + H_2O_{insens} + H_2O_{sweat}) \quad (9.2\text{-}1)$$

In general, the human body eliminates about a pint more water than it takes in as a result of the gain associated with the metabolic oxidation of food. Water intake resulting from water mixed with food and water gained from metabolic oxidation are both relatively constant quantities, providing the individual's diet does not undergo any exaggerated changes. By far the largest variant in water consumption is liquid intake supplied by drinking liquids. The observed variation in water-liquid intake is between 500 and 12,000 ml per day and changes widely depending upon activity, clothing cover, and microclimate factors such as temperature, solar radiation, humidity, and air velocity. Water intake by drinking liquids is an important part of the body's thermal regulation mechanism. The other two mechanisms for water ingestion rarely supply more than about 300 to 500 ml each.

Water eliminated by the human body is directly associated with waste removal and the maintenance of thermal regulation. As such, the voided water is a continuous load on the life-support systems. For low to medium activity levels performed with moderate clothing and bioclimatic conditions, the major release of body water is urine, ranging from 500 to 9000 ml per day. The mean quantity of urine eliminated by an individual such as the construction engineer would be about 1400 to 1600 ml per day. Urea, which is a major element of urine, and is the principal waste mechanism for nitrogenous materials, could be used after processing as a nutrient source for the plants described previously. Fecal water is small in quantity relative to urine and, following some processing, would probably be passed directly to the plant farms of the lunar colony.

Water eliminated by (1) insensible water loss (that lost during respiration and from diffusion through the skin) and (2) sweat loss will be part of the responsibility of the atmospheric support systems. Both mechanisms are primarily heat regulators and are functions of activity, clothing cover, and the micro-climatic conditions. The insensible water loss generally varies from 300 to 1500 ml per day. The sweat loss is the most variable form of water loss, covering a range from 0 to 10,000 ml per day. Each source would put water vapor into the colony atmosphere, and removal of this fluid would be required on a continuous basis.

9.2.4 ATMOSPHERIC COMPOSITION AND PRESSURE

For a given diet composition, we can determine oxygen consumption and carbon dioxide production by the following two equations (see [3]):

$$(O_2)_{in} = 0.83\ C + 2.02\ F + 0.97\ P \quad \text{Liters per Unit Time} \quad (9.2\text{-}2)$$

$$(CO_2)_{out} = 0.83\ C + 1.43\ F + 0.79\ P \quad \text{Liters per Unit Time} \quad (9.2\text{-}3)$$

For these equations, the amounts of carbohydrate, fat and protein are recorded in grams per unit time. If we consider the mixed and high carbohydrate diets listed in Table 9.2-2, we can determine the oxygen consumption for the plant pathologist and the construction engineer. Using a mixed diet, the former will consume 0.61 kilograms of oxygen per day and the latter will use 0.92 kg per day. For the high carbohydrate diet, the usages would be 0.63 kg per day and 0.95 kg per day respectively.

A comparison of volume of carbon dioxide produced to oxygen consumed is identified as the respiration quotient (RQ) and is an indication of what food materials are consumed during metabolic oxidation. The range for the RQ runs from about 0.70 for a diet either totally composed of fat or dependent upon fat oxidation to 1.00 for a high carbohydrate diet or metabolic oxidation. A second indicator analogous to the respiration quotient and used for carbon dioxide consumers is the assimilation quotient (AQ) which is defined as the volume of carbon dioxide consumed to the volume of oxygen produced. In a more advanced lunar colony--one probably based on a comprehensive ecosystem encompassing human beings, plants, animals, and appropriate mechanistic supports--we would seek to balance the respiration quotient with the assimilation quotient, thus maximizing the efficiencies of the production and consumption of gaseous and food exchanges.

Developing guidelines for pressure and composition raises a great deal of uncertainty. We know that an atmospheric pressure and composition approximating earth conditions would be ideal, if it were practical. Barring this possibility, we can establish other guidelines:

1. an oxygen partial pressure as closely approximating 160 mm Hg as possible should be implemented;
2. an inert gas is essential to help minimize fire dangers, to reduce oxygen toxicity (experienced with high, relatively pure levels of oxygen), and to serve as a supplement to oxygen in providing suitable pressure levels; nitrogen will be required as an inert gas if plants are to be grown in the lunar colony; and
3. a minimum pressure of 260 mm Hg should be maintained.

A number of experiments using reduced pressure for human beings in simulated space cabin environments has been carried out and is well-documented (see [3]). In general, the reactions of test subjects to extended exposures to atmospheres of 200 to 400 mm Hg were not beneficial. Changes in body fluid, blood composition were noted. A reasonable conclusion that might be drawn from these experiments would be that much additional work must be done in this area. A choice of a suitable atmosphere for the lunar colony might, at best, be a speculation which attempts to optimize such factors as work efficiencies, bodily comfort, psychological strain, atmosphere regeneration capabilities, the ability to maintain a constant and homogeneous enclosed pressure, and minimized loss due to leakage and diffusion.

An additional major guideline concerns the presence of carbon dioxide in the atmosphere. Partial pressures of carbon dioxide should be maintained below 4 mm Hg for prolonged exposure if physiological strain is to be minimized. At partial pressures in the range between 4 mm Hg and 23 mm Hg, adaptive biochemical changes with resultant mild physiological strain have been generally noted for similarly extended exposure. For shorter exposures (such as 10 to 20 minutes), much higher concentrations can be tolerated with only minimal loss in work efficiency.

REFERENCES

1. E. L. Michel, "Report on Metabolic Rate Measurement During EVA Training at KSC", Technical Memorandum DB6-72-75, Environmental Physiology Laboratory, Manned Spacecraft Center, Houston, March, 1972.

2. J. M. Waligora, et al, "Apollo 16 Mission Report Metabolic Assessment Team", Manned Spacecraft Center, Houston, May 26, 1972.

3. Lovelace Foundation for Medical Education and Research, Compendium of Human Responses to the Aerospace Environment, Volume III, Albuquerque, New Mexico, November 1968.

4. F. M. Lappe, Diet for a Small Planet, New York, Ballantine Books, 1971, Page 42.

5. Private Communication Dr. Paul Rambaut, Food and Nutrition Section, Manned Spacecraft Center, Houston, July, 1972.

9.3 PSYCHOSOCIAL ASPECTS

9.3.1 A SERIES OF BEHAVIORAL QUESTIONS

In this section we would like to explore a number of psychosocial concepts and to look at the possibility of using this material as a primary consideration during the design of the lunar base and colony. Our goal in pursuing such an exploration is to develop a basis or technique by which we could insure a supportive psychosocial habitability. Much of the difficulty associated with this task results from the fact that the greater majority of current research and applications work in the behavioral sciences has been geared to observing and evaluating behavior and performance rather than offering prescriptive criteria for the design of responsive shelters. There has been some work done in model building for the latter purpose, and we shall describe three contemporary theories later in this section. The other major problem is that there have been few attempts to design shelters using behavioral observations and thus there is little available experience.

What we would like to pursue here is to ask a number of questions without necessarily providing any rigorous answers for them. We are able to quote a number of sources who have observed behavior during various hydrospace and closed, earth-bound habitats [1, 2, 3]; and we can describe a series of models which have been predicated upon observed behavioral data and which seek to reconcile the synthesis of shelter provision with these data. But, throughout, our primary questions will be what makes or is a "good" environment and does a "good" environment encourage good behavior and performance? Of course, an additional uncertainty central to these questions is what does one mean by the adjective "good"? This question is indicative of the further impediment created by the varied individual perceptions of the surroundings and experiences of those who occupy and use the shelter. This impediment causes resultant uncertainties among behavioral scientists who try to relate the differing perceptions.

Much of the difficulty can be ascribed to the lack of a common or well-understood communication basis. The perceptions cause a myriad of complex behaviors which are manifested by the presence of many variables and involved interactions. The conceptual tools for dealing with these variables and interactions are inadequate. Thus, there is a need for some mechanism for either reducing the variable space or alternately maximizing the effects or influences of a limited number of variables. Only then can we hope to obtain any quantifiable facts.

The three models that we have chosen as potentially applicable to the designing of a lunar colony are based on the work of several contemporary practitioners. The models are

1. the stimulus-response or operant conditioning of Skinner [4] and Studer[5];
2. the ecological psychology of Barker [6] and Gump [7]; and
3. the archetypal place of Spivack [8].

Each of these models attempts to describe behavior and to provide bases for the design of shelter responsive to the described behavior. The Skinner work even includes a speculative fiction, Walden II [9], which formulates a society or microculture in which his theories of controlled behavior are implemented. A fourth model that is only briefly mentioned here and that perhaps has some interesting lessons for the development of a lunar psycho-social habitability is the Israeli kibbutz. The kibbutz is a folk or communal village based on the general interdependence of all the participants. The individuals perform a variety of tasks, each of which contributes directly to the community's basis for continuance [10]. From a nonrigorous vantage, the fictional Walden II of Skinner and the kibbutz studied by Spiro [11] appear to have genuine similarities.

If we attempt to formulate the problem and to develop a solution, we will see that the problem statement is easily put. Design a lunar colony with reference to questions concerning psychosocial habitability. But the problem is complicated by the question--How does environment influence behavior? This more general problem exists essentially because of insufficient data and the difficulty involved in determining what data will allow an adequate view of this specific problem environment. The solution opportunities include not only model building but also the development of analytic techniques for comparing behaviors in various spatial and sensual environments. By isolating conditions under which specific behaviors occur, it may become possible to predict the reactions to the use of various facilities or the performance of various tasks. This approach has been advocated by a number of behavioral scientists working with simulated or controlled closed habitat testing. From this research, it is hoped that such scientists may be able to predict the behavioral "costs" or the expected behaviors associated with future shelter design. Whether these people will be able to develop specific guidelines for the design of facilities which minimize these "costs" is problematical.

The designer of a lunar base or colony is faced with a difficult problem: Will he be successful if he employs a functionalistic attitude in which all elements of the lunar colony are present because they perform or fulfill a specific function? Or should he also design the colony in response to the psychological and social variables, to which we have alluded? Seemingly, he must develop a discipline which incorporates both of these attitudes. But the difficulty in pursuing this discipline is presented in the accumulation of qualifications or regulations necessary to direct the designer. The question thus becomes: Can we develop a prescriptive set of regulations which will predict or control behavior? An alternative to this question would be: Can we describe a cause-and-effect model for psychosocial habitability? The first of these two opportunities may be identified with the work of Maslow [12] who developed a list of nine attributes, which reflected the qualities necessary for psychological well-being. This listing was compiled to indicate to the designer what psychological qualities must be enhanced to assure stability. The list consists of two groups: those attributes to be minimized (sensory deprivation and isolation) and those to be maximized (comfort, variety, identity, territoriality, adaptability, privacy, and communication). The task for the designer becomes one in which he must translate these qualities into physical form, and this is again complicated by the lack of quantifiable data.

The design of the shelter depends on the purpose of the shelter. It is responsible for providing the survival and safety needs, including the psychological requirements for habitability discussed in the previous section. Additionally, the shelter must assist the individual in finding self-fulfillment and acceptance in his living and working activities. The development of productive group interactions is also essential to the colony establishment. These human needs may be encouraged by a shelter which has been designed with these attributes in mind. Whether shelter can be created to initiate feelings of recognition or appreciation or friendship is questionable. Nevertheless, the minimization of interpersonal stresses and the development and enhancement of group effectiveness and homeostasis are all potential, realizable goals for the shelter designer. A landmark work by Leighton [13] has identified a number of behavioral attributes for which support must be provided. These attributes (Table 9.3-1) are called "essential striving sentiments" and result from a combination of cognition (or awareness) and ambitions, instrincts, and tendencies. This combination is manifested as a basic desire in striving to develop and maintain a psychosocial equilibrium. The striving is reflected in a search to create means for fulfilling human behavioral expectations. Leighton [14] has maintained that these can be generalized to the population and that they represent qualities required in any life situation.

9.3.2 THE IMPOSITION OF LIMITS AND A REQUIRED ADAPTATION

Should the colony be designed to place specific limits on activities and to channel resources or should it be designed to recognize and circumvent restraints which occur as limits to growth? In either instance, such limits can either impede behavior or cause

Table 9.3-1 "Essential Striving Sentiments" from Leighton [13]

- Physical Security
- Sexual Satisfaction
- Expression of Hostility
- Expression of Love and Affection
- Securing Love and Affection
- Securing Recognition
- Expression of Spontaneity (Manifested as Creativity or Personal Joy)
- Orientation in terms of one's place in society and the relationship between the individual and his immediate peers
- Establishing and continuing a membership in a group recognizable by size, scope, and emotional and intellectual stance
- Sense of belonging to a moral order and the feeling of being right in one's actions and values

behavior, and the interaction between inhabitant and shelter will thus be modified. To impose limits to the range of behaviors possible for the inhabitant may be a conscious choice introduced by the designer or the project director. This choice has the effect of imparting controls and it will determine the nature of the activities that occur within the shelter. Similarly, the quality of the performance obtainable for this colony will depend on the comprehensiveness of the controls. If instead the colony is designed to recognize limits to its capabilities, then a primary activity of the inhabitants may well be to develop methods to anticipate and solve the problems created by these inherent limits. The lunar base, and subsequently the colony, are predicated on the ability to grow, expanding both size and scope. Therefore, the colony will seek to expand its limits or to look for opportunities to encourage change. Of the two alternate questions at the beginning of this paragraph, the second approach would be preferable. In a lunar colony which is initially, if not finally, dependent upon earth supply (for life and psychological support), the promise of self-administered growth would be of primary importance. The general problem present in dealing with either set of limits is complicated when these limits have been imposed subconsciously.

To analyze and overcome such limits is essential to a group psycho-social stability.

The individual who lives and works in the lunar colony is likely to be a highly systematic and goal-oriented person. The primary interaction between this person and the shelter will be directed toward satisfying the basic survival needs. But once this has been accomplished, the individual will attempt to manipulate his surroundings to fit his living and working needs. This response to the immediate environment seeks generally to organize the attributes of the surrounding for the purpose of increasing performance. Proshansky, et al, [15] have suggested that these activities are also an attempt to maximize the flexibility and freedom of choice universally inherent in such settings. The individual's ability to function in the lunar colony will be primarily determined by his ability to adapt to a bizarre life condition. Adaptation is essentially a function of cause and diversity--both for the individual and the environment. The individual's ability to respond will be predicated upon his ingenuity and the capability to recognize nonordinary situations. For the designer, the development of a capability to describe statistical limits of human adaptation as a function of the shelter or the environment would be strongly advantageous. But the range of variables which describe adaptation indicates that the capability will not soon be a reality.

While the colony will be designed to provide life and activity support for a generalized population, it will not be configured for a specific individual. Therefore, gaps will exist between the individual and the colony-support capacities, and the individual will have to fill them. Behavioral change and expansion may thus become a natural phenomenon. It appears that, if adaptability is not openly manifested in a specific individual, it may be developed by conditioning experiments designed to bring out this attribute. The ability to adapt will be essential to the lunar colonist; this area requires much additional work.

9.3.3 COMMENTS ON RELATED CLOSED HABITAT STUDIES

Various experiments with hydrospace and closed, earth-bound habitats have been conducted. Perhaps the most interesting experiments have been carried out by Helmreich [1], Watters [2], and Wortz [3]. These researchers have observed the behavior of several sets of crew members for the undersea habitats, Sealab II and Tektite II. While we do not wish to fully discuss and offer critical comments on their work, we would like to emphasize a few specific points from their observations as guidelines for the lunar colony design. A most interesting observation taken from the Tektite experiment was the determination of what the aquanauts missed most [16]. The two areas that ranked highest were

1. not being with their wives and family, and
2. more specifically, isolation from women and having sexual relations with them.

A third, less frequent reply was the lack of variety to the daily living and working routines. This was manifested as boredom and complaining about the lack of free choice. Additionally, importance was attached to the adequacy of the work station facilities. The crews were generally willing to accept minimally-effective living qualities, but inadequate work equipment caused rampant consternation. The initial acceptability of the habitat accomodations was also important. If the crews were pleased with the living and working facilities at their introduction to the habitat, then their later reactions, if less positive, were mellowed by the early perceptions. The quality of work accomplishment appeared to be a function of mood and motivation or devotion to the task. A good mood produced good work (this observation is in some contrast to results from Sealab II where the crew tended to overestimate their mediocre performances and, alternately, to minimize their good work.)

We do not intend to offer specific conclusions drawn from these observations, except to indicate that the work in this area is valuable at least as a means of predicting probable behaviors and for recognizing behavioral patterns vis-a-vis the environment. This work should be continued. Whether data can be drawn from these experiments to directly influence the lunar colony designer remains unclear. The undersea habitat work does tend to confirm the difficulty associated with trying to develop quantifiable or "hard" design criteria. Perhaps, as an exception to this statement, one directive appears clear and should be stated: It will be imperative to have a male-female population, mixed to the proportions as nearly approximating earth conditions as possible. The advantages to this directive are multiple, the most outstanding issue being the ability to allow the creation of working and living relationships similar to the earth psychosocial environment.

9.3.4 THREE MODELS FOR DEVELOPING A PSYCHOSOCIAL HABITABILITY

We would like to describe briefly the three models mentioned earlier in this section. The direct application of these models to the lunar colony concept is problematic. But, whether the fit between each model and the projected reality is good or not, it is hoped that each scheme can at least influence the design of the colony.

9.3.4.1 The Stimulus-Response Paradigm

In this model, the human being is presented most simply as a machine that functions according to various behavioral patterns. The reasons for or initiators of behavior are two-fold:

1. the human being experiences certain physiological drives which call for voluntary action (e.g., hunger, sex, sleep); and
2. the individual acts from a series of basic emotions like anger and love-hate.

The model increases in complexity with the recognition that the human being not only experiences these fundamental drives and emotions but also acquires and learns wants or needs that are not predicated on simple survival and a primitive awareness. Among these acquired or learned drives are capabilities for dealing with people and for developing self-fulfillment and self-actualization. In general, these acquired needs arise from a complex array of stimuli which surround the individual. The nature of the stimuli and the interest in the stimuli are reflected in the varied responses which result from the individual's perception of the stimuli and the connection to previously learned practices.

The important element of the paradigm is not the stimulus, but rather the response to the stimulus. The response seeks to fulfill or to answer the stimulus. This behavior is often carried out in expectation of accomplishment or in anticipation of pleasure. The reaction to the stimulus may thus be an effort to seek a reward. If it is provided, the pleasure or sense of accomplishment may serve to reinforce behavior and help to establish a pattern. The use of reinforcement can develop a conditioned response to any set of stimuli. By controlling the reward structure, in relation to a desired response, it may be possible to create habits or accustomed reactions to specific stimuli. Skinner [4], particularly, has worked in this area attempting to develop techniques for establishing patterned behaviors. Much of his work has dealt with issues relating to reinforcement and the learning and acquiring of prescribed responses.

Studer [17] has taken a slightly different tack. His primary interest is in the manipulation of the environment to control behavior and to use the physical enclosure as a means of establishing activities or accomplishments which the programmer or designer seeks. He argues for an environment which will elicit a "specified state of behavioral events" and he suggests that, by carefully preprogramming and monitoring environmental stimuli, the "acquisition of, or modification toward, a new system of behaviors" is possible.

The application of this theory to the design of a lunar colony could be based on the wish of the designers to somewhat limit or discourage actions which are thought to be negative to the colony's welfare. Similarly, such techniques could be applied to the development of adaptive capabilities for the crew members. More generally, however, the stimulus-response paradigm could perhaps assure requisite levels of performance guaranteeing colony success.

9.3.4.2 An Ecological Psychology

This model results from research conducted by Barker [6], Wright [18] and Gump [7] at the Midwest Psychological Field Station at Oskaloosa, Kansas. Nearly all of the tenets of this approach has been described in depth in a book, Ecological Psychology, written by Barker. The model indicates which elements of the environment designers are responsible for creating. It also shows the degree to which the designer, in creating physical form, is able to influence behavior. But the work of Barker and his associates also appears to demonstrate that much of normal behavior occurs despite the degree of support provided by the designer.

The ecological psychology model is based on a number of terms which form the vocabulary for this work. The primary environmental unit is the behavioral setting (or, more precisely, the synomorph) which is the localized environment in which the activity of interest happens. The milieu is the nonhuman surrounding which includes the enclosure, the furnishings, and the objects which support the activities and are consumed in the activities. An example of a milieu could be the chemistry laboratory in which a scientist pursues an experiment. The enclosure is, of course, the building and specifically the room; the furnishings are the laboratory desks, the centrifuge, and the pH meter; and the objects would be the test tubes and the chemicals, respectively. In the chemistry lab, a standing pattern of behavior is maintained and this can be described as the manner in which the individual pursues his normal activity. In this mode, the individual is involved in the setting and the setting supports the activity. The combination between the standing pattern of behavior and the milieu generates the synomorph. The synomorph describes a similarity of shape which exists between the standard pattern of behavior and the milieu. Thus, the key to the use of this model is predicated upon the ability to discern configural similarities between activities (patterns of behavior) and the support sought from the environment. The synomorph is most successful when the form of the activity fits the form of the environment. In a lunar chemistry laboratory, the chemist will mix chemicals to determine the properties of the lunar soil. The action of the chemist will be influenced by the height of the table on which his glassware sits. He will be most comfortable pouring the contents of a test tube into a beaker placed at some height. In this simplified example, the basis for synomorphy is founded on the fitting of the pouring action to the table top and the placement of the glassware. If a similarity of shapes exist, then a synomorph would be present.

The development of synomorphy is made much more difficult when the interactions between an individual and his milieu become dependent on or are modified by the actions of other people, existing in close proximity to this single individual. An equally more difficult situation may exist when the interaction between two or more individuals and the milieu is directly influenced by the physical setting (e.g., a meaningful conversation between two scientists could not take place in a conference room or private office if either was next to a materials-handling facility in which someone was using a ball mill).

In any case, a designer who is familiar with this vocabulary could attempt to create a milieu which he expects will support and influence the tone of a standard pattern of behavior. To accomplish this task, the designer would have to be fully aware of the range of activities associated with the lunar colony. Similarly, he would require information describing what kinds of facilities would be necessary to fulfill the activities. But given them, the development of the many necessary synomorphs could become the basis for the lunar colony.

9.3.4.3 The Model of Archetypal Place

The third behavioral model for the development of a psychosocial habitability for the lunar colony represents the work of Spivack [8]. This model is known as the theory of "Archetypal Place". In it, Spivack has sought to describe the breadth of human behaviors and to relate them to the spatial settings in which they occur. The theory presents a vocabulary of building blocks for the construction of an environment and a social organization. These building blocks are derived by identifying the fundamental human behaviors and classifying them according to the parts of the environment in which they happen (Table 9.3-2). Because many of these essential behaviors do not occur concurrently, but rather occasionally during the individual's lifetime, the theory supplies the catalogue of behaviors that comprise the life cycle. The theory also describes the spatial facilities required to make possible this range of behaviors, and this serves to denote the archetypal places. The effort of Spivack's work is to predict the use of shelter and the behavior of the occupants based on an analysis of the physical setting, the needs of the individual and the group, and the time in the life cycle.

The logic of Spivack's Theory is predicated on three basic elements; the archetypal place, the critical confluence, and setting deprivation. The archetypal place is defined [8], along with the configurations which result from efforts to develop these places, as a "space with highly specific, and for some species dimensionally exact, sets of specifications". The behaviors that occur in spaces [8]

> "are associated with characteristic settings in the physical environment, with certain constellations of space, and artifacts, with the walls and furniture, placing and focusing behavior patterns in specific and appropriate ways. Such settings, taken together, in their smallest irreducible group, are herein identified as archetypal places".

Table 9.3-2 Total Set of Behaviorally Defined Spatial Archetypes [8]

	Archetype	Behavior
1	Nesting	Elemental protection; protection for nesting activities; retreat from stimulation, aggression, threat, social contact; emotional recuperation.
2	Sleeping Place	Sleeping state; neurophysiological and psychological processes.
3	Mating	Courting rituals; pair bonding; copulation; affectional behavior; communication.
4	Childbirth	Labor and birth process; postnatal care and protection of mother and child in earliest infancy.
5	Nursery	Child-centered activities, safety and protection, containment, surveillance; informal education; play; exploration; early conditioning, socialization.
6	Healing	Recuperation; care of illness, injury; special rest out of phase with diurnal cycle; reduced stimulation in controlled environment; special ritual, props, instruments, foods; death.
7	Grooming	Washing; social or mutual grooming.
8	Nourishment	Eating, feeding, slaking thirst; communication; social gathering.
9	Excretion	Excreting; territorial marking.
10	Storing Place	Hiding of food and other property, storage, hoarding.
11	Looking out	Spying; contemplating; meditating; planning; waiting; territorial sentry.
12	Playing	Motor satisfactions; role testing; role changing; rule breaking; fantasy; exercising; creation; discovery; dominance confirmation; synthesis.
13	Locomotion Route	Perimeter checking; territorial confirmation; motor satisfactions.
14	Meeting	Social gathering; communication; dominance confirmation; governing; educating.
15	Working	Hunting; gathering; earning; building, making.
16	Competing	Formal agonistic ritual; dominance assertion; ecological competition; inter-species defense; intra-species defense and aggression; mating competition; conflict.
17	Learning	Formal education, conditioning, socialization.
18	Worshipping	Meditation, cosmic awe, mysticism, reverence to deity, moral concerns.

The critical confluence results from the "combination of the drive, the drive's object, the time, and the archetypal place in which all are brought together". The critical confluence is determined by four "essential boundary conditions" which focus the behavior of the individual and the relative supportive quality of the environment surrounding the person. These four boundary conditions [8] follow:

1. "having experienced or being in the grip of a motivating need or drive"
2. "having that urge occur within an appropriate time context"
3. "having access to an appropriate archetypal space or place"
4. "having the object available, as in the case of a nursing mother, the infant"

The question of setting deprivation arises when the environment does not support or respond to the needs or drives of the individual or the group. Setting deprivation will result when the critical confluence does not fulfill the behavior common to a specific archetypal place.

This model [19] offers an interesting view of the link between the physical environment and the behavior of the inhabitants. The archetypes displayed in Table 9.3-2 represent a complete set of human behaviors common to living and working activities. A colony designed to provide for their needs would support all behaviors. An auxiliary opportunity for this model would be the use of the archetypes as an analytical tool to ascertain the presence of all the required supports for the colony population.

9.3.5 SUMMARY

The major task for further research appears to be the establishment of quantifiable statements that can influence the colony designer. Additionally, the psychosocial researcher, and subsequently the designer, would want to know if

1. the colony can support the required professional activities;
2. the design of the colony allows the lessening of stressful conditions;
3. the responses allowed for specific stimuli in the colony fit accustomed or practiced patterns of behavior; and
4. adaptation will occur and the design allows for maximum flexibility in personal and social behavior.

It may not be possible to sufficiently model the composite behavior and performance for the colony population. This inadequacy will probably leave unsolved problems that can only be guessed at until data based on the observation of behavior become available after the inception of the lunar base. The behavior that occurs during the early generations of the base may have great value when design of the colony begins. It is likely that lunar social patterns will develop whether prescribed or not. The development of such patterns will be possible if

1. appropriate motivation is present, and
2. the designer and occupants are able to simulate earth conditions as closely as possible [20].

At this moment, the area of psychosocial habitability requires much additional research. We know that the environment influences interpersonal behavior and personal accomplishment. Similarly, we also know that it is possible to change the environment to suit or to stimulate behavior. We would like to maximize diversity, growth, and the feeling of autonomy. We would need to provide a shelter which fits existing behavioral patterns and allows adaptation.

We have attempted to display current research which we feel has immediate application to the design of a lunar colony. We would like to encourage the support of further research in these areas.

REFERENCES

1. Helmreich, R., Groups Under Stress, New York, Appleton-Century-Croft, 1970.

2. Nowlis, D. P., Wortz, E. C., and Watters, H., Tektite II Habitability Research Program, NASA Report No. 71-6192-1, January, 1972.

3. Seeman, J. S. and McLean, M. V., "Behavioral Program" in Preliminary Results from an Operational 90-Day Manned Test of a Regenerative Life Support System, NASA SP-261, 1971.

4. Skinner, B. F., Science and Human Behavior, New York, MacMillan, 1953.

5. Studer, R. G., "The Dynamics of Behavior - Contingent Physical Systems" in Design Methods in Architecture, G. Broadbent (ed.), London, Lund Humphries, 1969.

6. Barker, R. G., Ecological Psychology, Stanford, California, Stanford University Press, 1968.

7. Gump, P. V., "Milieu, Environment, and Behavior" in Design and Environment, Spring 1972, pages 49-50, 60.

8. Spivack, M., Archetypal Place, Research Report Series: Number Four, Harvard University Laboratory for Community Psychiatry, Boston, 1971.

9. Skinner, B. F., Walden II, Toronto, Collier-MacMillan, 1969.

10. Hillery, G. A., Jr., Communal Organizations: A Study of Local Societies, Chicago, The University of Chicago Press, 1968.

11. Spiro, M. E., Kibbutz: Venture in Utopia, Cambridge, Harvard University Press, 1956.

12. Maslow, A., The Psychology of Being, New York, Viking, 1968.

13. Leighton, A. H., My Name is Legion: Foundations for a Theory of Man in Relation to Culture, Volume I of the Stirling County Study of Psychiatric Disorder and Sociocultural Environment, New York, Basic Books, 1959.

14. Perin, C., With Man in Mind: An Inter-Disciplinary Prospectus for Environmental Design, Cambridge, The Mit Press, 1970.

15. Proshansky, H. M., Ittelson, and Rivlin, L., (editors), Environmental Psychology, New York, Holt, Rinehart, 1970.

16. Nowlis, D. P., Wortz, E. C., and Watters, H., op cit, page 5-17.

17. Studer, R. G., op cit, pages 14, 15, 18.

18. Wright, H. F., Recording and Analyzing Child Behavior, New York, Harper and Row, 1967.

19. For an Application of Savack's Work as an Analytic Tool, see also Snyder, L. H., "Archetypal Place - An Application and an Evaluation of Mayer Spivack's Theory", Unpublished Paper Prepared for a Course at Cornell University (Department of Architecture), Ithaca, New York, June, 1972.

20. Heinlein, R. A., The Moon is a Harsh Mistress, New York, Berkley, 1966, a novel may prove amusing and interesting reading. The book partially describes a psychosocial habitability, evolving uniquely to an advanced lunar colony.

9.4 PHYSICAL ASPECTS

The physical aspects of habitability are those most often ascribed to the architectural and environmental design professions. Because of the experience of several thousand years of experimentation and construction, some of the qualities regarding the physical design of shelter are well known. Most of those are at least understood in intuitive terms, if not quantitative statements. The problem relative to the discussion of the physical aspects of habitability for a lunar colony is dual:

1. the transfer of relevant earth-bound shelter design experience to the planning of a lunar colony; and
2. the development of quantifiable design or performance criteria for the colony.

Additionally, the design of the base, and subsequently the colony, must be predicated upon a prime directive: to provide a shelter that is as much earth-like as possible. Habitability will be generally assured if this dictum is closely followed. The primary difficulty, though, might not be the provision of earth-like, accustomed facilities. Rather, it may be knowing what constitutes an earth-like experience.

The most commonly considered aspects of the designed environment are the volume of the shelter, the organization of the spaces, and the environmental factors such as the acoustics, lighting, and temperature. Minimum-volume standards have been established by a number of researchers and practitioners. Unfortunately, these standards differ radically. The range generally discussed is between 200 to 500 cubic feet (5.8 to 14 cubic meters) per man. The range of minimum volume requirements is generally accounted for by variations in crew size and mission length. Current space vehicle standards provide 75 cubic feet (2.1 cubic meters) per man for the Apollo spacecraft and approximately 11,000 cubic feet (310 cubic meters) for three men for the Skylab vehicle. The accessible volume of the Skylab craft is somewhat of an anomaly because the dimensions of the orbital workshop, the primary part of the vehicle, were not determined by habitability requirements. Rather, that section was originally configured as the third stage of the Saturn V rocket and the volume was determined by the fuel-storage tank requirements. The volume provided by Apollo standards is clearly too small if directly implemented to the development of colony standards. Instead, it will be necessary to increase the volume-per-man figures to allow better work performances and living experiences. The rush to markedly increase the shelter volume and thus to assure better facilities, however, has some limits. Providing greater volumes has practical limitations and is not necessarily the answer to offering greater habitability. What also may be done is to try to seek better arrangements of available space with regard to how each space is planned and how each space (and its activity or use) relates to its surrounding area. As guidelines, we may try to apply experiences from closed habitats such as hydrospace experiements, simulated manned closed-cycle tests, and possibly prisons and high density urban residential units.

A further goal for designing for physical habitability is to provide complete, localized control for the various environmental factors such as sound, illumination, and atmospheric temperature and humidity. Ideally, the shelter should provide a shirt-sleeve environment where the colony inhabitants can work and live in facilities which, as nearly as possible, approximate earth conditions. This observation recounts the prime directive mentioned earlier in this section. Consistent with the emphasis on environmental factors control, we would also expect to offer comprehensive support in the areas of food systems and hygiene facilities. These areas have been well-documented by the habitability section at the Manned Spacecraft Center [1] and will not be further discussed here. Instead, we would rather emphasize the need for further development of the various distribution systems relative to application in the lunar colony. The specific distribution systems that are of greatest interest are

1. energy (light, sound, and heat),
2. air,
3. water and waste,
4. food, and
5. transportation.

Detailed discussions of most of these systems will be offered in Chapter 13. The design of the physical shelter for the lunar colony will depend upon the materials and energy balancing for these systems.

Earlier in this chapter, we spoke of the design process as an effort to manipulate materials and energy in a predictive mode, thus anticipating the future behavior of the occupants of the shelter. In general, the physical design of the lunar colony will be based on the allocation of space for the following activity areas:

1. colony command,
2. landing site,
3. research and applications facilities,
4. life-support and medical facilities,
5. maintenance and repair shops, and
6. living areas (residential, dining, and meeting facilities).

The planning of these areas will be discussed further in Section 16.2. Designing for physical habitability essentially requires the establishment of guidelines which will allow the development of physical enclosures which can reinforce and direct human activities and behaviors. To aid in the production of such physical enclosures, we have compiled a vocabulary (Table 9.4-1) of design elements or concerns which should influence the design of a lunar shelter. This list has been adapted from a catalog of such properties developed by Perin [2]. Many of these elements or properties are formal expressions considered by architects and environmental designers as they design buildings. The design of a physical enclosure for the colony should, therefore, be based on the manipulation of these qualities.

Table 9.4-1 A Vocabulary of Design Elements or Qualities

Dimensional	Sensual	Technical	Controlling
Size	Order	Communication	Boundaries
Density	Continuity	Circulation	Intersections
Volume	Sequence	Service	Enclosures
Proportion	Adjacency		
	Mixture		
	Variety		
	Repetition		
	Frequency		
	Linkage		
	Texture		

The four adjectival headings; dimensional, sensual, technical and controlling, indicate methods of influence. The Dimensional category refers to elements which directly determine the physical configuration. Sensual describes those awarenesses associated with human perceptions. The Technical attributes should suggest assistance mechanisms devoted to extending activities pursued in the shelter. The Controlling elements are responsible for imposing limits. All of these qualities should be regarded as design criteria by which the physical enclosure is analyzed. If these elements can be provided, then physical habitability will be generally enhanced.

Some recommendations for insuring general habitability are immediately evident when we compare the various observations concerning the physical and psychosocial habitability attributes. Among these are

1. each individual should have a separate room which is designated as his or her private space (thus assuring privacy and perhaps a sense of belonging),
2. living and working areas should be separated (minimizing noise and increasing recreational sense), and

3. there should be at least one or two spaces large enough for the whole colony population to get together (to offer opportunities for group interaction or empathy).

These are posed mostly as examples and are only a few of the programmatic statements that must be developed for establishing rigorous criteria for the design of a lunar colony. Much additional research must be done in this area, especially relative to psychosocial habitability.

REFERENCES

1. Habitability Data Handbook, Volumes 1-6, Prepared by Habitability Technology Section, Manned Spacecraft Center, NASA, Houston, Texas, July, 1971.

2. Perin, C., With Man In Mind: An InterDisciplinary Prospectus for Environmental Design, Cambridge, The MIT Press, 1970.

9.5 SAFETY

The issue of personnel safety is of extreme importance in any analysis of a developing lunar colony. The projected population and the desired duration of presence on the lunar surface make it highly probable that potentially hazardous incidents will occur, and steps must be taken to minimize the damage that result from such incidents. The individuals that inhabit the colony must have a high degree of confidence in the systems that support them and in the capability of the overall system to respond to an emergency. Absence of this measure of confidence would impose a psychological burden that would inhibit the performance of intended functions. Planning and design must be performed to the extent that, when an unfortunate incident does occur, the response of the overall system is rapid and adequate; the outcome would hopefully strengthen the confidence of the colony inhabitants.

Aside from the attitudes of the colony personnel, the political viability of the colony project is also at issue when hazardous situations arise. There is no reason to assume that the mechanism through which the colony project is funded will differ markedly from present procedures, and it has been learned through hard experience that a disaster can endanger an entire program. A carefully planned and efficient emergency action plan would serve, therefore, to buoy confidence not only among colony personnel but also among the public at large and the elected representatives of the public who are responsible for funding.

It is the purpose of this section to stress the importance of safety as a design consideration and to examine several specific areas in which hazardous situations could arise. The basic premise throughout the discussion is that the lunar colony itself, as a concept and a living entity, shall survive those incidents that do occur.

9.5.1 SAFETY AS A DESIGN PARAMETER

In the design of any system, subsystem, or structure for the lunar environment the consideration of safety is paramount. The hostility of the environment, compared to that to which man is accustomed, has been described previously in some detail, and it is apparent that, if the proper steps are not taken, "ordinary" incidents could grow into disaster. Furthermore, the interrelationships between systems must be considered in some detail; a minor fire that resulted in loss of air-handling capability, for example, would have much more serious consequences in a lunar dwelling than in an earth dwelling. Each system, device, or item destined for use in the lunar environment must be assessed on the basis of a safety criterion; those which are potentially hazardous must be deleted from the program in favor of others.

It is significant to note that there is no viable abort mode for an established lunar colony. It is not reasonable to assume that a continuous capability would be maintained, on earth, adequate for the prompt rescue of, say, 150 individuals. The systems which support the colony at population levels in excess of twelve individuals must be sufficiently flexible that survival is possible until repairs or replacements can be performed.

9.5.2 REDUNDANCY AND BACK-UP SYSTEMS

Improper operation of a system is not the only mechanism by which a hazardous situation can occur; for some systems, failure to operate can also create a safety problem. For all of those functions which are critical to the safety of colony inhabitants, there must be at least two systems capable of adequately performing the function for an indefinite period. Preferably, some method for automatic monitoring and control of critical functions would be employed (with suitable back-up), and demands could be shunted to functioning systems. An alarm system that would announce the failure of a particular device would also be required.

In most present man-rated space systems, a third-order redundancy is required in order to assure personnel safety during a mission. However, any detailed plan for a lunar colony must include some repair and maintenance capability. Critical systems will be required to operate for long periods of time. It is expected that their operation will be observed and monitored, that preventive maintenance will be performed, and that some repair will be possible. The assumption of repair capability, in most cases, removes the necessity of a third system to perform each critical function. Secondary systems for each function must still, however, be required to perform the function for at least the period of time required for replacement, from earth, of the primary system. It should also be observed that, in many cases, duplicate systems would be used to serve different elements of the colony, and some interplay between these systems would be possible.

Some systems may not be amenable to repair. For example, the 1 mwe reactors proposed elsewhere in this study may not be approached after installation. In this case, however, three reactors are present, and back-up power capability is present in the form of radioisotopic thermal generators.

9.5.3 SPECIFIC SAFETY PROBLEMS

Although there is probably some truth to the adage which specifies that "if anything can possibly go wrong, it will", there are some situations that are so obviously connected to the topic of safety that they require individual discussion. It is the purpose of this section to elaborate on several such situations, and to emphasize the design features or constraints which are derived from safety considerations.

9.5.3.1 Fire and Explosion

In any environment which provides a living and working capability for humans, the threat of a fire or an explosion is present. By comparison with other space program missions, the fire and explosion hazards for the lunar colony are more difficult to define. The personnel will be performing a wide variety of functions, with a large number of devices, in a relatively large space instead of a series of carefully programmed activities with specific equipment in a small module. The flexibility which is allowed by multiple canisters and lunar-construction techniques greatly complicates the safety problem.

9.5.3.1.1 Fire Hazards

The primary source of potential fires in the lunar colony can be specified as the extensive complement of electrical and electronic equipment. There may be other sources, such as flames used in particular instruments and laboratories, excessive friction in rotating or reciprocating machinery, or compression processes, but the electrical sources predominate.

Electrical sources of fires may occur from sparks, due either to circuit switching or electrostatic discharge, or from accidental overloads of a circuit to a current in excess of its capacity [1]. In addition, a short to ground or a short between wires may occur in situations where insulation is damaged or subjected to abrasion. The danger associated with circuit switching may be reduced by careful attention to switch design. In the case of electrostatic discharges, coatings may be used for sensitive materials, and appropriate attention to grounding in the overall design would assist in the solution of the problem. In the case of circuit overloads, fast response fuses in all circuits would effect a partial solution; enormous overloads can cause circuit elements to explode prior to the action of a fuse. The problem of shorting due to insulation degradation or abrasion is more subtle; advance prediction of potential trouble spots is difficult. Since the occupants of the colony will be responsible for the installation of a vast quantity of wiring, the most effective solution might be an absolute specification for the use of armored cable. A weight penalty would be incurred, and shorts in armored bundles of wire might still occur, but the danger to the colony would be minimized. Particular care should be devoted to cables and individual wires in locations where abrasion or chafing is likely to occur.

A fire does not always result when a spark occurs, nor does the presence of an open flame imply an uncontrolled conflagration. A fire must have fuel and oxygen, and adequate fire prevention requires attention to these subjects as well as to ignition sources. Previous experience with spacecraft fires has resulted in a large body of knowledge concerning appropriate materials for use in sensitive locations [2, 3, 4], and this information can be used to advantage in the design of structures and furnishings for the lunar colony. It would be appropriate to assume that any material, whether undergarment or bulkhead, is a potential source of fuel, and flame resistance should be an absolute criterion for materials selection.

The importance of oxygen to the burning process has been mentioned; in most cases the oxygen for combustion is supplied from the atmosphere. The atmosphere selected for the lunar colony structures, a mixture of oxygen and nitrogen at 14.7 psi, will certainly allow combustion to occur. However, indications are that the mixed atmosphere is far superior to a low pressure, pure oxygen atmosphere from a fire safety standpoint.

9.5.3.1.2 Fire Extinguishing Systems

Despite the precautions directed toward supression of ignition sources and flames, it would not be prudent to assume that fires would not occur. Some system must be incorporated in the shelter construction process to obtain rapid control of fires that do occur. It appears that water is an excellent general purpose fire-extinguishing agent [2], and it should be available in sufficient quantity at the colony site. A pressurized-water system equipped with nozzles and detectors should be incorporated into the structure designs. Water pressure at the nozzle should be at least three atmospheres, and at least one nozzle should be provided for each square meter of wall space.

The spaces behind decks and panels cannot be ignored, although in some cases it may be preferable to provide these areas with separate fire-extinguishing systems, using other materials such as carbon dioxide, water-based foam, or inert gases. Water damage to other materials located within the spaces would thus be minimized, and the substances mentioned are effective so long as the atmospheric composition is not changed from the earth standard.

The fire-detection system should be designed with both thermal and optical sensitivity. An ample number of detectors, such as one per nozzle, should be used. The detection system should be equipped with redundant elements. It should be possible to verify proper operation from a central location at regular intervals.

9.5.3.2 Radiation

The radiation environment on the lunar surface has been described in Section 8.1.3 of this study. In summary, the three main sources of radiation are cosmic rays (galactic radiation), solar flares (high energy particles), and man-made sources. These three types of radiation are quite different in character, and each poses a different degree of potential harm.

9.5.3.2.1 Man-Made Radiation

The man-made radiation may be treated most easily. It is the one form over which control may be exercised at the source. The control philosophy, stated simply, is that the radiation from devices transported to the moon should be minimized. The use of radioactive devices, such as power sources, is virtually inevitable, but adequate steps can be taken, such as burial of the power reactors, to insure that these sources constitute a minimum hazard.

9.5.3.2.2 Solar Radiation

The other forms of radiation, described in [5, 6, 7] and the additional sources cited therein, are of a much more serious nature because no source control can be exercised. The solar radiation is particulate in nature, and the energy is relatively low by comparison with galactic radiation. The average equivalent dose rate of solar radiation to a receptor at the lunar surface is about 38 rem per year. This amount, by some standards, would be tolerable. However, the occurrence of solar events, or flares, can cause the equivalent dose rate to increase by about one order of magnitude. Such a dose rate, in excess of 300 rem per year, would be intolerable by any standards. Solar events can occur at any time, although their magnitude tends to follow an eleven year cycle. Since the colony is expected to occupy the moon for many years, it is virtually certain that a number of intense solar events will occur. Thus, appropriate steps for shielding must be taken. Because of the relatively low energy associated with the solar radiation, the shielding is comparatively easy. Specific amounts of shielding are discussed in Section 9.5.3.2.4.

9.5.3.2.3 Galactic Radiation

Galactic, or cosmic ray, radiation causes the most serious shielding problem of the three radiation types. Such radiation is continuous, intense, and omnidirectional; a surface receptor would receive an equivalent annual dose rate of about 12 rem per year. This value is roughly half of that which would be received in free space; the remainder is blocked by the mass of the moon. Galactic radiation poses a particularly difficult shielding problem. Because of the secondary radiation which occurs as galactic radiation decays in the shield, a small shield thickness may result in a higher equivalent annual dose rate.

9.5.3.2.4 Lunar Soil as a Radiation Shield

According to English [7], lunar soil exhibits solar-particle shielding characteristics similar to those of aluminum. Experiments with high-energy radiation effects on chrondritic rock can be used to assess the shielding effect of lunar soil with respect to galactic radiation. The results of a comparison of expected dose rates and shielding capabilities are described in Table 9.5-1, which lists the total dose rates which might be expected at various depths below the lunar surface. Note that a soil thickness of 0.3 to one meter is sufficient as a shield against even the most energetic solar events. However, the equivalent dose due to galactic radiation increases with depth, and it reaches a maximum in the vicinity of 0.3 meter. This depth, then, should be avoided if adequate shielding is desired. At depths on the order of five meters (16 feet), the equivalent dose rates approach those that are measured as background values on the earth.

9.5.3.2.5 Radiation Dose Limits

Radiation dose limits which can be tolerated by humans have been, and will continue to be, the object of much impassioned discussion. Experiments are conducted, and the results are debated, but the limits which are set, and which have the fource of law, are decided by a panel of informed experts in the field. Figure 9.5-1 depicts some of the limits which have been suggested or adopted for space missions. At the time when the lunar colony becomes a reality, the Atomic Energy Commission limit for the general population may be set at five percent above the ambient earth background. If the colony inhabitants are to be furnished with an environment which adheres to these requirements, then it can be observed from Table 9.5-1 that a soil depth of about five meters (16 feet) would be required for shielding. This would be the case even though the maximum earth background was employed in the calculations.

It can be argued, with considerable persuasion, that the dose limits set according to the present process are unnecessarily conservative. Such an argument is presented in Appendix C of

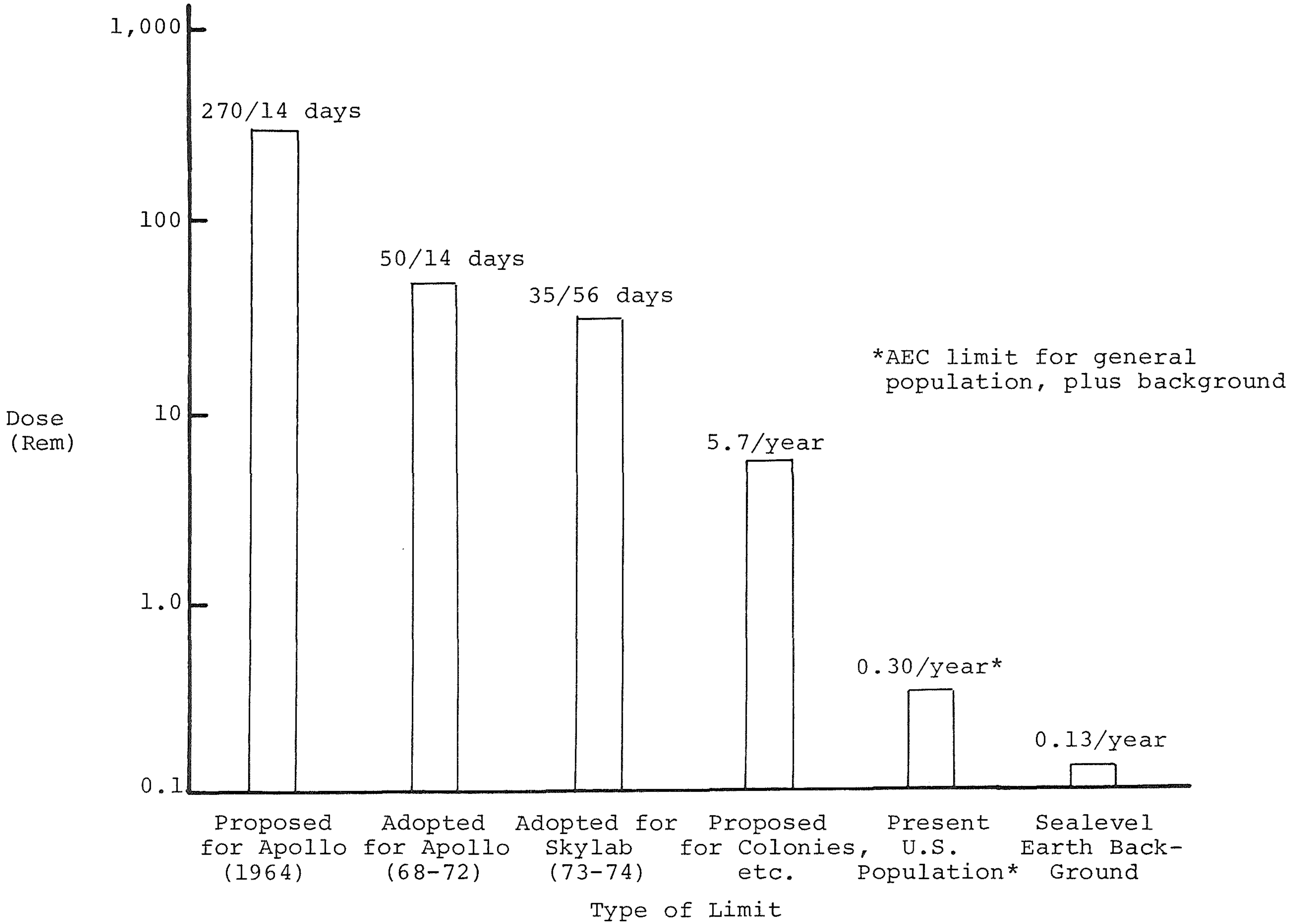


Figure 9.5-1 Comparison of Various Radiation Dose Limits for Space and Earth (from English [7])

Table 9.5-1 Yearly Average Dose Equivalents for Galactic and Solar Radiations At and Below the Lunar Surface (from English [7])

Depth of Shielding*	Dose Equivalent Per Year (rem): Galactic (Skin and 3 cm)	Max. Solar (Skin)	Max. Solar (3 cm)	Av. Solar (Skin)	Av. Solar (3 cm)	Total @ 3 cm Tissue (Max. Solar)	Total @ 3 cm Tissue (Av. Solar)
Surface	12	319	35	38	7	47	19
4 cm	27	31	8	4	2	35	29
30 cm	78	2	1	-	-	79	78
1.0 m	32	-	-	-	-	32	32
2.4 m	7.5	-	-	-	-	7.5	7.5
3.8 m	0.7	-	-	-	-	0.7	0.7
5.2 m	0.1	-	-	-	-	0.1	0.1

* Shielding of lunar material in addition to an assumed 1.0 gm/cm^2 (aluminum equivalent) habitat.

this study. If the proposals in Appendix C were adopted, then the majority of the structures for the lunar colony could be erected on the surface, and subsurface shelters would be necessary only for use during solar events. The colony, however, is expected to become a microcosm of earth society, albeit at some point beyond the scope of this study. If this is the case, then the colony might be required by its sponsors to supply a radiation environment similar to that on earth. If this is the case, then the five-meter soil depth will be required.

9.5.3.3 Loss of Atmospheric Pressure

Because of the high vacuum which characterizes the lunar environment, maintenance of a suitable atmosphere in the occupied structures is imperative. It is felt that the responses of the inhabitants would be most favorable if the selected value for the internal pressure was approximately equal to that at sea level on earth, and this pressure will be maintained by a gas-supply control system equipped with redundant elements. Failure of the control system is one obvious manner in which atmospheric pressure could be lost, but there are other accidental circumstances which must also be considered.

The physiological effects of sudden decompression have been documented in the literature, see Roth [8]. Among the usual symptoms are painfully distended, if not ruptured, eardrums, extreme respiratory difficulty, and nitrogen bubbles in the bloodstream; all are notably unpleasant. It is vital that steps be taken to reduce the possibility of the occurrence of sudden decompression.

The effects of a gradual decompression, on the other hand, are much more subtle. If sufficient time is available, the body can equilibrate differential pressures, and the real danger becomes the onset of unconsciousness without adequate warning. Some alarm system, therefore, should be included to detect pressures even slightly lower than normal.

The point in the above paragraph is important because, in the environment of the lunar colony, the probability of a small leak is much greater than that of a large leak. Even a puncture, by a meteoroid or by some other means, would not necessarily result in sudden decompression. Given a typical volume for a lunar structure, several minutes would be required for the pressure to drop to a dangerously low level if the air were escaping through a hole having a diameter of several centimeters. In fact, unless the structural damage was extensive, the occupants would have quite enough time to proceed to an adjacent structure.

With regard to structural design, it is important to provide some deterrent to leak propagation. If an initially small penetration could grow, or if a structure could fracture as a result of a small penetration, then the material or the technique cannot be considered acceptable for lunar construction.

There are several safety measures which could be adopted to minimize the danger of a loss of atmosphere. The number of pressure suits should exceed the number of colony inhabitants, and the suits should be distributed throughout the inhabited region. It is possible to envision a minimum-requirement type suit, not rated for continuous or lunar-surface use, which would serve in this capacity. In addition, emergency doors should be affixed to all compartments. Such doors would be controlled by pressure sensitive switches; activation due either to low pressure (from a decompression process) or high pressure (from a fire) would be appropriate. The doors might be of the gravity operated, hinged louver variety. An absolute seal would not be necessary if the leak rate is slowed sufficiently. A maintenance crew could provide an absolute seal if the condition was severe. Furthermore, an occupant of a damaged area, who might otherwise be trapped, could escape more easily through a door that provided a partial seal.

The possibility of a major catastrophe still exists from, say, a large meteoroid or a massive systems failure. In some situations, no economically feasible structure would survive, and no emergency procedure would be adequate. The best defense against such a situation would appear to be an attempt to minimize the probability of occurrence; particular emphasis should be placed on attempts to prevent the occurrence of a catastrophe as a result of an otherwise minor incident.

9.5.3.4 Exposure to Pathogenic Substances

The environment proposed for the lunar colony is virtually closed, and it is expected that it will be inhabited for long periods. Of necessity, a high degree of recycling is employed; air and water are processed to remove foreign materials and returned to the system almost immediately. In such a situation, all substances not specifically identifiable as water or as part of the breathing atmosphere must be regarded as potential pathogens. The processing equipment must be capable of removing a vast number of substances, including microscopic particles and trace gases, from the processed streams. Some substances, such as viruses, are quite resistant to detection and removal, but a concentrated attempt to remove them must nevertheless be made.

Another factor which requires attention is the possible decrease in resistance to disease which may occur in isolated groups, see Muchmore [9]. Little is known about the critical group size at which the apparent decrease in resistance ceases to exist, but a potential hazard may exist at least during the initial stages of the colony.

9.5.3.5 Loss of Power

The possibility of an electrical power failure is one of the most severe hazards present at the lunar colony; virtually all of the systems are electrically powered. The most appropriate solution would appear to be extensive redundancy. Any of the three nuclear reactors specified in this study would be sufficient for the operation of the colony. In any event, backup power sources are available in the form of portable radioisotopic thermal generators.

Even though alternate sources are available, prevention of a power failure still requires a fail-safe switching system. Such a system might be powered by batteries, continually maintained in a charged state, that would operate alarm and switching circuits when the need arose.

9.5.3.6 Loss of Air Conditioning

Failure of the system which provided atmospheric circulation and thermal control would result in a condition that was not only uncomfortable but also hazardous to health. Experience with fallout shelter design has shown that, if the occupancy rate is high, both the temperature and the humidity quickly attain unacceptable values when only natural ventilation is employed. In the lunar-colony environment, air not passing through the processing unit would quickly become stagnant. Sensors and control systems must be provided to activate back-up systems when abnormal atmospheric conditions are detected.

9.5.3.7 Seismic Disturbances

Seismic disturbances are present on the moon; they occur at frequent intervals as described in Chapter 8. Although the magnitude of the disturbances is generally small by earth standards, the possibility of structural damage does exist. All buildings which become a part of the colony, particularly those which are larger and are constructed from lunar materials, must be designed with the possibility of seismic disturbances in view. Most of the design techniques presently in use for active areas on earth would be applicable.

9.5.3.8 Meteoroids

The consequences of meteoroid collisions with colony structures (or inhabitants) have received considerable attention in both the popular and technical literature. The probabilities of meteoroid collision are described in Section 8.1.4, and the consequences of structural penetration are assessed in Section 9.5.3.3 of this report.

In general, a balance must be struck between a structure which is economically and technologically feasible and the collision probability for a meteoroid large enough to damage the structure, see Cosky and Lyle [10]. A covering of about one meter of lunar soil will provide protection from a vast majority of meteoroids, and if the colony designers elect the five-meter depth for habitable structures, as suggested in Section 9.5.3.2, then even greater protection is attained.

9.5.3.9 Flight Control

There is an element of risk involved in spacecraft landings on the lunar surface. Since many of the landings will be unmanned there is some risk to the colony inhabitants. In the proposed colony configuration, Section 6.2, the landing site is specified as being separated from the main colony structures by a distance of several kilometers. This distance is somewhat inconvenient because of the amount of transportation involved, but the reduction of risk to the colony in the event of an unfortunate incident makes the separation worthwhile.

Although extra equipment would be required on the lunar surface, it would be advisable for unmanned flights to be controlled and for manned flights to be guided from the lunar surface. In this way, fixed and calibrated radar installations could be employed. In addition, the surface installations would have an input to the contingency plan for aborting a landing.

9.5.4 MEDICAL FACILITIES

The population of the lunar colony will be characterized, particularly in the early stages, by multiple functions and tasks for each individual. Because of the necessary interaction, it is important that each person present be a functioning member of the group. If members of the group become incapacitated, the schedule for performance of tasks will be affected. It is important, therefore, for adequate medical facilities and trained medical personnel to be available.

Both medical practice and medical research will be important functions in the colony, and the two should interact extensively. For example, an otherwise unexplained incapacitation of one or more persons might occur due to an inaccurate estimate of human capabilities in the lunar environment. In such a case, both medical functions would be required to effect a solution. A similar statement could be made with regard to a possible previously unobserved pathogenic effect of some substance.

9.5.4.1 Disease

The medical facilities designed for the lunar colony must have the capability for treating diseased patients, both prior to and subsequent to diagnosis. An isolation capability would be desirable; a small area with a separate life-support system and appropriate doors would probably suffice. The possibility of encountering hitherto unknown pathogens or pathogenic effects makes the isolation feature necessary.

As is the case with any medical situation, the attempt to cover all possible contingencies results in bulk and expense. Medical supplies that are never used might be regarded as unnecessary, but only in retrospect; all might have seemed equally valuable when plans were made. It will be necessary to exert a concerted effort to organize a package of drugs, diagnostic equipment, and surgical tools which will achieve maximum effectiveness with minimum weight.

9.5.4.2 Accident

In any situation involving a number of people engaged in an activity such as construction, accidents must be regarded as inevitable. Accidents that occur in the lunar environment, particularly if the victim is using a pressure suit, are likely to be more serious than similar accidents on earth. The medical facility for the colony must include the capability for emergency treatment of accident cases, and emergency procedures should be developed to expedite treatment.

9.5.5 RESCUE

It has been observed in Section 9.5.1 that rescue of a large number of people from the lunar colony is not a likely possibility. The colony, therefore, must be equipped to survive a number of situations, any of which might cause damage to structural elements or personnel.

However, the inhabitants of the colony may require rescue capabilities on a local basis, and plans should be developed for use in emergencies. The prime movers, for example, are equipped with life-support systems that could be used in an emergency.

REFERENCES

1. Roth, Emanuel M., "Space Cabin Atmosphere, Part II, Fire and Blast Hazards", NASA SP-48, National Aeronautics and Space Administration, 1964.

2. "Proceedings of the NASA Conference on Materials for Improved Fire Safety", National Aeronautics and Space Administration, 1970.

3. "Nonmetallic Materials Design Guidelines and Test Handbook, revision C", National Aeronautics and Space Administration, Document T72-14053.

4. "Flammability of Electrical Components in Spacecraft Environments", Factory Mutual Research Corporation, National Aeronautics and Space Administration, Document T72-10374.

5. Reetz, Arthur, Jr., ed., "Second Symposium on Protection Against Radiations in Space", National Aeronautics and Space Administration, NASA SP-71, 1964.

6. Reetz, Arthur, Jr., and O'Brien, Keran, "Protection Against Space Radiation", National Aeronautics and Space Administration, NASA SP-169, 1968.

7. English, Robert A., "The Lunar Radiation Environment", Kelsey-Seybold Clinic, Report, 1972.

8. Roth, Emanuel M., "Space Cabin Atmospheres, Part I, Oxygen Toxicity", NASA SP-47, National Aeronautics and Space Administration, 1964.

9. Muchmore, Harold G., et al, "Neutropenia in Healthy Men at the South Polar Plateau", Archives of Internal Medicine, V. 125, p. 646, 1970.

10. Cosby, William A., and Lyle, Robert G., "The Meteoroid Environment and its Effects on Materials and Equipment", NASA SP-78, National Aeronautics and Space Administration, 1965.

CHAPTER 10 SITE SELECTION

This chapter discusses the relative merits of several locations on the lunar surface as the place for the colony. A specific site is recommended (Kopff Crater), primarily because of astronomical considerations.

10.1 SELECTION CRITERIA

This section discusses the various physical phenomena and parameters which enter into the site-location determination.

10.1.1 AVERAGE TEMPERATURE

A place where the average temperature is extremely cold would require considerable heat input to the colony. This extra energy expenditure can be avoided by judicious site selection.

10.1.2 TEMPERATURE VARIATION

The lunar diurnal cycle is more than 270°K peak-to-peak at the equator. Heated rocks are a slight advantage for the oxygen process. However, cooling of surface structures, using a combination of high albedo, high emissivity coatings and refrigeration may be necessary. The extreme latitudes necessary to significantly lower the diurnal cycle range have a very low average temperature. We feel that heating, which requires an external energy source, will be a bigger problem than cooling, which requires mostly shade.

10.1.3 SUNLIGHT

Available everywhere except near the poles. The days and nights are about 354 hours each, with only small seasonal variation. It should be noted that there are no places of perpetual sunlight on the moon. Indications are that a massive structure, at least several hundred feet high, would be required at either pole to get continuous sunlight.

10.1.4 EARTHLIGHT

At lunar latitude 0°, longitude 0°, the full earth is straight overhead at midnight. The full earth as viewed from the moon is 50 to 60 times brighter than the moon seen from earth. This provides a reliable source of nighttime illumination, so the colony inhabitants will not have to grope around in the dark. The astronomical brightness magnitude of the earth as seen from the moon is -17.3, compared to -28.8 for the sun; so the incoming energy from reflected earthlight is small (0.11 watts/m^2) compared to the 1,400 watts/m^2 from the sun. However, based on terrestrial experience with moonlight, it should certainly be possible to see fairly well under a light sixty times as bright.

10.1.5 ECLIPSES

Lunar eclipses occur about twice a year. The duration is approximately one hour (in the umbra), preceded and followed by about one half hour in the prenumbra. Eclipses cause precipitous temperature drops on the front side of the moon, which would have a disrupting effect on daytime operations.

10.1.6 GEOGRAPHY

The presence or absence of interesting geological features (such as maria, highlands, notable craters, rilles, and volcanic remains) is a consideration in choosing a site.

10.1.7 LOGISTICS

The problem of getting supplies from the lunar orbiter and returning, while minimizing orbital correction energy, should be considered.

10.1.8 ASTRONOMY

For astronomy, particularly radio astronomy, it is desirable to be on the backside of the moon to avoid interference from earth. It is also desirable to be near the equator, to obtain a maximum view of the celestial sphere.

10.1.9 COMMUNICATIONS

Direct line-of-sight communication with earth would be simplest. However, a relay satellite in a holding pattern above the backside of the moon (a "halo" satellite) could be used.

10.1.10 PERPETUAL SHADE

This is desirable for cryogenic storage of gases. A deep oven-topped hole, dug at such an angle that the sun would never shine straight down on it, would create such shade.

10.1.11 MINERALS

The colony will need Ilmenite, which is apparently more likely in the maria areas than in the highlands. Rocks and boulders might find some use as construction materials. It might be very helpful if a concentration of meteoric iron could be found. Unfortunately, mineral exploration of the moon is in its early infancy, so we can only extrapolate what has been found at five places as a reasonable guess for what might be elsewhere.

Table 10.1-1 summarizes the advantages and disadvantages of various locations for a lunar colony.

10.2 SELECTION OF LOCATION

Kopff Crater (see Figure 10.2-1) is recommended as the site of the lunar colony. The reasons follow:

	Polar	Front Equatorial	Back Equatorial	Limb Equatorial	Mid Latitudes
Average temperature	220°K	254°K	256°K[1]	255°K	$220° < T < 255°$
Temperature cycles	±10°K[2]	±140°K	±140°K	±140°K	±110°K
Sunlight	long days and long nights[3]	354 hour days	354 hour days	354 hour nights	354 hour nights
Earthlight & line-of-sight communication	sometimes	yes	no	sometimes	if on front side
Eclipses	sometimes	mid-day	no	sunrise or sunset	if on front side
Geography	highlands	varied	varied	varied	varied
Logistics	Once per orbital period		Once per orbital period		once/day
Astronomy (view)	1/2 view	----------all of celestial sphere------			$1/2 < V < all$
Perpetual shade	much[4]	----------none naturally occurring-----			maybe
Minerals	water (??)	various oxide rocks		various oxide rocks	

Notes:

[1]The back side of the moon is closer to the sun at noon than the front side is, so it gets ≈1% more solar energy.
[2]Average temperature has a yearly variation which makes it very cold ($T<200°K$) for several weeks.
[3]Day length varies from 0 to 708 hours.
[4]"Mountains of Perpetual Light" have not been found.

Table 10.1-1 Advantages and Disadvantages of Various Locations

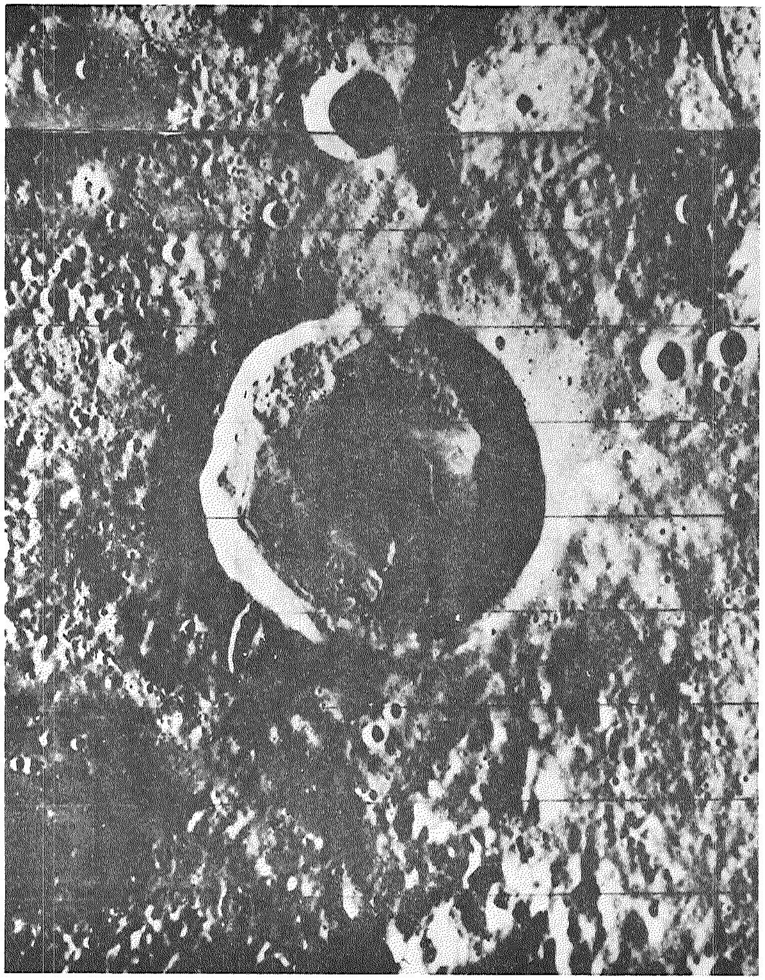


Figure 10.2-1a Kopff Crater
Scale 1:1,000,000

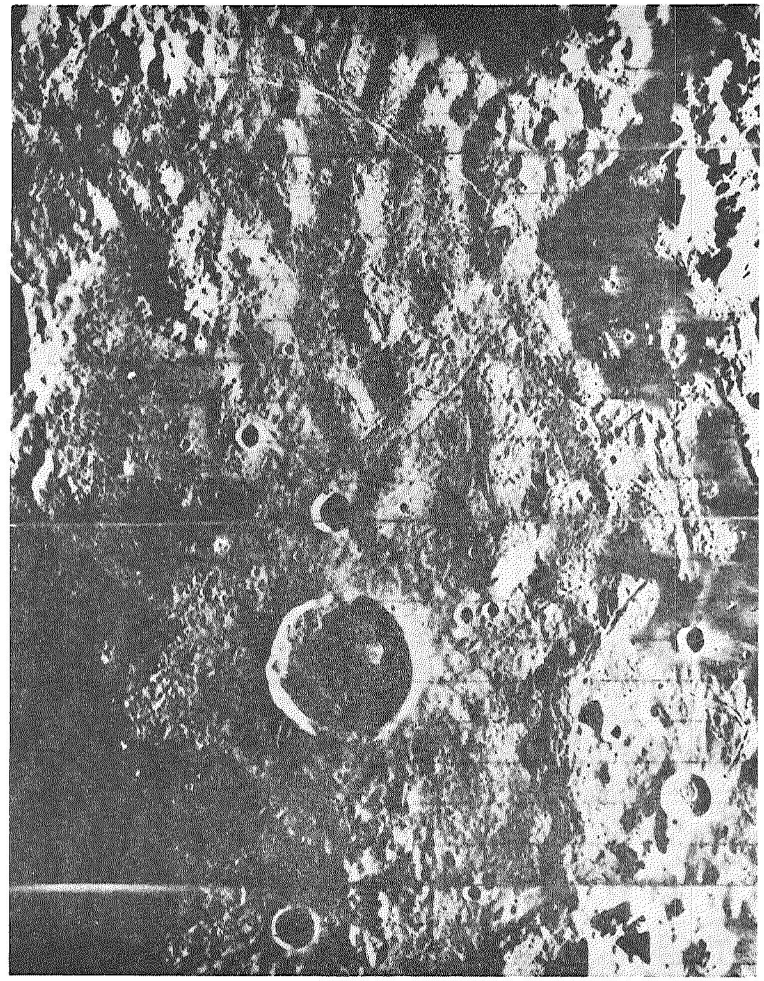


Figure 10.2-1b Kopff Crater
and Vicinity
Scale 1:2,500,000

(1) At 17.5° latitude, it receives 95 percent of the equatorial solar energy. The diurnal temperature cycle can be expected to be as shown in Figure 10.2-2. The average temperature at the chosen site compares well with the earth's average (black body) temperature of 254°K. The average temperature at the bottom of the crater may be a few degrees warmer than indicated in Figure 10.2-2 due to the focusing effect of the walls and longer heat storage in rocks near the bottom.

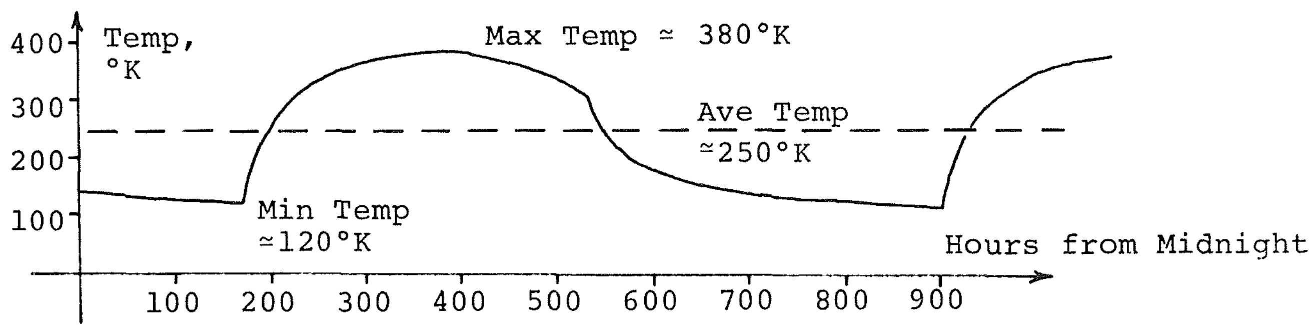


Figure 10.2-2 Temperature Cycle at Kopff Crater

(2) Being at 89.5° W longitude, it is near the center of the libration band. Direct line-of-sight contact with part of the earth will be available about 360 hours out of every orbital period (more or less depending if one is at the top or the bottom of the crater). For 295 hours out of each orbital period, the colony will be behind the moon, which is desirable for astronomical observations. The earth's center will oscillate between +7.2° and -6.2° on the east horizon, so the inhabitants will be treated to the psychological boost of seeing "home" regularly. Full earthshine will light the evening, waning to a cresent earth in the morning, at

position 1 in Figure 10.2-3. Darkness will prevail through the night at position 2.

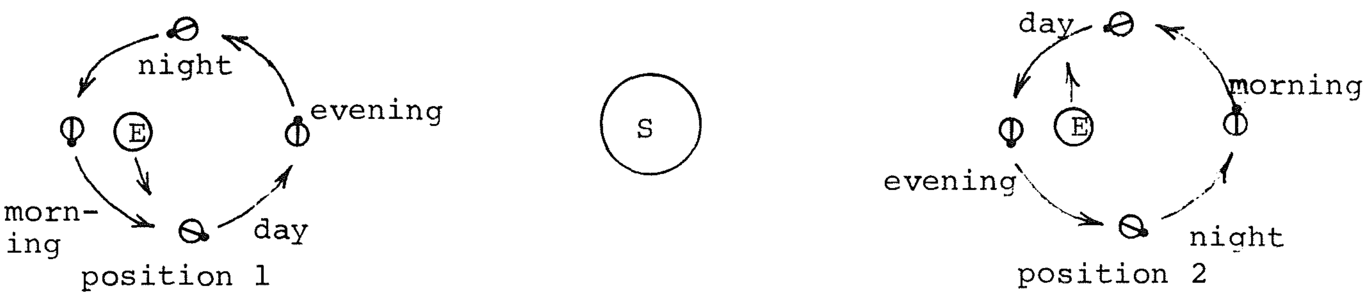


Figure 10.2-3 Libration and The Moon's Orbit

(3) The crater's diameter is about 40 km rim-to-rim, and the walls are about 1,500 ±500 m high. It has a fairly smooth floor, which is desirable for astronomy. The steep, high walls are good for occultation measurements in X-ray astronomy. The walls might also be useful for gravitational energy extraction and for building lean-to's and caves. The south end of the crater has a gentle slope so surface vehicles can get in and out.

(4) The site is on the edge of Mare Orientalé, the 600 km diameter "bullseye" that is the most striking feature on the moon. To the north and east are highlands, Lacus Veris (a lunar "lake") and rilles. It has been suggested [1, 4] that because of the lack of ejecta material and the sharpness of its edges, Kopff Crater itself may be a volcanic caldera and not an impact crater.

(5) Lunar eclipses would only delay sunrise for an hour or two and would have minimal disrupting effect on daytime operations.

It should be noted that this same crater was one of the sites chosen by the North American Rockwell Lunar Base Synthesis Study [2] pages 2, 3, 8.

10.3 ASSUMPTIONS

The following conditions must be assumed:

10.3.1 SUPPLY LOGISTICS

The supply logistics problem will have been solved. A lunar orbiting station could pass overhead once per lunar sidereal day. A polar orbiter could pass over twice per lunar day. "Tugs" could be landed or launched with no energy penalty whenever the orbiter was pasing over.

10.3.2 COMMUNICATIONS

Communications with earth will be via satellite in a holding pattern far above the backside of the moon, or done only intermittantly over line-of-sight.

10.3.3 MINERALS

Ilmenite and other useful minerals will exist nearby in mineable quantities.

REFERENCES

1. Kosofsky, L. J. and El-Baz, Farovk, The Moon as Viewed by Lunar Orbiter, NASA Special Publication No. 200, 1971, p. 72.

2. North American Rockwell Corp., Lunar Base Synthesis Study, Volume II, Mission Analysis, May 15, 1971.

3. NASA Map, LOC-1, #3LSBF-BA1 (shows 40°N - 40°S; 140°W - 40°W).

4. Ulrich, G. E., "Advanced Systems Transverse Research Project Report with Problems for Geologic Investigations of the Orientalé Region of the Moon", an interagency report by the U. S. Department of Interior (Geological Survey).

CHAPTER 11 CRITERIA FOR SELECTION OF SUBSYSTEM

11.1 SELECTION PHILOSOPHY

Historically, the selection of subsystems for space systems has been based on a high performance and low equivalent-weight basis. For the unique case of a lunar colony, the selection of the most viable subsystems becomes a problem of increased complexity. The unique features of the lunar environment will most likely impose selection criteria which in the past have not been considered. Since one of the primary lunar-colony development objectives is to become semi-independent of earth by maximum utilization of lunar resources with minimum resupply; the concept of maintainability and high degree of performance may override any equivalent weight considerations. This is reflected by the fact that the need to abort must, by colony development definition, be minimized. Also, new or reoriented evaluation criteria will evolve due to the unique nature of some of the subsystems being considered for development for the lunar colony. Oxygen production from lunar soil, new mining and excavation techniques in a lunar environment, use of lunar materials for metal and materials development and use of lunar resources for construction of lunar shelters are all unique subsystems which may dictate new evaluation criteria or techniques. At any rate, the nature of the evaluation scheme will be complex.

Despite the argument of complexity, we felt it necessary to define a base-line evaluation scheme for selection of subsystems. The scheme selected was adapted from an evalumatrix scheme developed by Hamilton Standard, a division of United Aircraft Corporation [1].

The general guidelines for the evaluation scheme are as follows:

(1) The selection of criteria is based on a cognizance

that some requirements are absolute, some are of primary importance and some are of secondary importance;

(2) Absolute criteria should reflect the capability or potential capability of a subsystem to perform;

(3) Primary criteria should stress hardware considerations or the likelihood for future development of hardware; and

(4) Secondary criteria should include considerations which are desirable but not necessary.

11.2 EVALUATION SCHEME

11.2.1 ABSOLUTE CRITERIA

Absolute criteria define the minimal acceptable standards for a candidate subsystem. No further consideration should be given to a subsystem which cannot meet these requirements. If a concept does meet the absolute criteria, then a relative ranking of the candidate subsystems should be assigned. Such a preferred ranking would be very good, good or fair. This may only be necessary if primary and/or secondary criteria fail to produce a definitive selection.

11.2.2 PRIMARY CRITERIA

Primary criteria are imposed when a candidate subsystem satisfies the absolute criteria. Relative ranking should also be applied to the candidate subsystems. Consistent with the approach selected under absolute criteria, a ranking might be very good, good, fair and poor. A poor rating should automatically disqualify a candidate subsystem from further consideration. A candidate subsystem should be selected if its overall rating at the primary level is obviously the best of the candidate subsystems. When two or more candidate subsystems are rated equivalent, then reference should be made to the absolute criteria to determine if a selection can be made. If no selection is evident, then reference should be made to the secondary criteria for evaluation.

11.2.3 SECONDARY CRITERIA

Secondary criteria for evaluation of subsystems need only be imposed when there is no clear-cut evidence of the superiority of one subsystem candidate over another. Secondary criteria may also be assigned the relative rankings of very good, good, fair and poor. At this stage of evaluation, however, a poor rating does not necessarily omit the candidate subsystem from competition.

11.2.4 CHOICE OF ABSOLUTE, PRIMARY AND SECONDARY CRITERIA

Figure 11.2.4-1 shows the criteria selected for baseline evaluation for lunar-colony subsystems. It must be noted that the criteria represented in the figure may have been juggled to conform to an alternate designation dictated by a particular lunar colony

Absolute Criteria

- Performance
- Safety
- Availability/ Confidence/ Developmental Capability

Primary Criteria

- Efficiency
- Growth Opportunity/ Expandability
- Reliability/ Maintainability
- Resupply/Use of Lunar Resources
- Flexibility

Secondary Criteria

- Weight
- Volume
- Energy/Power Requirements
- Interfacing
- Contamination/Leakage
- Cost

Figure 11.2.4-1 Baseline Evaluation Criteria function. The ranking of criteria represented in this figure was intended only as a broad guideline, with the addition or subtraction of criteria being encouraged where applicable. Table 11.2.4-1 describes in more detail the impact of each evaluation criteria on selection.

11.2.5 GENERATION AND USE OF EVALUMATRIX

Once criteria have been selected and assigned their relative level of importance in the absolute, primary, and secondary scheme, an evalumatrix may be generated which has a listing of criteria on one axis of the matrix and a listing of the candidate subsystem con-concepts on another axis.

In order to demonstrate the use of the evalumatrix, consider the hypothetical example represented in Table 11.2.5-1. The evalumatrix identifies four candidate concepts for making the lunar environment habitable; (1) pollute the lunar surface to more nearly represent earth-based conditions, (2) shrink the moon in order to improve its gravitational pull such that it may support an atmosphere; (3) import an artificial atmosphere; and (4) if all else fails, attach rockets to the lunar surface to provide power for use of moon as vehicle for interplanetary space travel.

Disregarding the risibility of some of these concepts, important features of this example are summarized below:

(1) The concept of lunar pollution is rejected on the absolute level due to the lack of confidence in its ability to perform.

(2) The concept of shrinking the moon was eliminated at the primary level since the other two concepts rated much higher in the absolute and primary criteria ranking scheme.

(3) Two concepts survived the first two levels of competition. Note that a comparison of the relative ranking of the absolute criteria still offers no clear cut choice, indicating that the secondary evaluation criteria must be considered.

Table 11.2.4-1

Detailed Description of Evaluation Criteria

Criteria	Description
A. Absolute	
A.1 Performance	A.1 To be considered candidates, all concepts or subsystems must be capable of operating under the conditions dictated by the lunar environment.
A.2 Safety	A.2 Each subsystem must be considered with respect to potential hazards of fire, contamination, explosion hazards, bacteriological problems or any other form of crew hazard. The subsystem concept should be eliminated if any potential hazardous problem cannot be eliminated by careful design, by using additional control, by using different materials or other possible engineering materials, or engineering development.
A.3 Availability/Confidence/ Development Capability	A.3 This criterion should include a measure of the probability of a subsystem concept being operational by the point in time required by expansion of the lunar colony. Also, some amount of confidence should be attached to the existing information on the proposed subsystem. Ultimately, availability/confidence is evaluated by an analysis of the candidate subsystem's present status, concept approach, interface capability and hardware requirements to resolve problems and eliminate design qualms.
B. Primary	
B.1 Efficiency	B.1 The efficiency of a particular subsystem over a wide range of potential operating conditions should be evaluated. This may be particularly true for mechanical systems.
B.2 Growth Opportunity/ Expandability	B.2 Consideration of a subsystem's growth or expansion capability may be critical evaluation criterion with regard to the lunar-colony's growth rate. Modularity may be an important consideration.
B.3 Reliability/Maintainability	B.3 To be considered under this criterion is the unspared reliability of a particular subsystem. Considered items should be the factors related to limited-life subsystems and the complexity of the maintenance require-

Table 11.2.4-1 (Continued)

Detailed Description of Evaluation Criteria

Criteria	Description
	ments. Mean time between failure (MTBF) predictions can provide a quantitative assessment of a subsystem's reliability.
B.4 Resupply/Use of Lunar Resources	B.4 This criterion is a highly motivational factor for lunar colony development particularly when utilization of lunar resources implies minimal resupply causing a trend towards lunar independence from earth.
B.5 Flexibility	B.5 A measure of a subsystem's capability to perform under more than one set of operating conditions at minimum or no penalty. This may be particularly true with respect to power supplies. Also, part of subsystem flexibility assessment would be to evaluate the subsystem's capability for being used for different purposes than originally intended.
C. Secondary	
C.1 Weight C.2 Volume	C.1 C.2 For purposes of payload comparison from lunar orbit to lunar surface, the equivalent weights and volumes of subsystems should be considered. These comparisons may be very important with regard to growth of colony potential. Considerations would include fixed weight, expendables, power and heat-rejection requirements, spares and redundancy items necessary to achieve reliability goals.
C.3 Energy/Power Requirements	C.3 The quantity and type of power or energy required for a subsystem's reliable operation should be established. Insensitivity to the type of power supply could also be considered along with the power duty cycle.
C.4 Interfacing	C.4 The number and types of interfaces may be assessed as a measure of the ability of a subsystem to integrate with other subsystems.
C.5 Contamination/Leakage	C.5 A candidate subsystem's potential for contamination of crew, equipment, atmosphere, other life forms, etc. must be assessed. Bacteria contamination or generation may be particularly important. Leakage must be considered since this will affect the capacities of certain subsystems.

Table 11.2.4-1 (Continued)

Detailed Description of Evaluation Criteria

Criteria	Description
C.6 Operational Sensitivity	C.6 The subsystem should be as insensible as possible to upsets in the stability of the lunar-colony system. This may imply need for redundancy.
C.7 Cost	C.7 The requirements for this criterion should be evident. Cost evaluation will become a part of the evaluation scheme when two subsystems are being compared which have equal acceptability.

Table 11.2.5-1

Hypothetical Example of Use of Evalumatrix

Function: Lunar Habitability Concepts

Concept / Criteria	Candidate Concepts: Lunar Pollution	Moon Shrink	Bogus Atmosphere	Rocket Propulsion
•Performance	Good	Very good	Good	Very good
•Safety	Fair	Good	Very good	Good
•Availability/ Confidence Developmental Capacity	Poor	Good	Good	Good
	ELIMINATED			
•Efficiency		Fair	Very good	Good
•Growth Opportunity/ Expandability		Very good	Good	Very good
•Reliability/ Maintainability		Fair	Good	Fair
•Resupply/Use of Lunar Resources		Poor	Very good	Good
•Flexibility		Fair	Fair	Very good
		ELIMINATED		
•Weight			Very good	Fair
•Volume			Good	Good
•Energy/Power Requirements			Fair	Very good
•Interfacing			Good	Good
•Contamination Leakage			Good	Very good
•Operational Sensitivity			Good	Good
•Cost			Fair	Very good
			ELIMINATED	SELECTED

(4) A comparison of the secondary criteria indicates that the concept of rocket propulsion is the most viable candidate.

REFERENCES

1. ________, "Trade Off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems (AILSS)," Hamilton Standard, Division of United Aircraft Corporation, Windsor Locks, Conn., Contract No. NAS 1-7905, NASA CR-1458.

PART III

SUBSYSTEMS SELECTION

CHAPTER 12 OXYGEN*

12.1 INTRODUCTION

In any manned extraterrestrial activity, oxygen is a critical consumable. Establishment of a lunar colony presents a first opportunity to produce this commodity in space. Preliminary design studies have shown that, if electric power and solar energy are available, a plentiful supply of oxygen can be obtained from lunar fines.

The availability of oxygen for spacecraft fuel will permit a tug system to greatly increase payloads to the lunar surface. Additionally, life-support system makeup oxygen and water can be supplied at reduced costs. With oxygen more readily available, cost-effective designs of the future will make greater use of this "lunar gas" than conventional designs. It is important to realize that a viable subsystem design for a lunar colony may consume the lunar-resource oxygen.

The Working Group on Extraterrestrial Resources as well as several other organizations have devoted attention to the problem of oxygen production on the moon.

Most of this work took place before Apollo 11 returned the first lunar samples; therefore, much conjecture was involved. Some of the proposed methods, such as recovering the water of hydration from minerals, are not at all suited to the materials on the lunar surface as we know it. However, other processes are still workable.

In this study of the oxygen production subsystem, we have attempted to gather together the applicable pre-Apollo designs as well as the limited Apollo-based work which has been done mainly at NASA centers

*The authors wish to acknowledge the helpful cooperation and encouragement of Dr. W. Richard Downs of NASA/MSC in our study of lunar-oxygen production.

[1, 2]. These designs, plus several proposed during this study, have been compared and evaluated both in terms of their basic feasibility and the present knowledge of critical process variables. Of course, an important criterion in process selection is the ability of the process to regenerate any chemical reagents which are consumed.

Examination of seven proposed processes has revealed that two (hydrogen reduction and electrolytic reduction) provide the best potential methods for lunar oxygen production. Lack of definitive information on the electrolysis cell requires that experimental work be done in this area before a final selection can be made. Two alternate processes (hydrogen-sulfide reduction and fluorine reduction) have been identified as possible backup processes should unexpected difficulties occur in developing the primary processes. Additionally, attention should be given to any new process that is simple and involves low plant maintenance.

As an illustrative example of a preliminary plant design and because of its relatively predictable technical future, a design for the hydrogen-reduction process is presented in Section 5 of this chapter. This design highlights some of the considerations necessary in a process plant that operates in the lunar-surface environment.

12.2 CHEMISTRY OF LUNAR FINES IN OXYGEN PRODUCTION

Analyses of lunar fines returned from the moon by the Apollo program indicate that chemically bound oxygen is a major constituent. Table 12.2-1 lists the oxides in order of their abundance in a typical sample from Apollo 11. Notice that more than half of the lunar oxygen is combined as SiO_2 and that only six oxides contain more than 99 percent of the oxygen available.

The oxygen production nomograph (Figure 12.2-1) relates various oxygen consumption rates with plant capacity and the amount of lunar fines required. Plant size is based on operation during the

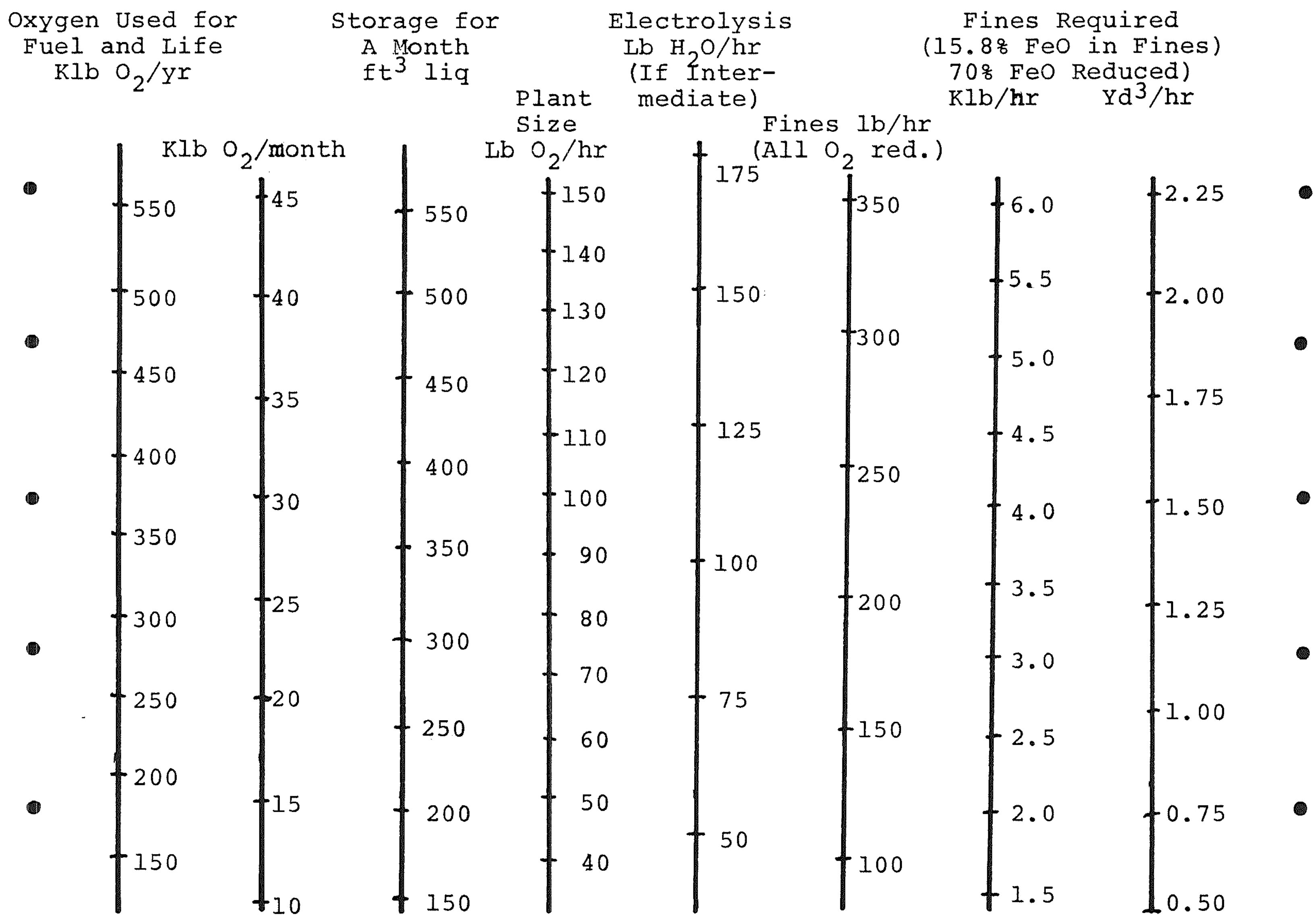


Figure 12.2-1 Oxygen Production Nomograph

lunar day only and with an onstream efficiency of 85 percent. The amount of water electrolysis required is shown for those processes in which water is an intermediary. The three columns for lunar fines required show a theoretical lower limit (all O_2 recovered), a plausable feed rate for the hydrogen-reduction process, and a rough estimate of volumetric requirements for hydrogen-reduction.

Table 12.2-1 Oxygen Production Potential of Lunar Fines

Oxide	Weight % Oxide in Fines (by Analysis)	Weight % Oxygen in Oxide	Weight % Total* Oxygen in Fines in this Oxide
SiO_2	42.0	53.2	52.74
FeO	15.8	22.3	8.38
Al_2O_3	14.0	47.0	15.50
CaO	12.0	28.6	8.15
MgO	8.0	39.7	7.50
TiO_2	7.6	40.5	7.30
Na_2O	0.44	25.7	0.26
MnO	0.21	22.6	0.12
K_2O	0.13	17.0	0.05
Total	100.18		100.00

* 42.2% by weight of lunar fines is oxygen

When dealing with the problem of processing lunar fines to remove oxygen, it is important to consider three characteristic areas: the mineral makeup of the fines, the overall chemical composition, and the physical state or size distribution of the particles. Experiments run with simulated lunar fines must be corrected for any deviations in these three broad areas.

Limited experimental work has been done with simulated lunar fines, but fortunately we can rely on thermodynamic and other data gathered for terrestrial compounds to tentatively predict the performance of proposed processes. Kubaschewski [3] is an excellent source for such data and Tables 12.2-2, 12.2-3, and 12.2-4 have been compiled primarily from his text. Properties are listed for elements, oxides, and other compounds likely to be encountered in the alternative oxygen-production processes (Section 12.3) we have considered.

The free energy change in a reaction of the type A + B = AB is called the free energy of formation of the compound AB from its elements and is a measure of the stability of the compound. The tabulated expressions for the free energies of the oxides in lunar fines and other selected compounds are shown plotted in Figure 12.2-2. The more stable the compound, the lower its line will be on the figure. Thus, it is easily seen that FeO is the most likely candidate for reduction.

We now consider the matter of hydrogen reduction of FeO. For the reaction

$$H_2 + FeO \rightarrow Fe + H_2O, \qquad (12.2\text{-}1)$$

the free energy of reaction ($\Delta G°$) at any temperature (T) is simply the difference between the free energies of formation of H_2O and FeO. The free energy of reaction can be related to the equilibrium concentration of H_2 and H_2O as

$$[H_2O]/[H_2] = \exp\ (-\Delta G°/RT) \qquad (12.2\text{-}2)$$

where [ ] indicates concentration in moles/liter, R is the gas constant and other symbols are as mentioned above.

Figure 12.2-3 shows the computed equilibrium concentrations over a range of temperatures for the hydrogen reduction of FeO. Notice that the molar ratio of H_2O to H_2 is less than 1.0. This is a consequence of the free energy of reaction being positive over the temperature range considered and generally indicates equilibrium conditions favor the reactants over the products. Figure 12.2-2 (or the equations tabulated) can be similarly used to determine the equilibrium conditions for other reactions.

TABLE 12.2-2

PROPERTIES OF CHEMICAL ELEMENTS FOUND IN LUNAR FINES

NO	NAME	ST	MW	MP(C)	BP(C)	-FREE ENERGY FORMATION (CAL) A	B	C	RNG (K)	-HEAT FORM KCAL/GMOLE	FUSE (KCAL/GMOLE)	EVAP (KCAL/GMOLE)	HEAT CAPACITY CAL/GMOLE/K[1] A	B	C	RNG (K)
1	AL	S	27.0	659.	2450.						2.5	69.5	4.94	2.96	.00	298-MP
													7.00	.00	.00	MP-1273
2	CA	S	40.0	843.	1483.						2.0	36.0	1.50	7.74	2.50	713-MP
													7.40	.00	.00	MP-1220
3	CL2	G	70.9	-101.	-34.						1.53	4.9	8.82	.06	-.68	298-3000
4	F2	G	38.0	-220.	-188.	FREE ENERGY AND HEAT OF FORMATION					-	-	8.29	.44	-.80	298-2000
5	FE	S	55.9	1536.	3070.						3.3	81.3	4.18	5.92	.00	273-1033
6	H2	G	2.0	-259.	-253.	IS ZERO FOR ELEMENTS IN STATE SHOWN					-	-	6.52	.78	.12	298-3000
7	K	S	39.1	64.	779.						.57	18.9	7.80	.00	.00	MP-600
8	MG	S	24.3	650.	1105.						2.1	30.5	8.10	.00	.00	MP-1130
9	MN	S	54.9	1244.	2010.						3.2	52.7	5.16	3.81	.00	298-1000
10	N2	G	28.0	-210.	-196.						.17	1.3	6.66	1.02	.00	298-2500
11	NA	S	23.0	98.	882.						.63	23.7	7.50	.00	.00	MP-500
12	O2	G	32.0	-219.	-183.						.11	1.6	7.16	1.00	-.40	298-3000
13	S	S	32.1	112.	445.						-	-	5.40	5.50	.00	MP-BP
													8.54	.28	-.79	298-2000
14	SI	S	28.1	1410.	3280.						12.1	91.6	5.72	.59	-.99	298-MP
15	TI	S	47.9	1667.	3285.						4.5	101.7	6.91	.00	.00	TP-1350

1. $C_p = A + BT + C/T^2$

TABLE 12.2-3

PROPERTIES AND CONCENTRATION OF OXIDES FOUND IN LUNAR FINES (APOLLO 11)

NO	NAME	Wt%	MW	MP(C)	BP(C)	-FREE ENERGY FORMATION (CAL)[1] A	B	C	RNG (K)	-HEAT FORM KCAL/GMOLE	FUSE (KCAL/GMOLE)	EVAP	HEAT CAPACITY CAL/GMOLE/K[2] A	B	C	RNG (K)
1.	SIO2	42.0	60.1	1610.	DEC	215600.	.00	-41.50	700-1700	217.0	-	DEC	11.22	8.20	-2.70	298-848
2.	FEO	15.8	71.9	1378.	DEC	62050.	.00	-14.95	298-1642	63.2	7.4	DEC	12.38	1.62	-.38	298-1200
3.	AL2O3	14.0	102.0	2050.	DEC	400810.	3.98	-87.64	298-923	400.0	26.0	DEC	25.48	4.25	-6.82	298-1800
						405760.	3.75	-92.22	923-1800							
4.	CAO	12.0	56.0	2615.	3500.	151325.	.00	-23.66	298-1124	151.6	19.0	-	11.86	1.08	-1.66	298-1177
						153550.	.00	-25.64	1124-1760				.00	.00	.00	
5.	MGO	8.0	40.3	SUB	2770.	144350.	2.95	-33.95	298-923	143.7	-	-	10.74	2.44	-2.26	273-1200
						145350.	.24	-26.95	923-1380							
						181600.	7.37	-75.70	1380-2500							
6.	TIO2	7.6	79.9	1870.	DEC	218458.	.00	-41.80	700-2000	225.5	15.5	DEC	17.97	.28	-4.35	298-1800
7.	NA2O	.44	62.0	920.	DEC	100700.	.00	-17.00	APPROX[3]	100.7	-	DEC	15.70	5.40	.00	298-1100
8.	MNO	.21	70.9	-	-	91950.	.00	-17.40	298-1500	92.0	13.0	-	11.11	1.94	-.88	298-1800
9.	K2O	.13	94.2	-	DEC	86600.	4.60	-44.60	298-	86.4	-	DEC				NO INFO
	TOTAL	100.18														

1. $-\Delta G^{o} = A + BT\log_{10}T + CT$ 2. $C_p = A + BT + C/T^2$ 3. APPROX $-\Delta G = -\Delta H_{298} + T\Delta S_{298}$

TABLE 12.2-4

PROPERTIES OF CHEMICAL COMPOUNDS INVOLVED IN PRODUCTION OF LUNAR OXYGEN

NO	NAME	ST	MW	MP(C)	BP(C)	-FREE ENERGY FORMATION (CAL)[1] A	B	C	RNG (K)	-HEAT FORM KCAL/GMOLE	FUSE (KCAL/GMOLE)	EVAP (KCAL/GMOLE)	HEAT CAPACITY CAL/GMOLE/K[2] A	B	C	RNG (K)
1.	H2O	G	18.0	0.	100.	57250.	-4.48	2.21	298-2500	57.8	1.44	9.8	7.17	2.56	.08	298-2500
2.	KF		58.1	857.	1510.	135500.	.00	-15.90	APPROX[3]	134.5	6.75	44.6	11.02	3.12	.00	298-MP
3.	SIF4	G	104.1	SUB	-95.	385000.	.00	-67.40	APPROX	385.0	SUB	6.2	21.86	3.17	-4.70	298-1000
4.	FEF2		93.9	1020.	1800.	167000.	.00	-31.60	298-1350	168.0	-	-				NO INFO
5.	ALF3		84.0	SUB	1280.	356000.	.00	-15.90	APPROX.	356.0	SUB	67.0	17.27	10.96	-2.30	298-727
6.	CAF2		78.0	1418.	2510.	293300.	7.70	-64.40	298-1123	292.0	7.10	74.6	14.30	7.28	.47	-
7.	MGF2		62.3	1263.	2230.	267200.	.00	-40.20	298-923	266.0	13.90	65.3	16.93	2.52	-2.20	298-MP
8.	TIF4		123.9	SUB	283.	392500.	.00	-32.00	APPROX	392.5	SUB	21.5				NO INFO
9.	SICL4	G	99.0	-70.	58.	155600.	3.64	-43.90	298-1000	38.9	1.85	6.8	24.25	1.64	-2.75	298-1000
10.	FECL2		126.8	677.	1012.	82770.	6.98	-50.84	298-950	81.8	10.30	30.0	18.94	2.08	-1.17	298-950
11.	H2S	G	34.1	-86.	-60.	20105.	-3.62	.60	298-1750	4.9	0.59	4.5	7.02	3.68	.00	298-1800
12.	SIS2		92.3	1090.	1130.	49000.	.00	-19.20	APPROX	49.0	-	-				NO INFO
13.	FES		88.0	1195.	DEC	35913.	.00	-12.56	412-1179	22.8	7.73	DEC	12.20	2.38	.00	598-MP
14.	AL2S3		150.3	1100.	DEC	198000.	.00	.00	298	172.9	-	DEC				NO INFO
15.	CAS		72.1	-	-	129550.	.00	-22.96	673-1124	110.0	-	-	10.20	3.80	.00	273-1000
16.	MGS		56.4	-	-	101800.	.00	-25.65	923-1380	83.0	-	-				NO INFO
17.	CO	G	28.0	-205.	-192.	26700.	.00	20.95	298-2500	26.4	-	-	6.79	.98	-.11	298-2500

1. $-\Delta G^{O} = A + BT\log_{10}T + CT$ 2. $C_p = A + BT + C/T^2$ 3. APPROX $-\Delta G = -\Delta H_{298} + T\Delta S_{298}$

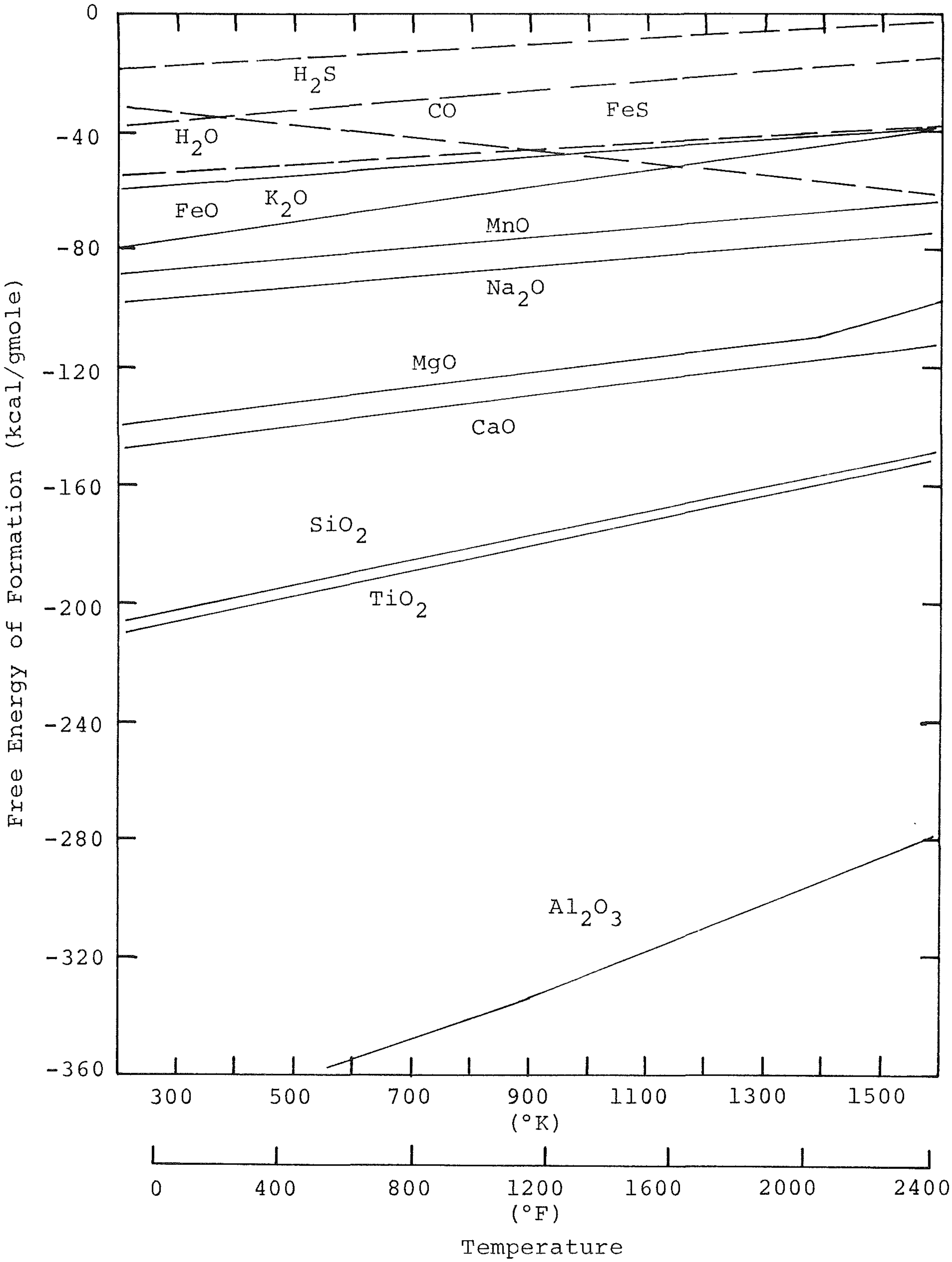


Figure 12.2-2 Free Energies of Formation

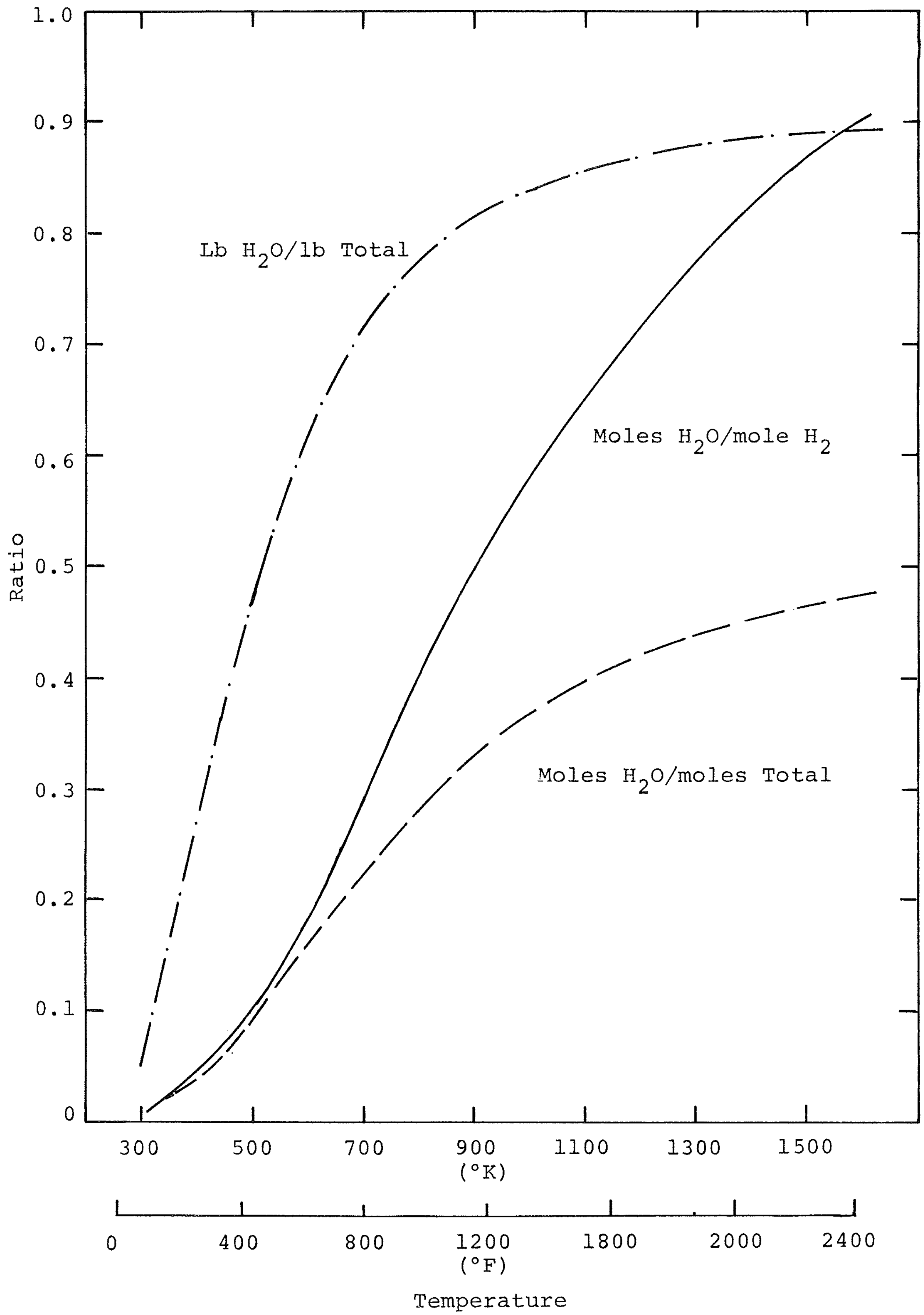


Figure 12.2-3 Theoretical Equilibrium Ratios for Hydrogen Reduction of FeO

Heat capacities and heats of formation were used to compute the energy required for the hydrogen reduction of FeO. Figure 12.2-4 shows that the reaction is endothermic over the temperature range of interest. This information can be used in determining process heat loads.

It has been the purpose of this section to illustrate the theoretical calculations that can be made for various oxygen-production processes. However, note that these calculations do not indicate anything about the speed of these reactions nor the effect of the actual mineral and physical condition of the lunar fines. Kinetic information in this chapter is based on the limited experiments that have been conducted and is very qualitative in nature. The large percentage of fused material (glass) in the fines will reduce the yields for most of the proposed processes. However, some sort of beneficiation process for the fines might significantly upgrade the feed to the process. Laboratory experiments are necessary before more quantitative statements can be made.

12.3 ALTERNATIVE OXYGEN PRODUCTION PROCESSES

Seven of the processes that have been proposed for oxygen production on the lunar surface are discussed in this section. Although this is not an exhaustive list of proposed processes, we have selected these based on merit and on range of approach to the problem of oxide reduction.

12.3.1 HYDROGEN REDUCTION

The hydrogen-reduction process involves flowing hot hydrogen gas over or through lunar fines. The FeO in the mineral ilmenite is reduced to Fe and H_2O. The water is then electrolyzed and the oxygen recovered. The hydrogen is heated and recycled for further reduction of the fines. The hydrogen-reduction process is summarized in the following:

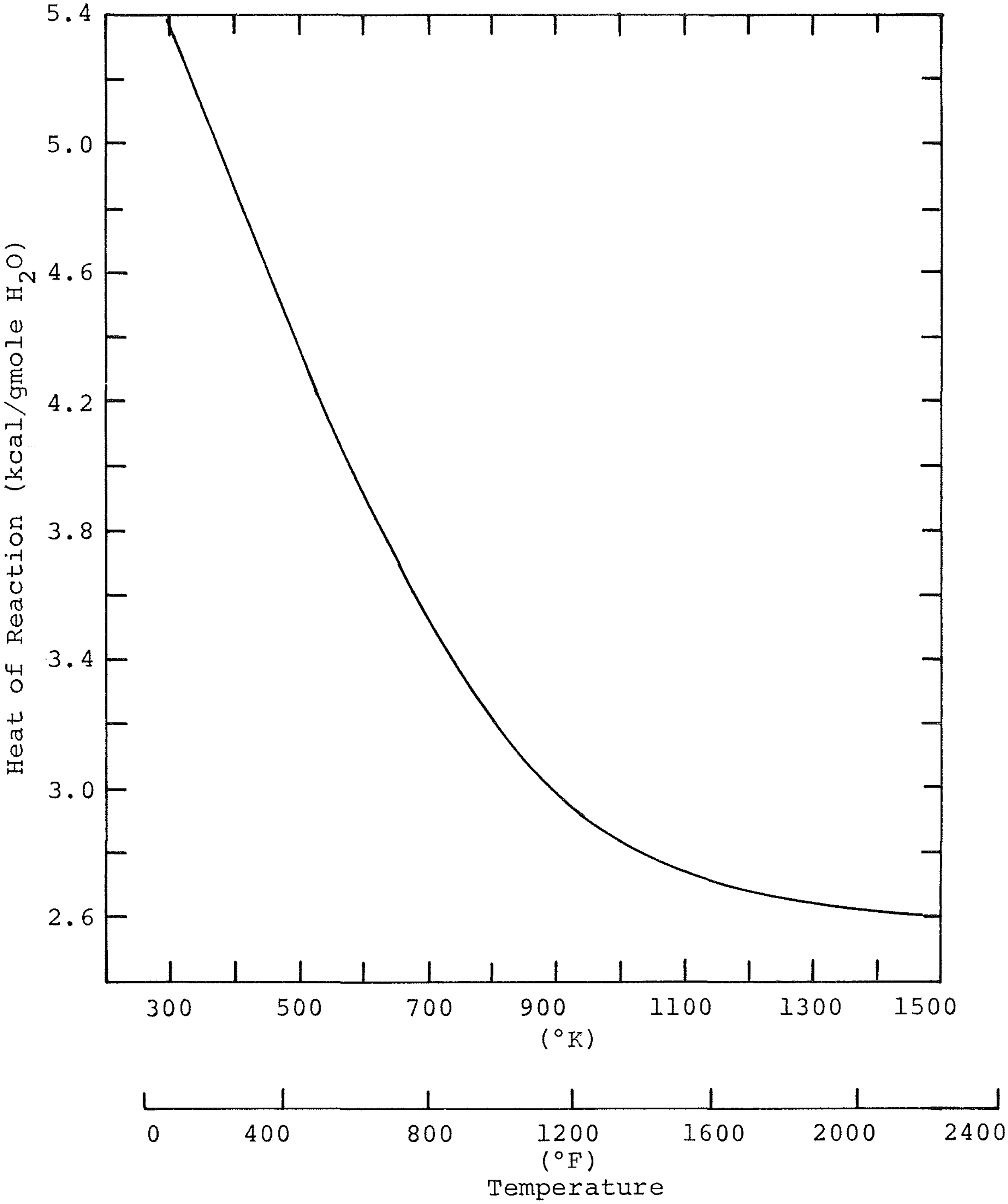


Figure 12.2-4 Heat of Reaction for Hydrogen Reduction of FeO

Reactions: $FeO \cdot TiO_2 + H_2 \rightarrow Fe + H_2O + TiO_2$ (Reduction)

$2H_2O \rightarrow 2H_2 + O_2$ (Electrolysis)

Thermodynamics: Poor

Kinetics: Slow

Lunar Fines: 40.5 lb fines per lb O_2 estimated

28.4 lb fines per lb O_2 if all FeO reduced

Estimated Power Required: 150 kw electrical

(20,000 lb O_2 per month) 500 kw thermal

Advantages: The process is a "clean" operation and its chemistry is simple. All processes will require some reactant makeup and hydrogen is the lightest weight reactant that could be transported from the earth to the moon. If vapor-phase electrolysis is used, both reactions can be conducted at about the same temperature and heat transfer problems are simplified. Power requirements are comparable to other processes.

Disadvantages: Hydrogen only reduces iron oxide (FeO) which constitutes just 15% by weight of the oxides in lunar fines from the Mare Tranquillitatis (Apollo 11). Therefore, it will be necessary to process a large quantity of lunar soil with attendant transport and heating problems. Hydrogen is not a particularly good reducer as shown in Figure 12.2-3. Even at chemical equilibrium, the molar ratio of water to hydrogen will be about 1 to 3 in the temperature range (730°C) of interest. Thus, an important problem area with the process is the removal of water or oxygen from a hydrogen-rich stream. We have proposed a vapor-phase electrolysis cell as a possible solution.

12.3.2 HYDROGEN-SULFIDE REDUCTION

To obtain a better reducing agent, we have proposed using hydrogen-sulfide gas (H_2S). Hydrogen sulfide will reduce oxides (FeO, CaO, and MgO) which constitute about 35% by weight of the lunar fines. The metal sulfides and water that are formed separate and the water is electrolyzed. The metal sulfides are then decomposed by heating. Hydrogen recovered from electrolysis and the sulfur from decomposition are recombined forming H_2S for recycling. The hydrogen-sulfide process is summarized in the following:

Reactions:

$$FeO + H_2S \rightarrow FeS + H_2O$$
$$CaO + H_2S \rightarrow CaS + H_2O \quad \text{(Exchange)}$$
$$MgO + H_2S \rightarrow MgS + H_2O$$

$$FeS \rightarrow Fe + S$$
$$CaS \rightarrow Ca + S \quad \text{(Decomposition)}$$
$$MgS \rightarrow Mg + S$$

$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{(Electrolysis)}$$
$$H_2 + S \rightarrow H_2S \quad \text{(Regenerative)}$$

Thermodynamics: Good

Kinetics: Good

Lunar Fines: 18. lb fines per lb O_2 estimated
9.9 lb fines per lb O_2 if all FeO, CaO, and MgO reduced

Estimated Power Required: 150 kw electrical
(20,000 lb O_2 per month) 1100 kw thermal

Advantages: The process is simple. It is more efficient thermodynamically and uses less lunar soil than the hydrogen-reduction process. The production of iron, magnesium, and calcium is possible. Electrical power and temperature requirements are about the same as the hydrogen-reduction process. Thermal power probably will increase, depending on the thermal decomposition of the metal sulfides.

Disadvantages: The thermal decomposition of the metal sulfides needs investigation. It is possible that complete decomposition of all the sulfides formed may require a temperature too high to contain in a reactor vessel. Also, since H_2S is highly toxic, a reliable O_2 purification process is essential.

12.3.3 CARBOTHERMIC

The carbothermic process was initially proposed before lunar samples were returned by the Apollo flights [4] and has been studied in some detail. The process, which was designed to reduce the very stable silicates, involves melting the lunar fines at about 1600°C and passing methane through the molten mixture. The CO produced is reacted with H_2 over a nickel catalyst at 250°C to regenerate CH_4 and more water. The water is then electrolyzed to recover H_2 and to yield oxygen. The carbothermic process is summarized in the following:

Reactions:

$$\text{Lunar fines} + CH_4 \rightarrow CO + 2H_2O + \text{Metals} \quad \text{(Reduction)}$$

$$CO + 3H_2 \xrightarrow[\text{catalyst}]{} H_2O + CH_4 \quad \text{(Exchange)}$$

$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{(Electrolysis)}$$

Thermodynamics: Good

Kinetics: Catalyst required

Lunar Fines: 3.3 lb fines per lb O_2 estimated
2.37 lb fines per lb O_2 if all oxides reduced

Estimated Power Required: 260 kw electrical
(20,000 lb O_2 per month) 1100 kw thermal

Advantages: This process will reduce nearly all the oxides in the lunar fines thereby providing very good oxygen yield per pound of lunar soil. Additionally, there is the possibility of using the metals formed, although a separation technique for this has not been developed.

Disadvantages: The process takes place at extremely high temperatures. In laboratory tests, it has been difficult to get CH_4 to flow into the melted material. Also, because of the corrosivity of the molten silicates, the service life of the refractory crucibles has been unsatisfactory. Possible use of an electric arc has been suggested; however, the carbon electrodes are consumed and recycling this carbon would be a difficult problem.

12.3.4 CARBONATE/OXYGEN

This process has been proposed in an effort to reduce the temperature required for oxygen production. Some experimental work has been done at NASA/MSC. Lunar fines are reacted with sodium hydroxide and carbon at 500°C in the presence of a nickel catalyst to form carbonates, carbon monoxide and water. The carbonates are then reacted with hydrochloric acid to form metal chlorides. Carbon oxides from these reactions are reduced on an iron catalyst with hydrogen to form carbon and water. The water collected can be electrolyzed. The metal chlorides are also electrolyzed and the chlorine is reacted with hydrogen to be recycled. This process is summarized in the following:

Reactions:

$$\text{Lunar fines} + NaOH + C \xrightarrow[\text{Ni Catalyst}]{} (\text{Metal})\,CO_3 + CO + H_2O \quad \text{(Exchange)}$$

$$(\text{Metal})\,CO_3 + HCl \rightarrow (\text{Metal})\,Cl + CO_2 + H_2O \quad \text{(Exchange)}$$

$$CO + CO_2 + H_2 \xrightarrow[\text{Fe Catalyst}]{} H_2O + C \quad \text{(Bosch Process)}$$

$$(\text{Metal})\,Cl \rightarrow \text{Metal} + Cl \quad \text{(Electrolysis)}$$

$$2H_2O \rightarrow 2H_2 + O_2 \quad \text{(Electrolysis)}$$

$$H_2 + Cl_2 \rightarrow 2HCl \quad \text{(Regeneration)}$$

Thermodynamics: Average

Kinetics: Nickel and iron catalysts required

Lunar Fines: 11. lb fines per lb O_2 estimated
9.9 lb fines per lb O_2 if all FeO, CaO, and MgO reduced

Estimated Power Required: 400 kw electrical
(20,000 lb O_2 per month) 1500 kw thermal

Advantages: The process requires relatively low temperatures and reduces oxides which constitute about 35% by weight of the lunar fines.

Disadvantages: The process is very complex, having many reactions, separations, and recycling processes. For example, the Bosch process forms carbon in the presence of an Fe catalyst coating the catalyst. The method of cleaning the catalyst is not clear. Also, the reaction of Na and H_2O to form NaOH for recycling is difficult to control. The power requirements are high, since two different electrolysis processes are required for recycling.

12.3.5 FLUORINE-EXCHANGE PROCESS

All of the metal oxides in lunar fines will react with fluorine to liberate oxygen and form the metal fluorides. This can be accomplished at a low temperature by passing fluorine through or over lunar fines. The fluorine is recycled by reacting the metal fluorides with potassium vapor to form the metals and potassium fluoride. The potassium fluoride is then electrolyzed and the elements can be recycled. This process is summarized as follows:

Reactions:

Lunar fines + F_2 → Metal Fluorides + O_2 (Exchange)

Metal Fluorides + K → Metals + KF (Reduction)

2KF → 2K + F_2 (Electrolysis)

Thermodynamics: Excellent

Kinetics: Fast

Lunar Fines: 2.5 lb fines per lb O_2 estimated
2.37 lb fines per lb O_2 if all oxides reduced

Estimated Power Required: 250 kw electrical
(20,000 lb O_2 per month) 800 kw thermal

Advantages: This process does offer the possibility of producing metals from lunar soil. For example, SiF_4 is gaseous at temperatures below 0°C and is easily separated from the other metal fluorides. The other metal fluorides have sufficiently different physical properties to allow their separation. Once separated, the metal fluorides could be reacted with potassium to form the free metal. However, this is a difficult reaction to carry out physically because of the high melting point of potassium fluoride. Another slight advantage for processing fluorine on the moon is lack of water or moisture. No hydrofluoric acid will be formed, as compared to processes on the earth.

Disadvantages: In general, all the reactions involved are very fast and difficult to control. It is also very difficult to react gaseous metal fluorides and potassium vapor since solids may be formed depending on temperature. Purification of the oxygen (free of F_2) is essential to prevent fatality. A very reliable system of purification is essential and possibly very costly because of the very corrosive nature of fluorides.

12.3.6 CHLORINE-EXCHANGE PROCESS

In an effort to reduce problems with handling, the most reactive halide (F_2), we have proposed a nearly identical process using chlorine. Unfortunately, this halide is only reactive enough to reduce iron oxide, although the reaction occurs at a low temperature. This process is summarized as follows:

Reactions:

$$2FeO + 2Cl_2 \rightarrow 2FeCl_2 + O_2 \quad \text{(Exchange)}$$

$$FeCl_2 + 4K \rightarrow 4KCl + Fe \quad \text{(Reduction)}$$

$$2KCl \rightarrow 2K + Cl_2 \quad \text{(Electrolysis)}$$

Thermodynamics: Good

Kinetics: Good

Lunar Fines: 35.0 lb fines per lb O_2 estimated

28.4 lb fines per lb O_2 if all FeO reduced

Estimated Power Required: 250 kw electrical

(20,000 lb O_2 per month) 800 kw thermal

Advantages: Chlorine is easier to handle than fluorine although extensive purification is still necessary.

Disadvantages: Only iron production is possible and the lunar fines requirement has increased. Reaction of the iron chloride with potassium is still a difficult problem.

12.3.7 ELECTROLYTIC REDUCTION

Electrolytic reduction has been proposed as an alternative that does not rely on the chemical reactivity of reagents but rather uses an electrical potential to produce oxygen from lunar fines. Sodium hydroxide is used to dissolve the oxides at about 400°C. The solution is then electrolyzed. Oxygen comes off at the anode and sodium at the cathode. As soon as the sodium is formed, it reacts with the oxides to form the metals. This process is very similar to the electrolytic production of aluminum used on the earth. Nickel electrodes have been used on initial experiments with this process and they are consumed, although electrode life is not accurately known. This process is summarized as follows:

Reactions:

Lunar fines + NaOH $\rightarrow$ H_2O + Solution	(Solution)
$2Na_2O \rightarrow O_2 + 4Na$ (in solution)	(Electrolysis)
2Na + Solution $\rightarrow$ Metals + Na_2O	(Reduction)

Thermodynamics: Good

Kinetics: Fast

Lunar Fines: 2.4 lb fines per lb O_2 estimated
2.37 lb fines per lb O_2 if all oxides reduced

Estimated Power Required: 350 kw electrical
(20,000 lb O_2 per month) 500 kw thermal

Advantages: The process is very simple, safe and reliable. The oxygen yield is high and temperatures are low. Electric power required is higher than most of the other processes; however, it is not excessive. Metal production looks very promising if silicon can be removed from the melt.

Disadvantages: Quantitative experimental data is needed on the process and possible electrodes. Electrode consumption may be a severe problem. If electrodes which are consumed slowly can be devised or if lunar materials can be used as electrodes, the process should be developed. Also, there is the possibility of recovering the electrode material if it is consumed and casting or forming it for reuse.

12.4 SELECTION OF AN OXYGEN PROCESS

The alternative processes for producing oxygen were compared using criteria at three levels: absolute, primary, and secondary. This system of evaluation is discussed in detail in Chapter 11 and has served (Table 12.4-1) to identify those processes for which research and development work can profitably be conducted.

12.4.1 HYDROGEN-REDUCTION

The Hydrogen-Reduction process was selected as a candidate subsystem even though its yield, efficiency and performance can be classed as fair to poor. The process is simple both chemically and in operational form. This is a distinct advantage in a process one hopes to operate on the lunar surface. Little new technology is needed in comparison to all other suggested processes. The greatest problems with this process are the handling of relatively large volumes of lunar fines for small amounts of oxygen and the large volume of flowing hydrogen required with the constant removal of small amounts of water from this hydrogen in order to obtain a reasonable yield from the process.

We believe the water removal problem can be solved through the use of a vapor-phase water electrolysis cell. This would result in a substantial simplification and power savings over the process as originally proposed.

The Hydrogen-Reduction Vapor-Phase Electrolysis Process is the best candidate for immediate production of lunar oxygen. It can be developed with present technology and a minimum of research. For long range use, the process only offers oxygen production. The production of iron for use in a lunar colony looks unlikely.

12.4.2 HYDROGEN SULFIDE

The hydrogen-sulfide process was eliminated because the decomposition of all the metal sulfides formed is not certain. Hydrogen

Table 12.4-1 Oxygen Process Comparison

Design / Criteria		Candidate Processes for Oxygen Production			
		Hydrogen Reduction	Hydrogen-Sulfide Reduction	Carbothermic	Carbonate/ Oxygen
Absolute	Performance	Fair	Good	Fair	Poor
	Safety	Very Good	Fair	Good	Fair
	Availability	Very Good	Good	Poor	Poor
				Eliminate	Eliminate
Primary	Cost	Good	Fair		
	Efficiency	Poor	Fair		
	Reliability	Good	Good		
	Maintainability	Good	Fair		
			Eliminate		
Secondary	Weight/Volume	Fair			
	Growth Opportunity	Fair			
	Energy/Power	Very Good			
	Interfacing	Fair			
	Flexibility	Fair			
	Contamination/ Leakage	Good			
	Operational Sensitivity	Fair			
		Selected			

Design / Criteria		Candidate Processes for Oxygen Production		
		Fluorine Exchange	Chlorine Exchange	Electrolytic Reduction
Absolute	Performance	Very Good	Fair	Good
	Safety	Poor	Fair	Very Good
	Availability	Poor	Good	Good
			Eliminated	
Primary	Cost	Fair		Very Good
	Efficiency	Very Good		Fair
	Reliability	Poor		Very Good
	Maintainability	Poor		Good
		Eliminate		
Secondary	Weight/Volume			Very Good
	Growth Opportunity			Very Good
	Energy/Power			Fair
	Interfacing			Very Good
	Flexibility			Good
	Contamination/ Leakage			Fair
	Operational Sensitivity			Good
				Alternate Selection

sulfide will readily reduce FeO, CaO, and MgO, forming water and the metal sulfides; however, other sulfides may be formed. If thermal decomposition of the metal sulfides is possible, then it is relatively easy to recombine the hydrogen from water electrolysis and sulfur to form hydrogen sulfide for recycling. The uniquely simple nature of this process, similar to that of hydrogen reduction and electrolytic reduction, deserves special mention. The process should be researched if unforeseen difficulties occur with either the hydrogen reduction or the electrolysis process.

12.4.3 CARBOTHERMIC

The carbothermic process was eliminated because of the problem of high temperature molten silicate corrosion of the refractory reactor vessel. It does not appear that this problem can be overcome in the near future. The process also requires the bubbling of methane through molten lunar soil. Efforts at NASA Centers to do this have not been successful. No further research is recommended on this process.

12.4.4 CARBONATE OXYGEN

The carbonate oxygen process, originally proposed as a method to lower temperature requirements was eliminated because of its complexity. The two electrolysis processes for recycling could probably be made to work; however, the Bosch process does not look feasible for recycling the carbon. The carbon deposits on the finely divided or porous catalyst. Cleaning the catalyst and collecting the carbon has severe disadvantages, especially on the lunar surface where manpower and equipment (facilities) are not abundant. No further investigation is recommended for this process.

12.4.5 FLUORINE EXCHANGE

Fluorine exchange is a highly efficient technique which was eliminated as a possible process because of inherent safety and corrosion problems. Fluorine is extremely reactive and poisonous. The reaction between potassium vapor and the metal fluorides form the relatively high melting point compound potassium fluoride. It is difficult to imagine this reaction being carried out in a chemical process so that the potassium fluoride could be separated from the metals and electrolyzed. However, the process does offer the possibility of metal production. While there are some processes on the earth using fluorine gas in chemical processing, the reactions are not of the same magnitude and safety precautions are extreme and costly. On the lunar surface with limited personnel and facilities, it does not appear feasible.

If the safety problems could be overcome, this process does offer the possibility of metal production important to a lunar colony. Should development of this process be pursued, research on safety should be the first effort. Research on the process is not recommended until other more attractive candidate processes have been studied.

12.4.6 CHLORINE EXCHANGE

The chlorine exchange process was eliminated because it did not offer any significant advantages over hydrogen reduction. Like hydrogen, chlorine only reduces the iron oxide in lunar fines. Although it does this more efficiently than hydrogen, the process has most of the difficulties of the fluorine process.

12.4.7 ELECTROLYTIC REDUCTION

The electrolytic reduction process was selected as an alternate process for development. It has the attributes of simplicity, safety, low temperature requirement, reasonable power requirement, and the possible production of metals. However, at this time there is some evidence which indicates that nickel electrodes tend to be consumed in the process. Research is needed to determine the rate of comsumption of the electrodes, possible recovery of dissolved electrode and recasting of the electrode, and the possible use of other metals or materials as electrodes. It may be reasonable to make electrodes from the residue of metals left after reduction of lunar fines.

We strongly recommend doing research on the electrode problem. It appears that this process has the most advantages of all the candidate processes. The only other problem with this process is the recycling of sodium hydroxide. The sodium remaining after electrolysis of the lunar soil needs to be separated and reacted with water to form the sodium hydroxide for dissolving new lunar fines. These reactions can probably be carried out in the same electrolysis vessel, although some techniques will have to be developed for sodium collection and for adding the water. Other solvents instead of sodium hydroxide should also be investigated.

While the electrode and sodium hydroxide problems need much research, it is felt that these problems are not insurmountable.

12.4.8 CONCLUSIONS

The hydrogen-reduction technique is recommended as the method to produce oxygen on the moon if that is the only chemical we wish to remove from lunar fines. With present day technology, we think that this process will perform satisfactorily. Should metal production be desired concurrently with oxygen production, electrolytic reduction should be the first process investigated.

The hydrogen-sulfide process and fluorine process look less promising than electrolytic reduction. Of course, all four of these processes need more research and development before any meaningful cost-analysis work can be done. Plant-operating life, maintenance requirements, and ease of plant operation will all be significant factors affecting a design choice. At this point we have no quantitative data on these factors. Additionally, if an efficient and simple process were developed to beneficiate the lunar fines and increase the available ilmenite ($FeO \cdot TiO_2$), the advantage of the hydrogen-reduction process would improve.

12.5 PRELIMINARY DESIGN OF THE HYDROGEN-REDUCTION VAPOR-ELECTROLYSIS PROCESS

In this section we have attempted to outline a preliminary design for an oxygen-production plant that will give suitable service on the moon. A plant "outdoors" is anticipated, since at this time we do not foresee any significant advantages in placing the process in a pressurized structure.

Prime importance must be attached to insuring trouble-free operation and convenient maintenance in the lunar environment. We feel it is important to recognize the value of process simplicity and incorporate it in the design at the conceptual level where the most freedom for innovation exists. A pilot plant of the type we describe could be built in the near future after a limited amount of research and development.

12.5.1 BASIC PROCESS DESCRIPTION

The process employs a semicontinuous fluidized bed reactor in which the solid lunar fines are suspended by flowing hydrogen. It is in this fluidized bed that the hydrogen gas reduces the iron oxide in the mineral ilmenite to water and the free metal. The temperature in the bed is about 1000°K with a nominal pressure of one atmosphere. The reaction is theoretically independent of pressure while greater yields and faster kinetics will be experienced at higher temperatures for the endothermic reaction. However, temperatures are limited by construction materials and the desire to keep the bed a fluidized solid, not a liquid. Cyclones prevent the fines from leaving the reactor. (These may be internal to the reactor to reduce heat loss). The water vapor and hydrogen from the reactor flow to a series of vapor-phase electrolysis cells where the water is converted to hydrogen and oxygen. The nickel-zirconia cells are designed in such a way that the oxygen ions formed are transferred through the cathode. The hydrogen remains and is heated in a solar furnace for recycling to the fluidized bed. Solids are periodically added and removed from the reactor through airlocks. Water required for a lunar colony can be obtained by a coldtrap on the reactor effluent with makeup hydrogen added as needed. A sketch of the process is given in Figure 12.5-1.

The fluidization process in the reactor is necessary to provide good contact between the lunar fines and the hydrogen. This permits rapid heating of the fines when they are added and fast removal of the water formed to obtain better yields. The small particle size of the fines and high temperature makes a fixed-bed process unattractive.

The vapor-phase electrolysis cells we have suggested to replace the conventional liquid electrolysis cells in the process as originally proposed lead to considerable simplification. Several heat exchangers and the condenser are removed completely because the water no longer has to be separated or condensed from the hydrogen. This, of course, results in both equipment and energy (thermal and electric) savings.

The zirconia (ZrO_2) and nickel cells with which General Electric [5] has experimented can operate at temperatures in excess of 1000°K. The mixture of water vapor and hydrogen from the reactor can flow directly into a bank of the small diameter cells that are studded with nickel-coated cathodes. The anodes are similarly placed outside the thin tubular electrolyte of doped zirconia. A potential difference causes the water to decompose and the oxygen ions formed are transported through the electrolyte with gaseous oxygen forming outside the cell. This oxygen is then compressed and can be used to heat incoming fines before being piped to the liquefaction plant or to storage.

12.5.2 MATERIAL BALANCE

A process material balance is summarized in Figure 12.5-2. A

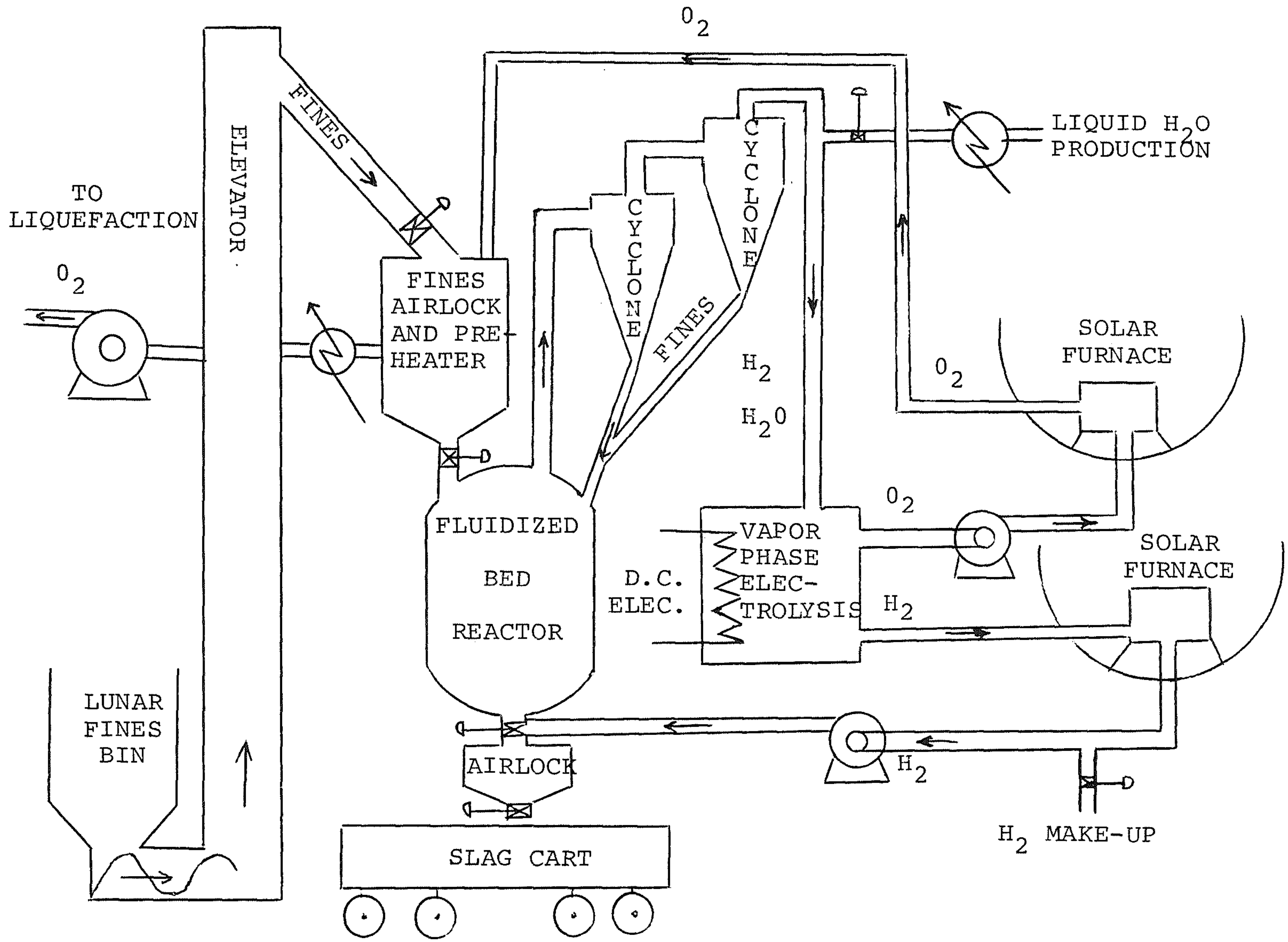


Figure 12.5-1 Hydrogen Reduction-Vapor Electrolysis Process

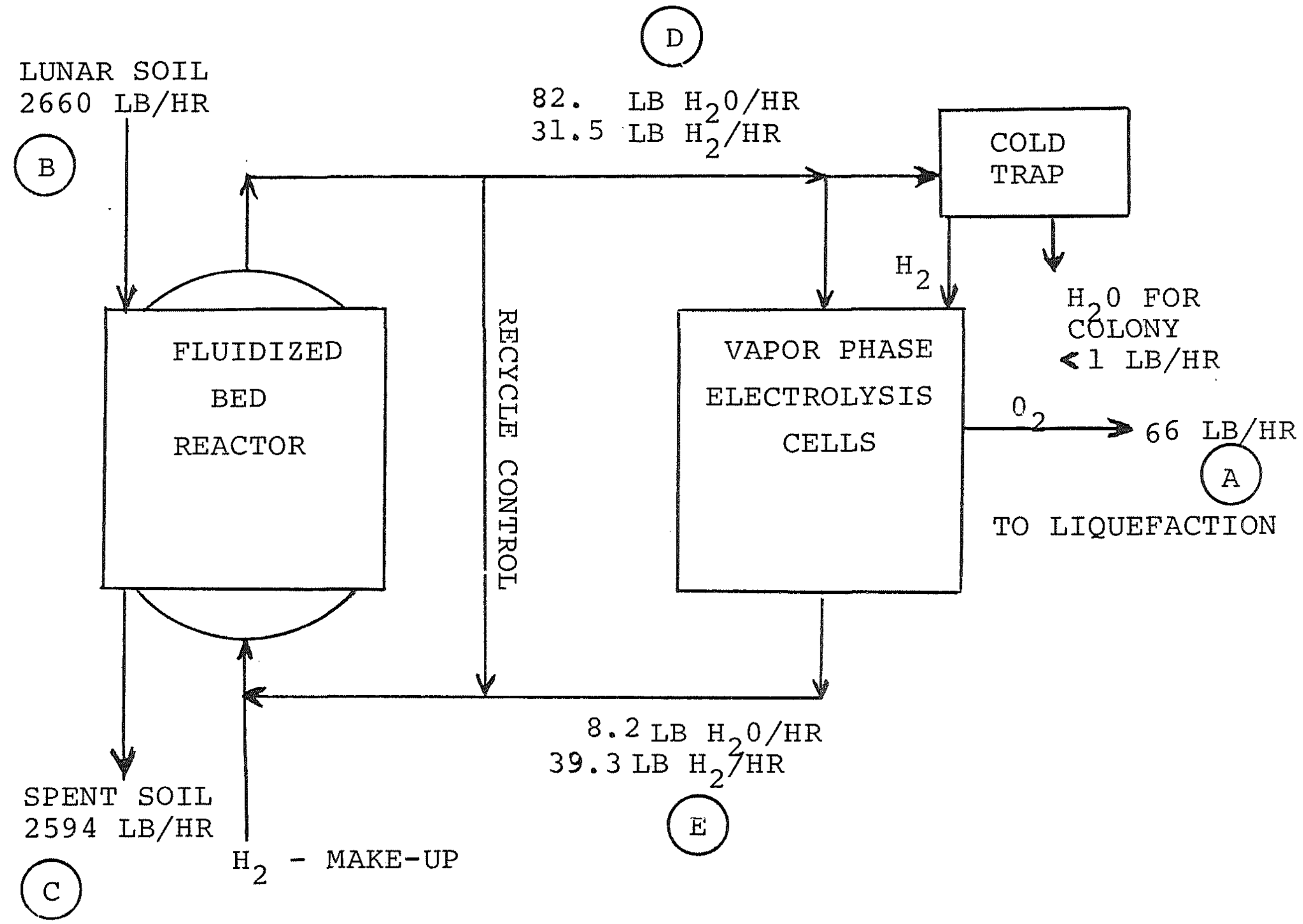


Figure 12.5-2 Material Balance 20,000 lb O_2/Month Plant

recycle control not shown in the previous figure would permit operation over a wide range of conditions in both the reactor and electrolysis cells. The following assumptions were made:

1. The design basis is 20,000 lb O_2 per month. This number is not necessarily the amount of oxygen needed by the colony for fuel and support, but will serve as a base line from which extrapolations can be made. For example, we recommend a pilot plant on the moon with a capacity of 2,000 to 4,000 lb O_2 per month. On the other hand, if the colony decided on ten lunar landings per year, a plant capacity of about 45,000 lb O_2 per month would be needed to supply tug fuel and base needs.
2. No operation in the lunar night and 85% onstream time during the daylight periods is estimated based on terrestrial experience with this type of solid-fluid chemical process.
3. Before the fines are removed from the reactor, 70% of the iron oxide is assumed to be converted. The equilibrium conversion is much less than this but recycling the gases to remove water formed should raise the total conversion to about 70%.
4. The average H_2/H_2O ratio leaving the reactor is assumed to be 50% of the equilibrium value. See Section 12.2 for equilibrium information.

12.5.3 HEAT BALANCE

An approximate process energy balance is summarized in Figure 12.5-3. The following assumptions were made to calculate process requirements:

1. No convective heat losses on the lunar surface.
2. Radiative heat losses are limited by insulation to 5 to 10% of the heat added to the reactor from recycled gas.
3. Heating of the hydrogen will be by means of a solar furnace

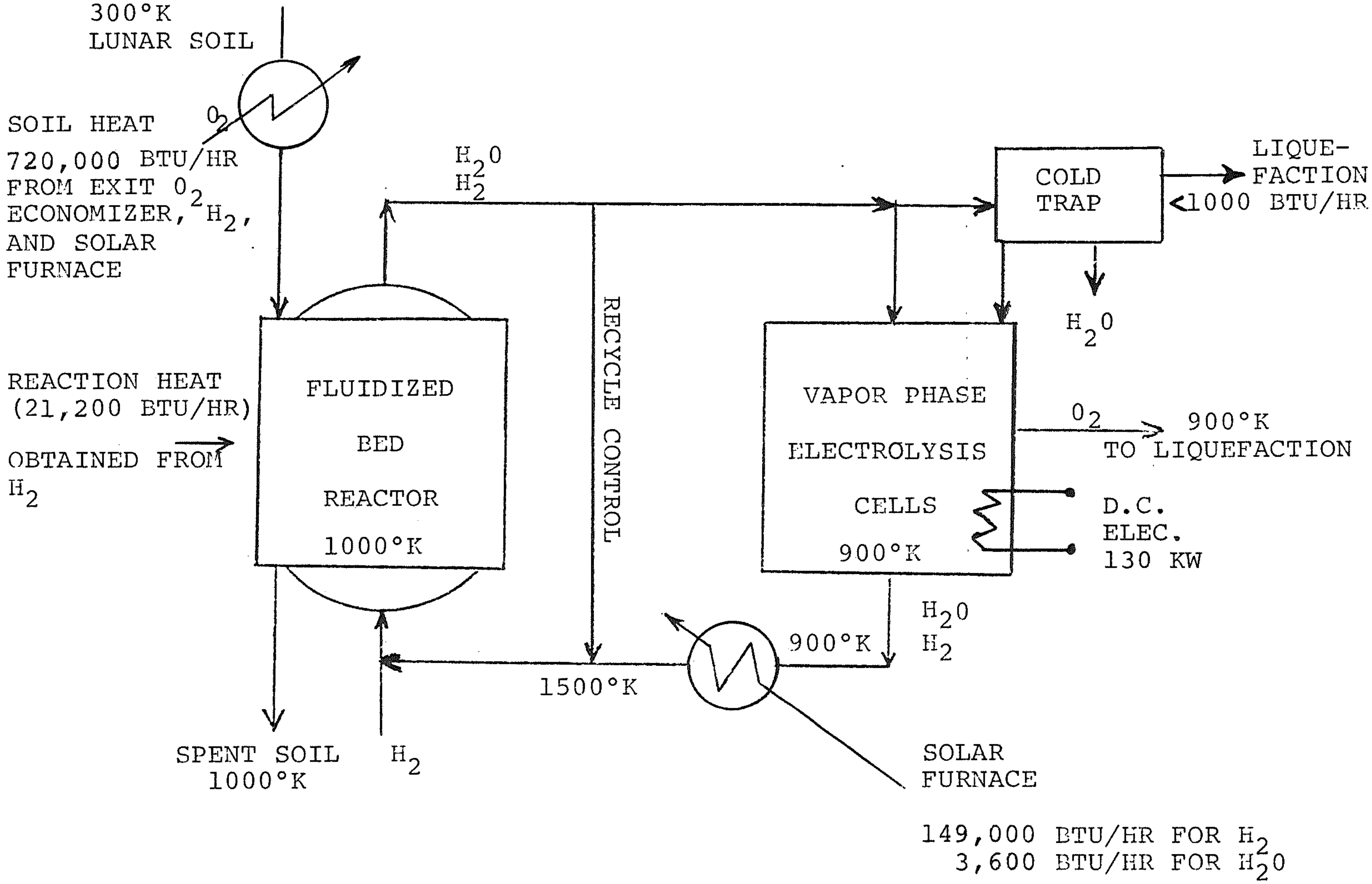


Figure 12.5-3 Energy Balance 20,000 lb O_2/Month

capable of reaching temperatures around 1500°K.

4. The heat transfer in fluidized beds is generally high. It is therefore assumed that as fines are introduced, they can be heated to 1000°K by the hydrogen in a reasonably short time period.
5. The vapor-phase electrolysis cells operate essentially isothermally.

12.5.4 EQUIPMENT SIZE

1. Fluidized bed reactor: A residence time of one hour is estimated for the lunar fines. Therefore, the volume of fines in the reactor is about 27 ft^3. This must be multiplied by a factor of about two in order to account for the fluidization expansion [6]. In order to minimize plant height which we think will be a handicap on the lunar surface, the reactor has the following approximate dimensions: 5 feet high by 4 feet in diameter.

   The reactor is equipped with a line for recycling hydrogen and water as needed to maintain space velocity or to increase contact time in the reactor. Fluidization velocity on the moon should be about 41% ($\sqrt{1/6}$) of that required on the earth.
2. Vapor-phase electrolysis cells: To produce 66 lb oxygen per hour, about 130 kw electricity will be needed. The cells will be grouped in series to raise the voltage to a level that is compatible with the generator and other colony needs for electricity. About 40 ft^2 of cell surface area is needed and this could be provided by a battery of about 50 cells 1 inch in diameter and 3 feet long.
3. Pipe sizes: The heated gas (1500°K) to the reactor will be the largest volume flow in the plant. If one atmosphere pressure is maintained, almost 40,000 ft^3 per hour gas flow will be necessary. If the gas velocity is 20 fps, a pipe roughly 10 inches in diameter will be needed. In an actual plant, this can probably be reduced by increasing

velocity or pressure.

12.5.5 PROBLEM AREAS

1. The area which we feel needs to be given the largest amount of engineering-hardware design consideration is the input and outlet of fines from the reactor. This is not a unique problem with hydrogen reduction and will have to be solved for any oxygen process. The airlocks and valving must be designed to allow entry and exit of lunar fines while preventing hydrogen loss (or minimizing hydrogen loss). While the lunar fines are fairly uniform in particle size, the temperature near the airlocks is about 1000°K. It is suggested to attempt to lower the temperature at the valves and use double valving with automatic piston pump-down techniques to evacuate the airlocks. Conventional techniques for continuous feed, steady-state operation of fluidized beds will provide a starting point for the design.
2. Solar heating of the hydrogen to 1500°K needs detailed design. Materials of construction need careful consideration.
3. Actual fluidization of the lunar fines is not considered to be a problem around 1000°K. However, it will be necessary to carefully determine at exactly what temperature the lunar fines tend to agglomerate when not fluidized, e.g., when removing them from the reactor. Temperatures down as low as 800°K may be necessary to maintain the finely divided solid state.
4. Operating parameters and life time of the vapor electrolysis cells should be investigated. Optimal pressure levels on the cells should be determined. A long life is anticipated but this should be investigated. The cells are relatively light weight and could possibly be replaced if necessary.

12.5.6 THE OXYGEN PLANT AND A LUNAR COLONY

We believe a full-scale plant could be delivered to the moon partly disassembled in the tug system described in Chapter 5 of this report. The plant could be skid mounted and transported to the desired site.

A work force of three men could then deploy the solar furnace and connect the plant to the electric power system. A gaseous oxygen pipeline would also have to be constructed to connect the plant with the tug fuel storage area where liquefaction would take place. Oxygen for life support needs would be compressed and stored as a gas. Water could also be produced and stored as needed. Hydrogen-makeup tankage would be adjacent to the plant.

In operation, it is anticipated that the plant would be computer controlled and fully automatic with operator attention directed towards solids-handling operations.

12.6 OXYGEN LIQUEFACTION AND STORAGE

The majority of oxygen produced by the lunar colony plant will be used as tug fuel. This oxygen will need to be liquefied and stored so that it can be pumped aboard the tugs conveniently. Life support makeup oxygen will probably be compressed and stored in pressure vessels near the colony.

The oxygen transportation, liquefaction, and storage system that seems best suited for the lunar colony tug system is based on a liquefaction plant and cryogenic storage vessel brought from earth. The liquefaction plant and storage tank will be fitted into a 15 by 30 foot canister module. The module can be buried at a safe distance from the tug landing area. But, it should be close enough to permit pumping the liquid oxygen to the tugs. Gaseous oxygen will be piped to the canister from the oxygen production plant. Electrical power will need to be provided and a radiator deployed.

The self-contained system could be completely assembled and tested on the earth before delivery. Maintenance work on the compressor and other components inside a pressurized canister could be in a shirt sleeve environment. Also, storage and liquefaction capacity could grow in modules as needed. In summary, the canister system offers many advantages other storage systems do not have [7].

REFERENCES

1. Downs, W. R., "Oxygen and Water from Lunar-Surface Material", NASA TMX-58061, June, 1971.

2. Battey, R. V. (Chairman), "Minutes MSC Lunar Colony Functional Analysis Team", Jan-Feb, 1972.

3. Kubaschewski, O., et al, Metallurgical Thermochemistry, Pergamon Press, New York, 1967.

4. Rosenberg, S. D., et al, "Manufacture of Oxygen from Lunar Materials", Annals of the New York Academy of Sciences, Vol. 123, pp. 1106-1122.

5. Mrochek, J. E., "The Economics of Hydrogen and Oxygen Production by Electrolysis and Competitive Processes", Abundant Nuclear Energy Symposium. Gatlinburg, Tennessee, Aug 26-29, 1968, pp. 107-122.

6. Perry, John (editor), Chemical Engineer's Handbook, 4th edition, 1963.

7. Davis, M. L. and Allgeier, R. K., "The Development of Cryogenic Storage Systems for Space Flight", NASA SP-247, 1970.

CHAPTER 13 LIFE-SUPPORT SYSTEM

13.1 INTRODUCTION AND SUMMARY

Life-support systems for space application have, in general, relied upon a storage system for certain life-support needs. This system has been successfully applied for missions of short duration. However, for lunar-colony development consistent with discussed growth philosophy, the weight and volume requirements for resupply of selected life-support needs would be inappropriate. Thus, it may be safely stated that the ultimate desired result of life-support system development for the lunar colony is to progress from a partially closed life-support system to a closed life-support system. For the lunar colony, two main objectives must be achieved if the colony is to have a closed life-support system. They are the following:

1. Food production techniques in the form of plants, animals, and/or synthetic foods on the lunar colony surface must be achieved.
2. Maximum potential utilization of wastes for closure of the food-waste loop must be realized.

The most important element of a life support system is man himself. His preservation in a lunar-colony environment is the main objective of the life-support system. For this reason, planned redundancy should be an elemental part of the life-support system design.

The attainment of a closed life-support system for the lunar colony is envisioned to proceed in two phases of development. During the first several generations of lunar colony manpower growth, an extensive lunar-based research and development program will be oriented to realizing the viability of plant production, animal support, closure of the food-waste complex, and use of food-synthesis techniques. Life-support needs (food, nitrogen, etc.) will in part be provided by earth resupply. Also, waste recycling will be minimized. This will require a waste-processing technique which will effectively sterilize the wastes. This period of development will be referenced in subsequent discussions as Phase I.

Assuming the solutions to the problems associated with lunar food production and nutrient-waste complex closure have been obtained, a closed life-support system would be ready for implementation. A second period of development is then envisioned during which complete conversion to a closed life-support system with nominal resupply will occur. This period is termed Phase II.

As a result of this study, two life-support configurations evolved; that is, Phase I and Phase II configurations. The Phase I configuration is a regenerative integrated life-support system which will support the lunar-colony personnel. The development of this configuration assumed state-of-the-art achievable concepts by 1985 to 1990. Most of the selection subsystems for the lunar-colony life-support system will require comprehensive manned-system testing in addition to fundamental research and development efforts. The subsystem concepts which make up the Phase I configuration are shown in Figure 13.1-1.*

The Phase II configuration is shown in Figure 13.2-2. Many of the subsystems shown in the figure are the same as those in the Phase I configuration. The important characteristics of this configuration are that

1. plants, animals, and synthetic foods are incorporated as part of the food provision scheme for man, and
2. maximum utilization of processed man, plant and animal wastes is implied.

*Symbol notation for subsequent figures is presented at the end of the chapter (Figure 13-1).

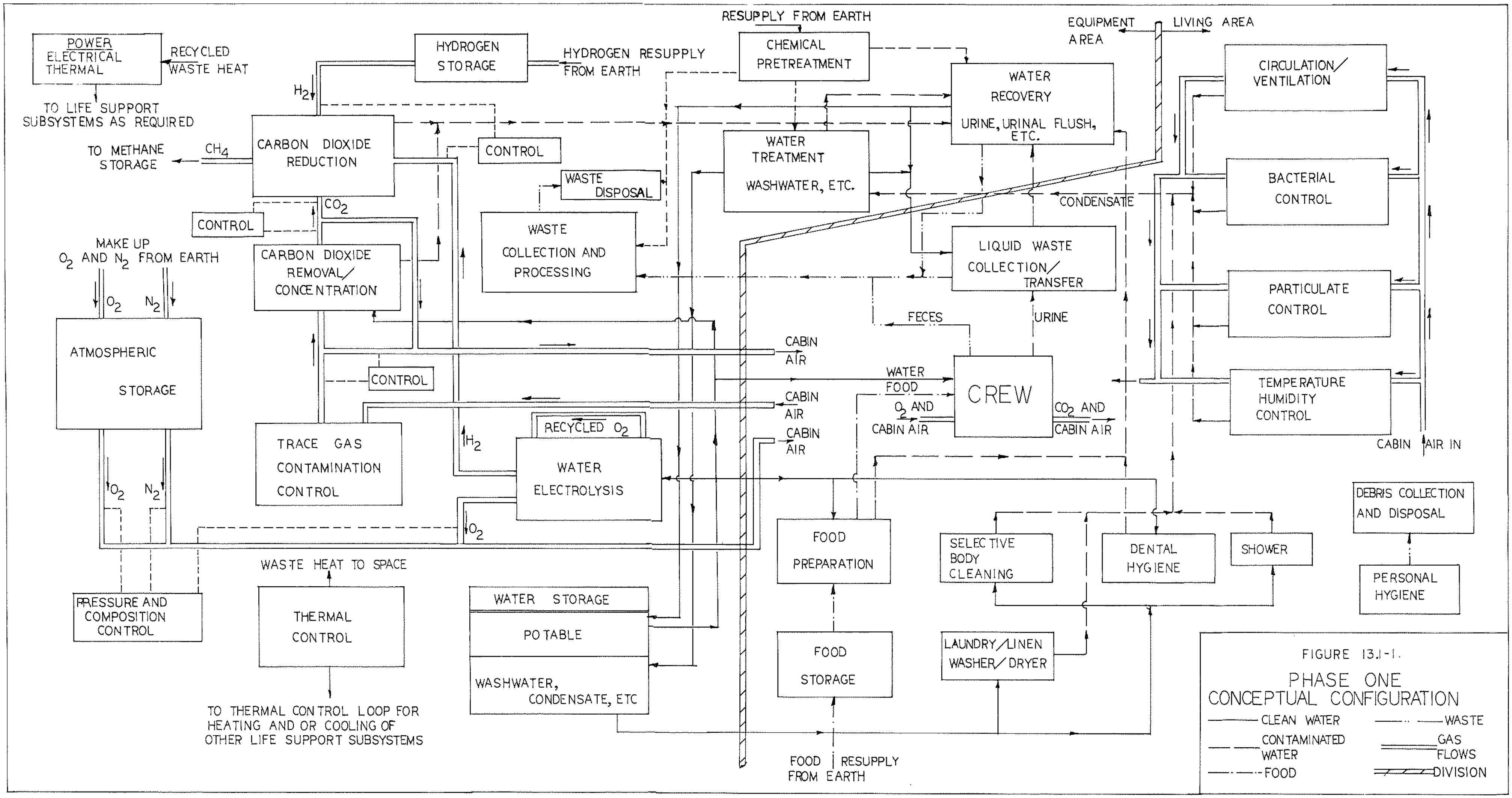


FIGURE 13.1-1.
PHASE ONE
CONCEPTUAL CONFIGURATION

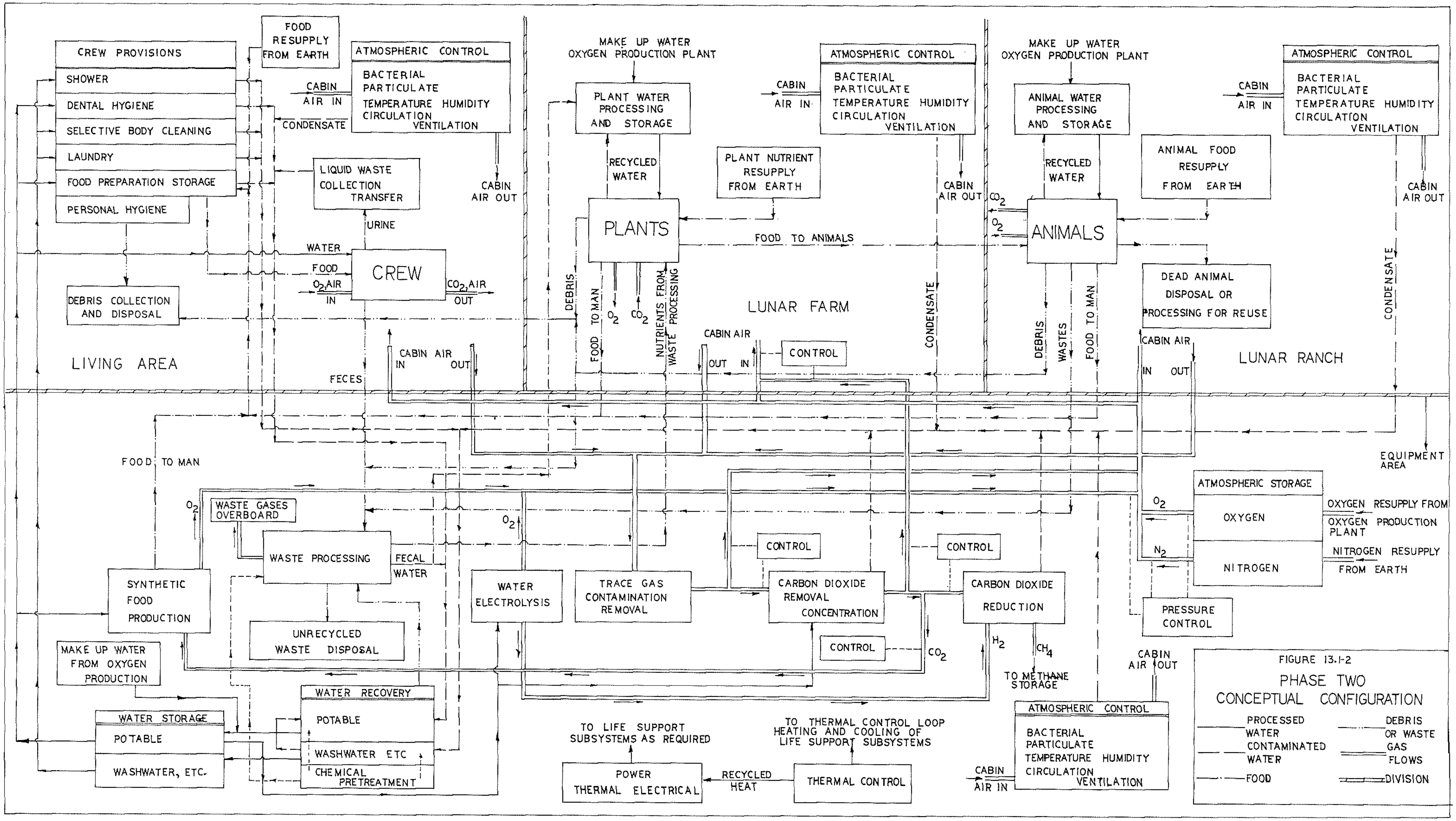


FIGURE 13.1-2
PHASE TWO
CONCEPTUAL CONFIGURATION

It was felt that selection of a particular subsystem for food provision or waste-processing subsystems for Phase II would serve no useful purpose except demonstrate personal bias.

Therefore, it was determined as our objective to limit our discussions to known or projected candidate subsystems, delineating in detail the exhibited or envisioned capability of these subsystems to satisfy lunar-colony Phase II growth requirements; that is, closure of the lunar-colony life-support system by achieving

1. lunar food production capability, and
2. closure of the food-waste complex.

This approach allowed the development of a basic set of research and development recommendations for life-support subsystem implementation in lunar colony configuration. These recommendations are summarized in Chapter 19.

The remainder of this section is devoted to discussion of (1) the basic study approach used to achieve the final two configurations, (2) the generation and the selection of the most viable subsystem candidates, (3) the integration of these viable subsystem candidates into conceptual configurations for life-support systems for Phase I and Phase II.

13.2 DEVELOPMENT AND SELECTION OF LIFE-SUPPORT SUBSYSTEMS

13.2.1 STUDY APPROACH

In order to evolve a system overview as early in the study as possible, a search was made to determine the functions served by a life-support system. The result was an expanded form of the functional analysis presented in an earlier chapter. Figure 13.2.1-1 is the result of that initial effort.

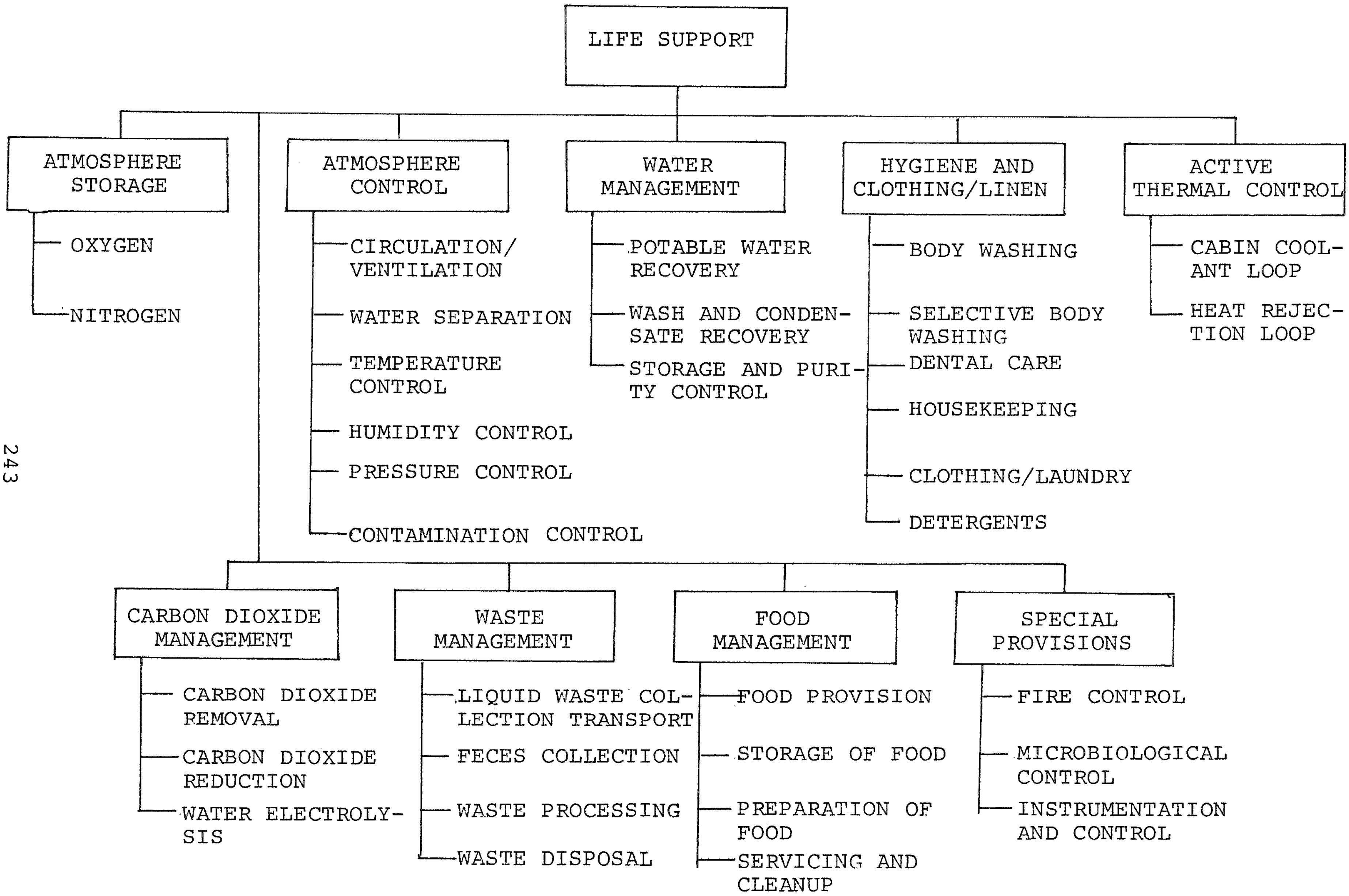


Figure 13.2.1-1 Functional Analysis for Life Support System

The second step was the development of guidelines for each of the subsystems presented in the functional analysis in addition to the guidelines presented in Chapter 9. Table 13.2.1-1 represents a summary of these guidelines for the various life-support subsystems. Note that in some cases two sets of guidelines are presented for a subsystem. This is required by the different life-support system configurations for Phases I and II.

Selection of subsystem candidates for Phase I and Phase II configurations was based on trade-off studies using the evaluation scheme presented in Chapter 11. Also, much reliance was placed upon trade-off studies for life-support systems performed by other groups. In particular, studies by North American Rockwell [1] and Hamilton Standard [25], with various reports and/or symposiums [2, 3, 18] were referenced heavily. In many cases, the results of trade-off studies prepared by these references for life-support subsystems were adopted for lunar-colony configurations. The general approach to select subsystems for lunar-colony life-support functions was to

1. search the literature for candidate subsystems to perform various life-support functions,
2. perform a quick trade-off study to determine which candidate subsystems could be eliminated at the absolute and primary evaluation levels, and
3. select the most aparent viable subsystem candidates based on trade-off studies at the secondary level.

The final step in the study approach was integration of these subsystems into Phase I and Phase II conceptual configurations.

13.2.2 SUMMARY OF RESULTS

The results of the studies described above are summarized in Tables 13.2.2-1 through 13.2.2-4 and Appendix B. Table 13.2.2-1 summarizes the candidate subsystems for the various life-support

Table 13.2.1-1

Summary of Function Requirements for Life Support Subsystems

Function	Requirements
Atmospheric Storage	Provide back-up oxygen, nitrogen (also hydrogen for CO_2 management subsystem) for atmospheric supply (leakage and repressurization)
	For oxygen supply, use more than one tank since tank failure can be catastrophic
	Use at least one redundant nitrogen tank suggested
Atmospheric Control	
Circulation/Ventilation	Distribution and collection of thermal and humidity control air, carbon dioxide production and trace contaminant, particulate and bacteria control flow
	Avoidance of hot and cold spots
	Provide metabolic cooling convection currents
	Avoidance of water vapor, carbon dioxide and trace gas pockets due to low diffusion rates
	Low noise level and least disturbance to crew
	Air flows of 15.3 m/min (50 fpm) [1]
Water Separation	For use in separating water from gases in conjunction with heat exchangers, humidity control, etc..
	Requirements vary depending on amount of liquid to be removed. Unfortunately commonality not feasible [25]
Temperature/ Humidity Control	Cabin temperatures must be maintained between approximately 18 to 24°C.

Table 13.2.1-1 (Continued)

Function	Requirements
	Humidity range of 55 $\pm$ 5 percent is required
	Must process fairly high air-flow rates
Pressure Control	Must maintain O_2 partial pressure of 160 mm Hg (3.5 psia). May not be necessary for plants
	Nitrogen used as dileut gas with possible variable pressure requirements
	Must provide for cabin leakage, repressurization and make-up supplies of O_2
Contamination Control	Maintain and limit concentration of trace gases, such as ammonia and acid gases
	Maintain and limit concentrations of biological microorganisms
	Maintain wet and dry particulate matter at acceptable levels
	Provide mechanisms for dust control during ingress/egress operations
Carbon-Dioxide Management	Removal of carbon dioxide from cabin atmosphere to maintain a nominal CO_2 partial pressure of 4 mm Hg
	Regenerate oxygen from carbon dioxide through water electrolysis if needed
	CO_2 production rate variable depending on metabolic activities
	Must interface with plant subsystem
	Purity of concentrated $CO_2 \geq 98$ percent
Food Management	Metabolic requirements are covered in chapter on habitability
	Provision must be made for storage of frozen foods, freeze-dried foods and canned foods

Table 13.2.1-1 (Continued)

Function	Requirements
	Adequate arrangements must be made for preparation of food
	Associated housekeeping activities with food management must provide for contaminant control
	Acceptability of foods and associated food management areas to man must be high
Waste Management	Phase I Requirements
	Collect, treat and/or dispose of all solid and liquid wastes
	Eliminate odors, aerosols and gases
	Sterilize waste matter to inhibit or eliminate microorganism production prevent production of undesirable gases prevent crew contamination
	Reduce disposal mass and volume
	System must be flexible enough to handle a variety of wastes such as feces, urine, unused food, biodegradable solid debris, urine sludge, vomitus, etc.
	Man's contact with the waste management system should be limited for psychological and physiological reasons
	Rapid collection and treatment of urine required to prevent ammonia production
	Phase II Requirements
	Phase II requirements are essentially the same as Phase I except that the waste is now processed for nutrient recovery. However, minimal contact by man is again stressed. The subsystem for waste processing will be

Table 13.2.1-1 (Continued)

Function	Requirements
	different than that used in Phase I. However, the Phase I subsystem will be used as backup.
Water Management	Any water produced by subsystem must be sterile, free of organic and inorganic toxic matter and free of pathogenic organisms.
	Stored water must remain sterile
	Servicing of equipment should not contaminate water, crew or atmosphere
	A system for rapid sterilization must be provided in case of contamination of water management subsystem
	Water must be delivered at proper temperature
	A contaminant monitoring system must be provided
	Chemical pretreatment should be provided
Hygiene	
Whole Body Cleaning	Must remove body surface contaminants
	Must leave skin dry with satisfactory bactericidal properties
	Process must be psychologically acceptable
Dental Hygiene	Water used for cleaning shall not contain bacteria
	Process must maintain teeth free of cavities, reduce plaque buildup and prevent gum deterioration
Selective Body Cleaning	Technique should be flexible enough to allow cleaning of all parts of body area
	Technique used should not contain potential for bacterial contamination
Housekeeping	Must provide for microbiological control

Table 13.2.1-1 (Continued)

Function	Requirements
	Must control any particulate matter released
Clothing (Laundry)	
Type	Clothing must be reusable
	Clothing must be comfortable
	Clothing must provide proper insulation
	Clothing must be compatible with chosen atmosphere
Laundry Management	Process used must adequately cleanse clothing, reusable wipes to free clothing of dirt, bacteria, etc.
	Process must also dry clothing
Detergents	In general a cleansing agent is needed for body washing, clothes washing, dish washing, and general cabin cleaning tasks. Other requirements are [25] the following
	Good surfactant
	Good bacterial action
	Nonflammable to itself or clothing
	Low foaming
	Nonclogging to water-management system membrane
	Nonprecipitating
	Nonallergenic
	Nontoxic
	Non gas or odor producing
	Effective in low concentrations

Table 13.2.1-1 (Continued)

Function	Requirements
Special Provisions	
Fire Protection Control	System should provide for prevention of ignition Selection of nonflammable or fire retardant materials Eliminate ignition sources System should provide for defensive capability Minimize propagation Maximize detection Extenguishing capability Recovery plan
Microbiological Control	System must provide for destruction, elimination or reduction of microorganisms to levels which maintain good health and well being of flight personnel A detection system must be provided to determine presence, concentration, and viability of microorganisms.
Instrumentation and Control	Must provide necessary instruments and sensors, with appropriate signal conditioning and controls, to provide the capability of controlling, monitoring, locating and analyzing problems of the operation of the life-support systems Number of sensors will be a function of the data requirements for control, fault detection alarm, fault isolation, crew readout and telemetry

Table 13.2.2-1

Summary of Candidate Subsystem

Concepts for Life-Support Functions

Function	Candidate Concepts
Atmospheric Storage	
Oxygen	High pressure gaseous storage Steel tankage or filament-wound tankage High pressure gaseous storage with an oversized electrolysis unit Steel tankage or filament-wound tankage Solid cryogenic storage Cryogenic storage Subcritical with positive expulsion Subcritical thermal pressurization Supercritical with thermal pressurization Chemical storage Alkali and alkaline earth peroxides and superoxides Chlorate candles Catalytic decomposition of H_2O_2
Nitrogen	High pressure gaseous storage Titanium tankage or filament wound tankage Chemical storage Catalytic decomposition of nitric oxide Hydrazine/nitrogen tetroxide reaction Cryogenic storage Subcritical with positive expulsion Subcritical with thermal pressurization Supercritical with thermal pressurization
Atmospheric Control	
Circulation/Ventilation	Fans-distribution ducts
Water Separation	Inertial Concepts Motor driven centrifugal Air turbine centrifugal Vortex centrifugal Capillary Integral wick with heat exchanger Face wick on heat exchanger Membrane devices Combined Porous plate labyrinth Elbow/wick Hydrophobic/hydrophilic screen

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
Temperature/Humidity Control	Air reheat with integral wick, face wick or free moisture separator Variable speed fan with integral or face wick Air bypass with integral or face wick Separate condensor and cooler with integral wick, face wick, or free moisture separator
Pressure Control	Regulator valves and automatic control
Contamination Control	
Trace-Gas Control	Regenerable charcoal/catalytic oxidation Catalytic oxidation/sorption Nonregenerable charcoal/catalytic oxidation
Bacterial Control	Filtration and filter storage Electrostatic precipitation Impingement Air Centrifuge Electrophoresis
Particulate Contamination	Particulate filters or screens
Dust Control	Venturi-Scrubber Centrifuge-electrostatic precipitation Centrifuge filter Air jet wash and multifiltration
Carbon-Dioxide Management	
Carbon-Dioxide Removal/Concentration	Molecular sieve Solid Amine Steam desorbed resin Electrodialysis Carbonation cell Hydrogen depolarized concentrator Membrane diffusion Liquid adsorption Mechanical freezeout Chemical scrubbers

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
Carbon-Dioxide Reduction	Fused salt Solid electrolyte Bosch reactor Sabatier reactor-methane cracking Sabatier reactor-methane utilization Sabatier reactor-acetylene dump Molten carbonate
Water Electrolysis	Cabin air unit Wick feed Circulating electrolyte Gas circulation Solid polymer Rotating Porous electrode cell Double membrane cell Hydrated phosphorous pentoxide matrix cell
Food Management	
Food Provision	Resupply from earth (dried, frozen, freeze dried, liquid, chemical) Biological Foods (Phase II) Hydrogen bacteria Fungi Algae Higher Plants Animals Multispecies climax ecosystem Physicochemical Synthesis (Phase II) Carbohydrate Protein Fat
Food Storage	Refrigerator/Freezer Concepts Space radiator Thermoelectric system Turbo-compressor/air cycle system Ambient Storage Storage locker/room Flexible storage
Food Preparation (Heating Concepts)	Hot air convection heating oven Microwave heating oven Self-heating food package Combination hot air convection and resistance heating oven

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
	Electrically heated food tray Combination microwave and resistance heating oven
Food Serving	Eating in galley Steward service Self-serving

Food Cleanup	Sanitary wipe concepts
	    Reusable galley/dining area wipes
	    Disposable galley/dining area wipes
	    Disposable/reusable personal wipes
	Wipe dispenser concepts
	    Reusable wipe dispenser
	    Disposable wipe dispenser
	Soiled wipe storage concepts
	    Temporary storage of reusable soiled wipes
	    Temporary storage of debris and waste foods
	Utensil washing concepts
	    Automatic dishwasher/dryer
	    Galley sink hand/utensil washer

Inventory Control	Food recording
	    Manual recording
	    Small bookkeeping machine
	    Computer recording (data management)

Waste Management (Metabolic)	
Liquid Waste Collection and Transport	Collector/bladder with manual transfer Liquid/gas flow with sponge/bladder pressurized transfer Liquid/gas flow with centrifugal phase separation transfer
Feces Collection	Bag system with manual or mechanical transfer Dry tank system Dry tank system with anal spray Wet system with waste H_2O slurry Wet system with reclaimed H_2O slurry
Waste Processing	Activated sludge-anaerobic digestion (Phase II) Trickling filter (Phase II) Composting (Phase II) Oxidation ponds (Phase II)

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
	Liquid-germicide addition Irradiation (Phase I) Integrated vacuum drying Integrated vacuum decomposition Flush-flow oxygen incineration Pyrolysis/batch incineration Wet oxidation Steam reformation
Disposal of Wastes	Storage Dump Recycling (Phase II)
Water Management	
Potable Water Recovery	Vacuum distillation/compression Vacuum distillation/thermoelectric Vacuum distillation/pyrolysis Flash evaporation/pyrolysis and flush evaporation/compression/pyrolysis Closed cycle air evaporation Open cycle air evaporation Vapor diffusion and vapor diffusion/compression Electrodialysis
Wash and Condensate Recovery	Reverse osmosis Multifiltration
Storage and Purity Control	Bladder tanks with high temperature for purity control Bladderless tanks with high temperature for purity control
Hygiene	
Whole Body Cleaning	Shower Reusable or disposable body wipes Automatic sponge Immersion bath Sauna
Dental Hygiene	Toothbrush, liquid dentrifices and associated water delivery and waste collection units
Selective Body Cleaning	Reusable body wipes

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
Housekeeping	
Tools, small parts cleaning, microbiological control	Wet or dry heat Ultraviolent radiation Chemosterilants
Cleaning and control of microbiological contamination	Disinfectants Biocidal aerosols Vacuum cleaning
Clothing and Linens (Laundry) Management	Disposable Reusable Laundry system concepts Diaphragm actuated washer/dryer Reciprocating washer/dryer Oscillatory system-water solvent Rotary system-hydrocarbon solvent Rotary system-water solvent Hand laundry concepts Manual clothes washing device Flexible water bag
Detergents	Anionics Cationics Nonionics
Active Thermal Control	
Cabin coolant loop heat rejection loop	Use of heat transport fluid circuit, cold-plates (for equipment) and space radiators
Special Provisions	
Fire Protection Control	Water Straight stream Water fog Water (protein form) Water (high expansion foam) Water (methyl cellulose foam) Carbon dioxides Nitrogen Liquid nitrogen Dry chemicals Freon 1301 Decompression

Table 13.2.2-1 (Continued)

Function	Candidate Concepts
Microbiological Control	Filters and/or filtration Biocides Heat, wet and dry Pyrolysis Sterilization Use of nonbiodegradable material Ultraviolent radiation Immunization Medicines and drugs Biocidal soaps and lotions
Instrumentation and Control	Fully automatic control

Table 13.2.2-2

Summary of Viable Candidate Subsystems

Function	Candidate Concepts
Atmospheric Storage	
Oxygen	High pressure gaseous storage Steel tankage of filament-wound tankage High pressure gaseous storage with an oversized electrolysis unit Steel tankage or filament-wound tankage Cryogenic storage Subcritical thermal pressurization Supercritical with thermal pressurization
Nitrogen	High pressure gaseous storage Titanium tankage or filament-wound tankage Cryogenic storage Subcritical with thermal pressurization Supercritical with thermal pressurization
Atmospheric Control	
Circulation/Ventilation	Fans-distribution ducts
Water Separation	See Table 13.2.2-4
Temperature/Humidity Control	Air reheat with face wick for water separation Air bypass with both integral wick and face wick combinations Variable speed fan with both integral wick and face wick combinations
Pressure Control	Regulator valves
Contamination Control	
Trace-Gas Control	Regenerable charcoal/catalytic oxidation Catalytic oxidation/sorption
Bacterial Control	Filtration and filter storage
Particulate Contamination	Particulate filters or screens

Table 13.2.2-2 (Continued)

Function	Candidate Concepts
Dust Control	Air-jet wash and multifiltration
Carbon-Dioxide Management	
Carbon-Dioxide Removal/Concentration	Steam-desorbed resin Hydrogen-depolarized concentrator Membrane diffusion Molecular sieve
Carbon-Dioxide Reduction	Solid electrolyte Bosch reactor Sabatier reactor - methane dump
Water Electrolysis	Gas circulation Solid polymer Wick feed Circulating electrolyte Double membrane cell
Food Management	
Food Provision	Resupply from earth (dried, frozen, freeze dried, liquid, chemical) Biological Foods (Phase II) Hydrogen bacteria Fungi Algae Higher Plants Animals Multispecies climax ecosystem Physicochemical Synthesis (Phase II) Carbohydrate Protein Fat
Food Storage	Refrigerator/Freezer Concepts Turbo-compressor/air cycle system Ambient storage Storage locker/room Flexible storage
Food Preparation (Heating Concepts)	Combination microwave and resistance heating oven
Food Serving	Self-serving (Phase I) Steward service (Phase II)

Table 13.2.2-2 (Continued)

Function	Candidate Concepts
Food Cleanup	Sanitary wipe concepts Reusable galley/dining area wipe Reusable personal wipes Wipe dispenser concepts Reusable wipe dispenser Soiled wipe storage Temporary storage of reusable soiled wipes Temporary storage of debris and waste foods Utensil washing concepts Automatic washer/dryer Galley sink hand/utensil washing
Inventory Control	Tie in to data management
Waste Management (Metabolic)	
Liquid-Waste Collection and Transport	Liquid/gas flow with centrifugal phase separation/transfer
Feces Collection	Dry tank system Dry tank system with anal spray Wet system with waste H_2O slurry Wet system with reclaimed H_2O slurry
Waste Processing	Activated sludge-anaerobic digestion Trickling filter Liquid germicide addition Integrated vacuum drying Integrated vacuum decomposition Pyrolysis/batch incineration Wet oxidation Steam reformation
Disposal of Wastes	Storage Dump Recycling
Water Management	
Potable-Water Recovery	Vapor diffusion Vapor diffusion/compression
Wash-and-Condensate Recovery	Reverse osmosis

Table 13.2.2-2 (Continued)

Function	Candidate Concepts
Storage and Purity Control	Bladderless tanks with high temperature for purity control
Hygiene	
Whole Body Cleaning	Shower
Dental Hygiene	Toothbrush, liquid dentrifice and associated water delivery and waste collection units
Selective Body Cleaning	Reusable body wipes
Housekeeping	
Tools, small parts cleaning, microbiological control	Dry heat (autoclave or oven)
Cleaning and control of microbiological contamination	Vacuum cleaner for dry contaminants Reusable wet wipes with detergent and disinfectant
Clothing and Linens (Laundry) Management	Reusable Laundry System Concepts Automatic laundry-rotary-water solvent
Detergents	Nonionics
Active Thermal Control	
Cabin Coolant loop heat-rejection loop	Use of heat transport fluid circuit, coldplates (for equipment) and space radiators
Special Provisions	
Fire Protection Control	Water Straight stream penetration of solids Water fog High expansion foam-total cabin flooding Methyl cellulose foam-for equipment and equipment bays Freon 1301 - explosion suppression

Table 13.2.2-2 (Continued)

Function	Candidate Concepts
Microbiological Control	All candidates may be viable depending upon application [See appropriate discussion]
Instrumentation and Control	Data Management System

Table 13.2.2-3

Summary of Candidate Subsystems Eliminated at Absolute and Primary Levels

Function	Candidate Subsystem	Explanation
Atmospheric Storage		
Oxygen	Solid cryogenic storage	Problems associated with transportation of solid cryogenic oxygen. Rejected on basis of performance.
	Cryogenic - Subcritical with positive expulsion	Problems associated with hardware operating at cryogenic temperatures for extended periods of time. Rejected on basis of performance for amounts needed.
	Chemical storage	
	Alkali and alkaline earth peroxides and superoxides	Technique does not encourage a closed life-support system. Rejected on basis of performance
	Chlorate candles	Concept requires a large amount of crew time for maintainability. Also, candles are a large resupply item. Rejected on basis of maintainability.
	Catalytic decomposition of H_2O_2	H_2O_2 vapors represent a potential safety hazard. Rejection on this basis.
Nitrogen	Chemical storage	
	Catalytic decomposition of nitric oxide	Only a theoretical concept. No real evidence reaction will occur. Rejected on performance level.

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
	Hydrazine/nitrogen tetroxide reaction	At present state of development represents a crew safety hazard because of presence of NH_3. Rejected on basis of safety. If this problem is solved, the concept may become viable.
	Cryogenic storage - subcritical with positive expulsion	See oxygen discussion
Atmospheric Control		
Temperature/Humidity Control	Air reheat with integral wick and free moisture combinations	Potential operational maintenance problems with temperature control valves. Rejected on basis of maintainability.
	Separate condensor and cooler	System is subject to upset by fluctuations in dew point temperature. Rejected on basis of reliability. However system is widely used. Weight penalties may also prove prohibitive (number of heat exchangers required).
Contamination Control		
Trace-Gas Control	Nonregenerable charcoal/catalytic oxidation	System possesses bacterial contamination potential, high resupply required, maintenance requirements high Therefore rejected on safety, resupply and maintenance bases
Bacterial Control	Electrostatic precipitation Impingement	See discussion in Section 16.2.2.3.

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
	Air centrifuge Electrophoresis	See discussion in Section 16.2.2.3.
Dust Control	Venturi Scrubber	This system requires a water-dust separator on which no development has been done. Also, associated equipment with this concept is complex. Rejected on basis of poor performance.
	Centrifuge - electro-static precipitator Centrifuge filter	System operation complex when compared with other options. Rejected on basis of poor performance. Also, much developmental work needed.
Carbon-Dioxide Management		
Carbon-Dioxide Removal/Concentration	Solid amine	Possible safety hazard due to amine carryover. Also, some doubt about life of chemical beds used in process. Rejected on basis of lack of confidence in performance.
	Electrodialysis	Maintainability requirements very high. Also, possible explosion hazard. Rejected on basis of maintenance time required.
	Carbonation cell	High predicted rate of component failure. Also maintenance problems associated with corrosive liquids. Rejected on basis of poor reliability/maintainability.
	Liquid adsorption	Maintenance problems associated with corrosive liquids. Rejected on basis

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
		of maintainability.
	Mechanical freezeout	High predicted rate of component failure. Also, a large resupply item. Rejected on basis of reliability and resupply criteria.
	Chemical scrubbers	High resupply item. Rejected on this basis.
Carbon-Dioxide Reduction	Fused salt	Possibility of carbon monoxide generation. Also, the projected availability is low [25] and is rejected on this basis.
	Sabatier reactor-methane cracking Sabatier reactor-acetylene dump	In both these concepts, high temperatures along with flammable gases presents a potential safety hazard. When compared to other processes, rejected on safety basis.
	Molten carbonate	Possibility of CO_2 regeneration. Lack of confidence in performance. Rejected on this basis.
Water Electrolysis	Cabin air unit	High predicted rate of component failure. Rejected on basis of reliability.
	Rotating	Potential for electrolyte carry-over, leakage, spillage and therefore rejected on lack of confidence in performance.

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
	Porous electrode cell	Performance of concept questionable due to gas-liquid interface problems. Rejected on basis in lack of confidence in performance.
	Hydrated phosphorus pentoxide matrix cell	Cathode problems expected in operation. Rejected on basis of lack of confidence in performance.
Food Storage	Refrigerator/Freezer Concepts	
	Space radiator	Based on recommendation by Whirlpool Corporation [1]
	Thermoelectric system	
Food Preparation (Heating)	Hot air convection heating oven	
	Microwave heating oven	
	Self-heating food package	Based on Recommendation by North American Rockwell [1]
	Combination hot-air convection and resistance heating oven	
	Electrically heated food tray	
Food Serving	Eating in galley	Incompatible with lunar-colony growth

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
Food Cleanup	Disposable galley/dining area wipes and disposable personal wipes	Incompatible with concept of minimal resupply
	Disposable wipe dispenser	Not needed on basis of above rejection
Inventory Control	Manual recording Small bookeeping machine	Eliminated on basis of comparative performance
Waste Management (Metabolic)		
Liquid-Waste Collection and Transport	Collector/bladder with manual transfer	Eliminated due to psychological disadvantage of handling wastes.
	Liquid/gas flow with sponge/bladder pressurized transfer	Materials selection for sponge/bladder arrangement critical. Possible contamination. Rejection on basis of poor performance when compared to selected technique.
Feces Collection	Bag system with manual or mechanical transfer	Eliminated due to psychological disadvantage of handling wastes and/or potential of contamination.
Waste Processing	Composting	Eliminated due to possible survival of pathogens in process.
	Oxidation ponds	Eliminated due to large volume requirements and poor interfacing.
	Irradiation	Manual transfer operations required. Due to high potential contamination to crew, concept eliminated on safety basis.

Table 13.2.2-3 (Continued)

Function	Candidate System	Explanation
	Immersion bath Sauna	Although the shower has higher weight and power penalities than the other concepts, it is selected on basis of crew acceptability.
Housekeeping		
Tools, small-parts cleaning, micro-biological control	Ultraviolent radiation Chemosterilants	Both possess capability for bio-logical contamination on toxicity. Rejected on basis of poor safety characteristics.
Cleaning and control of micro-biological contam-ination	Biocidal aerosols	Biocidal vapors can cause pulmonary disorders if inhaled by man. Re-jected on basis of poor safety characteristics
Clothing	Disposable	Incompatible with resupply requirements
	Laundry system concepts	
	Automatic laundry systems	
	Diaphragm actuated washer/dryer Reciprocating washer/dryer	Rejected on basis of poorer perfor-mance relative to rotary system with water solvent. Chosen system has lower water and power requirements.
	Oscillatory system water solvent	
	Rotary system-hydro-carbon solvent	

Table 13.2.2-3 (Continued)

Function	Candidate Subsystem	Explanation
	Flush-flow oxygen incineration	High operating temperatures imply disadvantages for reliability and safety of unit. Eliminated for not satisfying reliability criteria.
Water Management		
Potable-Water Recovery	Open-cycle air evaporation	High potential for bacterial contamination. Rejected on basis of safety.
	Vacuum-distillation concepts Flash-evaporation concepts Electrodialysis Closed-cycle air evaporation	The most important requirement of a water reclamation system is production of potable water, chemically and microbiologically. These concepts compared with the vapor diffusion concepts are expected to produce a less potable water [25].
Wash and Condensate Recovery	Multifiltration	Multifiltration is only satisfactory for condensate recovery [25]. Therefore, it has been rejected on basis of performance when compared to reverse osmosis.
Storage and Purity Control	Bladder tanks with high temperature for purity control	Probability of a high need for redundancy of tanks since bladders represent an additional mode of failure. Rejected on basis of poor performance.
Hygiene		
Whole Body Cleaning	Reusable or disposable body wipes Automatic sponge	Strictly from the point of view of psychological acceptibility the shower is superior. Also, the shower will cleanse more thoroughly.

Table 13.2.2-3 (Continued)

Function	Candidate System	Explanation
	Hand-washing concepts	Poor reliability. Also requires too much crew time.
	Manual clothes washing	
	Flexible water bag	
Detergents	Anionics	Foaming characteristics cause rejection on performance level.
	Cationics	Not a good detergent. Rejected on basis of performance.
Special Provisions		
Fire-Protection Control	Carbon dioxide	
	Nitrogen	Fire protection control methods chosen on basis of recommendations by Hamilton Standard [25]
	Liquid nitrogen	
	Dry chemicals	
	Decompression	

Table 13.2.2-4

Summary of Selected Subsystems

Function	Selected Concept	Reason(s) for Selection
Atmospheric storage	Filament-wound high-pressure gaseous storage for oxygen, nitrogen and hydrogen.	Interfaces well with candidate subsystems for oxygen production Repressurization occurs more rapidly than other subsystems High pressure storage systems less subject to influences of environmental temperature extremes Higher reliability; expected mean time between failure higher than other candidates [25] Filament-wound tankage chosen over steel tankage because of lower weight
Atmospheric control		
Circulation/ventilation	Fans-distribution ducts	High reliability of performance on earth-based systems
Water separation	Motor-driven centrifugal (urine/air separator)	High resistance to clogging
	Porous plate condensor/separator (CO_2 concentration, H_2O/CO_2 reduction, water electrolysis)	No moving parts; minimizes replacement time
	Hydrophobic-hydrophilic screens (shower water/cabin air separator, ventilation, deaeration in liquid lines)	High acceptability on basis of performance

Table 13.2.2-4 (Continued)

Function	Selected Concept	Reason(s) for Selection
Temperature/humidity control	A condensing heat exchanger with variable speed fan and face-wick water separator	Noise level lower than other candidates Less interface requirements for variable speed fan
Pressure control	Pressure regulators	High degree of performance on earth
Contamination control		
Trace gas control	Catalytic oxidation/sorption	Low maintenance requirements and low power consumption; catalyst in oxidizer does not take place in reactions
Bacterial control	Filtration	High degree of performance on earth
Particulate control	Filtration	High degree of performance on earth
Dust control	Air-jet wash and multifiltration	Chosen for relatively low weight requirements and not requiring interface with water-management subsystem
Carbon-Dioxide Management		
Carbon-dioxide removal/ concentration	Steam-desorbed resin	High reliability; expected MTBF is high [25] Interfaces well with reduction and electrolysis concepts Concept is simple Volume requirements are low Predicted resupply requirements are low [25]

Table 13.2.2-4 (Continued)

Function	Selected Concept	Reason(s) for Selection
Carbon-dioxide reduction	Sabatier-methane utilization	Potential for utilization of methane; otherwise no significant difference from the solid electrolyte process
Water electrolysis	Gas circulation	Low weight penalty
		No water feed or gas collection problems
		Good thermal process control
Food management		
Food provisions	See discussions in Section 13.3	
Food storage		
Refrigerator/freezer concept	Turbo compressor/air cycle system	Study by Whirlpool [1]
Ambient storage	Storage locker/room Flexible storage	Both concepts are chosen to give adequate flexibility to food storage
Food preparation (heating)	Combination microwave and resistance heating oven	For quick heating of small items, microwave oven is very efficient. However, for large items where longer cooking may be desirable, the resistance oven is more appropriate [1].
Food serving	Self serving (Phase I) Steward service	Techniques consistent with concepts of growth of colony

Table 13.2.2-4 (Continued)

Function	Selected Concept	Reason(s) for Selection
Food cleanup		
Sanitary wipe concepts	Reusable galley/dining area wipes and reusable personal wipes	Chosen because concepts satisfy minimal resupply requirements
Wipe dispenser concept	Reusable wipe dispenser	Chosen because concepts satisfy minimal resupply requirements
Soiled wipe storage	Temporary storage of reusable wipes	Provision required since washing will most likely not occur right after use
	Temporary storage of debris and waste foods	Provision required since manual transfer may not occur right after cleaning operation
Utensil washing concepts	Automatic washer/dryer Galley sink and/utensil washing	Both provisions supplied for maximum flexibility
Waste management	See discussion in Section 13.3	
Water management	See discussion in Section 13.3	
Hygiene		
Whole body cleaning	Shower	High acceptability from psychological viewpoint; also less frequent cleaning required
		Provides proper microbiological control
Dental hygiene	Toothbrush, liquid dentrifice and associated water delivery and waste collection units; also dental floss may be provided	High acceptability and performance; commonly used earth technique

Table 13.2.2-4 (Continued)

Function	Selected Concept	Reason(s) for Selection
Selective body cleaning	Reusable hand wipes	Most flexible technique; chosen for recycling capability
Housekeeping		
Tools, small parts cleaning	Dry heat(autoclave or oven)	Well established as an effective and reliable procedure
Cleaning and control of microbiological contaminants	Vacuum cleaner for dry contaminants	Well established earth based techniques which will be adaptable to lunar based systems
	Reusable wet wipes (with detergent and disinfectant to remove vomitus, dried food, etc.)	
Clothing and linen management		
Type	Reusable	Chosen on basis of recycling capability and high degree of performance
Laundry system concept	Automatic laundry-rotary-water solvent	
Detergents	Nonionics	Anionics were eliminated because of foaming problems. Cationics were eliminated because of poor detergent quality. Nonionics were selected because they are low foam, good detergents in small concentrations, will not cause clogging of membranes and are non-precipitating. Also they tend to be biodegradable but not biocidal. A disinfectant may be necessary.

Table 13.2.2-4 (Continued)

Function	Selected Concept	Reason(s) for Selection
Active thermal control		
Cabin-coolant loop	Use of heat transport fluid circuit, cold plates and space radiators	A high level of engineering experience is associated with these techniques. Water should be used as the heat transport because of nontoxic characteristics.
Cabin-heat rejection loop		
Special provisions		
Fire-protection control	Water	
	Stream / Fog — penetration of solids	Based on recommendations by Hamilton Standard [25]
	High expansion foam--total cabin flooding	Based on recommendations by Hamilton Standard [25]
	Methyl cellulose foam--for equipment and equipment bays	Based on recommendations by Hamilton Standard [25]
	Freon--explosion suppression	
Microbiological control	See discussion in Section 13.3	
Instrumentation and control	Fully automatic system	See discussion in Section 13.3

functions. Table 13.2.2-2 summarizes the candidate subsystems which survived first stage trade-off analyses (elimination at absolute and primary level of evaluation). Table 13.2.2-3 summarizes the eliminated candidate subsystems and the reasons for their elimination. Table 13.2.2-4 summarizes the selected candidate subsystems for Phase I and Phase II configurations along with the reasons for their selection. Appendix B gives process descriptions and schematic diagrams for the selected candidate subsystems for life-support functions. Unless otherwise indicated, subsystems are considered candidates for both Phase I and Phase II configurations. Heavy emphasis was placed on the following criteria in the selection of the most viable candidate subsystems:

1. projected candidate subsystem development,
2. ability of candidate subsystem to regenerate life-support needs,
3. modularity,
4. commonality (use of a particular concept for a number of functions), and
5. minimum resupply requirements from earth,

13.3 DISCUSSION OF VARIOUS SELECTED SUBSYSTEMS

13.3.1 FOOD PROVISION

"Man cannot live by bread alone" and so it will be necessary to provide a variety of food and drink which is both psychologically and physiologically acceptable to the lunar colonists.

13.3.1.1 Food Acceptance

In a purely survival situation, a food's nutritional value is of paramount importance. Factors dealing with a food's acceptability, such as taste, smell, consistency, bulk and the like, become secondary. The lunar food source, however, cannot be based solely on survival conditions. Therefore, the problem of food acceptability must be considered.

It should be understood from the outset that food is not food until eaten. Appetite alone is not a guarantee that a food will be ingested. Therefore, it is evident that nutritional adequacy is not the sole nor possibly even the most important measure of a food's value. On long duration missions where morale and personnel efficiencies become critical factors, it may well be that food-production efficiencies will have to be sacrificed somewhat in favor of maintaining the colony's psychological well-being [5].

13.3.1.2 Candidate Subsystems

The following is a review of both biological and physiochemical food-producing candidate subsystems with an emphasis on the final configuration subsystems.

13.3.1.2.1 Hydrogen Bacteria (Hydrogenomonas Eutropha)

This is a biosynthetic CO_2 reduction system where O_2 and H_2 are generated by the electrolysis of water. The bacteria cells are harvested at a fixed rate to maintain a steady-state population and gas uptake rate [30, 32, 33, 40].

Advantages: No light required; O_2 produced; good automation potential; high rate of food production.

Disadvantages: Unknown acceptability; much processing would be required; potentially explosive mixture of O_2 and H_2 produced.

Action: Reject due to questionable acceptability. More work should be done here as possible efficient food source for farm animals [39].

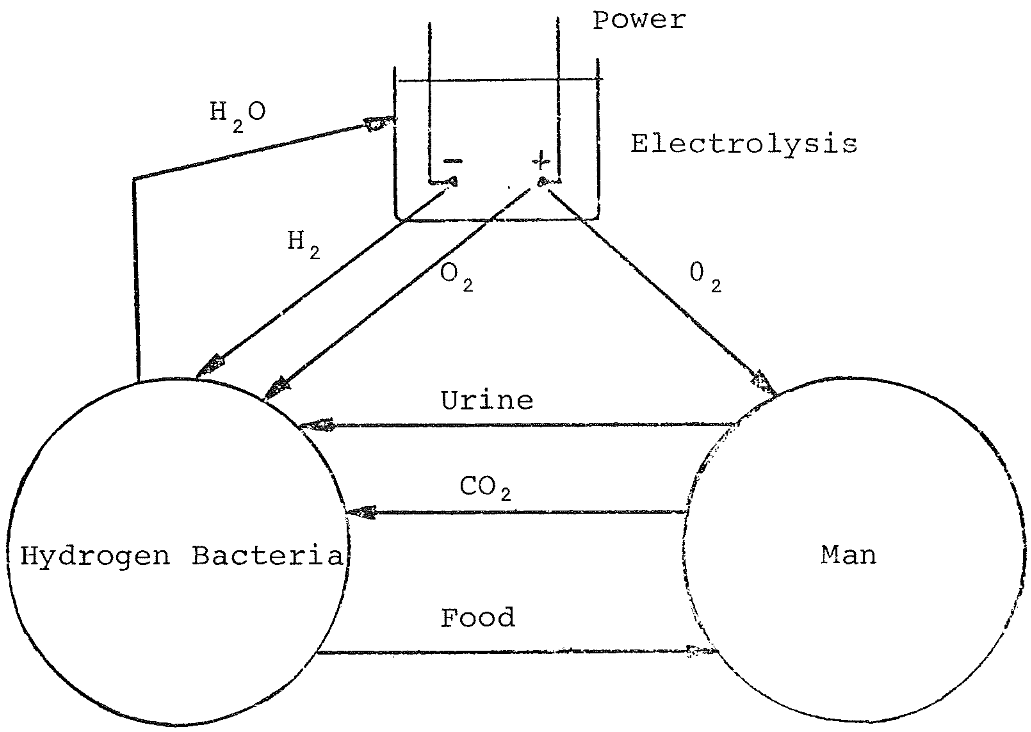


Figure 13.3.1.2-1 Schematic hydrogen bacteria system

13.3.1.2.2 Fungi (Mushrooms)

Fungi can be grown in a compost high in cellulose and nutrients from processed urine and fecal wastes [5].

Advantages : Adequate acceptability; no light required; can be grown from waste products;

Disadvantages: Low caloric value per pound; uses O_2 and produces CO_2; large area required:

Action: Accepted; recommend implementation at some time after second farm module has been installed to provide variety in the diet.

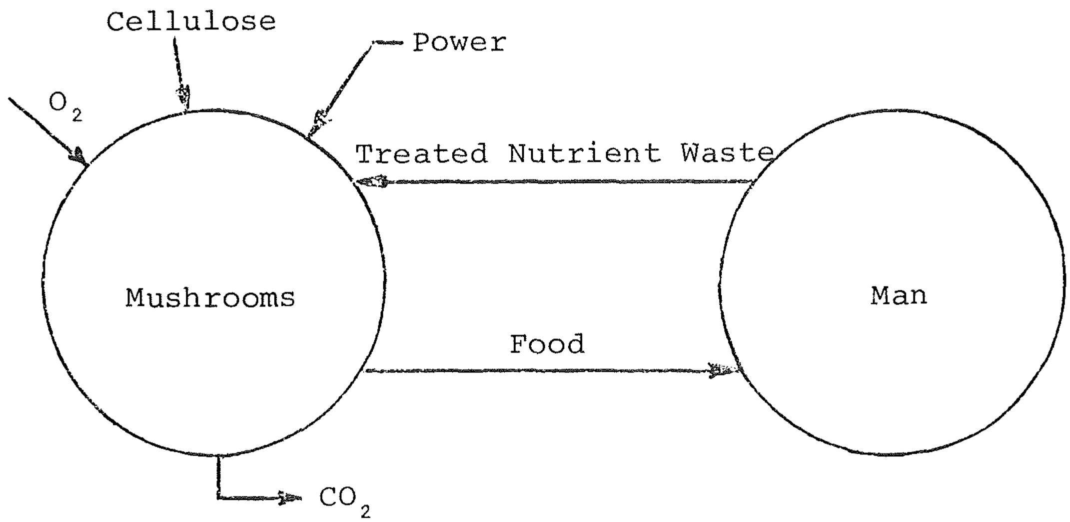


Figure 13.3.1.2-2 Schematic mushroom system

13.3.1.2.3 Algae

CO_2 enriched air is pumped through a light contact chamber containing an aqueous suspension of algae. The photosynthetic action of the algae causes removal of CO_2 dissolved in the water and produced O_2 and eventually more algae [5, 32, 33, 34].

Advantages: System now developed [32]; produces O_2 and uses CO_2; can use solar energy during the day.

Disadvantages: Light required (96 percent of the energy supplied is removed as low grade heat [32]); low acceptability; large area required.

Action: Reject due to low acceptability [34]. Consideration should be given to this system as an efficient source of possible animal food.

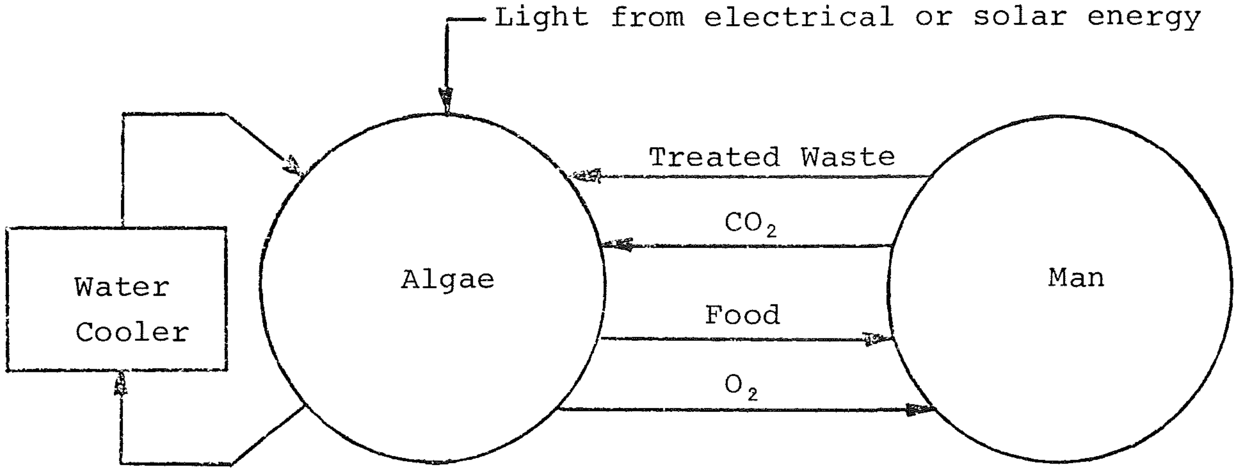


Figure 13.3.1.2-3 Schematic algae system

13.3.1.2.4 Higher Plants

Examples of higher plants are tomatoes, cabbage, endive, soy beans, carrots, eggplants, sweet potatoes, cucumbers, radishes, turnips, sorghum, and the like.

The plants could use lunar soil or be grown by hydroponics. Lunar soil seems to be preferable since it contains all the required minerals for plant growth with the exception of nitrogen, zinc, boron, and molybdenum. The last three are required only in trace amounts. Nitrogen would have to be provided in larger amounts as fertilizer [28]. Future soil nutrients would also have to be tied up in the system. Area requirements of 150 ft^2 per man would be required for 100 percent food supply. This is approximately a third of an acre at the 100 man level.

The major problem seems to be the large power requirements necessary for lighting during the lunar night. If full rate growth is desired, power requirements would be approximately 30 KW per man. However, if only enough light is provided for dormant growth, approximately 8 KW per man would be sufficient.

This dormant state of growth would reduce the rate of food production by about 50 percent or would require larger areas. A trade-off study should be made in this area. Significant power reductions could also be realized if more efficient light bulbs are developed or if the bulbs could provide light only at selected wavelengths required for plant growth. Power requirements during the lunar day are estimated at 5 KW per man. All the above power requirements are based on 100 percent farm food supply [30, 35, 36, 41]. Figure 13.3.1.2-4 shows a schematic diagram of the plant system.

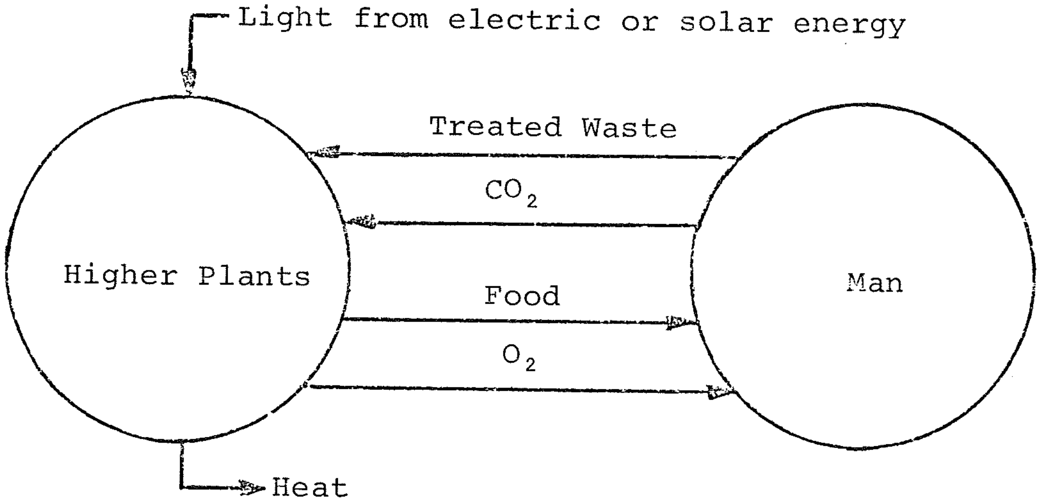


Figure 13.3.1.2-4 Schematic of plant system

Advantages: High acceptability; great deal of experience and information in this area; CO_2 removed and O_2 produced.
Disadvantages: High power requirements; slow food production rate; low automation possibilities.
Action: Accepted as main source of lunar produced food.

13.3.1.2.5 Animals

Examples include chickens, Japanese quail, fish, and miniature mammals.

From the energy point of view, the use of intermediates in the food chain is costly since the system must be penalized due to the inefficiency in food production of the intermediate. For this reason only the most efficient plant food to animal food converters could be used [30, 37, 38].

Advantages: High acceptability of foods such as eggs, fried chicken, brook trout, etc.

Disadvantages: Large power requirements; extra load on life support systems; uses O_2 and produces CO_2.

Action: Reject at initial stages of colony development due to low food production efficiency. This system may be implemented at a later stage of colony development or an efficient food source for the animals may be developed. Figure 13.3.1.2-5 shows a schematic diagram of the plant and animal system.

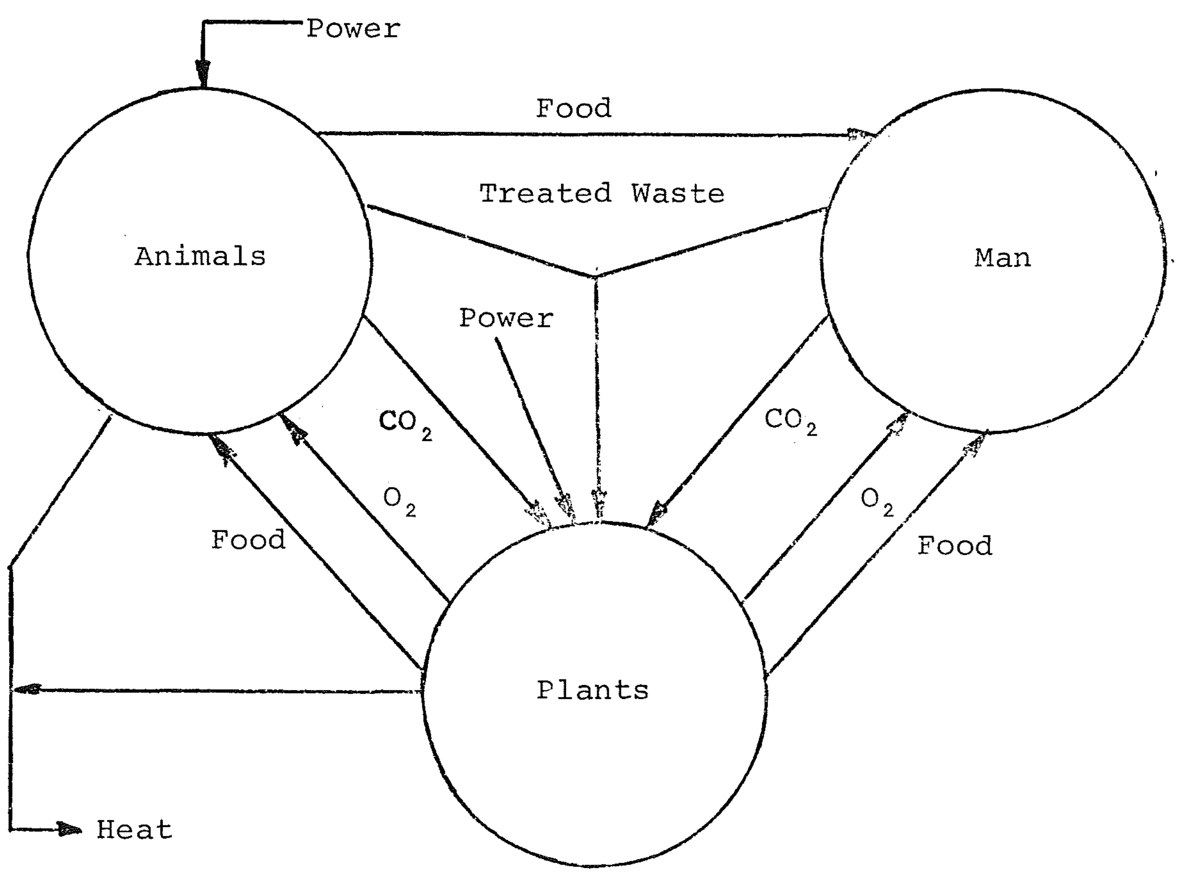


Figure 13.3.1.2-5 Schematic of plant animal system

13.3.1.2.6 Carbohydrate Synthesis

There are currently several methods of producing sugars from formaldehyde water solutions by polymerization, the products being glycerol, fructose, and ethanol [30, 33, 42]. The main problem is that both nutritional and nonnutritional sugars are produced with no technology for their separation.

Advantages: Could form a large part of the diet, not dependent on living organisms.

Disadvantages: No adequate method of processing; high voltage and high temperature required.

Action: Accepted as initial food source to be implemented at the lunar colony assuming a refining process can be developed. Figure 13.3.1.2-6 shows a schematic diagram of the carbohydrate synthesis system.

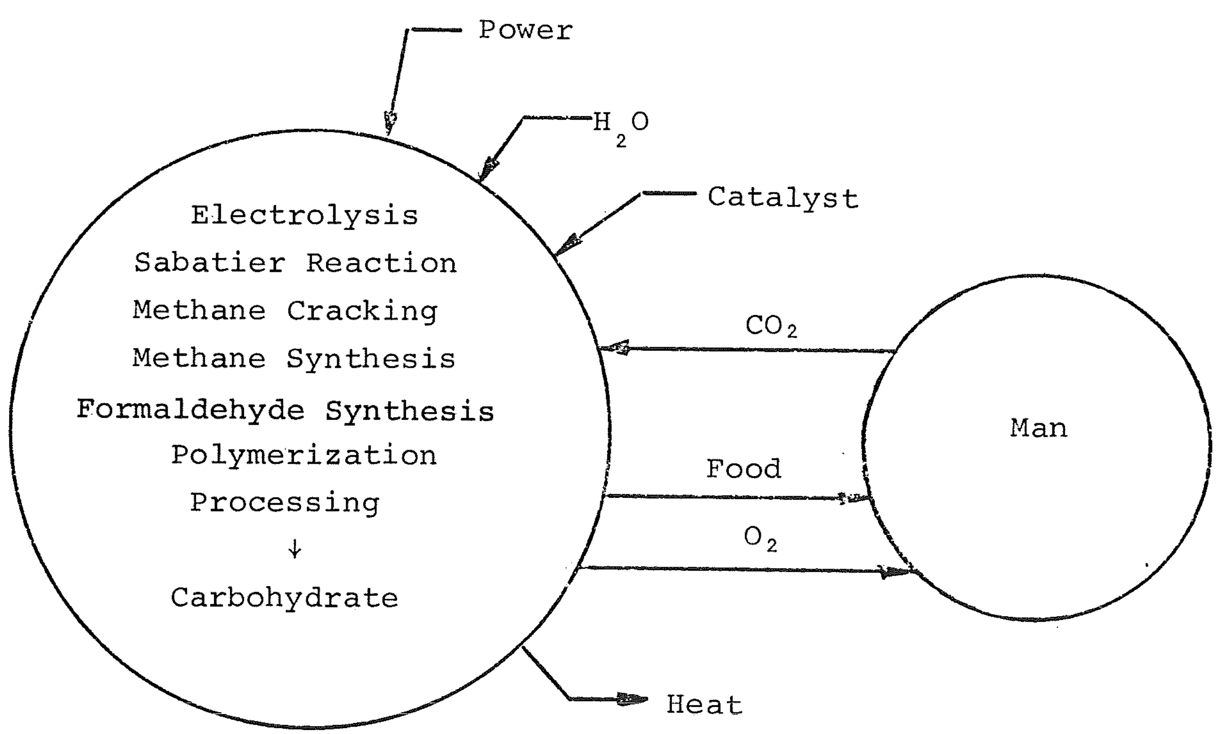


Figure 13.3.1.2-6 Schematic Carbohydrate synthesis system

13.3.1.2.7 Protein Synthesis (Amino Acids)

Although amino acids can be synthesized in the laboratory at low yields, there is no indication that this can be done with man's metabolic wastes, nor that the produced amino acids could be used as food [30, 33, 43].
Action: Reject.

13.3.1.2.8 Fat Synthesis (Fatty Acids)

Although there has been work in this field [30, 43], there are no known methods to produce nutritionally acceptable fatty acids as a food for man.
Action: Reject.

13.3.1.3 Food Storage and Inventory

Adequate provision must be made for food storage, processing and preparation. A three-month emergency reserve of food and water should always be in storage and should be periodically rotated on a "last-in last-out" basis. Accurate records of food consumption and food inventory in storage must be kept.

On the basis of 500 pounds of dry food per man per year and 250 gallons of drinking water per man per year, the emergency reserve should have 125 pounds of dry food per man and 65 gallons of water per man.

Although a great deal of food resupply is expected in the early stages of the colony's growth, most water would be reclaimed and any additional water required would be resupplied initially from earth. For future generations, make-up water will be obtained from oxygen production process.

13.3.1.4 A Concept of Growth

Considering the lack of research that has been done to date as regards the quality and acceptability of food produced by the various candidate subsystems, it becomes a risky task to select the viable subsystem(s).

Although specific recommendations have been made, it should be noted that as new information is collected and as breakthroughs are made, any or all of the listed candidate subsystems could be used at the colony. With this in mind, the following is a possible concept of growth for the colony.

It is envisioned that, in the early stages of the colony's development, most of the reliance would be on stored food shipped from earth. During this initial period, no effort would be spent on food production, but rather the effort would be channeled toward research for the implementation of future food production. At the 24-man level, production of synthetic carbohydrates would be initiated. This could potentially replace a large portion of the diet, assuming the problems of processing and acceptability could be solved. This same system would also serve as a back-up system in future generations of the colony. The implementation and acceptance of this physiochemical system could reduce the dependence on earth-supplied food by 90 percent. It is felt, however, that the problem of acceptability may be a major one at these high levels. It may well be that the chief value of the synthetic carbohydrate system will be as a back-up for emergency survival situations. In any case, it is felt that the synthetic carbohydrates will be able to supplement some percentage of the earth-stored food and thus be the first step in achieving an independent food source.

It is during this period that final research work should be completed, looking toward the introduction of higher plants as a food source. Before any actual plant selections are made, a large number of criteria listed in Table 13.3.1.4-1 should be evaluated.

Table 13.3.1.4-1 Criteria For Food Selection

Availability of the process (stage of development)
Content, nutritional value, and acceptability of food produced
Energy/power required and ability to convert or use light energy
Dependability--establishment and continuance
Rate of production
Efficiency--ratio of output to input
Real time required for initiation and "growth" of food product--
How long for food product to reach maturity
Crew time for maintenance
Ability to interface with other life support subsystems
Opportunity/ability to grow continuously or be generations
Atmospheric requirements--composition, pressure, temperature
Resistance to specific pathogens, fungi, bacteria
Vitamin and mineral presences in food products
Food processing required
Volume required for germination and growth
Shipping weight of production and/or support facilities
Ability to adapt to lunar environment
Nitrogen-fixing capabilities
Required amounts of water, nutrients, carbon dioxide, atmospheric
pressure, temperature
Required amount of light--intensity and spectral quality
Ability to convery light energy
Volume required--"air" and soil
Growth form--vine, bush, individual (root or head)
Hardiness of plant
Soil pH requirements
Ability to grow by hydroponics
Heat rejection characteristics
Resistance to radiation outside of visible wavelengths
Possibility of growth acceleration

During the later stages of the 24-man colony, the first fully pressurized farm module should be delivered, installed and made operational.

This initial module would provide 600 ft^2 of growing area and would be able to provide 20 percent of the colony's food at the 24-man level. The psychological advantage of being able to provide fresh farm fruit and vegetables should well be worth the cost and manpower required for set up.

The first module would be made as secure as possible to maintain a high degree of reliability. The first module would have the following:

1) Be buried to protect both plants and operating personnel from radiation.
2) Be at normal colony pressure to provide for ease of entry and normal working conditions.
3) Have a "window" for sunlight during the lunar day at which time we would have a maximum growth rate.
4) Have electric lights to provide plants with full rate of growth during the lunar night. As the lunar farm grows in percentage of food produced and the available power becomes a limiting factor, the lunar-night illumination could be decreased to provide only a dormant growth rate.
5) Have provision for collection and recirculation of water and dissolved nutrients.
6) Provide pipes for heating and cooling.
7) Provide humidity control.
8) Provide fans for air circulation.
9) Provide for introduction of treated waste material or fertilizer.
10) Provide for collection of O_2 and introduction of CO_2.

When this first module has proved successful, additional modules would be added as required. These future modules could be of more economical design as the technology of lunar farming becomes understood. Changes such as plant growth at reduced pressure and thus lighter and more economical structure could be considered.

The possibility of introduction of animals to provide some "steaks and chops" for the colonists seems to be a rather long way off. Techniques such as fish farming could be considered once the colony has expanded sufficiently to be able to absorb the high cost of such a project. This would come somewhere well after the 48-man colony level. It might, however, be noted that the animal farm could come at an earlier date if efficient food production sources such as algea or hydrogen bacteria could be used as animal feed. Table 13.3.1.4-2 is a list of supplemental criteria to those listed in Table 13.3.1.4-1 for the evaluation and selection of various animal species.

Vitamins and minerals would be supplied from earth in pill form until the lunar farm is sufficiently developed to provide them through farm foods [49].

Table 13.3.1.4-2
Supplemental Criteria for Animal Selection

Gestation period

Size of litter

Frequency of birth

Food requirements for animal--forms and place on the ecosystem ladder (herbivore vs. carnivore vs. omnivore)

Amount of usable materials on carcass--lean, fat, bone, offal,other

Rate of increase (mass) of % fat or % lean meat

Food production capabilities in forms other than direct use of flesh

Optimum time in age for slaughter
- --Daily gain in weight
- --Maximum growth rate
- --Reproduction time in life

Possibilities of growth acceleration

Resistance to radiation outside of visible wavelengths

13.3.2 WASTE MANAGEMENT

The waste-management subsystems functions are

1. to collect and transport liquid and solid wastes to their respective treatment subsystems, and
2. to process these wastes for recycling and/or disposal.

The waste-management subsystem plays an integral part in the potential for closure of the food-waste loop. The potential reuse of nutrients found in waste for plant food presents an exciting challenge for technological development. Following is a discussion of the selected subsystems for

1. liquid waste collection and transport,
2. feces collection,
3. waste processing and
4. disposal of wastes.

13.3.2.1 Liquid Waste Collection and Transport

The selected subsystem for liquid waste collection and transport is the liquid/gas flow concept with centrifugal phase separation/ transfer. A schematic of this concept is presented in Figure 13.3.2.1-1. Upon urination, the urinal is flushed with water. At the same time, a centrifugal fan draws cabin air through the urinal to prevent escaping gases and vapor. The two-phase flow is taken to a motor-driven centrifugal water separator. The air is taken through bacteria and odor removal filters and returned to the living area. The liquid waste is pumped to the water recovery system.

13.3.2.2 Feces Collection

A basic requirement of the feces collection subsystem is to avoid the contamination of the atmosphere and man. Also, dual provision for collection must be available. The collection concept must be

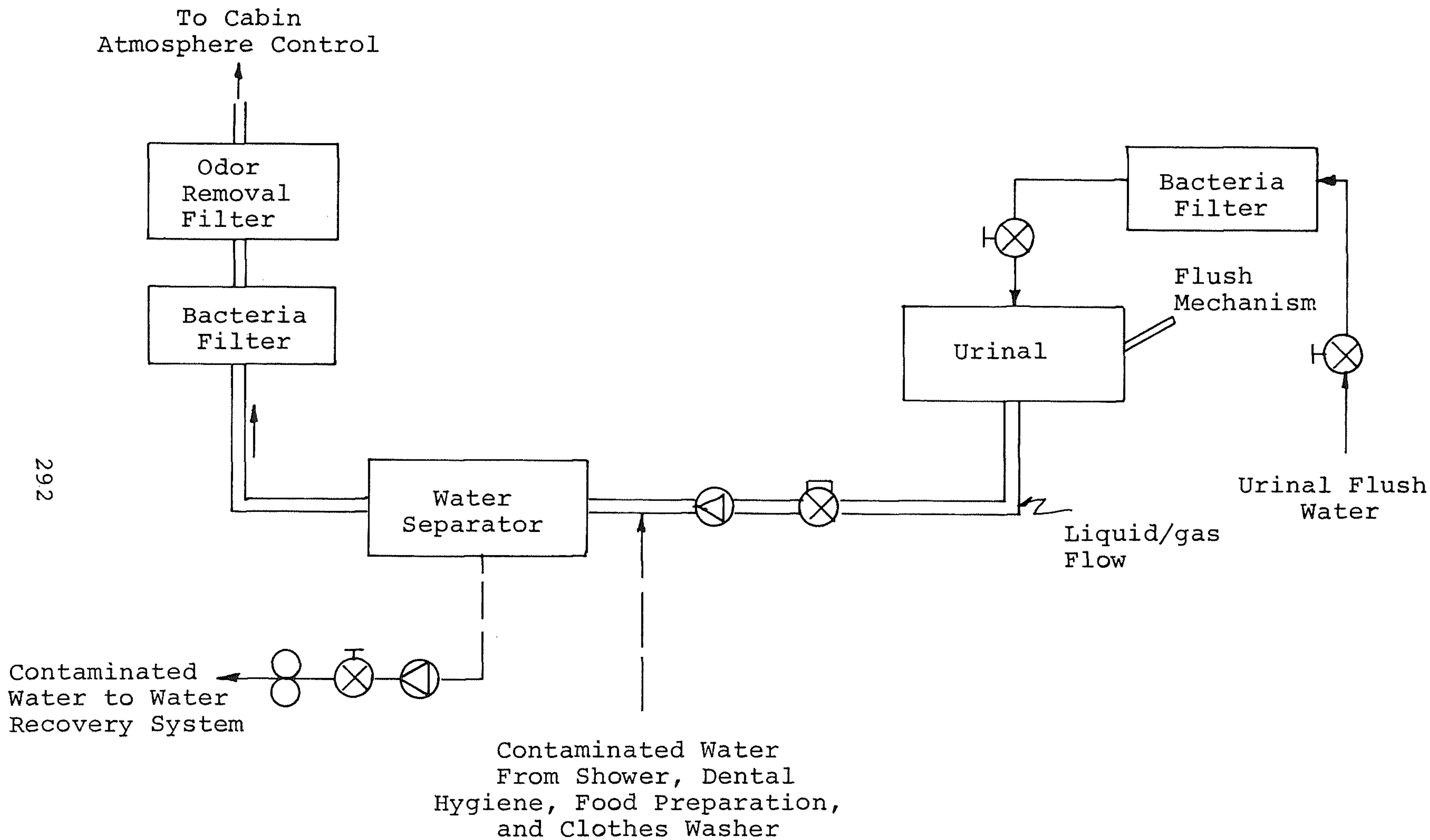


Figure 13.3.2.1-1 Liquid Waste Collection/Transport Subsystem
[After Reference 25]

able to

1. be an integral part of the waste-processing subsystem for Phase I application, and
2. be a collection transfer device for Phase I and Phase II application.

The selected feces collection concept is best described as a combination of the dry-tank system and the wet system with reclaimed waste slurry. Human defecation is collected in a container which can be heated for Phase I waste processing and can serve as a collection/transfer mechanism for Phase II processing. The collection system is equipped with a steam purge for contamination control when transfer is taking place during Phase II operations. The steam also provides water for wet slurry. Also, provision for disinfectant injection is included. The feces collection subsystem also included a process flow fan which draws odors, aerosols and bacterial contaminants through bacteria and odor removal filters. This component of the subsystem is common with the liquid waste/transport subsystem. The feces collection system also has provision for collection and transfer of vomitus and associated gases to the waste processing subsystem. Debris collection is provided by a vacuum type arrangement with a debris collector.

Animals may be a part of the food provision subsystem at the point of total lunar colony development. Waste (liquid and solid) collection and transport to the waste-processing subsystem would pose a serious problem. However, it is expected that the physical environment of the animals would be restricted. Potentially, a waste-collection technique could be developed to guarantee uncontaminated transfer of wastes to the waste processing subsystem. No solution is offered here.

13.3.2.3 Waste Processing

The closure of the food-waste complex is the most difficult problem associated with establishing a closed or partially closed life-support system. The recovery of useful nutrients from man's and (potentially) animal's metabolic wastes, particularly feces, will require potentially complex techniques. Studies have been performed which indicated potential use of nutrients from wastes for biosystems other than man. Table 13.3.2.3-1 summarizes some of the results of these studies. It is apparent that little effort has been devoted to waste-processing techniques which have had as their specific objective recovery of nutrients from wastes for food biosystems. The summary does indicate, however, that the potential is there. With proper research and development, the problems appear to be solvable.

Operating under the assumption that technological development will provide a process for waste treatment that will allow maximum utilization of potentially available nutrients, an obvious consideration is whether or not the quantity of waste generated by a lunar colony of 200 people is worth processing for recycling. Normal daily fecal production for an individual consists of approximately 100 ml of water with 15 grams of solids. For a lunar colony of 200 people, this represents 20 liters of water and 30 kilograms of solid material available for recycling per day. If the water was to be processed for potability, the recovered water would satisfy the daily requirements for approximately seven people (assuming 3000 ml average daily consumption requirement). More realistically, the water could be processed for use by biosystems other than man with a savings in hardware since the degree of purity required by these biosystems would be less than that required by man.

The solid matter in wastes could be treated for nutrient recovery also. Thirty kilograms/day (approximately seven pounds) of waste may be able, with the proper processing, to provide acceptable quantities of nutrients to other biosystems to make processing worthwhile.

Table 13.3.2.3-1

Summary of Waste Nutrient Application

Food	Application of Wastes as Nutrients
Algae	Untreated wastes are undesirable nutrients for algae. However, it is known that the byproducts of an activated sludge process will support growth of algae. However, for a system like this, supplemental requirements of urea and iron are required for algae growth. Incineration ashes contain all the nutrients except carbon, nitrogen and water. However, high concentrations of ash will inhibit algal growth. Reduction in incineration-ash toxicity is needed.
Hydrogenomonas entrophia Bacteria	Basic research indicates that these hydrogen bacteria can be grown using a combination of urine and fecal extract. However, no comparison with a control has been performed to indicate merits of waste application. Also, the growth of these bacteria appears to be very sensitive to the waste mixture provided as nutrients.
Higher Plants	Unprocessed wastes cannot be utilized by higher plants as a nutrient source. In earth-based systems a multiplicity of soil micro-organisms is required to convert wastes to usable nutrients by higher plant forms. Also, this conversion is extremely long. Initial efforts in applying processed waste (activated-sludge waste effluent) to higher plant forms for nutrient has not proven to be successful. Soluble inorganics inhibiting plant growth were found present. However, there is some indication that addition of other elements may make method acceptable. For example, dried sludge from an activated sludge process has been successfully applied to a culture of lettuce.
Yeasts and Molds	Yeasts and molds utilize a carbon source such as sugar for nutrition. There appears to be no known direct application of unprocessed or processed wastes to yeasts and molds as a nutrient.

The above discussion is not intended to imply that separation of water and solids in wastes would be necessary. Rather, it may be more desirable to treat the two phases together. This would be especially true if the product of their treatment would be nutrients for the same biosystem or set of biosystems. Also, the magnitudes may be larger if animals were to be incorporated into the systems. However, during the earlier stages of lunar colony development, there is proportionately smaller amounts of fecal waste available for processing for nutrient recovery. From an engineering viewpoint, this implies that there may exist a threshold population at which the viability of waste recycling becomes apparent. Prior to the threshold point, a waste processing-disposal system appears to have greater feasibility. Also, and perhaps just as important, a full-scale plant production program is not expected in the earlier phases of lunar-colony growth. Therefore,the potential for total usage of recycled wastes would be low. Storage of recycled wastes for subsequent application is possible. However, it is conceivable that due to the unique lunar-colony environment, waste-nutrient recovery may prove impractical.

For these reasons and from a safety viewpoint, it is envisioned that there will be a two-phase development of the waste-processing subsystem. The first phase would use a waste-processing concept which would be capable of sterilizing and disposing of the waste. Also provided would be the capability of testing in conjunction with plant-development research, the viability of waste processing for biosystem nutrient recovery on the lunar surface. The second-stage waste-processing subsystem would be a recyclable concept with the Phase I system providing backup. An additional requirement for the second-phase waste-processing subsystem would be the capability of treating plant and animal wastes for maximum utilization of recoverable nutrients.

The selected subsystem concept for waste processing for Phase I is the integrated vacuum-decomposition technique. This subsystem was chosen on the basis of trade-off studies by Hamilton Standard [25]. The integrated vacuum-decomposition concept was chosen based on

1. relatively safe operation,
2. low contamination potential,
3. low maintenance requirements, and
4. high flexibility.

A schematic of this process is shown in Figure 13.3.2.3-1. Note the provision for bypassing of waste (wet) slurry to the waste-processing subsystem to be used for second-stage implementation.

The selection of the waste-processing subsystem for second-stage development (and first-stage development testing with plant-growth testing) should ultimately be made on the basis of

1. the concept's capability for total recycling of wastes, and
2. the concept's safe operation such that the potential for contamination of man's other life-support needs is minimized.

It is extremely difficult to predict technological developments which might provide the lunar colony with this capability. For this reason, it was decided to describe state-of-the-art candidates for closure of the food-waste complex. The list of candidates is by no means exhaustive but perhaps does represent the most likely candidates that with the proper research and development could close the food-waste complex. The concepts presented are activated sludge, anaerobic digestion, trickling filtration, wet oxidation, steam reformation and combustion. Table 13.3.2.3-2 summarizes process descriptions for these candidates. Table 13.3.2.3-3 summarizes inputs and outputs to the processes. Figures 13.3.2.3-2 through 13.3.2.3-5 show schematics of the concepts (except for steam reformation). Table 13.3.2.3-4 summarizes advantages and disadvantages of these concepts.

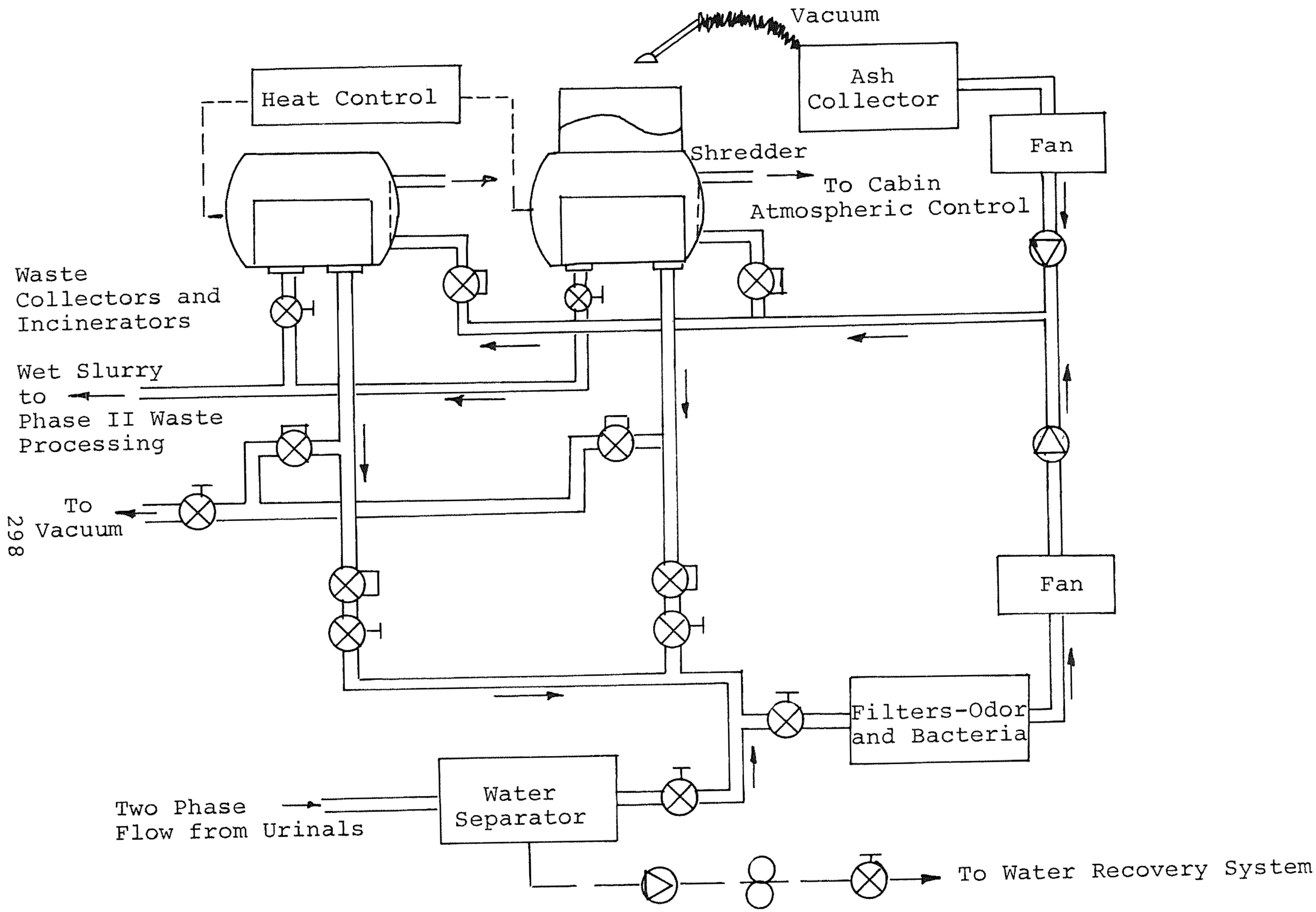


Figure 13.3.2.3-1 Integrated Vacuum Drying Concept [After Reference 25]

Table 13.3.2.3-2

Process Descriptions for Candidate Subsystems for Stage-Two Development of Waste Processing

Concept	Process Description
Activated Sludge	The activated sludge process is an aerobic biological process which uses aerobic micro-organisms to biodegrade organic wastes into compounds potentially utilizable by photo-synthetic systems. Ninety percent reduction of biochemical oxygen demand (or higher) may be expected under optimum conditions. Microbial growth rates are a function of oxygen available. Also growth may be in-hibited by absence of particular micro-organisms. The consistency of the food to microorganism ratio is important.
Anaerobic Digestion	Anaerobic digestion is a biological process which utilizes microorganisms to biodegrade organic matter in the absence of oxygen. The process proceeds in two phases in a single vessel governed by different types of microorganisms. The first stage is liquefaction whose primary end products are simple acids and alcohols. During the second or methane-fermentation stage, bacteria metabolize the organic acids and alcohols to methane, carbon dioxide, water and a sludge (a part of which will be micro-bial cells admixed with refractory organisms). The anaerobic digestion system is normally operated in conjunction with activated sludge systems. Stable degradation requires fixed temperatures, neutral pH, uniform non-toxic wastes, and uniform loading rates.

Table 13.3.2.3-2 (Continued)

Concept	Process Description
Trickling Filtration	Trickling filtration is an aerobic biological process with essentially the same as the activated sludge process with the method of aeration being different. The waste is passed over a film of microorganisms on coarse aggregate. Oxygen is provided by diffusion from the atmosphere while oxygen is mixed in a slurry in the activated sludge process.
Wet Oxidation	Wet oxidation is a high pressure, moderate temperature, chemical oxidation of organics in waste matter. The wastes are burned in the presence of water as if the water was evaporated before combustion.
Steam Reformation	In the steam-reformation process, supercritical steam is exposed to the wastes at 1000°F. The wastes are reduced almost completely to hydrogen, carbon dioxide, nitrogen and inorganic ash.
Combustion Process	In this process, wastes are supplied to the system with air. The mixture is passed through a heat exchanger where all water is vaporized. The solid wastes then enter a combustor and are burned at 1000°F.

Table 13.3.2.3-3

Summary of Inputs-Outputs to Candidate Subsystems

(Based on Materials Balances)

Concept	Inputs	Outputs
Activated Sludge	Degradable organic wastes	Carbon Dioxide
	Oxygen	Biomass
	Nondegradable organic wastes	Nondegradable organic matter
	Minerals	Minerals
	Water	Water
Anaerobic Digestion	Organic solids from activated sludge system	Methane
		Carbon dioxide
		Water
		Sludge
Trickling Filtration	Same as activated sludge	Same as activated sludge
Wet Oxidation	Degradable and nondegradable organic matter	Steam
		Nitrogen
	Minerals	Carbon dioxide
	Water	Inorganic ash
	Air	
Steam Reformation	Degradable and nondegradable organic matter	Hydrogen
		Carbon dioxide
	Minerals	Nitrogen
	Steam	Inorganic ash
	Water	
	Oxygen	
Combustion	Degradable and nondegradable organic matter	Water
		Gases
	Air	Inorganic ash
	Water	Carbon dioxide

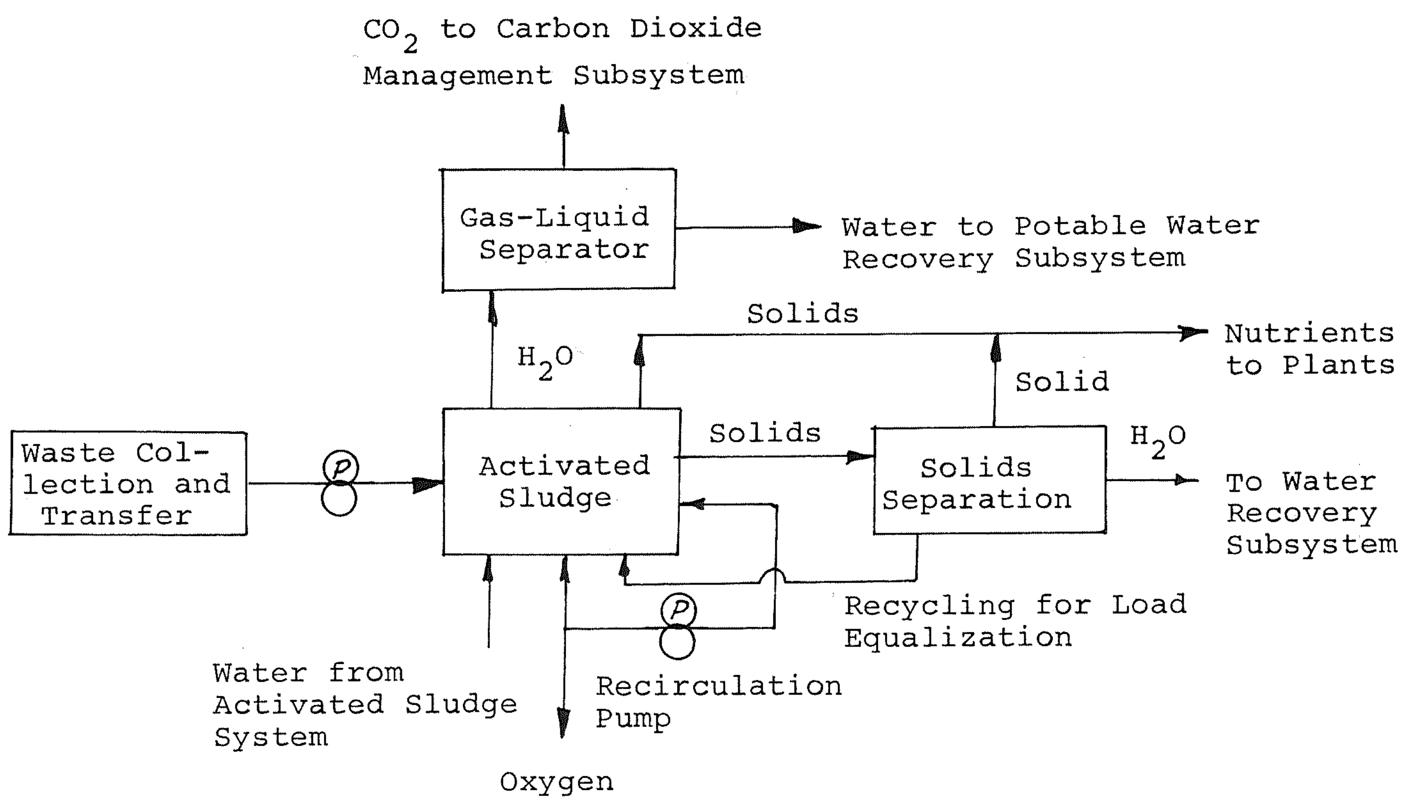


Figure 13.3.2.3-2 Schematic of Activated Sludge System [After Reference 26]

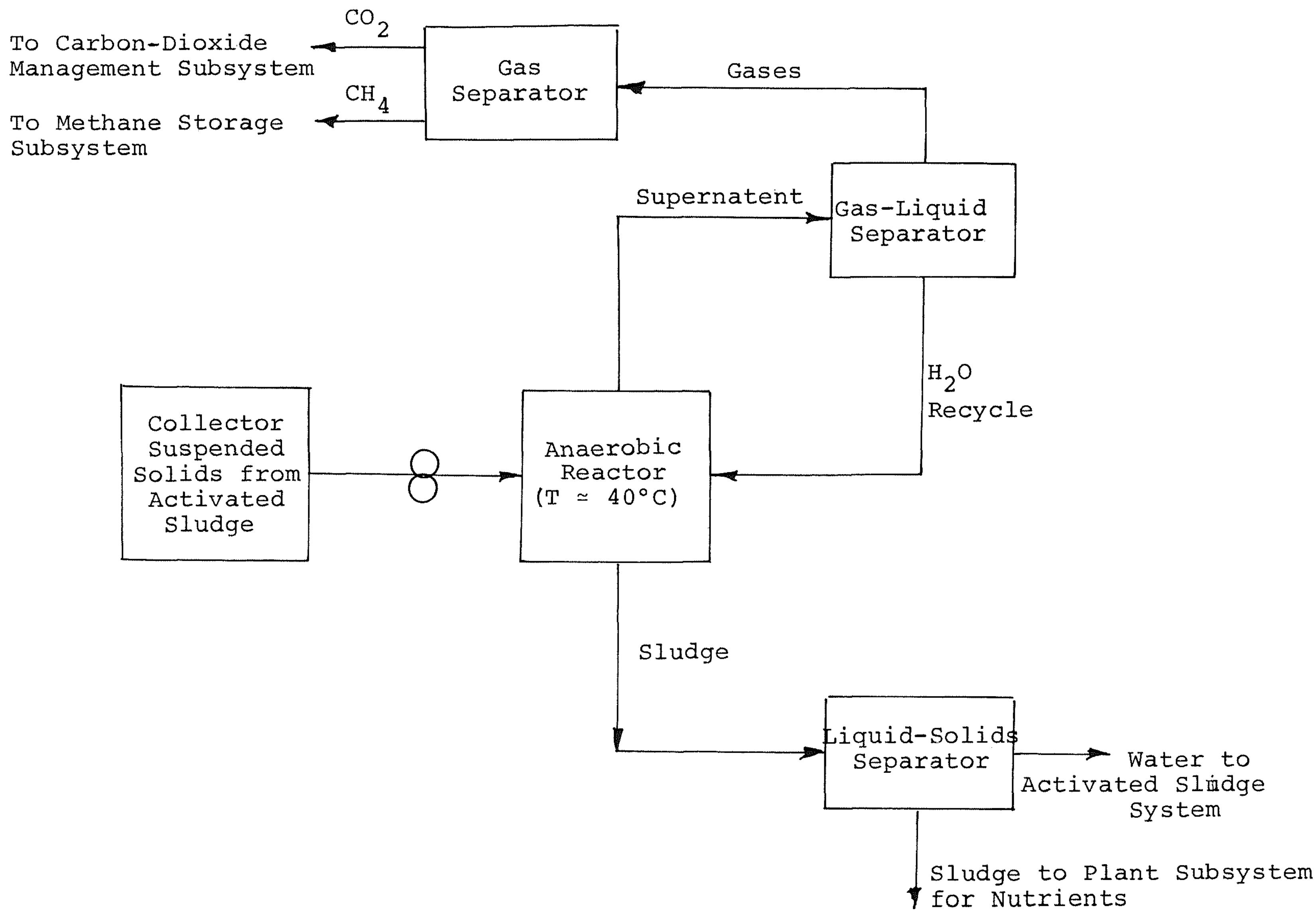


Figure 13.3.2.3-3 Schematic of Anaerobic Digestion System [After Reference 26]

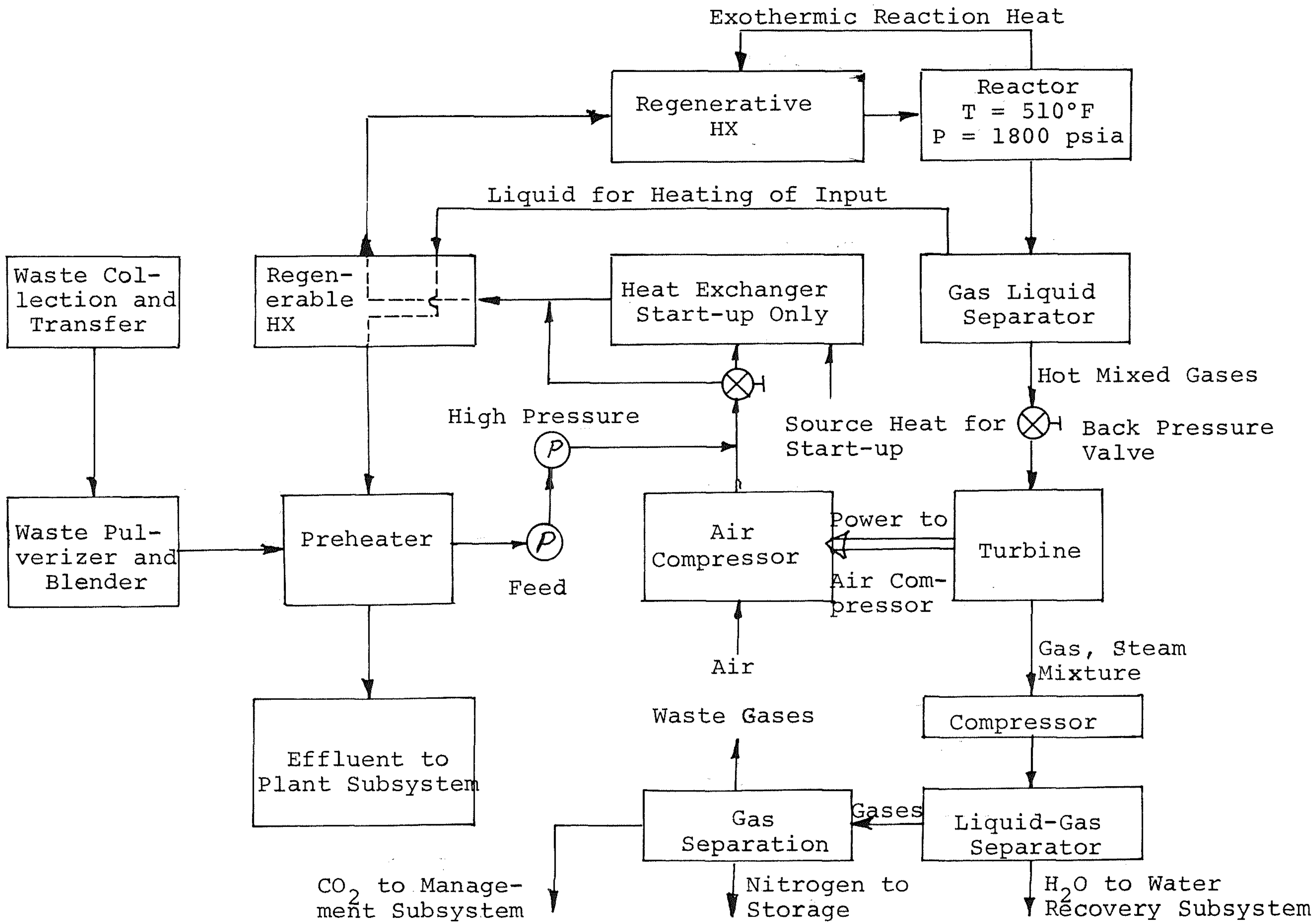


Figure 13.3.2.3-4 Schematic of Wet Oxidation Process [After Reference 26]

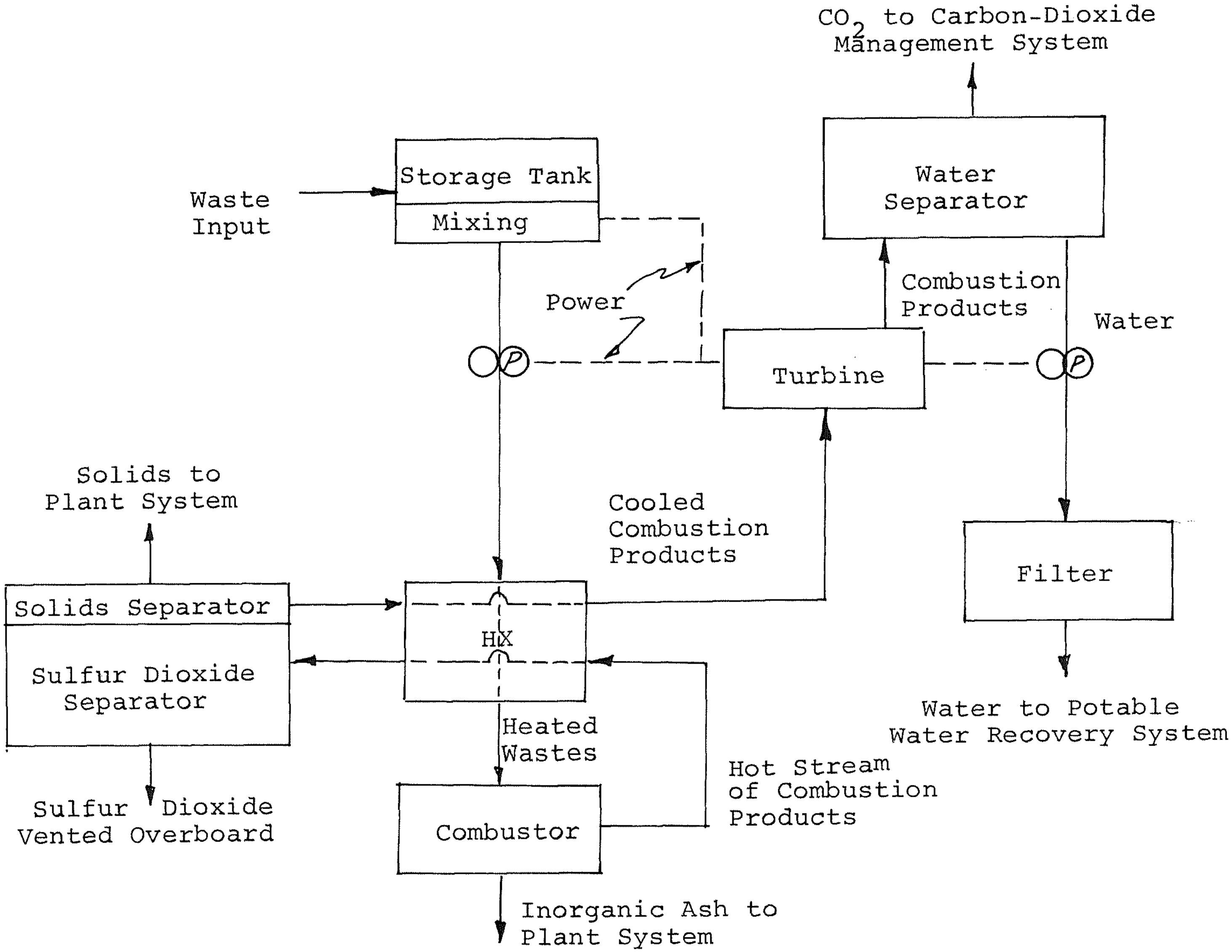


Figure 13.3.2.3-5 Schematic of Combustion Process for Water Recovery [After Reference 26]

Table 13.3.2.3-4

Summary of Advantages and Disadvantages of Waste Processing Candidate Subsystems for Second Stage Development

Concept	Advantages	Disadvantages
Activated Sludge	Activated sludge systems can transform organics into nutrients useful in photosynthetic systems	Process requires gas-liquid and solid-liquid separation subsystems
	Microbial flora can operate under a wide variety of environmental conditions and can oxidize a wide spectrum of wastes	Require oxygen
	Large quantities of noxious gases are not produced assuming sufficient oxygen supply	Under suboptimum oxygen supply anaerobic microbes will be activated and other undesirable end products may occur
	Activated sludge process proceeds under low temperature and pressure requirements	Complete mineralization of organic matter may not be guaranteed in a reasonable period of time
	Volatile wastes are partially stabilized	Process application to non-continuous flow systems is relatively unknown
	Operating costs are generally lower than for other treatment systems	Possible microbial contamination of environment
Anaerobic Digestion	Compliments activated-sludge system by further degradation of organic wastes	Process is slow
	Low temperatures and pressures required	Carbon dioxide and solids separation processes required

Table 13.3.2.3-4 (Continued)

Concept	Advantages	Disadvantages
	Wide range in waste composition may be processed	Pathogenic organisms may survive anaerobic digestion
	No requirement for oxygen	Admission of oxygen will adversely affect process
	Methane byproduct may be useful fuel source	Process adaptation to small pulse inputs is unknown
Trickling Filter	Essentially same as activated sludge with additional possible advantage of utilization of lunar aggregate for filtering media	Essentially same as activated sludge with additional volume and weight restraints
	Interfaces well with anaerobic digestion	
Wet Oxidation	Dehydration of wastes not required prior to oxidation	High temperatures and pressures constitute a potential burn and explosion hazard
	Little oxygen required	The product water is not potable and will need further processing
	Ash residue is biologically stable	Use of residue ash as plant nutrient not established
	Operating temperatures lower than most incineration processes	
	Possible industrial-waste interface	
	No air pollution or odor from process	
	Wastes are processed rapidly	
	Power requirement is low because energy is recovered from exothermic reaction	

Table 13.3.2.3-4 (Continued)

Concept	Advantages	Disadvantages
	Volume requirements low	
	Process easy to operate and maintain	
Steam Reformation	Byproducts of process are usable	High temperatures and pressures required constitute potential burn and explosion hazard
	Dehydration of wastes not necessary for processing	
	Wastes are processed rapidly	Use of solid byproducts for plant nutrients not established
	Requires oxygen	
		Process application to metabolic waste treatment relatively unknown
Combustion	Low power and weight requirements	Requires oxygen
	Oxidizes fully organic matter and bacteria	Complex process
	Provides for fecal water recovery	Possible burn, explosion and contamination hazards
	High-water recovery efficiency	Application to cyclic type process not known

13.3.2.4 Waste Disposal

Waste-disposal subsystem candidates are storage, dump or burial of wastes or recycling. Recycling of wastes is, of course, the ultimate goal of the waste-management subsystem. An interim solution is required, however, since full utilization of wastes is not envisioned until latter stages of colony growth. It is recommended that the disposal of nonutility wastes be performed by lunar surface burial. Although, it is conceivable some wastes may be stored for research and development use, it is not recommended because of potential contamination.

13.3.3 WATER MANAGEMENT

The water-management subsystem is also a very important element in the closure of the life-support subsystem. The recovery of potable water from urine and urinal flush-wash water, condensate and potentially fecal water is an absolute necessity in order to avoid any weight penalties associated with water import. Also, any water available from the oxygen-production subsystem may be polluted and would require advanced treatment methods not compatible with normal water-recovery methods.

Therefore, the function of the water-management subsystem is to collect and purify liquid-waste waters and to store them such that they retain their purity.

The water-management subsystem must be essentially contaminant free. If contamination occurs, a provision for steam purge must be included. Other important auxiliary functions for the subsystem include

1. chemical pretreatment for bacterial and volatile nitrogen control, and
2. a continual water-quality monitoring system.

The water-management concept selected must provide water which satisfies potable-water standards. A summary of the potable-water standards suggested by the United Stated Public Health Service, the World Health Organization and the Ad-Hoc Panel on Water Quality Standards of the Space Station Science Board is given in Table 13.3.3-1 [25].

A knowledge of the contaminants in wash water, condensate, urine, and fecal water is necessary for proper water quality control. Typical condensate contamination, wash-water contamination, and urinal-water contamination levels are summarized in Tables 13.3.3-2 through 13.3.3-4 respectively [25]. Fecal-water contamination concentrations were not found.

There are two approaches to the treatment of the waste liquids described above. The first concept is to treat all waste liquids to obtain the degree of purity required by the potable-water standards. The second approach is dual treatment of waste waters; i.e., one form of treatment for urine, urinal water, and fecal water and a less complex treatment for wash water and condensate. This latter concept is feasible since the purity requirements for shower and other hygiene water are not so rigid as the requirements for potable water.

Due to the potential use of the dual treatment concept, two water recovery subsystems were selected. For treatment of urine, urinal-flush water and fecal water the vapor-diffusion/compression distillation concept was chosen. The primary advantage this concept has over the vapor diffusion distillation concept is the recovery of the heat of vaporization of the distillate. This concept would also treat effectively wash water and condensate.

The vapor-diffusion concept is an ambient pressure distillation process. Water evaporates from a membrane surface, diffuses through a gas-filled gap and condenses on a porous metal condensing separating surface. The semipermeable membrane prevents the

Table 13.3.3-1

Potable Water Standards[25]

Compound or Property	Space Science Board	United States Public Health Service	World Health Organization
Chemical (mg/l)			
Ammonia	----	----	0.50
Arsenic	0.50	0.05	0.05
Barium	2.00	1.00	1.00
Boron	5.00	----	----
Cadmium	0.05	0.01	0.01
Chloride	450.00	250.00	200-600
Chromium	0.05	0.05	0.05
Copper	3.00	1.00	1-1.5
Cyanide	----	0.20	0.20
Fluorine	2.00	1.70	1-1.5
Iron	Unobjectionable	0.30	0.3-1.0
Lead	0.20	0.05	0.05
Magnesium	----	----	50-150
Manganese	Unobjectionable	0.05	0.1-0.5
Nitrate	10.00	45.00	45.00
Selenium	0.05	0.01	0.01
Silver	0.50	0.05	----
Sulfate	250.00	250.00	200-400
Zinc	----	5.00	5-15
Alkyl benzene sulfonates (ABS)	No foam	0.50	0.5-1.0
Carbon chloroform extract (CCE)	----	0.20	0.2-0.5
Chemical oxygen demand (COD)	100.00	----	10.00
Phenols	----	0.001	0.001-0.002
Physical			
Turbidity (Jackson) max.	10.00	5.00	5-25
Color (Pt-Co) max.	15.00	15.00	5-50

Table 13.3.3-1 (Continued)

Compound or Property	Space Science Board	United States Public Health Service	World Health Organization
Odor (TON)*	Unobjectionable	3.00	Unobjectionable
pH	----	----	6.5(7.0-8.5)9.2
Solids (ppm)** max.	1000.00	500.00	500-1500
Taste	Unobjectionable	----	Unobjectionable
Radiological (c/l)			
Radium-226-alpha	----	3.00	10.00
Strontium-90-beta	----	10.00	30.00
Gross beta emitters	----	1000.00	1000.00
Microbiological			
Coliform test (MPN)***	----	less than 2.2	less than 1.0
Total count/ml.	10.00	----	----

*Threshold Odor Number **Parts Per Million ***Most Probable Number

Table 13.3.3-2

Typical Condensate Contamination Characteristics [25]

Contaminant	Concentration (ppm)
Particulates	25
Dissolved solids	45
Total	70
COD	450 ppm
Odor	positive
Turbidity	positive
Color	positive (yellowish)
pH	7.1
Bacteria	positive (numerous)

Table 13.3.3-3

Typical Washwater Contamination Levels [25]

Dissolved materials	Concentration (ppm)
Chloride (NaCl)	340
Urea	100
Sebum	180
Lactic acid	75
Other	205
Subtotal	900
Particulates	1000
Detergent	1000
Total	2900
COD	1200 ppm
Odor	positive
Turbidity	positive
Color	positive
pH	4.8
Bacteria	positive (numerous)

Table 13.3.3-4

Typical Urinal Water Contamination Levels [25]

Organics	
Urea	8900
Phenols	590
Amino acids	580
Lactic acid	360
Creatinine	280
Ammonia	180
Citric acid	180
Uric acid	180
Hippuric acid	140
Hydroxyliamine	100
Other organic acid	70
Vitamins	20
Miscellaneous	40
Subtotal	11620
Inorganics	
Chloride (NaCl)	3370
Sodium	1070
Potassium	530
Phosphorous	320
Sulfur	280
Nitrates	140
Calcium	50
Magnesium	40
Subtotal	5800
Gases	250
Particulates	460
Total	18130

passage of solids, microorganisms and other contaminants into the condensor. Replacement of the membrane on a schedule will be necessary. Recovery of nutrients from the membrane for plant food should be considered. This will require some development.

Returning to the dual-concept mode, the subsystem selected for wash water and condensate recovery is reverse osmosis since multifiltration produces an unsatisfactory effluent [25].

Reverse osmosis is a process that utilizes high pressure to force water from a solution through a semipermeable membrane to a less concentrated solution. The semipermeable membrane prevents the passage of solid microbial and other contaminants. Removal of the membranes is a scheduled maintenance item. When the low concentration solution reaches a desired level of water recovery efficiency, it is removed and sent to the vapor diffusion/compression unit for further processing. In its place, a fresh charge of low concentration solution is added.

The integrated concept (vapor diffusion/compression) and the dual concept (vapor diffusion/compression-reverse osmosis) compare favorably on the absolute, primary and secondary evaluation levels based on a study by Hamilton Standard [25]. The main points of distinction are as follows:

1. The integrated concept possess better contamination control characteristics since microbiological contamination is more likely with the dual concept (the effect of the reverse-osmosis unit).
2. The dual concept requires less power than the integrated concept [1]. This might change if the processed wash water and condensate were thermally stored.
3. The dual concept has lower resupply and volume requirements [1].
4. The integrated concept has a lower systems weight [1, 25].
5. The integrated concept has a higher reliability since its MTBF is projected to be higher than the dual concept due to differences in complexity [25].

Despite the potential for microbiological contamination, the selected water-management subsystem is the dual concept. It is suggested that

1. the heat rejection loop be integrated with the storage system for wash water and condensate, and
2. chemical pretreatment be used for the reverse-osmosis unit.

A schematic for the dual concept is shown in Figure 13.3.3-1. Note that a valve provision has insured that the integrated concept may be used singularly if the dual concept is not guaranteeing acceptable quality product water.

Potable-water storage and purity control may be provided by bladderless tanks heated to 160°F for maintenance of purity. A similar storage technique is recommended for wash water and condensate except that the thermal source be the heat rejection loop.

13.3.4 MICROBIOLOGICAL CONTROL

Microbiological control is a very important aspect of life-support considerations. Microorganisms can be antagonistic, symbiotic or inactive in their relationship to man and his environment. Conversely, man's own defense mechanisms or an hostile environment may destroy or at least neutralize a microorganism. Also, normal defenses may be ineffective.

It must be assumed that, in a lunar-colony environment, the microorganism/man balance shifts in favor of the microorganism. A closed environment such as the lunar colony presupposes that some or all of man's natural defenses would be minimized. Under circumstances such as these, all microorganisms must be considered pathogenic. This emphasis becomes particularly important when closure of the food-waste complex is considered in colony develop-

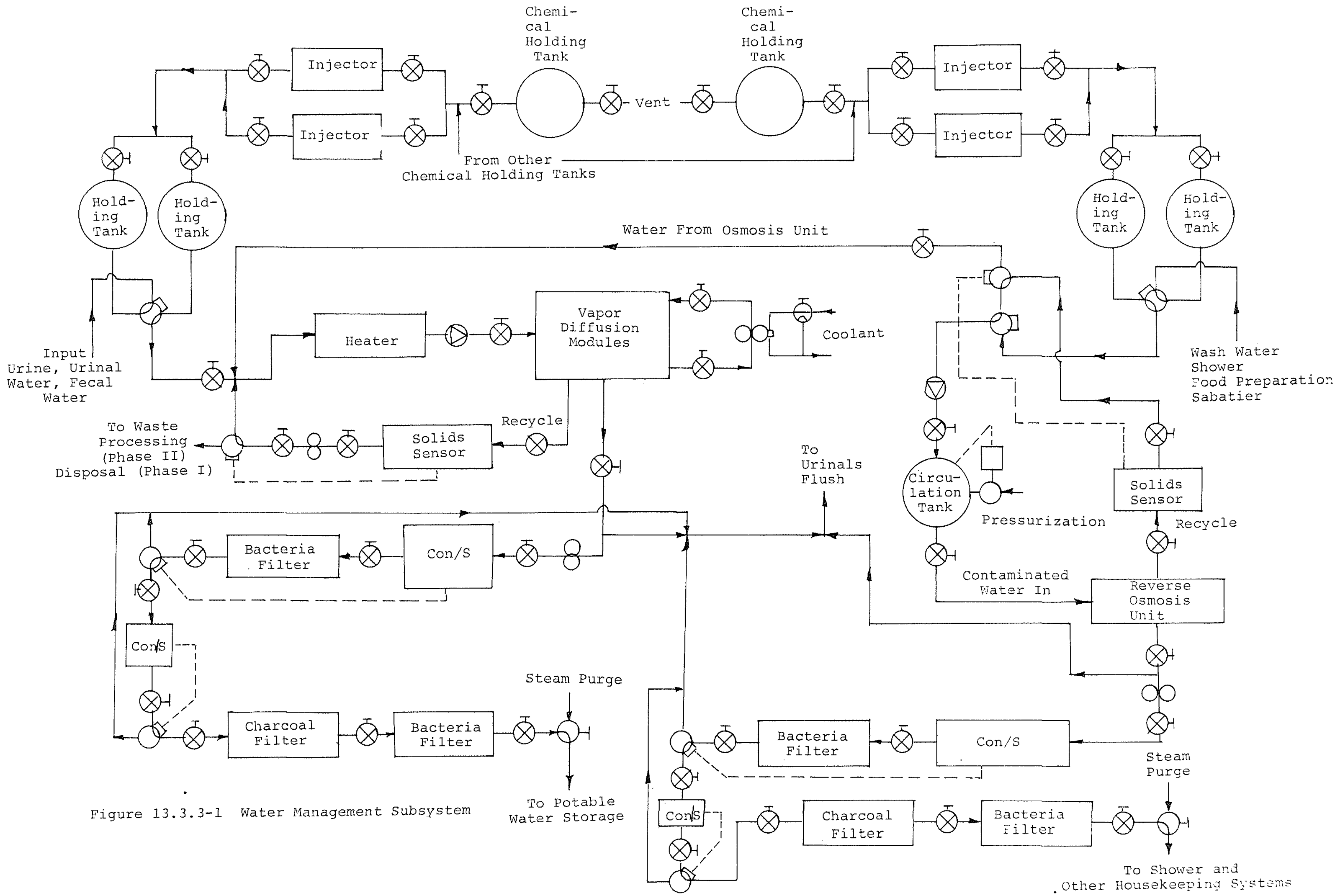


Figure 13.3.3-1 Water Management Subsystem

ment. Some of the waste-processing techniques suggested for closure of food-waste loop possess necessary microbial functions. Proper control is paramount.

Also requiring emphasis for microbial subsystem considerations is the requirement for well developed detection and monitoring procedures. These are required to determine the presence, concentration and viability of the microorganisms. Other aspects of proper microbial control is that effective control methods be used routinely. The selected methods would be required to sterilize and contaminate infected areas.

Table 13.3.4-1 summarizes known microbial control methods. Table 13.3.4-2 summarizes suggested microbial control methods for critical subsystems in the life support areas [25].

13.3.5 INSTRUMENTATION AND CONTROL

The instrumentation and control subsystem is very critical in the proper evolution of a regenerative life-support system for the lunar colony. Since man is the most important aspect of the life-support system, more than adequate provision for control of life-support systems is absolutely necessary. Proper instrumentation for control, fault-detection alarm, fault isolation, crew readout, automatic correction where possible and telemetry is paramount in the lunar colony.

The suggested concept for the instrumentation and control subsystem for life support is a fully automatic system. In this system all controls, sensors, telemetry, display and maintenance indicators are fully automatic. When a fault is detected, it is then isolated, displayed and corrected if manual correction is not required. The displayed output tells whether automatic correction has been made or manual correction is required. All information is also telemetered back to earth. This system also incorporates redundant sensors for detection of critical parameters.

Table 13.3.4-1

Microbial Control Methods [25]

Temperature	Other Physical Methods
Heat, wet	Ultrasonic
Heat, dry	Osmotic Pressure
Refrigeration	Microflotation
Freezing	Centrifugation
Freezing-thaw cycles	Filtration
Pyrolysis	Scrubbing
Oxidation	Maceration
Distillation	Rapid Decompression
	pH
Radiation	**Chemical**
Beta Particles	Biocidal Agents
Gamma Rays	Gas Sterilants
X-Rays	Photodynamic Agents
Ultraviolet Rays	Antibiotics
Microwaves (heat)	Sonochemical
Infrared (heat)	Metallic ions
	Aerosols
Electrical	**Biological**
Electrohydraulics	Bacteriophage
Electrolytic Shock	Colicins
Electrophoresis	Enzymes
Electrostatic Precipitation	Immunization
	Isolation
	Personal Hygiene

Table 13.3.4-2 Suggested Microbial Control Methods [25]

Atmosphere Control

Atmosphere - filters, prefilters and catalytic oxidation

CO_2 concentration and reduction - heat, biological filters, pH control and scrubbing

Equipment

Presterilization
Nonbiodegradable materials
Vacuum and filtration cleaning
Ultraviolent radiation
Biocides
Clothes washer

Crew

Personal Hygiene
Immunization
Medicines and drugs
Biocidal soaps and lotions
Treated clothing
Shower

Water Management

Biocides
Heat
Biolocical filters
Membrane filtration
Continuous monitoring

Waste Management

Filters
Heat
Biocides
Continuous Monitoring

Consistent with projected lunar-colony application, the fully automatic concept would be supported by a "minicomputer" especially suited to its needs. As a backup, the lunar-colony's main computer would be available.

The liklihood of the development of a fully automatic system by time of predicted lunar-colony growth is questionable. However, the need for such a system is evident. The harsh environment of the moon and man's capability for existence in such an environment should dictate the development of such a system.

13.3.6 REQUIREMENTS FOR INTEGRATION OF SUBSYSTEMS

Subsystem integration implies the synthesis of the life-support subsystems schematics into one total schematic representing process flows for the life-support system. Also, part of a system's synthesis requirements are the following four factors:

1. Materials balance - required to define ranges and quantities of materials.
2. Energy balance - required to insure all electrical quantities have been determined.
3. Subsystem interactions - considered to identify and design subsystems and operational interfaces.
4. Configuration considerations - included to assure that life-support subsystem hardware is compatible with other lunar-colony subsystem hardware.

Time limitations precluded the completion of studies of material and energy balances. The Phase I and Phase II conceptual configuration presented earlier represent the outgrowth of a integration study which identifies the basic subsystem's interactions for life support.

The selection of the life-support subsystems for lunar-colony support was based on forecasted technological improvements. It goes without saying that comprehensive basic research and development for all life-support functional areas must be contained, both on the selected concept and possible backup alternative concepts. The harsh living environment of the lunar surface dictates that utmost care be placed upon the development of supportive hardware for man's life support. Extensive manned tests are imperative. Man's successful interaction with his life-support subsystem is the most critical of considerations.

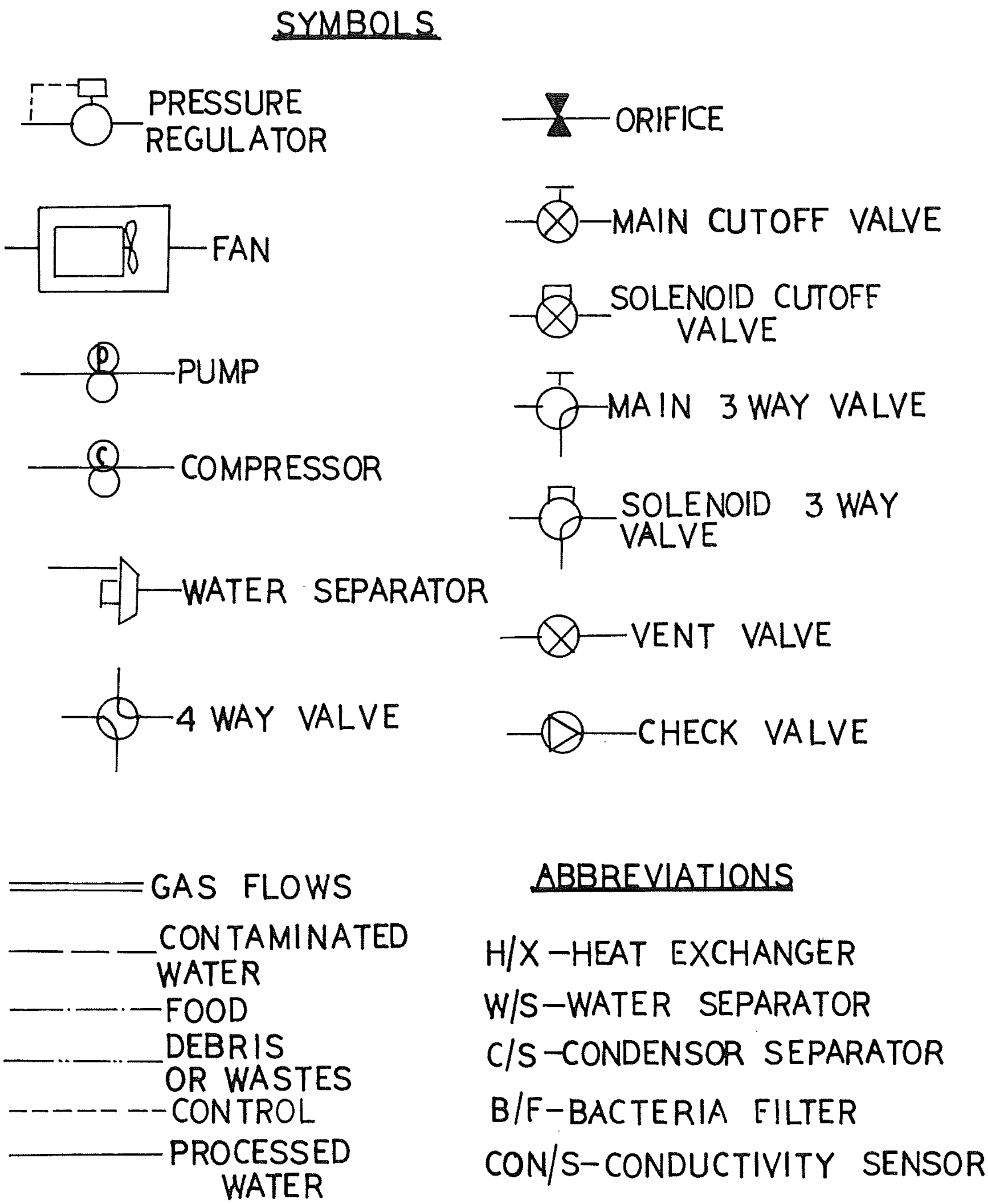


FIGURE 13-1. SYMBOLS AND ABBREVIATIONS

REFERENCES

1. ________________, "Lunar Base Synthesis Study. Final Report. Volume III. Shelter Design", North American Rockwell; NAS 8-26145, 15 May 1971.

2. Kammermeyer, Karl, editor, Atmosphere in Space Cabins and Closed Environments, Appleton-Century. Crafts, Division of Meredith Publishing Company, New York, New York, 1966.

3. Heitchue, Regis D., Jr., editor, Space Systems Technology, Reinhold Book Corporation, New York, 1968.

4. ________________, "Portable Life Support Systems", NASA SP-234, Office of Technology Utilization, NASA, Washington, D.C., 1970.

5. ________________, "Conference on Nutrition in Space and Related Waste Problems", NASA SP-70, Scientific and Technical Information Division, NASA, Washington, D.C., 1964.

6. ________________, "Aerospace Food Technology", NASA SP-202, Scientific and Technical Information Division, Office of Technology Utilization, NASA, Washington, D.C., 1970.

7. ________________, "Moonlab", NASA Contract NSR 05-020-151, School of Engineering, Stanford University, Stanford, California, August, 1968.

8. ________________, "Bioregenerative Systems", NASA SP-165, Scientific and Technical Information Division, Office of Technology Utilization, NASA, Washington, D.C., 1968.

9. ________________, "Preliminary Results from an Operational 90-Day Manned Test of a Regenerative Life Support System", NASA SP-261, Scientific and Technical Information Office, NASA, Washington, D.C., 1971.

10. ________________, "Lunar Stay Time Extension Module (STEM), Final Report", Contract NAS1-4277, Space Systems Division, Goodyear Aerospace Corporation, Akron, Ohio, 21 August 1965.

11. ________________, "Lunar Base Synthesis Study. Final Report", Vols. I, II, IV and Appendices, Contract NAS 8-26145, Space Division, North American Rockwell, 15 May 1971.

12. ________________, "Biologistics for Space Systems Symposium", Tech. Doc. Report No. AMRL-TDR-62-116, Biomedical Laboratories, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, May, 1962.

13. Elikan, Leonard, editor, "Aerospace Life Support", Chemical Engineering Progress Symposium Series, No. 63, Vol. 62, 1966, AlChE, N.Y., N.Y.

14. Culp, R. L. and Culp, G. L., Advanced Waste Water Treatment, Van Nostrand-Reinhold Environmental Engineering Series, Van Nostrand Reinhold Company, 1971.

15. Eckenfelder, W. W., Jr., Industrial Water Pollution Control, McGraw-Hill Book Company, N.Y., 1966.

16. McCabe, Brother J. and Eckenfelder, W. W., Jr., coeditors, Biological Treatment of Sewage and Industrial Wastes. Vol. 2. Anaerobic Digestion and Solid-Liquids Separation, Reinhold Publishing Corporation, N.Y., 1958.

17. Sawyer, C. N. and McCarty, P. L., Chemistry for Sanitary Engineers, McGraw-Hill Book Company, 1967.

18. ________________, "Aviation and Space: Progress and Prospects", ASME, N.Y., N.Y., 1968.

19. Reveley, W. F., "Performance of a Water-Waste Water Management System for Spacecraft", AICHE, 48th Annual Meeting, Dec. 1965.

20. Nuccio, P. P., Hurley, T. L., Chybik, F., Sr., Bambenek, R. A., "Refurbishment and Testing of the Integrated Waste Management System", Contract NAS 9-9014, AMGLO Corporation, Chicago, Illinois 60616, Oct., 1969.

21. ________________, "60-Day Manned Test of a Regenerative Life Support System with Oxygen and Water Recovery, Part I, Engineering Test Results", Contract NASW-1612, NASA CR-98500, McDonnell Douglas Astronautics Company - Western Division, Santa Monica, California, December, 1968.

22. King, C. D. and Kuraw, E. A., "Closing the Ecology", AIAA Third Annual Meeting, Boston, Mass., Dec., 1966, AIAA Paper No. 66-935.

23. Bolles, T. V., "Atmospheric Contaminant Control Subsystem Evaluation for Space Flights of One Year Duration", Contract No. NAS 1-2934, General Dynamics Astronautics, Oct., 1963.

24. Akl, L. and Doyle, W., "Maintainability Evaluation, Analysis, and Predictions for the Phase "A" Air Evaporation Unit (AEU), Rep. No. ADR 09-05-71.1, Grumman Aerospace Corporation, Bethpage, N.Y., April, 1971.

25. ________________, "Trade-off Study and Conceptual Designs of Regenerative Advanced Integrated Life Support Systems (AILSS)", Cont. No. NAS 1-7905, NASA CR-1458, Hamilton Standard, Division of United Aircraft Corporation, Windsor Locks, Conn., 1970.

26. ________________, "The Closed Life Support System", NASA SP-134, Scientific and Technical Information Division, Office of Technology Utilization, NASA, 1967.

27. ________________, "Habitability Data Handbook. Volume 4. Food Management." Habitability Technology Section, Spacecraft Design Division, Manned Spacecraft Center, Houston, Texas, MSC-03909, July 31, 1971.

28. Walkinshaw, C. M., Johnson, P. H., "Analysis of Vegetable Seedlings Grown in Contact with Apollo 14 Lunar Surface Fines", HortScience, Vol. 6, No. 6, Dec., 1971.

29. ________________, "Habitability Data Handbook. Volume 3. Housekeeping." Habitability Technology Section, Spacecraft Design Division, Manned Spacecraft Center, Houston, Texas, MSC-03909, July 31, 1971.

30, Drake, G. L., King, C. D., Johnson, W. A. and Zuraw, E. A., "Study of Life Support Systems for Space Missions Exceeding One Year in Duration. NASA SP-134, The Closed Life Support System, 1966.

31. Foster, J. F., Litchfield, J. H., "The Effects of Controlled Environment on the Growth of Hydrogenomonas Bacteria in Continuous Cultures", NASA SP-134, The Closed Life Support System, 1966.

32. Ward, C. H., Miller, R. L. "Algal Systems for Biological Food Synthesis" NASA-SP-134, The Closed Life Support System, 1966.

33. Jagon, R. B., Thomas, R. S., "Study of Life Support Systems for Space Missions Exceeding One Year in Duration", NASA-SP-134, The Closed Life Support System, 1966.

34. McDowell, M. E., Leveille, G. A., "Algae Systems" NASA SP-70, Conference on Nutrition in Space and Related Waste Problems.

35. Walkinshaw, C. H., "Lunar Horticulture", HortScience, Vol. 6, No. 6., Dec., 1971.

36. Annual Report 1970-1971, Environmental Research Laboratory, University of Arizona, Arid Lands Research Center, ABU DHABI.

37. Kleiber, M. "Animal Food for Astronauts", NASA SP-70 Conference on Nutrition in Space and Related Waste Problems.

38. Cooke, G. D., Bevers, J. R., Odum E. P., "The Case for the Multispecies Ecological System with Special Reference to Succession and Stability" NASA SP-165 Bioregenerative Systems, 1966.

39. Calloway, D. ., "Nutritional Properties of Harvested Hydrogenomonas Eutropha" NASA SP-165 Bioregenerative Systems, 1966.

40. Goldner, B. H., Dittman, J. B., "Growth of Hydrogenomonas Eutropha in Urine for Application to a Bioregenerative Life Support System." NASA SP-165 Bioregenerative Systems, 1966.

41. Wilks, S. S., "Plant Systems as Long Term Flight Nourishment Sources" NASA SP-70 Conference on Nutrition in Space and Related Waste Problems, 1964.

42. Smapira, J. "Design and Evaluation of Chemically Synthesized Food for Long Space Missions". NASA SP-134, The Closed Life Support System, 1966.

43. Fox, S. W., "Prospectus for Chemical Synthesis of Protheinaceous Foodstuffs" NASA SP-134, The Closed Life Support System.

44. Engel, R. W., "Mineral and Vitamin Requirements of Long Flights" NASA SP-170 Conference on Nutrition in Space and Related Waste Problems.

45. ________________, "Habitability Data Handbook. Volume 5. Garmets and Ancillary Equipment" Habitability Technology Section, Spacecraft Design Division, Manned Spacecraft Center, Houston, Texas, MSC-03909, July 31, 1971.

46. ___________________, "Habitability Data Handbook. Volume 6. Personal Hygiene," Habitability Technology Section, Spacecraft Design Division, Manned Spacecraft Center, Houston, Texas, MSC-03909, July 31, 1971.

47. Byrne, J. P., and Littman, J. U., "A Forced-Circulation/ Flash-Evaporation Concept for Spacecraft Waste Water Recovery", Paper 68-3597, A. Research Manufacturing Division, Apr., 1968.

48. Feindler, K., "Filtering System for Aerospace Water Reclamation", Tech Rep. AMRL-TR-67-157, Aerospace Med. Res. Labs., Dec., 1967.

49. Glueckert, A. J., Nuccio, P. P., and Zeff, J. D., "Final Technical Report for a Prototype Regenerable Carbon Dioxide Removal System, MRD Div. of General American Trans. Corp., Aug., 1964.

50. "Human Waste Collection and Storage During Aerospace Flight", Rep. AMRL-64-3, Whirlpool Corp., Feb., 1964.

51. Warner, A. W., Brown, D. S., and Glass, W., "Recovery of Potable Water from Urine by Membrane Permeation", Tech. Rep. AMRL-TDR-64-73, Aerospace Med. Res. Labs, Sept., 1964.

52. Babinsky, A. D., and Derezinski, S. J., "Water and Carbon Dioxide Removal from Carbon Dioxide Reduction Systems", Tech. Rep. AMRL-TR-66-83, Aerospace Med. Res. Labs., June, 1966.

53. Wildermuth, Peter, "Regenerative Carbon Dioxide Adsorption System Using Charcoal", Tech. Rep. AMRL-TR-67-48, Aerospace Med. Res. Labs., May, 1967.

54. "Investigating of the Feasibility of Wet Oxidation for Spacecraft Waste Treatment", Whirlpool Corp., 1966.

55. Clifford, J. E., et al, "Investigation of an Integrated Carbon Dioxide Reduction and Water Electrolysis System", Tech. Rep. AMRL-TDR-66-186, Aerospace Med. Res. Labs., April, 1967.

56. Putnam, D. F., "Chemical Aspects of Urine Distillation", Preprint 65-Av-24, ASME, March, 1965.

57. Hansen, C. E., and Berger, C., "Urine and Waste Water Recovery by Electrodialysis", Preprint 65-AV-16, ASME, March, 1965.

58. Gully, A. J., Bethea, R. M., Graham, R. R., and Meador, M. C., "Removal of Acid Gases and Oxides of Nitrogen from Spacecabin Atmospheres". Inst. of Science and Engineering, Texas Tech. College, Lubbock, Texas, 1968.

59. Esten, H., Murray, R. W. and Cooper, L., "Vacuum Distillation, Vapor Pyrolysis Water Recovery System Utilizing Radioisotopes for Thermal Energy", Tech. Rep. AMRL-TR-67-80, Aerospace Medical Labs., November 1967.

60. Dora, R. A., Clarey, J. R. and Weber, T. B., "Monitoring the Bioeffluents of Man to Establish Space Wehicle Environmental Control Requirements", Beckman Instruments, Fullerton, Calif.

CHAPTER 14 MINING AND EXCAVATION

During the course of colony construction and operation, there are numerous requirements for transportation or relocation of lunar materials. This chapter contains a description of the mining and excavation requirements and an outline of the physical characteristics of the lunar material. A description of excavation systems appropriate to the beginning of the colony is presented, and recommendations for the most suitable basic equipment are made. In addition, several excavation systems which presently require technological development, but which may be available for the advanced colony, are discussed, and recommendations for research are made.

The lunar deep drilling experiments, with primarily scientific motives, are not included in this discussion.

The subject of lunar excavation and mining has been treated in several pre-Apollo-11 studies [1, 2, 3, 4, 5, 6, 7]*. Information from these studies, along with more recent data, has been used in the compilation of this chapter.

14.1 INTRODUCTION AND REQUIREMENTS

Numerous applications of soil-moving equipment are associated with the development of the lunar colony. The applications cover a wide spectrum of both quantity of material and handling precision, and selection of the optimum soil-moving device for each purpose would result in an excessive amount of equipment on the lunar surface. An attempt has been made to select a relatively small number of devices that will accomplish all of the proposed tasks; in some cases there is a sacrifice in efficiency associated with the selection.

In most cases, it is assumed that the material to be moved consists of unconsolidated fines as described in Section 14.2. Exceptions,

* See References at end of Section 14.3

such as the construction of large subsurface cavities, are noted in appropriate locations.

The soil-moving tasks which must be accomplished can be divided into groups; these groups are discussed in the following sections.

14.1.1 MINING

The occupants of the lunar base and the lunar colony will be involved in two types of mining operations, one associated with the production of oxygen and the other associated with the production of building materials. The oxygen-production process requires approximately 350 cubic meters of lunar material per 28-day cycle, and the efficiency of the process is such that the quantity of the plant effluent is not significantly different. The requirements of the building material production facility are lower and more variable than those of the oxygen plant; there is in fact a high probability that the oxygen-plant residue would be desirable raw material for the manufacture of building materials. If the materials can be used in this fashion, then proximity of the two facilities would eliminate the need for a second mining operation.

The mining operations require removal of material from the lunar surface and transportation to the point of use. These requirements may be fulfilled either by special purpose machinery or by multi-purpose machinery; the advantages of each will be discussed in a subsequent section of this chapter.

14.1.2 EXCAVATION

The term excavation, in this context, implies the creation of a depression or subsurface cavity for some purpose other than the use of the material originally contained by the depression or cavity. For example, the radiation environment of the lunar surface requires the burial of living spaces; virtually all construction will therefore require some excavation. In addition, subsurface storage facilities such as tanks will require excavation.

The possible relationship between excavation and mining should not be neglected. Through judicious selection of the site for the mining enterprise, an excavation sufficient for a large structure can be obtained over a period of time. For example, the projected rate of use of lunar material by the oxygen-production plant would result, after a three-year period, in an excavation appropriate for a five-story structure having a diameter of 30 meters.

14.1.3 CONSTRUCTION

The requirements imposed on soil-handling equipment by the construction process are more extensive than those for mining and excavation. In addition to simple digging, construction of an inhabitable space may require a grading operation and a backfilling operation. The grading capability is also required for construction site preparation, landing-site maintenance, and road maintenance.

14.2 SOIL PROPERTIES*

The mechanical properties of soils are not only necessary in the design of structures and planning of surface activities and future explorations of the moon, but also provide valuable information on the past history of the soil surface. Some of the results of the Apollo soil-mechanics experiments and returned soil samples are given below. The color of the soil is generally gray brown. The lunar soil may be classified as silty fine sand. The surface textures of soil particles of Apollo 15 are generally more irregular than common terrestrial soils. The soil compositions vary with locations. The composition for some soil samples of Apollo 15 is given in [4] and is partly reproduced in Table 14.2-1.

*See end of Section 14.3 for Section 14.2 references

Table 14.2-1 Composition of Soil Samples at Apollo 15

Type of Material	Composition, Percent		
	Apennine Front, Station 6	Lunar Module Area	Hadley Rille Station 9
Agglutinates and Brown Glass	~46	High	16 to 35
Clear Green Glass	4 to 6	-	<2
Mafic Silicates	10 to 20	15 to 20	10 to 30
Feldspar	18 to 20	6 to 10	20 to 35
Anorthosite	0 to 10	4 to 10	
Microbreccia	5 to 30	Trace	
Crystalline Basalt		5 to 6	5 to 25

14.2.1 GRAIN SIZE

The grain-size distribution has a bearing on the strength, optical, seismic and thermal properties of the soil. The median particle size is in the range of 40 to 130 μm. The soil conditions at the Surveyor and the Apollo-11 and Apollo-12 sites are generally similar and at the Apollo-14 site coarser material in the medium to coarse sand size range exist. The range of median grain size at the Apollo-15 and Apollo-11 sites are similar. The soil grain-size distribution of the Apollo sites is given [14] and reproduced in Table 14.2.1-1.

Table 14.2.1-1 Lunar Soil Grain Size Distribution

Mission	Number of Samples	D_{80} (mm)	D_{50} (mm)	D_{20} (mm)
Apollo 11	13	0.72 to 0.163	0.105 to 0.048	0.030 to 0.0157
Apollo 12	55	0.44 to 0.167	0.094 to 0.042	0.033 to 0.0126
Apollo 14	24	0.061 to 0.20	0.130 to 0.044	0.036 to 0.0133
Apollo 15	19	0.40 to 0.18	0.108 to 0.051	>0.019 to<0.014
Composite	111	0.72 to 0.163	0.128 to 0.042	0.036 to 0.0126

D_n is a particle size, in which n is the weight percent of soil finer than that size.

14.2.2 DENSITY

Density of a soil is closely related to strength properties. The density estimates of all investigators vary perhaps because of the different methods used in its determination. Soil density increases with the depth due to self weight. For the Apollo-15 mission, the density of 1.69 g/cm^3 at Hadley Rille is higher than the density of 1.35 g/cm^3 at Apennine Front. The soil densities are given in [15] and some typical values are reproduced in Table 14.2.2-1.

Table 14.2.2-1 Estimates of Lunar Soil Density [15]

Mission	Investigator	Bulk Density g/cm^3
Surveyor I	Christensen et al. (1967)	1.5
Luna XIII	Cherkasov et al. (1968)	0.8
Surveyor III and VII	Scott and Robertson (1967, 1968) and Scott (1968)	1.5
Apollo 11	Costes and Mitchell (1970)	1.54 to 1.75
Apollo 12	Houston and Mitchell (1971)	1.55 to 1.90
Luna XVI	Vinogradov (1971)	1.2
Lunokod-I	Leonovich et al. (1971)	1.5 to 1.7
Apollo 14	Carrier et al. (1972)	1.45 to 1.6
Apollo 15	Mitchell et al. (1972)	1.35 to 2.15

14.2.3 COHESION AND FRICTION

The Mohr-Coulomb theory of failure has been applied to the lunar soil. The shear strength internal-friction relation is

$$s = c + \sigma \tan \phi$$

where s is shear strength, c is soil cohesion, σ is normal stress on the failure plane, and ϕ is the angle of internal friction.

Self-recording penetrometer tests have been used to derive the strength parameter. The penetration resistance q is given by the following equation [4]:

$$q = cN_c \xi_c + \rho GBN_{rq}\xi_{rq}$$

where

c = cohesion,
ρ = soil density,
G = acceleration due to gravity,
B = diameter of loaded area (cone base),

N_c, N_{rq} = bearing capacity factors
= $F(\phi, \alpha, \delta/\phi, D/B)$,

ξ_c, ξ_{rq} = shape factors

ϕ = angle of internal friction,
δ = friction angle between penetrometer cone and soil,
α = half the cone apex angle

and

D = penetration depth (cone base).

Flagpole penetration tests give the relation between cohesion and angle of internal friction. The flagpole is a chrome-anodized aluminum hollow tube with an outside diameter of 2.226 cm and a wall thickness of 0.089 cm. This was pushed near the Apollo-15 lunar module to a depth of 119.05 cm by the full weight (about 27 kg) of the pilot before being hammered. The force of penetration is given by the following relation[4]:

$$F = qA_p + F_s A_s$$

where

q = unit end bearing capacity
= $cN_c\xi_c + \rho G\, BN_{rq}\xi_{rq}$
A_p = end-bearing area,
A_s = surface area in contact with the soil,

and

F_s = unit skin friction.

For a linear variation of skin friction from zero at the surface to a maximum at the bottom of the pole, F_s is given by the relation,

$$F_s = \frac{\rho G\ DK\ \tan\delta}{2}$$

where

K = the coefficient of lateral earth pressure ≃ 0.5,

Tanδ= coefficient of friction between the pole and soil ≃0.5.

In the Apollo-15 mission, a soil-mechanics trench with vertical sides was made and tested to failure by a bearing plate on the top surface. In case of vertical walls, the strength parameters are independent of the shape of the failure surface. An analysis assuming a planar failure surface to derive a cohesion-internal friction angle is given in [4]. Estimates of values of cohesion and internal friction angle for the Apollo missions given in [4] and [15] are reproduced in Table 14.2.3-1.

Table 14.2.3-1 Estimates of Lunar Soil Cohesion and Angle of Internal Friction

Mission	Cohesion, kN/m^2	Angle of Internal Friction, Degrees
Apollo 11	0.8 to 2.1	37 to 45
Apollo 12	0.6 to 0.8	38 to 44
Apollo 14	0.03 to 0.3	35 to 45
Apollo 15	0.9 to 1.1	47.5 to 51.5

14.2.4 COMPRESSIBILITY

Vacuum odometer and direct shear tests on Apollo-12 soil are described by Carrier [16]. The soil sample was returned to the Lunar Receiving Laboratory at a pressure of 10^{-2} torr and stored at a pressure of less than 2×10^{-6} torr. The test specimens were prepared at a pressure of less than 2×10^{-6} torr and tested at a pressure of less than 5×10^{-8} torr. In test 1, the sample was compressed vertically in 4 increments up to a pressure of 31.21 KN/m^2 and sheared. Then, under a vertical pressure of 1.93 KN/m^2, the sheared sample was brought back into its original unsheared position and compressed again in 4 increments up to a pressure of 69.92 KN/m^2. Part of the test results given in [16] are reproduced in Table 14.2.4-1.

Table 14.2.4-1 Lunar Soil Vacuum Odometer Data [16]

Void Ratio e	Vertical Stress KN/m^2
0.684	0
0.667	2.27
0.641	6.96
0.638	11.85
0.612	31.21
Sheared and Compressed Again	
0.622	1.93
0.597	11.56
0.575	30.95
0.561	50.40
0.551	69.92

Assuming a specific gravity of 3.1, we get

$$e = \frac{3.1}{\rho} - 1 \quad (\text{with } \rho \text{ in g/cm}^3)$$

The results showed that the elastic part of the compression is negligible relative to the plastic portion. Most of the compression occurred almost immediately after the loading with about 50% in less than 2 to 3 seconds and 90% in less than 7 to 8 seconds.

14.3 COMPARISON OF SUBSYSTEMS

There are many earth-moving devices that would be quite useful if they could be properly adapted and transported to the lunar surface. Some of these devices, however, function well only in a single application; their ability in other applications is limited. In order to be acceptable for work on the lunar surface, an item of equipment should be capable of adequate performance in several areas, and it should have a capacity appropriate to the functions which it supports.

General earth-moving devices and concepts have been compared on the basis of appropriate criteria. In applying the criteria, the performance of a device was assessed in the areas of mining, site preparation (grading), and construction (including backfill). In addition to the expected performance, candidate subsystems were judged on the basis of criteria such as safety, availability, cost, reliability, and maintainability. In the following paragraphs, the candidate devices are discussed, and their advantage and disadvantages are described.

14.3.1 PRIME MOVER ACCESSORIES

The Lunar Surface Base will be equipped from the beginning with several vehicles described as prime movers. A detailed description of the vehicles may be found elsewhere in this report; it is sufficient for the present purpose to note that at least one crane boom, of approximately ten-meter length, will be available as an accessory to the vehicle. The prime movers are designed to allow for the addition of other accessories, and this feature suggests their use in soil-moving applications.

The following devices may be specified as attachments to the prime movers; power for the attachments would be provided from a power-take-off on the prime mover chassis. All of the devices listed may be awarded a high rating in the area of availability; although some emphasis on weight reduction in the specific designs would be desirable, all of the systems are presently within the state-of-the-art. Furthermore, by comparison with some of the systems to be considered in subsequent sections, all of the prime-mover accessories are quite safe.

All of the prime-mover accessories are of approximately the same degree of complexity; they should not differ significantly in the areas of reliability or maintainability.

14.3.1.1 The Front-End Loader

A front-end loader, or skip loader, appears to be the most versatile of the prime-mover accessories. Equipped with a bucket having a capacity of one cubic meter, the loader could satisfy the 350 cubic meter mining requirements of the oxygen production plant within one to four working days (depending on transport distance). If the leading edge of the bucket is properly oriented, then the loader can perform a scraping or grading operation. In addition, the loader can perform the transportation and backfilling functions necessary for construction.

14.3.1.2 The Clamshell Bucket

Since the installation of the lunar-base modules requires the presence of a ten-meter boom for the prime mover, a clamshell bucket would be a relatively simple addition. The bucket would not serve well in a mining application, since a separate transportation system would be required. It is likewise inappropriate for a grading or scraping operation. However, in a construction application, the clamshell bucket offers the possibility of depositing material on the top of a surface structure to form a mound. Because of this capability, the presence of the bucket may be necessary during the early stages of the lunar base.

14.3.1.3 The Scraper-Loader

The scraper-loader is essentially a self-loading trailer that could be towed by the prime mover. It would have a larger capacity (four cubic meters) than the front-end loader or the clamshell bucket, and the loading should not be a problem in unconsolidated lunar material. There is a weight penalty associated with the scraper-loader by comparison with the other prime mover accessories; this investment would not appear to be justified prior to a substantial increase in the mining requirements. Furthermore, although the scraper-loader would be suitable for mining operations, it would not be an appropriate tool for grading or backfilling.

14.3.1.4 The Bulldozer Blade

A bulldozer blade could be attached to the prime mover; this combination would provide the best machine for grading, scraping, and road building. However, the difficulty associated with transporting material would make the blade inappropriate for mining operations. Certain backfilling operations could be performed with ease, but the blade would not be capable of depositing soil on the top of a fragile structure.

14.3.1.5 The Dragline

It would be possible to employ a dragline bucket on the crane boom of the prime mover. This combination would possess the same difficulties associated with the clamshell bucket in a mining operation; other vehicles would be required for transportation of material. The dragline would not function well in a grading or scraping situation, and backfilling operations could be accomplished with greater precision using the clamshell bucket.

14.3.2 SPECIALIZED DEVICES

Several devices can be envisioned that would perform soil moving operations without direct dependence on the prime movers. These systems would require either self-contained power sources or integral motors that could be connected to the colony power station.

The specialized soil moving devices are characterized by a somewhat lower degree of flexibility than the prime mover accessories. They would, necessarily, be erected or installed for a particular job; some effort would be required before the location or function could be changed.

14.3.2.1 The Cable Excavator (Dragline)

The cable excavator is basically a dragline bucket which operates on a tramway cable between a point of excavation and a material stockpile. Such a device could, for example, supply lunar material to the oxygen plant, but the excavator capacity would be far in excess of the plant requirements. For excavation purposes, the device is desirable so long as a trench is an acceptable configuration; other shapes would require relocation of cables and supports at frequent intervals. The utility of the cable excavator for grading or backfilling operations is minimal.

The cable excavator is quite acceptable when judged on the basis of safety, availability, reliability, and maintainability; and the weight and cost penalties associated with its use are moderate. The device would be a strong contender for use in later generations of the colony if large quantities of material are required.

14.3.2.2 The Bucket Conveyer

The bucket conveyer, similar to a trench or ditch-digging machine used on earth, could also be employed for the purpose of supplying a lunar manufacturing facility. Like the cable excavator, the device would not function well in a grading or backfilling capacity. It does, however, score adequately in the categories of safety, availability, reliability, and maintainability; it might be useful in particular applications in later stages of colony evolution. A self-powered, mobile bucket conveyer might be useful for production of large trenches for pipelines and power cables, but such a need is not anticipated during the early stages of the colony.

14.3.2.3 The Auger

A power auger could be employed as a means of loading a conveyer or transferring material from a stockpile to a manufacturing facility. The auger has a list of advantages and disadvantages which is virtually identical to that for the bucket conveyer; it should be considered only for specific process connected applications.

14.3.2.4 Automatic Meteoritic Iron Collectors

There is evidence that small quantities of loose ferromagnetic material exist on the lunar surface, and it should be possible to employ automatic collection devices to accumulate quantities large enough for processing.

From the published analyses of lunar fines [8], it appears that they contain 0.5 - 1.0 wt % metallic Fe from meteorites. There are also sizable trace concentrations (0.001 % - 0.020 %) of cobalt and nickel, presumably from meteorites [9]. These ferromagnetic metals are often embedded in small glass beads, but nevertheless they can be easily picked up with a magnet. In the absence of a braking atmosphere, it is questionable whether large chunks of meteoric iron will be found. However, the fact that no meteors have been found so far does not mean there are no kilogram or metric-ton sized pieces of high-grade iron scattered over the surface of the moon. The ore wagons described below might stumble across some of these, if such there are.

It is possible to envision several automatic ore wagons, Figure 14.3.2.4-1, which would roam the sunlit lunar surface carrying electromagnets. Power could be obtained from a solar-cell canopy on top of the wagon (100 W/m^2), which would power an electromagnet, drive the wheels, and periodically lift and unload magnets into the wagon. The wagons could be equipped with a homing device, such as a directional radio antenna, so they could be called home in the evening. A random walk (or roll) might suffice for the operating mode.

A powerful magnet simply passed over the surface at an elevation of 1 - 2 cm might reasonably be expected to lift iron particles

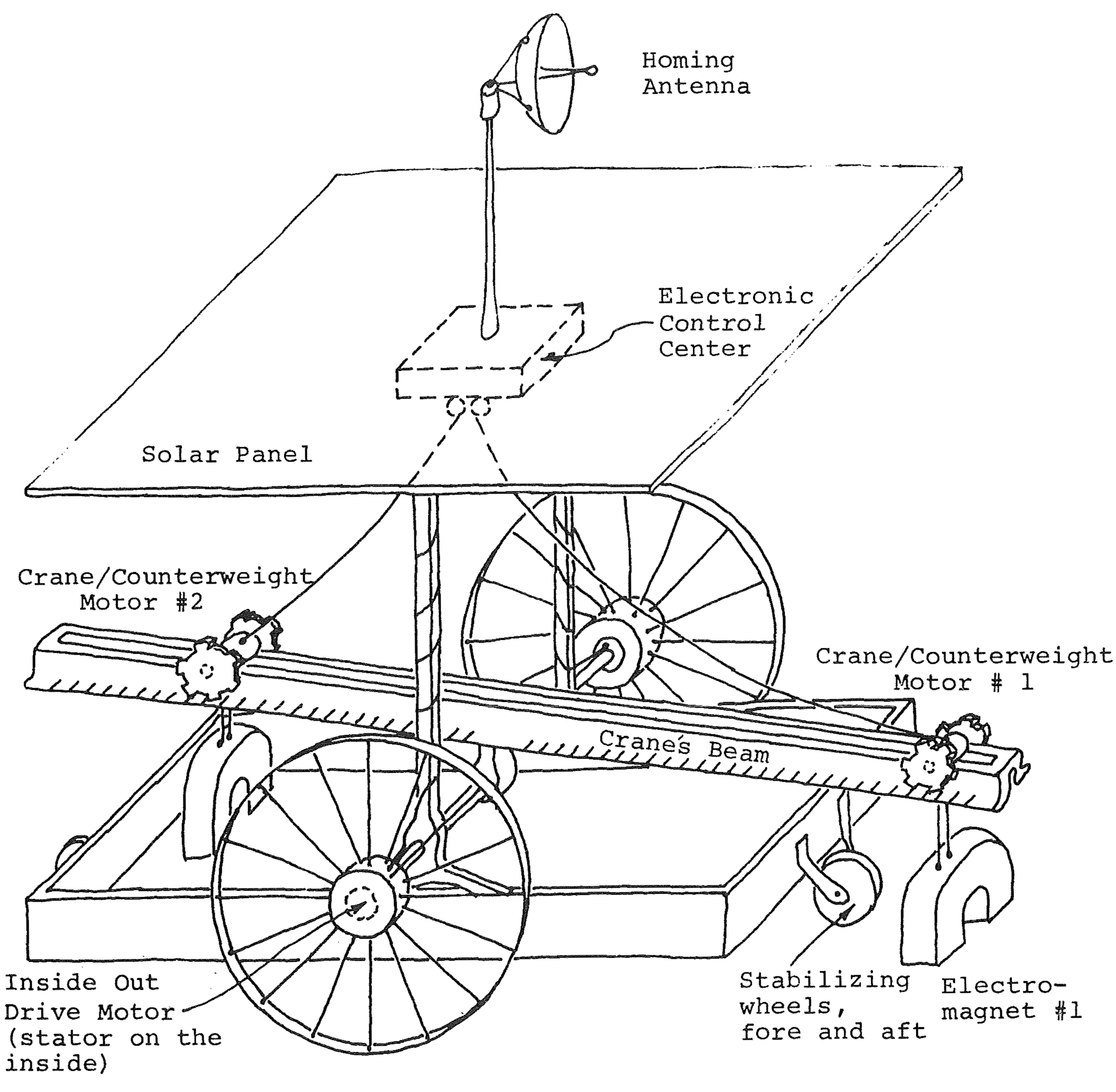


Figure 14.3.2.4-1 Sketch of Automatic Ore Wagon

from a depth of at least 5 mm. If the width of the path swept was 20 cm, then the wagon would have to travel 10^5 cm = 1 km to "process" 1 m^3 of soil, containing about 2 kg of iron. Sweeping for 300 hr of the lunar day, each ore wagon could harvest 10 kg of metal (mixed with perhaps 20 kg of glass), by moving at 30 cm/min. The glass could be removed by heating in a ceramic crucible to the melting point, 1810°K, and using gravity separation.

14.3.3 EXPLOSIVES

The use of explosives for excavation appears, at first, to be an obvious choice [10]. An explosive charge could be used to fracture a solid formation into pieces which could be handled by conventional means in a mining operation. Alternatively, a charge could be used to create a subsurface cavity which could be lived in some fashion and used as a dwelling. However, there are problems associated with the use of explosives on the lunar surface which decrease their practicability.

A paramount issue in the consideration of explosives is safety. Aside from the danger to construction workmen using the materials, it is possible that the shock waves from an explosion could damage previously constructed, and inhabited, structures. The physical integrity of such structures is vital; the consequences of even minor damage are much greater in a lunar environment than in an earth environment.

14.3.3.1 Nuclear Explosives

The creation of subsurface cavities with nuclear explosives is easy to imagine, but such a cavity would not be useful for the colony proposed in this study. A time span on the order of 100 years would be required for the decay of residual radioactivity to a level safe for human habitation. Furthermore, the shock wave considerations cited earlier would require that such explosions be detonated prior to the general inhabitation of the lunar surface; a possibility would then exist for irrevocably altering some of the selenological features that are important to the scientific mission of the colony.

14.3.3.2 Conventional Explosives

In addition to the safety considerations cited above, the use of conventional explosives on the lunar surface is further constrained by the efficiency of such charges. Explosive requirements for formation of a spherical subsurface chamber may be investigated by using Olsen's equation for crater volume, $V = 0.4\ W^{8/7}$, where V = volume of material and W = weight of TNT equivalent.

Table 14.3.3.2-1

Mass of Explosive Required for Subsurface Cavities

Chamber Diameter	Mass Of Liquid Explosive
20'	4,380 lbs
50'	61,000 lbs
100'	555,000 lbs

Assuming that a subsurface cavity requires twice the explosive charge associated with a crater and that the explosive employed is three times as effective as TNT, approximate weights may be calculated. Table 14.3.3.2-1 depicts the explosive requirements for cavities in the size range of interest for the lunar colony.

14.3.4 UNIQUE DEVICES

The items of equipment described in previous sections are, for the most part, conventional devices which could be adapted to lunar requirements. By contrast, there are several concepts or devices which might prove useful for lunar construction but which would require considerable research effort before they could be considered practical.

Several of the systems considered below would be useful only for excavation; their utility in the areas of grading or mining is negligible. However, several proposed devices offer the possibility of simultaneous excavation and structural wall formation, and they are therefore attractive concepts for habitat construction.

14.3.4.1 The Hydrogen-Oxygen Jet Drill

The hydrogen-oxygen drill is identical in principle to a gas welding torch. The drilling process would be initiated by manual excavation of a small cavity or shaft which could be sealed at the surface. Inlet pipes for hydrogen and oxygen and an outlet pipe for steam would be passed through the seal. In operation, the hydrogen and oxygen would burn in the cavity, rock would be melted, and the resulting glasslike material would form the wall of the cavity or tunnel. The product of the combustion process, steam, would be collected, condensed (perhaps by passage through a power producing turbine), and converted by electrolysis into hydrogen and oxygen.

The hydrogen-oxygen drill will obviously require considerable development before it can be considered as a viable tool for lunar excavation. The most prominent area in which research is required involves the structural capabilities of the product of the melting process; it is anticipated that precise control of melting and cooling will be required in order to achieve the goal of a structurally sound cavity wall.

14.3.4.2 The Thermal Drill

The thermal drill is similar in effect to the hydrogen-oxygen drill in that the final product would be a hole or tunnel having a glass-like, structurally sound wall. However, instead of melting rock with a flame, the heating is achieved through electrical or radio-isotope heat sources. The source is contained within a shaped tip which is weighted and allowed to sink into the rock or soil. Forming and cooling accessories located behind the tip would complete the formation of the structural wall. The primary advantage to the thermal drill is the possibility for virtually unattended operation. Once situated and activated, a properly designed unit would perform its function with a minimum of attention. Alternatively, habitat construction could proceed on the surface with additional stories being added to a structure as it descended.

Small thermal drills have been tested in laboratory situations [11, 12]; holes of five centimeter diameter have been drilled in tuff. The walls of test holes appear to have adequate structural properties, but no large holes or simulated lunar environment tests have been conducted.

The power requirements for thermal drills can be estimated from empirical data from the preliminary tests. In an earth environment, with losses included, approximately 4500 joules are required for the melting of each cubic centimeter of rock. Based on this data, Figure 14.3.4.2-1 depicts the energy requirement as a function of penetration rate for several useful hole diameters, assuming that the drill could be designed to operate at low penetration rate.

It should be pointed out that smaller holes, on the order of one meter in diameter, might be useful for storage of fluids in the lunar environment.

14.3.4.2.1 The Nuclear Thermal Drill

A nuclear thermal drill could be powered by a radioisotope such as cobalt 60. This substance, selected because of its availability, could provide approximately 18.8 kilowatts per kilogram; each kilogram would occupy a volume of about 125 cubic centimeters.

An advantage of the nuclear thermal drill powered by cobalt 60 can be realized by taking into consideration the five year half-

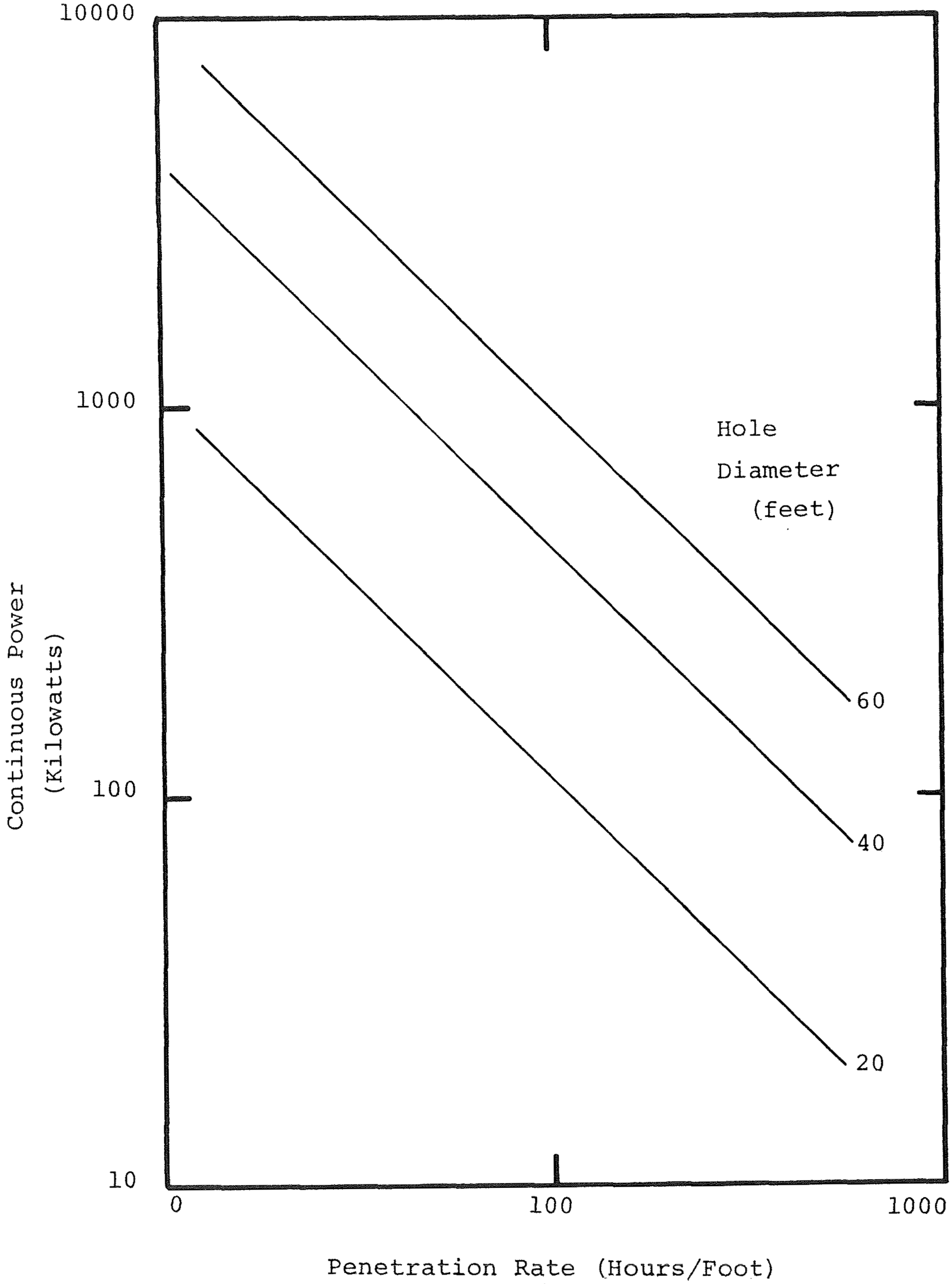


Figure 14.3.4.2-1 Energy Requirement for Thermal Drills

life of the substance. A drill unit could be designed to attain a specified depth at the time when decay of the substance caused loss of thermal power. In this application, the physical load applied to the back of the drill can be regarded as a variable which affects the depth.

The primary disadvantage of the thermal drill is the requirement for shielding the radioisotope. Although there is no residual radioactivity after decay, cobalt 60 is a strong gamma emitter and the transportation vessels must be shielded accordingly. Shielding alone for a large thermal drill might exceed 50000 kilograms; this mass would be excessive with the proposed transportation-to-lunar-surface systems. There is a possibility that another isotope, such as plutonium 238, could be used to eliminate the shielding requirement, but a special effort toward production of this substance in quantity would probably be required.

Another style of nuclear thermal drill could be constructed on the basis of a critical fission reactor. Such a device would be useful throughout the design life of the fuel; it might be transferred from one location to another. Proper design of the control elements would allow a substantial decrease in the mass devoted to shielding; the discussion of power reactors in Chapter 17 indicates that the thermal requirements for drilling could be met.

14.3.4.2.2 The Electric Thermal Drill

Instead of locating a reactor in the tip of the drill, it would be possible to use electric heaters connected to the colony power supply. Efficient thermal drilling might require a larger installed generating capacity, but the drilling tip could be used indefinitely if it were designed for removal from a completed hole.

14.3.4.3 The Plasma Torch

The plasma torch is a system which can produce a localized flame having a very high temperature. Such a device might have application in lunar construction for smoothing walls by melting the surface into an impervious layer or for cutting large rocks into manageable pieces.

In operation, an inert gas is passed through an electric arc, and the plasma jet is formed. There are several problems associated with the torch which would require resolution prior to its use in lunar construction. The inert gas should be collected and recycled through the torch in order to make the process economically feasable. In addition, the electrodes across which the arc is formed are typically cooled by a liquid flow system, and there is a severe safety hazard associated with burnout of the electrode cooling jacket. The electrical power requirement is high; the proposed use of the torch would require analysis in terms of available high-current, DC power on the lunar surface.

14.3.4.4 The Laser

The laser has been suggested as a possible tool for construction of subsurface facilities for the lunar colony. In principle, a sufficiently powerful laser would be capable of numerous cutting and melting functions, and it could probably be used more easily than some of the alternative devices. Laser power requirements, however, are at present excessive; much more efficient energy conversion will be required before the laser can be considered a viable tool. It is expected that efforts in this direction will continue quite apart from projected applications on the lunar surface, and if efficient, powerful lasers are developed prior to the initiation of the colony, then a reassessment of values will be in order.

REFERENCES (Sections 14.1 and 14.3)

1. Johnson, R. W., "Resources on the Moon-Implications for Manned Lunar Missions", Conference in Applied Sciences, Research and Utilization of Lunar Resources, International Academy of Astronautics, International Astronautical Congress, 19th, Lunar International Lab. Symposium, 4th, New York, New York, October 17, 1968, Proceedings, p. 153-165.

2. Shotts, Reynold Q., "Systems for Lunar Surface Mining", Fifth Technical Meeting of the Society of Engineering Science, Inc., Huntsville, Alabama, October 30, 1967.

3. Shotts, Reynold Q., and Cox, Robert M., Jr., "Lunar Resources: A Study of Surface Mining", Final Report, Contract NAS8-20134, Research Projects Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama, January 31, 1967.

4. Shotts, Reynold Q., "Early Water Mining on the Moon", Proceedings of the Seventh Annual Working Group on Extra-terrestrial Resources, NASA SP-229, Denver, Colorado, June 17, 1969.

5. Atchison, Thomas C., and Schultz, Clifford W., "Bureau of Mines Research on Lunar Resource Utilization", Proceedings of the Working Group on Extraterrestrial Resources, NASA SP-177, Brooks Air Force Base, Texas, February 19, 1969.

6. Pancne, James, and Schmidt, R. L., "Lunar Drilling", Proceedings of the Working Group on Extraterrestrial Resources, NASA SP-177, Brooks Air Force Base, Texas, February 19, 1969.

7. Johnson, Rodney W., "A Planning Logic for Exploration and Utilization of the Moon", Proceedings of the Working Group on Extraterrestrial Resources, NASA SP-177, Brooks Air Force Base, Texas, February 19, 1969.

8. Housley, R. M., et. al., "Mossbauer Studies of Apollo 12 Samples", Proceedings of the Second Lunar Science Conference, p. 2125.

9. Smales, A. A., et. al., "Elemental Composition of Lunar Surface Material", Science, January 30, 1970, pp. 509-512.

10. Cox, Robert M., Jr., "Explosives and the Lunar Environment", Proceedings of the Seventh Annual Working Group on Extra-terrestrial Resources, NASA SP-229, Denver, Colorado, June 17, 1969.

11. Smith, M. C., editor, "A Preliminary Study of the Nuclear Subyerrene", Los Alamos Scientific Laboratory, Report LA-4547, April, 1971.

12. Gido, R. G., "Verification of the Proportional Relationship Between Subterrene Penetration Rate and Melting Power", Office Memorandum, Los Alamos Scientific Laboratory, April 12, 1972.

REFERENCES (Section 14.2)

1. "Apollo 11 Mission Report", NASA SP-238, 1971.
2. "Apollo 12 Preliminary Science Report", NASA SP-235, 1970.
3. "Apollo 14 Preliminary Science Report", NASA SP-272, 1971.
4. "Apollo 15 Preliminary Science Report", NASA SP-289, 1972.
5. Smith, R. E., editor, "Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development", NASA TM X-64627, 1971.
6. Weidner, D. K., editor, "Natural Environment Criteria for the NASA Space Station Program", NASA TM X-53865, 1969.
7. "NASA Space Vehicle Design Criteria (Environment), Lunar Surface Models", NASA SP-8023, 1969.
8. "NASA Space Vehicle Design Criteria (Environment), Models of Earth's Atmosphere (120 to 1000 km)", NASA SP-8021, 1969.
9. "Surveyor I, A Preliminary Report", NASA SP-126, 1966.
10. "Surveyor III, A Preliminary Report", NASA SP-146, 1967.
11. "Surveyor V, A Preliminary Report", NASA SP-163, 1967.
12. "Surveyor VI, A Preliminary Report", NASA SP-166, 1968.
13. "Surveyor Program Results", NASA SP-114, 1969.
14. Carrier, W. D., III, "Lunar Soil Grain Size Distribution", MSC-06852, NASA MSC, Houston, 1972.
15. Mitchell, J. K., et al, "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction, Third Lunar Science Conference, Proceedings, Houston, 1972.
16. Carrier, W. D., III, "Strength and Compressibility of Returned Lunar Soil", Proceedings, Third Lunar Science Conference, Houston, 1972.

14.4 RECOMMENDATICNS

It is the purpose of this section to summarize, through a list of specific recommendations, the discussion in the preceeding part of the chapter. A distinction will be made between the early stages of lunar colonization, when space, weight, and power are particularly important, and the later stages of colonization when capacities and demands are larger. In the former case, specific items of equipment can be suggested. In the latter case, the recommendations will take the form of suggestions of promising candidates for further study.

14.4.1 THE LUNAR BASE AND EARLY COLONY

During the initial phases of the lunar colony, construction and mining operations will be accomplished primarily with machinery transported from earth and suited to a variety of tasks. The luxury of special purpose, heavy duty equipment cannot be afforded and will not be required. It is expected that most excavation and construction work will be conducted in unconsolidated soil, and the recommended equipment is oriented toward this purpose.

There are two specific tools, not previously mentioned, that will nevertheless play an important role in soil-moving operations. These two items are the manual shovel and the manual auger (or post-hole digger). Although they are wholly unsuited for general mining or excavation projects, they are quite important for use in the small tasks which will arise. The inclusion of these two items in the equipment complement is strongly recommended.

For larger operations, where power tools are required, the comparison of candidate subsystems to the list of criteria indicates that the front-end loader would be the best choice. The loader can be installed as an accessory to the prime mover, and it is capable of performing excavation, grading and backfilling functions.

The physical characteristics of the LSB modules suggest that one other item should be included in the basic list of equipment. The modules are to be covered by soil to a depth of five meters, and the proposed method for accomplishing the burial involves some excavation and some mounding of soil on top of the modules. Since the wall construction implies that a definite hazard would exist if a prime mover were driven over the modules, it is recommended that a clamshell bucket be included in the equipment list. The bucket would be operated from the prime-mover crane to complete the covering of the modules.

The items listed in this section; the manual shovel, the manual auger, the front-end loader, and the clamshell bucket, should provide for the soil-moving requirements of the colony until a population on the order of 150 individuals is achieved.

14.4.2 THE DEVELOPING COLONY

As the lunar colony develops, the space requirements and the mining requirements will expand, and it may be possible to make use of special purpose equipment. Several devices have been listed, in Section 14.3.2, that could be deployed on the lunar surface to accomplish large-scale tasks. All of these devices are presently within the state-of-the-art, and redesign for use in lunar applications would be a straightforward matter.

Another group of devices has been proposed in Section 14.3.4. None of these devices, at the present state of development, are capable of fulfilling lunar-excavation requirements. However, all of the devices listed would, in principle, be capable of performing excavation functions in solid rock rather than being restricted to unconsolidated material. In some cases, particularly laser and the thermal drill, considerable effort is presently being devoted to development for earth applications. The advances in these devices should be monitored, and appropriate concurrent research should be conducted to assure that one or more of the systems will be available for use by the lunar colony at the appropriate time.

CHAPTER 15 MATERIALS AND MANUFACTURING

This chapter is concerned with the separation and processing of lunar resources in order to obtain useful materials for manufacturing and construction. The first consideration will be the direct utilization of lunar resources (fines, breccias, rocks) for the fabrication of various products. As can be seen from the composition of the lunar resources [1, 2, 3], many useful minerals and elements are available on the moon. The problem, of course, is separation, extraction and concentration. Various physical and chemical methods for accomplishing these tasks are discussed. Once the basic materials are available in a usable form, the problem becomes one of processing and manufacturing into useful products. The lunar environment offers many advantages for materials processing and these will also be discussed in this chapter.

15.1 DIRECT UTILIZATION OF LUNAR RESOURCES

The three distinctive groups of lunar samples collected by the Apollo astronauts were the crystalline igneous rocks, the microbreccias, and the fines. The igneous rocks, which have come to be called lunar basalts, were once totally molten and are mainly volcanic, i.e., they cooled at, or very near, the lunar surface. The origin of the lunar craters has been much debated in the past. Some scientists believed that they were produced mainly by the impact of meteorites, whereas others contended that they were mainly due to volcanic eruptions. The lunar basaltic rocks attest to the major role of volcanic eruptions. The lunar fines and microbreccias show unmistakable evidence of subsequent impact processes. The chemical composition of various Apollo 11 samples are shown in Table 15.1-1. The fact that the composition of the rocks, fines and microbreccias are essentially the same, further indicates that impacting bodies play a major part in the formation of lunar fines and microbreccias. Minerals present include augite, pyroxene, ilmenite, plagioclase, clinopyroxene, and olivene. The direct utilization of the lunar fines, microbreccias and rocks, when possible, is much more desirable than using complex, power consuming techniques for separation of metals, oxides (glass, ceramic), and single elements (Si, Ca, etc.).

Table 15.1-1 Chemical Analysis of Typical Apollo 11 Samples [1]

	Ingneous Rocks (Avg.)	Fines	Microbreccia
SiO_2	40.38	42.16	41.96
FeO	19.32	15.34	16.51
CaO	11.05	11.94	11.38
TiO_2	10.90	7.75	9.02
Al_2O_3	9.43	13.60	11.85
MgO	7.20	7.76	7.63
Na_2O	0.46	0.47	0.49
Cr_2O_3	0.33	0.30	0.31
MnO	0.26	0.20	0.23
Fe	0.20	0.60	0.60
S	0.19	0.12	0.15
K_2O	0.17	0.16	0.20
P_2O_5	0.12	0.05	0.07
	100.01	100.45	100.40

The conglomerate lunar materials (fines, microbreccias and rocks) become a low viscosity fluid at about 1250°C, cooling to a glasslike monolithic substance. Under slow cooling conditions, the material becomes crystalline and can be classified as cast basalt when poured into molds. Cast basalt technologies have been developed in France, Germany, Poland, and Czechoslovakia [4, 5].

According to Green [6], terrestrial basalt is smelted at 1300°C-1350°C in furnaces similar to open-hearth processing of steel. The molten material then is conducted into a homogenizer drum where, at carefully controlled temperatures and slightly reduced pressures, the melt begins to crystallize. The casting process following this is similar to conventional metallurgical processing except for differences imposed by the greater viscosity and cooling rate constraints. Static casting in sand molds was originally employed, giving rough surfaces having wide tolerances. Metal molds are now used. Centrifugal casting of basalt pipes, milling balls, and other materials of high density, in metal molds at 900 rpm, has resulted in superior quality products. The cooling rate of the cast basalt must be carefully controlled in order to prevent bursting and other imperfections on annealing. The cast basalt is generally cooled from 800°C to ambient temperature in 24 hours. A high rate of heat loss also increases the danger of vitreous (noncrystalline) solidification.

Sintered basalt is valuable in the manufacture of many small articles. The sintering process is similar to that used in powder metallurgy. The lunar fines, for example, can be shaped under a pressure of 1000 kilograms per square centimeter (14,200 pounds per square inch) and sintered in a solar furnace at 1120°C to 1140°C.

Fibers or basalt wool are produced by processes similar to those used for producing certain kinds of glass fibers.

The physical and thermal properties of terrestrial cast basalt are summarized in Table 15.1-2. Under lunar-vacuum conditions, lunar cast basalt should have improved strength characteristics as compared to terrestrial cast basalt. Possible applications of cast, sintered and spun basalt for the lunar colony are given in Table 15.1-3.

Table 15.1-2 Physical and Thermal Properties of Cast Basalt [5]

Physical Properties	
Compressive Strength	4000 - 5000 kg/cm^2
Tensile Strength	250 - 350 kg/cm^2
Bending Strength	400 - 450 kg/cm^2
Hardness	8 - 9 MOH's
Thermal Properties	
Thermal Expansion	78×10^{-7} cm/cm/°C
Thermal Conductivity	0.8 - 0.9 cal/m^2/ m. hour °C
Specific Heat	0.2 cal/gm/°C

The lunar basalt foundry is eventually envisioned to consist of a complete automated surface operation with monitoring and control from an underground shelter. A flow diagram of the process is shown in Figure 15.1-1. Promising heat sources for melting the basalt include the electron-beam gun furnace and the solar furnace (lunar day operation only).

Rocks greater than 8 to 15 cm in diameter need to be crushed for ease of melting. The basalt should be melted at 1320°C to 1350°C and all visible particles fused. If makeup additives are required, a compositional analysis should be made at this point and the material added. For example, crystal nucleation is highly accelerated by magnetite and olivene. The molten material is then discharged into a homogenizing drum at about 1200°C. The melt is then cast similar to a metallurgical process. If re-inforcement is found to be feasible, it should be accomplished at this point. The molds can be fabricated from lunar fines for some applications, but metal molds will be needed for precise castings and centrifugally (dynamic) cast parts. In the molds, the material cools slowly and solidifies during crystallization.

Table 15.1-3 Lunar Base Applications of Processed Basalt
(Reproduced from Ref. 6)

Cast Basalt	Sintered Basalt	Spun Basalt (Fibers)
Furnace material for water extraction operations	Nozzles	Cloth and bedding
Crusher jaws	Tubing	Resilient shock-absorbing pads
Pipes and conduits	Wire-drawing dies	Acoustic insulation
Conveyor material (pneumatic, hydraulic, sliding)	Ball bearings	Thermal insulation
Linings for ball, tube, or pug mills and for flue ducts, ventilators, cyclers, drains, mixers, tanks, electrolyzers, mineral dressing equipment	Wheels	Filler in sulfur cement
Tiles and bricks	Low-torque fasteners	Fine springs
Sidings	Studs	Packing material
Nose cones (?)	Furniture and tableware	Strainers or filters for industrial or agricultural use
Track rails	Low-load axles	Nose cones (with resin binder)
Ties	Scientific equipment frames and yokes	
Pylons	Light tools	
Heavy-duty containers for "garden and orchard" use	Light-duty containers and flasks for laboratory use	
Radar dish frames	Pump housings	
Mirror bases		
Thermal rods		

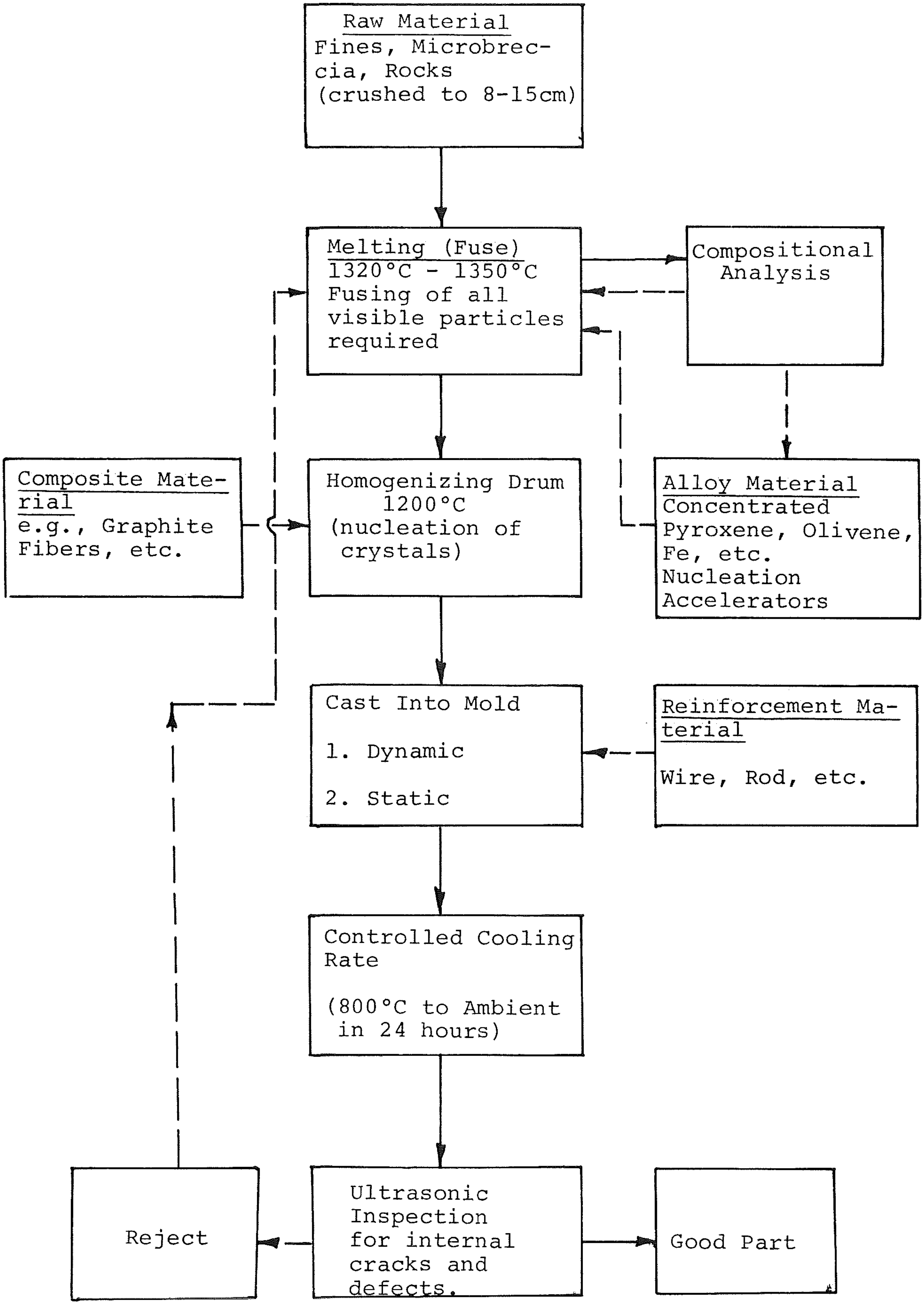


Figure 15.1-1 Flow Diagram of Basalt Casting Process

The rate of solidifying and crystallization depends upon the size of the casting. According to Kopecky [5], thin-walled products with wall thickness of 2 to 3 cm require three to six minutes for crystallization, the thick-walled sections require seven to ten minutes. At 900° to 1000°C, the cast material is glowing, but solidified. The casting is then placed into a slow cooling furnace and subjected to further thermal treatment and gradual cooling to release detrimental internal stresses. The casting is cooled from about 800°C to ambient temperature in 24 hours.

There are some interesting possibilities of controlling the cooling rate of the cast basalt from 800°C down to ambient temperature in 24 hours. Consider the following two cases. In the first case, a slab of cast basalt (10 ft by 6 ft by 1/2 ft), is cooled from 800°C by radiation into the lunar night. In the second case, the slab is cooled in the lunar day. The cooling rate curves are shown in Figure 15.1-2. These curves are based on equations developed by Howell [7] and are given in Appendix D. As expected, the cooling rate is very rapid at first and then it slows down considerably during the final stages. The total time required to cool the cast basalt from 800°C to 0°C is about 16 hours. If cooled during the lunar day, the time required to reach 99°C (day temperature of lunar surface) is 14 hours. If the basalt is then shaded, the time required to go from 99°C to 0°C is then 24 hours. The fast rate of cooling at the higher temperature might present problems during the annealing. A thermal radiation box could be used to slow the cooling rate during the initial stages if required. It is, therefore, possible to cool the basalt at the correct rate without using a furnace that requires power. The casting should then be subjected to nondestructive testing for detection of internal cracks and defects. Rejects can be remelted in the furnace and sent through the process again.

Anorthite (Plagioclase) is relatively plentiful on the lunar surface [1]. The chemical equation for anorthite is: $Ca\ Al_2\ Si_2\ O_8$.

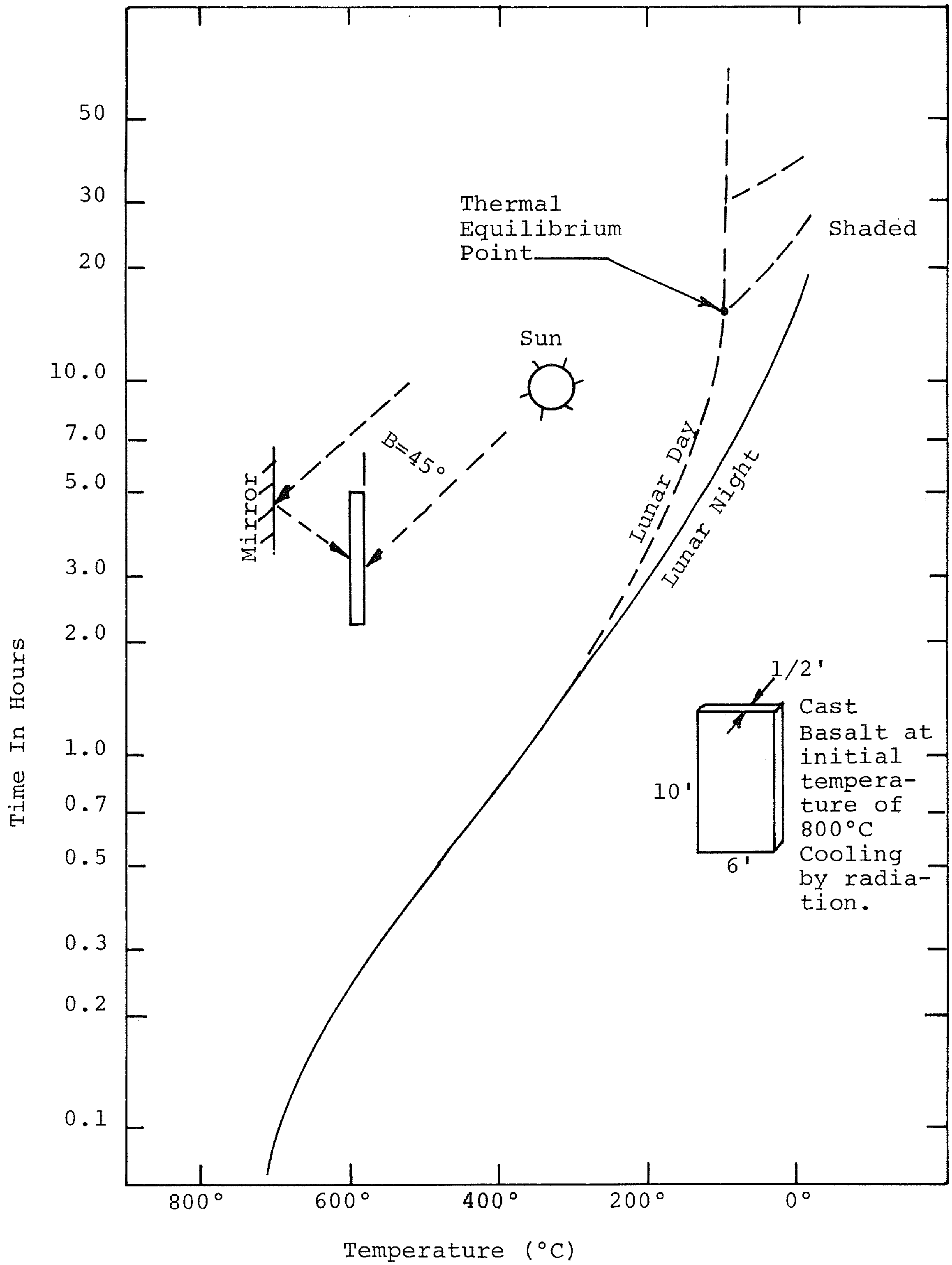


Figure 15.1-2 Cooling Rate Curve for Cast Basalt

The chief ingredients of portland cement are di and tricalcium silicate (Ca_2SiO_4, Ca_3SiO_5) and tricalcium aluminate ($Ca_3Al_2O_6$) [8]. Based on the similarity of the chemical equations, it appears possible to pulverize anorthite and it will react as a cement. The lunar fines and rocks could be used as the aggregate. Research would be needed to establish feasibility. The problem, of course, is the loss of water which is tied up as an hydroxide and unrecoverable. For example, the hydration reaction for tricalcium aluminate is $Ca_3Al_2O_6 + 6H_2O \rightleftarrows Ca_3Al_2(OH)_{12}$.

15.2 SEPARATING USEFUL MATERIALS FROM LUNAR FINES

This section deals with the topic generally referred to as extractive metallurgy. In its broadest sense, extractive metallurgy is not confined to the production of a single metal from an ore but to the total process of concentrating metals and associated nonmetals in ores to produce products of value [10].

Extractive metallurgy is still emerging from the state of an embryonic art to a comprehensive technology grounded in the appropriate chemistry, physics and mathematics. To reap the full value of the materials in the lunar environment will require significant advances in the techniques and technologies presently used in terrestrial ore processing

15.2.1 PHYSICAL SEPARATION METHODS

On the earth, ore is first collected and then concentrated to free it of gangue (valueless material). This is done by a series of processes known collectively as ore-dressing. The major steps are comminution (fragmentation to small sizes) and sorting (one or more physical operations to separate valuable mineral particles).

Preliminary data indicate that the step of comminution may not be needed for the vast quantities of fines found at the lunar landing sites. However, concentrated ore deposits that would require "hard rock" mining and comminution may be found near the lunar colony. The feasibility of exploiting such a deposit would have to be investigated. Crushing and other processing equipment is usually quite heavy and requires much maintenance.

The sorting or physical concentration processes used on the earth needs to be thoroughly studied before attempting to adapt any of them to an application on the moon. The reduced gravity will enhance the operation of some processes and severely limit the capabilities of others.

Operation of processes based on sedimentation and flotation seem problematic because of the reduced driving force (gravity) and the need to circulate and clean large quantities of fluid (probably water). The electrical and magnetic methods, on the other hand, seem to show promise for use on the moon. The driving force for these processes is not reduced by the lunar environment and, in fact, separation may be enhanced by the lower gravity. It should be noted, however, that the mineralogy of the lunar fines is important in these processes and work using simulated lunar fines must take into account any differences in mineral, chemical, or physical composition. For example, lunar ilmenite is essentially pure with all iron divalent as opposed to terrestrial samples in which other forms of iron are found.

15.2.2 CHEMICAL SEPARATION METHODS

The chemical separation of lunar fines into reasonably pure compounds or elements is a difficult task. Section 12.2 of this report discusses the stability of the oxides found in lunar fines and the difficulties involved in trying to reduce the metals to their elemental state. Two of the processes proposed for oxygen production seem to hold the best possibility for metal production.

The flourine-exchange process relies on the extreme reactivity of this halide. All of the oxides in the lunar fines will react with flourine to form metal flourides and oxygen. Once formed, these metal compounds can be separated with comparative ease and combined with potassium to form the free metal. The potassium flouride formed is then electrolyzed and each component recycled in the process. Chapter 12 outlines the process in more detail and discusses the operational difficulties.

Electrolytic reduction of the fines has also been proposed as a method to produce free metals and oxygen. However, it is difficult to predict at this time the likelihood of separating the mixture of metals and cilica that will be formed in the cell. Again, Chapter 12 discusses this process in more detail. Much research is needed in the area of electrowinning metals from the stable lunar fines.

15.3 LUNAR PROCESSING AND MANUFACTURING

After the separation, extraction and concentration of useful metals and nonmetals from the lunar resources, the materials must then be processed and manufactured into useful products. The lunar environment (hard vacuum, 1/6 g) presents many unique possibilities and advantages along these lines.

15.3.1 VACUUM

The advantages of processing materials in a vacuum are well known by materials scientists and metallurgists. The production of vacuum on earth consumes an overwhelming amount of energy, time, careful engineering and money. The thought of 10^{-14} torr vacuum without the confining limitations of steel wall containers and the separation of the work from the worker seduces the imagination of all vacuum technologists. Ruzik [9] says "Mechanical difficulties such as leakage caused by faulty seals, inadequate ability of pumping systems to handle outgasing, heat dissipation, lack of adequate room for mechanical components--all of these complexities would be eliminated on the moon." [10].

Well-developed vacuum processes (vacuum melting, casting, welding, etc.) can be incorporated into lunar production processes to great advantage.

Materials processing research conducted on the Skylab, Shuttle and Earth Orbiting Space Station [11, 12, 13] will lead to further production applications at the lunar colony. Promising areas include materials research, thin-film technology, metallurgy research, welding research, coating and deposition applications, spectroscopic studies, vacuum distillation, etc.

The combination of low gravity (1/6 g) and vacuum may prove to be highly advantageous in material-casting applications. On the earth, solidification and crystallization are irregular because of buoyancy and thermal disturbances so that cast material is not good enough for many applications [11]. Factories are built to refine these irregular crystals by hot rolling, cold rolling, forging, etc., and then the material is machined or formed into the shape and size required. This represents a sizable investment in industry. If liquid metals are mixed under vacuum, low gravity, low thermal-convection conditions, it may be possible to obtain full properties in a cast metal.

15.3.2 LOW GRAVITY

The unique advantage of materials processing and manufacturing in a zero gravity environment has received considerable attention from manufacturing technologists. Experiment implementation plans have already been prepared for the Skylab Orbital Workshop in this area. These experiments include materials processing in space, a metals melting experiment, an exothermic brazing experiment, a sphere-forming experiment, and a composite casting experiment.

Buoyancy and thermal convection sensitive blending processes such as alloying, composite casting, etc., might produce superior

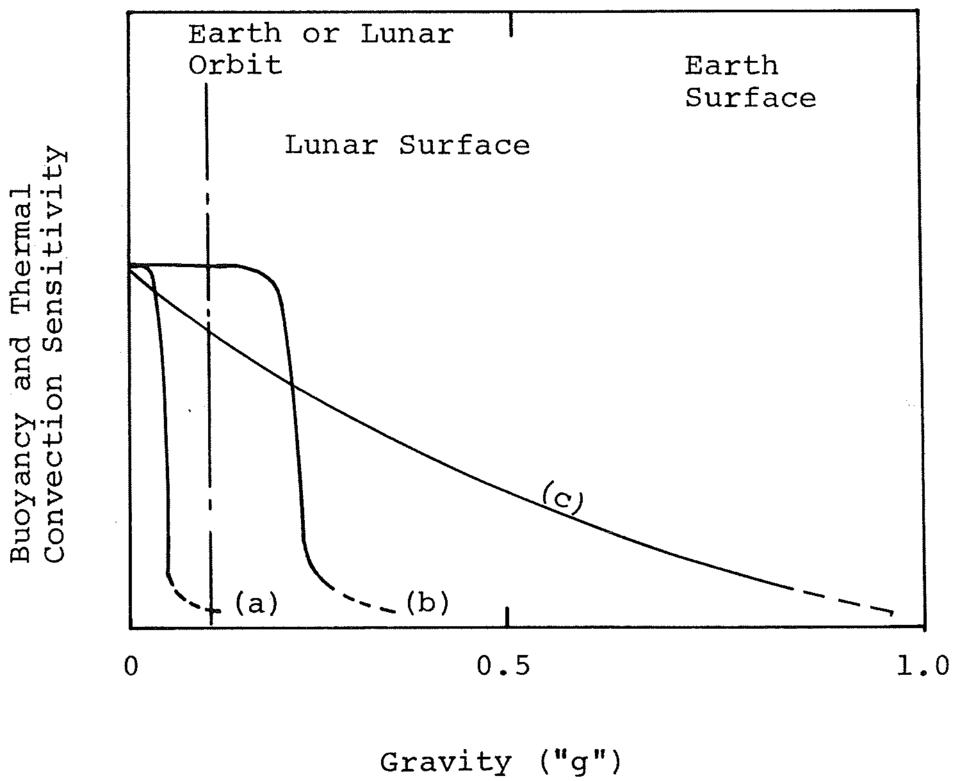


Figure 15.3-1 Possible Effect of Gravity on Buoyancy and Thermal Convection Sensitive Processes

quality products in a zero g environment. At present it is not known whether there is a continuous improvement from 1 g down to zero g or some threshold where a sharp transition occurs. This is illustrated schematically in Figure 15.3-1. Materials processing experiments can be performed in space using a centrifuge varying the gravity from zero to one. Special emphasis should be placed on 1/6 g experiments in order to simulate materials processing on the lunar surface.

REFERENCES

1. "Apollo 11 Preliminary Science Report", NASA SP-214, Scientific and Technical Information Office, NASA, Washington, D. C., 1969.

2. "Apollo 14 Preliminary Science Report", NASA SP-272, Scientific and Technical Information Office, NASA, Washington, D. C., 1971.

3. "Apollo 15 Preliminary Science Report", NASA SP-289, Scientific and Technical Information Office, NASA, Washington, D. C., 1972.

4. "NASA Science and Technology Advisory Committee for Manned Space Flight", NASA SP-196, Vol. II, Appendixes, December, 1968.

5. Kopecky, L., "The Cast Basalt Industry", Annals New York Academy of Science, Vol. 123, Art. 2, pp. 1086-1105, July 15, 1965.

6. Green, Jack, "The Geology of the Lunar Base", North American Aviation, Space and Information Systems Division, SID 61-358, 1961.

7. Siegel, R., and Howell, J. R., Thermal Radiation Heat Transfer, McGraw-Hill, New York, 1972.

8. Van Vlack, Materials Science for Engineers, Addison-Wesley Publishing Company, 1970.

9. Ruzic, Neil P., The Case for Going to the Moon, G. P. Putnams' Sons, New York, 1965.

10. Gilchrist, J. D., Extractive Metallurgy, Pergamon Press, Oxford, 1967.

11. "Manufacturing Technology Unique to Zero Gravity Environment", NASA-MSFC Presentations at Meeting, November 1, 1968.

12. "Space Processing and Manufacturing", George C. Marshall Space Flight Center, ME-69-1, October 21, 1969.

13. "Unique Manufacturing Processes in Space Environment", George C. Marshall Space Flight Center, ME-70-1, April, 1970.

CHAPTER 16 SHELTER

16.1 DESIGN CONSIDERATIONS

The lunar-colony shelter design involves consideration of environment, loads, utility, safety, growth potential, materials and construction techniques very different from those on earth. Some of the characteristics of the moon could be used advantageously, while others might have the potential to be hazards.

16.1.1 ENVIRONMENT

The lunar environment is described in Chapter 8 and in some of the other chapters. Some of the characteristics are low gravity field, rarefied atmosphere, exposure to meteoroids and interplanetary environment, low magnetic field, low level of seismic activity, slow earth-synchronous rotation and no detectable radio noise output.

16.1.1.1 Temperature

Direct sunlight, albedo (reflected sunlight from the moon's surface) and infrared energy emitted from the moon are factors contributing to the wide range of temperature. The temperature of the moon varies between 90°K and 400°K on the lunar equator. During the night,the only source of heat is the infrared emission which drops to a very low level at night. Site and shelter-wall geometry influence the temperature.

The design should keep the temperature of the shelter within the limits to which human, animal and plant life on earth are accustomed, and to the working range of scientific and other critical equipment. Properties of insulating materials are given in [2] and reproduced in Table 16.1-1.

Table 16.1-1 Properties of Insulating Materials

	Conductivity (Btu/hr-ft/°F)	Density (lb/ft^3)	Depth* (in)
Polyurethane Foam	0.01	4.0	24
Fiberglass Material	0.0016	2.0	8
Lunar Soil	0.0024 to 0.0068	~100	11 to 26

*For 1 Btu/hr ft^2 heat loss at lunar night conditions

Insulation is a must to reduce heat loss and eliminate condensation on the shelter walls.

16.1.1.2 Meteoroids

Meteoroids and lunar ejecta constitute a serious hazard. The shielding may be structural. A 10-ounce nylon or 0.0048-inch aluminum bumper is effective against meteoroids but not against ejecta. In order to provide effective protection against both meteoroid and ejecta, a shielding consisting of an outer nylon or aluminum bumper which breaks up the particles and an intermediate shielding placed between the outer bumper and the inner pressure wall to absorb the energy of the broken particles provides a probability of 0.9999 of no penetration [2]. As in temperature control, lunar soil of sufficient thickness provides adequate protection. An estimated thickness of 6 inches of soil is adequate for a probability of 0.9999 of no penetration. Meteoroid protection charts are given in [2].

16.1.1.3 Solar Flares

The probability and intensity of a flare varies in an 11-year solar cycle. In the course of the largest cumulative spectrum flare of the November 12, 1960 event, the dose-rate peak was reached rapidly within 20 hours from the initiation. Effects of radiation depends on the exposure (see Appendix C). The Atomic Energy Commission radiation-dose limit for U.S. population is 0.30 rem/year. Short-term yearly limit and lifetime-average yearly limit of radiation dose are 38 rem/year and 5.7 rem/year [19]. The yearly maximum radiation-exposure limits for bone, skin, eye and testes are 75, 225, 112 and 38 rem respectively [19]. For a 0.99 probability of not exceeding 200 rads to the skin on a 90-day cycle, the structural shielding is about 11 pounds per square foot of exposed area or a 2-inch thickness of lunar soil [2]. The lunar soil thickness shielding for a dose of 0.10 rem/year is about 5 meters [19].

16.1.1.4 Combined Environment

In order to provide adequate protection, a combination of structural shielding and lunar soil of about 6 inches has better than a 0.99 probability of not exceeding the radiation-dose limits and not causing a meteoroid puncture, on a 90-day exposure cycle [2]. For a lunar colony, a lunar-soil thickness of about 5 meters would provide adequate protection [19].

16.1.2 LOADING

The loading would include dead load, live load, internal and external pressures, soil pressure and the meteoroid impact. Under the rarefied atmospheric conditions, wind load need not be considered. The seismic activity of the moon is of much lower intensity than that of the earth and does not merit any special consideration. The low gravity field would result in much less dead and live loads and soil pressures and is a decided advantage in structural design.

The more critical factors are internal pressure and meteoroid impact. An atmosphere of 3.5 psia O_2 and 6.5 psia N_2 is recommended for a lunar surface base shelter for shirt-sleeve operations [3]. There are people who find it difficult to adjust to the atmosphere on mountain areas on earth. The colony residents who are accustomed to live and work in the earth's atmosphere would like an atmosphere similar to that of the earth and a 14.7 psia in the areas of predominantly human activity would contribute to the long range success of the colony. The pressure could be less in farms and other areas where there is less human activity. The following conditions might be considered critical:

1. Internal pressure, no soil pressure outside and live load;
2. No internal pressure, maximum soil pressure outside and no live load;
3. Condition number (1) with a lunar quake of low intensity, say number 2, on the Richter scale;
4. Condition number (2) with a lunar quake of low intensity, say number 2, on the Richter scale and;
5. Failure due to buckling.

16.1.3 STRUCTURAL CONFIGURATION

The nature of stress distribution in a structure is a function of its configuration. The stress distribution becomes rather important when resources of materials which can resist the necessary stresses are limited. In the initial phase of the lunar colony, the availability of steel and other metals may be limited either because the metal factories have not been set up on the moon or because the cost of transporting materials from earth is high. Lunar rock is an excellent building material. Cast basalt can have an ultimate strength of about 689 N/cm^2 in compression and about 207 N/cm^2 in tension. Rock is primarily a compression-resisting brittle material. Research on its behavior under alternating stresses and crack-propagation phenomena are necessary before structures of unreinforced basalt can be built. The stress in the wall of a cylinder under internal and external pressure is tensile and compression, respectively. A rectangular shape involving beams and slabs would also result in tensile and compressive stresses. A reasonable approach to the problem of tensile stresses would be to use the tensile strength of rock with a good factor of safety and provide metal reinforcement to resist the balance of the tension block. An alternative would be to prestress the structure with a high tensile metal to keep the tensile stresses in the rock within permissible limits with a good factor of safety.

Sphere, oblate spheroid, space frame, stiffened skin and composite materials are all possibilities. An interaction between material properties, stress analysis and construction techniques will be necessary in order to arrive at a final configuration.

REFERENCES

1. "Lunar Base Synthesis Study, Final Report", North American Rockwell, Space Division, 1971, Volume I - Executive Summary.

2. Ibid; Volume II - Mission Analysis and Lunar Base Synthesis.

3. Ibid; Volume III - Shelter Design.

4. Ibid; Volume IV - Cost and Resource Estimates.

5. Smith, R. E., editor, "Space and Planetary Environment Criteria Guidelines for use in Space Vehicle Development", NASA TM X-64627, 1971.

6. Weidner, D. K., editor, "Natural Environment Criteria for the NASA Space Station Program", NASA TM X-53865, 1969.

7. "NASA Space Vehicle Design Criteria (Environment), Lunar Surface Models", NASA SP-8023, 1969.

8. "NASA Space Vehicle Design Criteria (Environment), Models of Earth's Atmosphere (120 to 1000 km)", NASA SP-8021, 1969.

9. "NASA Space Vehicle Design Criteria (Environment), Meteoroid Environment Model-1970 (Interplanetary and Planetary)", NASA SP-8038, 1970.

10. "Proceedings of the Seventh Annual Working Group on Extra-terrestrial Resources", June 17-18, 1969, NASA SP-229, 1970.

11. Mason, B., and Melson, W. G., The Lunar Rocks, Wiley-Interscience, 1970.

12. Reetz, Jr., A., editor, "Second Symposium on Protection Against Radiations in Space, October 12-14, 1964", NASA SP-71, 1965.

13. Reetz, Jr., A. and O'Brien, K., editors, "Protection Against Space Radiation", NASA SP-169, 1968.

14. "NASA Space Vehicle Design Criteria (Environment), Meteoroid Environment Model-1969 (Near Earth to Lunar Surface)", NASA

SP-8013, 1969.

15. Malina, F. J., Applied Sciences Research and Utilization of Lunar Resources, Pergamon Press, 1968.

16. Carrier, W. D., III, "Lunar Soil Grain Size Distribution", MSC-06852, NASA MSC, Houston, 1972.

17. Mitchell, J. K., et al, "Mechanical Properties of Lunar Soil: Density, Porosity, Cohesion, and Angle of Internal Friction", Third Lunar Science Conference, Proceedings, Houston, 1972.

18. Carrier, W. D., III, "Strength and Compressibility of Returned Lunar Soil", Proceedings, Third Lunar Science Conference, Houston, 1972.

19. Minutes, Lunar Colony Functional Analysis Team Meeting, MSC, Houston, February 8, 1972.

20. Scipio, L. A., "Structural Design Concepts", NASA SP-5039, 1967.

21. Gatzek, L. E., "Advanced Space Structures Design: Optimization, Materials, Fabrication", U.C.L.A. Short Course, 1968.

16.2 SPACE PLANNING

16.2.1 PLANNING APPROACH

This section is primarily an attempt to catalogue required architectural facilities and the areas or volumes necessary to perform living and professional activities. Areal requirements are determined by the specific mix of personnel at the lunar base and the succeeding colony. As such, space planning will be dependent on the choice of occupations listed in Section 3.2. A second principal determinant for the allocation of facilities will be the growth sequence: we currently expect that the colony will experience three major time junctions. The first will occur with the initial establishment of a 12-person base. This first generation will be built using a series of canisters or sortie can-volumes initially brought up from earth by the shuttle orbiter. The second generation base, supporting 24 people, will at least double the volume and will also serve as an accurate microcosm of later base and colony configurations. The activities and the facilities present in this generation will include all of those planned for later growth periods. The only exception to this observation relates to the animal farm (this facility is indicated later in this section). This facility and its attendant research and applications will begin in the fourth generation. After the deployment of the 24-person configuration, growth will occur by adding whole or partial multiples of existing facilities. The third major growth point will occur during the sixth generation, by which time we anticipate the development of capabilities to build with lunar minerals. The growth of the base can then continue by constructing new facilities which will no longer be planned so as to fit earth-built canisters. This skill, along with others developed at this time, will allow the establishment of a true colony. Growth following this generation will proceed using shelters built entirely of lunar materials. The canisters will continue to be used although they may be rearranged internally depending on space requirements of that time.

During planning of the early generations of the moon base, we should keep in mind requirements that will be experienced in later generations. If we approach the initial space allocation with this attitude (i.e., maintaining an enforced foresight), we may be able to seek efficiencies which would not necessarily be apparent when one starts at the first generation and moves in increments of one to more advanced generations. The general organization of the 12-person base may perhaps be unsuitable if extended to 24-or 36-people configurations. To proceed from one generation to the next without careful planning could result in the need for constant renovation with coincident wastage of time and material. An optimal planning method may, therefore, be to establish specific guidelines for a lunar base housing 72 people and to then work backwards by generations.

A second observation or caution--this one fostered by a number of examples of American urban growth--is that many past colonies and cities have been programmed or designed for a specific size. When this size was established, no subsequent long-term planning was carried out. Growth thus became a random process which was not controlled by an ordered, rational management. In such circumstances, growth of the colony occurred without providing adequate support for the inhabitants, and services and infrastructural facilities (transport, environmental control systems, power, sewage, and even housing forms) were not distributed or integrated properly.

To illustrate a planning approach that could be suitable for organizing an early generation lunar base, we will consider the planning of the 24-person base. The importance of a base sized to this population has been indicated above. The space allocation and organization methods presented below will have direct applicability to the planning for later generations. The 12-person base configuration that will precede the 24-person size should be developed as an intermediate form. In both of these instances and also with later generations, the general space planning may be divided into two areas--physical and conceptual. The first concerns the allocation of space for residential and basic living activities; the second provides for professional and work activities. These two areas should be separated physically by either distance or walls.

16.2.2 RESIDENTIAL AND LIVING AREAS

In Table 16.2-1 we have catalogued activities associated with normal, nonprofessional living; and we have sought to list the locations or settings where living generally occurs. In addition to showing where these activities normally take place, the matrix also indicates the variability of uses to which a given space may be put. Table 16.2-2 displays a time-activity chart for an individual living at the lunar base. The location vs. time profile for work activities is not specified because of the highly individualistic nature of each person's professional activities.

Some of the locations (e.g., the conference room, the library, and the lounge) will be used for professional activities as well as residential functions. These spaces may thus become transition spaces between residential and work locales.

Table 16.2-3 provides a compilation of Table 16.2-1 and indicates the probable minimum dimensional requirements necessary to support the variety of activities described. Please note that this assortment of spaces is predicated upon a 24-person crew and that the total areal requirement is exclusive of facilities specifically devoted to storage and circulation. In earth-bound buildings, the amount of area or volume allotted to circulation and storage is 25 to 35% of the primary use areas. A 25% space allowance for storage and circulation will require an additional 765 square feet. The total living area required is therefore about 3800 square feet.

16.2.3 PROFESSIONAL AND WORK ACTIVITIES

The development of space requirements for work activities is predicated upon the choice of occupations listed in Section 3.2. With the exception of the individuals doing construction and maintenance, each member of the 24-person base represents a discipline that is, to varying degrees, unique from the other occupations.

Table 16.2-1 Activity-Location Matrix for the Residential Space

ACTIVITY \ LOCATION	Individ Living Unit	Bathroom	Dining Room	Kitchen	Pantry	Living Room	Library	Confer Rm-Small	LectRm/Auditorium	Chapel	Darkroom	Gymnasium	Exercise Room	Doctor's Office	Airlock	Lounge	Laundry	Snack Bar	Locker Room	Passageways
Sleep	X															X				
Rest/Relax	X					X	X	X		X						X				
Dress	X	X																	X	
Wash Clothes		X															X			
Wash Self		X																	X	
Eliminate Body Waste		X																	X	
Housekeep/Clean	X	X	X	X		X														
Store Personal Equip	X																		X	
Prepare Food				X	X													X		
Dine	X		X	X		X										X		X		
Store Food/Utensils			X	X	X													X		
Recreate			X		X			X	X		X	X	X			X				
Read/Study	X					X	X									X				
Watch Movie/Televis	X		X		X				X			X				X				
Perform/List Music			X		X			X	X	X		X								
Converse Sm Groups	X		X	X	X			X		X						X				X
Religious Activity	X							X	X	X						X				
First-Aid	X	X											X	X					X	
Medical/Surg/Psych													X	X						
Walk/Move Around																				X
General Storage						X	X				X	X								

Table 16.2-2 Time-Activity Profile for an Individual Crew Member of a 24-Person Lunar Base

Location	Average Time, Hours/Day Work Day	Off Duty
Living Space		
Individual Living Unit	9	10
Bathroom	1	1
Living Room	N	4
Lounge	N	N
Food Preparation and Consumption		
Dining Room	2	2
Kitchen	1	1
Pantry	N	N
Snack Bar	N	N
Service Facilities		
Library	N	N
Conference Room--Small	N	N
Lecture Room/Auditorium	N	2
Chapel	N	N
Darkroom	N	N
Gymnasium	N	2
Exercise Room	1	N
Locker Room	N	N
Doctor's Office	N	N
Laundry	N	1
Work Areas	9	N

(Note: N indicates nominal time or periods less than 1 hour/day on the average and would be determined according to each day's activities.)

Table 16.2-3 First Approximation--Space Planning, 24-Member Crew Population

Number	Place	Activities	Dimensions (ft)	Each Area (sq ft)
24 ea.	Individual living unit (bed, chair, desk, storage)	Sleep, relax, dress, snack, store, chat, read, watch television	7 x 7 x 6½	49
3 ea.	Bath (3 wc, 3 sinks, 2 showers)	Dress, wash, eliminate, first aid	10 x 15 x 7	150
1	Kitchen/galley (pantry)	Dine, store, food preparation, chat, wash utensils	10 x 14 x 7	140
1	Dining Room	Dine, recreation, religious activities, watch movie, whole group meetings	18 x 20 x 7½	360
1	Lounge (for up to six people)	Dine, converse, watch television, recreation, relax	8 x 12½ x 7	100
1	Conference Room	Briefing, small professional meetings, religious activities	9 x 12 x 7	108
1	Gymnasium (exercise room, sauna, shower, open area)	Exercise, recreation, physiological testing	15 x 20 x 8	360
1	Laundry	Wash and dry clothes, store	6 x 10 x 6½	60
1	First Aid Station/Doctor's Office	First aid, dental, minor surgical	9 x 12 x 7	108
1	Library	Study, computer tie with earth	12 x 15 x 7	180
		Without Storage and Circulation		3062
		25% Additional are for Storage and Circulation		765
		Total Living (Nonprofessional) Area		3827

Planning must include facilities which will support the range of activities while also minimizing duplication. Providing well-ordered locational relationships between two or more disciplines that may share equipment or in which a single individual may have responsibility will also be necessary. Later generations of the lunar base, and subsequently the colony, will probably require planning organizations similar to the one established for the 24-person base. Growth will thus occur by increasing the volume and providing additional services for activities already there rather than by adding facilities for disciplines which had not been represented previously.

Table 16.2-4 compares the occupations of the several crew members with the location or facility in which a specific activity is likely to occur. The frequency and the degree of personnel involvement with equipment or material occupying a location have been indicated by the three letters--A, B, and C. Each represents a use-level:

"A"--Major use of facilities by this individual; locale is primary to each occupant's fulfillment of professional goals.

"B"--Secondary use of facilities; the individual's role is intended to be supportive.

"C"--Occasional use of facilities; facilities would be used in situations where the individual serves as a consultant or invited guest.

A blank space in the matrix indicates no programmed usage of a specific area by the individual.

Individual office units should be provided for those professionals who do not have exclusive use of a specific laboratory or who require privacy for their work (e.g., the social psychologist or the base commander). These office units, with the exception of the base commander's space, would be minimal in size, offering a writing table, storage, two chairs, and perhaps a computer console

Table 16.2-4 Matrix of the Occupation-Location Profile(24-Person)

	OCCUPATION \ LOCATION	Colony Command					Biochemical Research							Medical Fac.				Life Support			
		Flight Control	Computer Facility	LSS Monitor Fac	Communic/Telem		Chemistry Lab	Biology Laboratory	Plant Room	Animal Farm	Microscopy/X-ray	Darkroom		Infirmary/Examin	Exercise Facility			LSS Mechanisms	Food Synthesis	Oxygen Generation	
First 12-Person Contingent	MD(intern)/Physiol			A			A	B	B					A	A	X			B		
	Power Systems Eng	B	A	B	A	X												B		A	
	Chemical Proc Eng		B	A														A		A	X
	Selenologist/Petrog		B				C				A	B	X							C	
	Mech Eng/Mat Eng		B	A							C							A	B	B	
	Hortic/Mineral Nutr						B	A	A									C	A		
	Plant Path/Micro **			C			B	A	A		A	A	X						B		
	Heavy Equipment Op																				
	Const Tech/Mech																				
	Const Tech/Elect																				
	Chemist		B	B			A	B	B		B		X					C	A	A	
	Astronomer		B																		
Second 12-Person Contingent	Microbio/Plant Path			C			B	A	A		A	A	X						B		
	Appl Biochem/Botant		B	C			A	A	A	B			X						A		
	Biotechnician			B			A	A	A	B			X						B		
	Oxygen Plant Oper		B	B			C													A	
	Food Technol/Dietic			B			A	A	A	A	B		X	C	C			B	A		
	Social Psychologist													A		X					
	Electronics E/Comp	A	A	A	A	X												B			
	Metallurgist						B				A	B									
	Materials Engineer						C				B										
	Commander	A	A	B	A	X															
	Vehicle Mainten & Op																				
	Const-Maint Tech/El																				
	Const-Maint Tech/M																				

** The Plant Pathologist/Microbiologist will be replaced by the Microbiologist/Plant Pathologist at the end of the first generation.

Table 16.2-4 Continued

	OCCUPATION \ LOCATION	Mat'ls Handling					Astronomical Obs					Mech, Elect, & Maint							Landing S	
		Foundry	Materials Testing	Fuel Development			Optical Telescope	Darkroom				Maintenance Shop	Mech Fabri & Ass	E Prod & Storage	Electronics Lab	Garage			Vehicle Maint Shop	Fuel Storage Fac
First 12-Person Contingent	MD(intern)/Physiol																			
	Power Systems Eng	C		C								B		A	A					
	Chemical Proc Eng	B		A								C								
	Selenologist/Petrog			B								C		C						
	Mech Eng/Mat Eng	A	A	A	X							B		C						
	Hortic/Mineral Nutr																			
	Plant Path/Micro **																			
	Heavy Equipment Op	A		B								A	B			A				
	Const Tech/Mech	A		C								A		B		A				B
	Const Tech/Elect	A		B								A		A	A	A				
	Chemist			B																
	Astronomer						A	A												
Second 12-Person Contingent	Microbio/Plant Path																			
	Appl Biochem/Botant																			
	Biotechnician											B	B							
	Oxygen Plant Oper			A								B	B	C						A
	Food Technol/Dietic																			
	Social Psychologist																			
	Electronics E/Comp													A						
	Metallurgist	A	A	C	X							C								
	Materials Engineer	A	A	B	X							B		B						
	Commander																			
	Vehicle Mainten & Op											A	A			A			A	A
	Const-Maint Tech/El											A	A			A			B	B
	Const-Maint Tech/M											A	A			A			B	B

** See note on the previous page.

and tablet. The commander's office would require a desk, three or four chairs, and a communications hook-up with the control points around the base or colony. In Table 16.2-4, an "X" designates the need for an office unit by the particular individual and indicates in what work area the office should be located.

The following two Tables, 16.2-5 and 16.2-6, have been compiled to demonstrate planning organizations. In the first of these two Tables, the various facilities required to support the professional activities of the base personnel have been grouped according to related or shared equipment and material. The groupings establish a series of primary facilities. Table 16.2-6 displays a schematic relationship between these primary facilities and a series of shared subfacilities. This table also shows that the landing site and the astronomical observatory, while essential elements of the base, will be located at some distance from the clustered base.

The use of the canisters as the basic "building blocks" of the 24-person base forces areal or volumetric planning to be accomplished by fitting specific functions into the canister spaces. Required areas will be of variable sizes depending on the breadth of the research and application efforts and the amount of equipment and personnel needed to fulfill base/colony goals. Many of these areas are indeterminate as of this moment because of the uncertainty associated with specifying what activities will be pursued in the early generations of the lunar base two decades from now. Recent studies, including The Blue Book [1] and RAM [2] efforts, have sought to describe scientific activities and the facilities required for the shuttle and space-station sortie labs. Guidelines from these studies, modified by shuttle and space-station experiences of the next decade, should be available for accurate planning descriptions for the moon base. We have tried to indicate likely combinations and adjacencies between probable scientific and technological activities in Tables 16.2-5 and 16.2-6. Such linkages are also the result of common earth-bound cooperations between disciplines. The likelihood of least interferences is high if the primary facilities are so grouped.

Table 16.2-5 Proposed 24-Person Colony Work/Professional Organization-Combined Facilities

I. Colony Command
   A. Flight Control
   B. Prime Computer Facility
   C. Life-Support System Monitor
   D. Communications and Telemetry

II. Biochemical Research
   A. Chemistry Lab
   B. Biology Lab
   C. Plant Room (Common with Life-Support Facility)
   D. Animal Farm (Common with Life-Support Facility)
   E. Microscopy/X-ray (Common with Medical and Materials Handling Facility)
   F. Darkroom (Common with Medical and Materials Handling Facilities)

III. Medical Facilities
   A. Infirmary/Examination Room
   B. Exercise Facility (Common with Gymnasium)

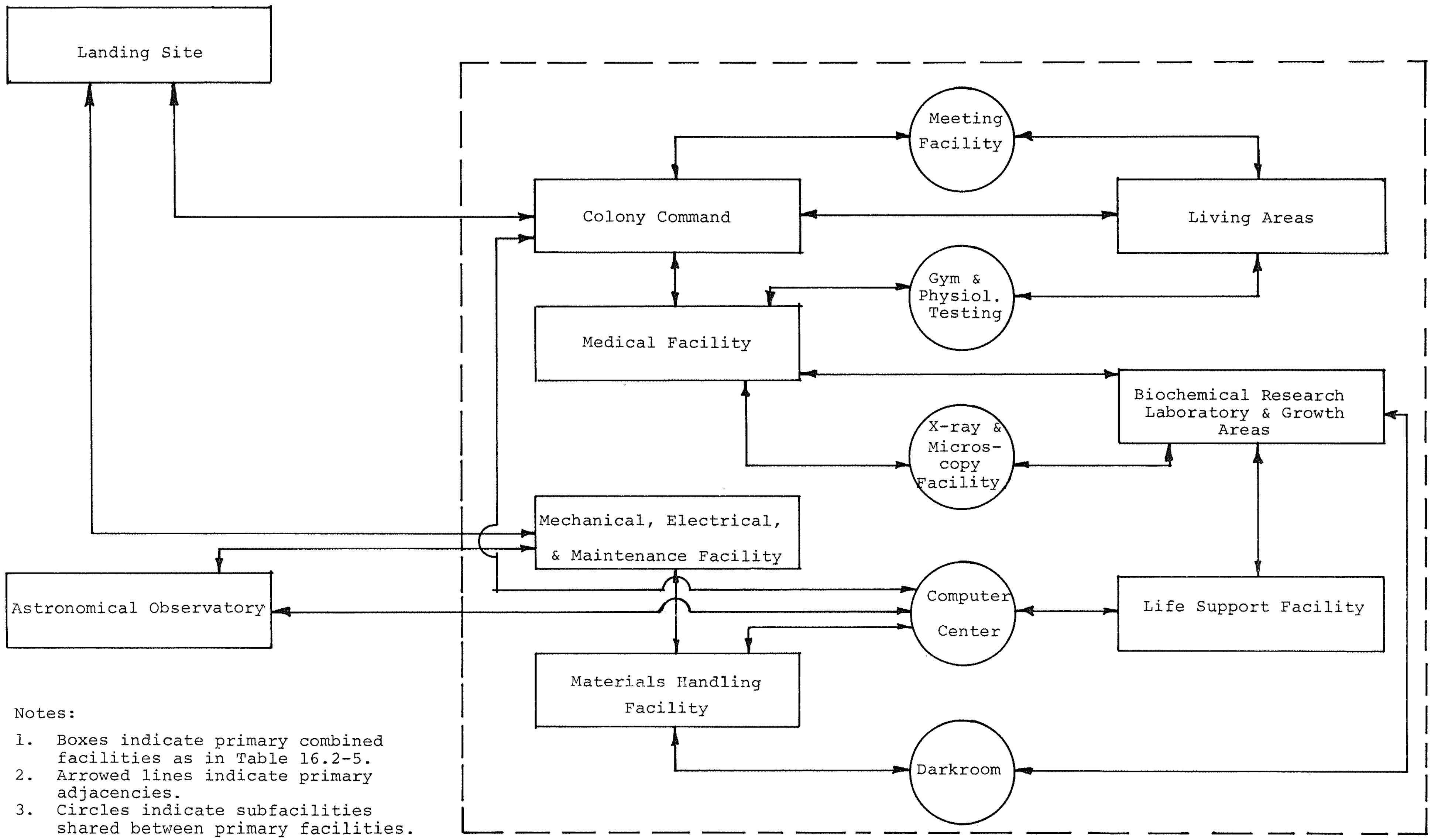
IV. Life-Support Facility
   A. Food Synthesis
   B. Oxygen Generation
   C. Mechanistic Life Support Systems

V. Materials Handling Facility
   A. Foundry
   B. Fuel Development
   C. Materials Testing

VI. Astronomical Facility
   A. Optical Telescope
   B. Darkroom

VII. Mechanical, Electrical and Maintenance Facilities
   A. Maintenance Shop
   B. Mechanical Fabrication and Assembly
   C. Garage
   D. Energy Production and Storage
   E. Electronics Lab

VIII. Landing Site
   A. Vehicle Maintenance Shop
   B. Fuel Storage



Notes:

1. Boxes indicate primary combined facilities as in Table 16.2-5.
2. Arrowed lines indicate primary adjacencies.
3. Circles indicate subfacilities shared between primary facilities.

Table 16.2-6 Schematic Displaying Relationships Between Primary Facilities

The living facilities indicated in Table 16.2-6 while separate and self-contained, should still have multiple entries to the research and application areas. A possible best configuration for the 24-person base might have the command facilities placed adjacent to the living areas. These two areas could then be oriented as the central node of the base with the professional areas radiating outward and also forming a concentric pattern around the living and command units.

We feel that it is imperative to emphasize the general need for flexibility while planning the living and work facilities. Similarly, foresight in planning with particular regard to anticipating later requirements must be maximized. Efficiency of use should also be maximized to properly justify the cost and difficulty present in delivery and establishment. During planning it should be remembered (from the section on habitability) that if it becomes necessary to reduce the relative amenities in the work or living areas, the living areas should be sacrificed to maintain appropriate professional opportunities.

In the near future when the lunar base is more rigorously planned (based on more fully delineated data), the best method of space allocation may be to provide a three-dimensional grid and to employ movable or easily adaptable walls, platforms, and furnishings to fit the grid. Such a technique would be particularly advantageous when developing and constructing the permanent lunar colony. The opportunities for growth and change would be maximized. In the meantime, rigorously determined floor plans must await further data concerning volume and equipment requirements necessary to support the various professional activities.

REFERENCES

1. Alternately known as Reference Earth Orbital Research and Applications Investigations, Prepared at NASA Headquarters, Washington, D.C., January, 1971.

2. Convair Aerospace Division of General Dynamics, "Research and Applications Modules Phase B Study, Convair Aerospace Division of General Dynamics, San Diego, California.

16.3 LAYOUT OF SHELTER MODULES

The initial phase of LSB expansion utilizes canisters in a repeated pattern very similar to the twelve-man configuration. Canisters should be designed so as to serve also as cargo carriers while in transit. After attachment to the existing facilities, the interior partitioning may be installed. The large majority of such partitions may be of the collapsible, accordian style. The floor and ceilings should have facilitate rearrangement. This will be particularly important after the colony achieves the 180 population level. It is evident that a wide variety of colony functions will be performed. This must be reflected in the adaptability of the canisters. All canisters should therefore be prefitted with life support, electric power, and water ducting.

No attempt to specify the floor plans of individual canisters will be attempted in this study. This is highly dependent upon the functions performed by the colony inhabitants. A specific floor plan would be most accurately developed after a detailed work-format study.

16.4 AIRLOCKS

The structures used for the lunar colony, whether transported from the earth or constructed from lunar materials, are characterized by the presence of atmospheric pressure on the inside and ultra high vacuum outside. Access between these two environments is necessary, and the usual concept involves an airlock. An airlock, quite simply, is a small room equipped with two doors, one opening to the inside of the structure and one to the outside. In operation, an individual would enter the airlock from one direction, equilibrate the pressure in the chamber with that at his destination, and proceed.

Although airlocks are simple in concept, the details are more complicated. One problem which must be addressed is the quantity of air necessary for one cycle. Assuming that the chamber is large enough to accommodate two men wearing pressure suits, and that some freedom of movement is allowed, then about 5 kilograms (11 pounds) of air would occupy the volume at atmospheric pressure. If this quantity of air was lost during each operation of the airlock, then the result would be an intolerable burden on the overall life-support system. The obvious solution would be the installation of a pumping facility to return the air to the life-support system during airlock operation.

Specific requirements for several types of airlocks have been mentioned [1, 2, 3]. In addition to the space requirements previously mentioned, it can be specified that the airlock shall have handles on both sides of each door suitable for operation by one crewman without special tools. Viewports should be installed in each door. Displays should proclaim the status of the airlock within the chamber, outside of both doors, and at a central command facility; malfunction alarms should be also provided. In addition, facilities for recharging pressure-suit life-support systems should be located within the airlock chamber. A further desirable feature would be the capability for voice communication between the inside and the outside of the airlock.

The time required for airlock operation is a major factor from the viewpoint of both convenience and safety. A time period on the order of two minutes would be required for operation of the airlock if direct venting were used; at this rate loss of the contained air would result. If the air in the airlock chamber is pumped back into life-support system storage, a time period on the order of twenty minutes would be required. This time period would probably become objectionable to users of the facility, and the time available for serious work would be reduced. A possible solution might be the installation of flexible bags, located outside the structure and having an inflated volume several times that of the airlock compartment. In operation, most of the air would be vented from the chamber into the bag, then the bag would be valved off and a final equilibration of pressure to the lunar environment would be achieved. Pumps could be arranged to operate continuously on the bag; it could be emptied and prepared for another cycle while the airlock was not in actual use. This scheme would allow most of the air associated with an airlock operation to be salvaged, and the operation time would be reduced to the order of a few minutes. Such a system would also allow low risk, in-service testing to be conducted on inflatable units for possible future use as habitable structures.

REFERENCES

1. "Space Base Concept Data (Phase A Definition), Volume III, Space Base Subsystem Requirements," McDonnell-Douglas Astronautics Company - West, 1970.

2. Jaax, James R., "Preliminary Requirements for Airlocks on Space Stations," CSD-SS-010, Manned Spacecraft Center, Document T72-11205, 1972.

3. Smith, E. A., "A Lunar Shelter Airlock," Northrop Space Laboratories, Technical Memorandum, NSL 63-251, Document X71-77120, 1963.

16.5 WINDOWS

There is every indication that windows or viewports will be required in structures for the lunar colony as a means of increasing the personnel acceptance of the environment. While their use in large number is desirable, there are technical difficulties associated with their installation, and large quantities or areas are not anticipated.

One discouraging aspect to the use of windows is the possibility that the colony structures will be buried to a depth of five meters. In this event, surface facilities are envisioned that would allow a colony inhabitant to view his surroundings. Contact between the outside and the buried structures would probably be achieved by means of television.

When windows are employed, some technique is necessary for attaching them to the surrounding structure. In modules that are transported from earth, this problem is not serious. However, attachment of a window to proposed building materials of lunar origin, such as cast basalt, may pose problems. A metallic flange arrangement for installation in a precast hole can be envisioned, but considerable development work on sealings, attachment, and resulting stresses will be required.

The windows themselves will probably be made from optical quality glass or fused quartz manufactured on earth. Lunar production of high quality glass is not anticipated until much later in the colony evolution. A thickness of about four centimeters will probably be employed for radiation protection and structural integrity.

One problem that may be encountered with windows is deterioration of optical quality from micrometeoroid bombardment. Some data on this possibility may result from further studies based on [1] or from data acquired during later lunar and orbital missions. It might be possible if deterioration does present a problem, to use a disposable shield of transparent material such as mylar which could be replaced at appropriate intervals.

REFERENCES

1. "Apollo-12 Preliminary Science Report", National Aeronautics and Space Administration, NASA SP-235, 1970.

16.6 CONSTRUCTION TECHNIQUES

The following sections describe various techniques of construction that progressively allow greater independence from earth-supplied components. Initially, additional utilization of the canisters is necessary for colony growth. The use of inflatable special-use structures to provide rapid areal and volumetric expansion is discussed. During the early phases of growth, many experiments will be necessary to determine the best methods of construction utilizing lunar resources. These methods are outlined and the most promising are extensively analyzed.

16.6.1 USE OF CANISTERS

The redefinition of the NASA Lunar Surface Base is outlined in Section 4.2. Since considerable effort must be expended in the covering of the canisters in the LSB, some attention must be devoted to the most efficient emplacement method. After establishing the LSB for long-term occupancy, the expansion of the base begins essentially by estending the basic LSB configuration. When sufficient construction personnel are available (projected when colony population totals 72) and lunar-materials research has proven feasibility of construction from locally derived components, another phase of expansion will commence.

16.6.1.1 Burial of the NASA LSB

The procedure of burying the canisters is directly related to the available excavation equipment. A minimum length of boom attachment for the prime mover can be determined from examining the unloading sequence of the proposed NASA LSB. The suggested prime-mover vehicle is employed to load and unload the canisters [1]*. Actual movement of the modules is accomplished by towing a transport trailer behind the prime mover. The limited stability envelope of the mover does not permit the movement of 2730 kg (6000 lb) canisters while being suspended from a crane. Figure

16.6-1 shows the geometry which allows proper positioning for minimum boom length. Notice the use of outriggers to increase the pitch stability of the prime mover. This is essential since the mover itself has a mass of 2730 kg. The requirement for outriggers also prevents movement of the mover while lifting canisters. The geometry shown suggests that a minimum boom length of 7.9 meters (26 ft) with a 1.2 meter (four ft) jib extension is required. Since this is the minimum length required for canister movement, the configuration is also assumed as that available for canister emplacement. The boom could be transported to the LSB in a single unit and would be lighter than booms of longer length.

The pitch stability of the mover can be increased by placement of the outriggers in a position forward of the pivot point. This allows stable lifting capabilities for a variety of loads and frontal load distance configurations. The 2730 kg canisters, for example, can be handled to a frontal distance of 7.3 meters with the outriggers deployed forward 1.2 meters. If the frontal load distance is only 5 meters, the outriggers need only be deployed forward 0.75 meter.

The requirement to provide a 5-meter soil barrier for long-term radiation protection has previously been discussed in Section 9.5.3.2. Figure 16.6-2 illustrates the envelope in which this protection may be provided. One extreme of the procedure is placement of the canisters on the lunar surface with subsequent covering with lunar soil to a height of 9.5 meters (31 ft). The other extreme method requires excavation to a depth of 9.5 meters with backfilling to the original lunar surface. Both methods are inefficient and lead to analysis which will indicate the optimum depth of excavation. The analysis involves the following terms:

V_e = volume of soil excavated,

V_b = volume of soil required to backfill the excavation over the emplaced canisters to the original lunar surface,

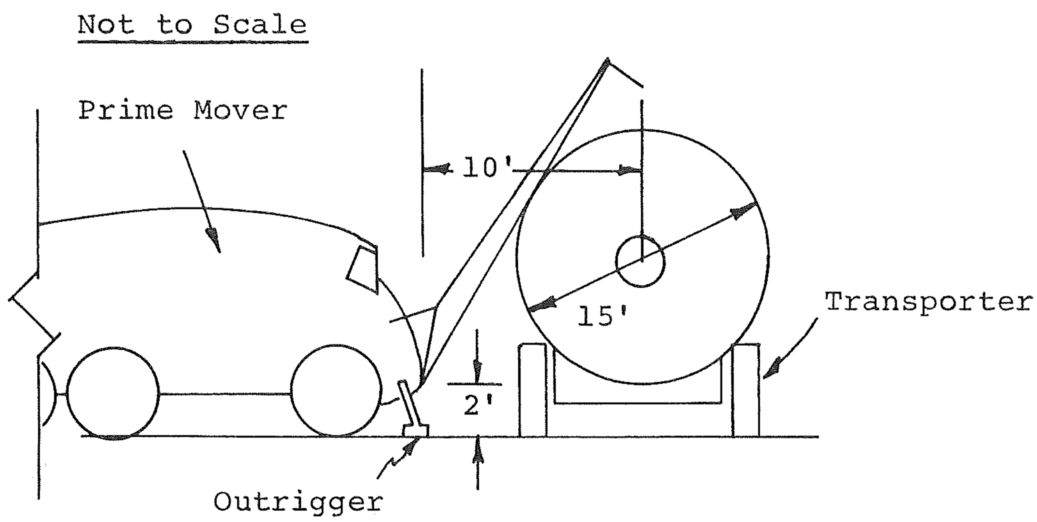


Figure 16.6-1 Determination of Boom Length

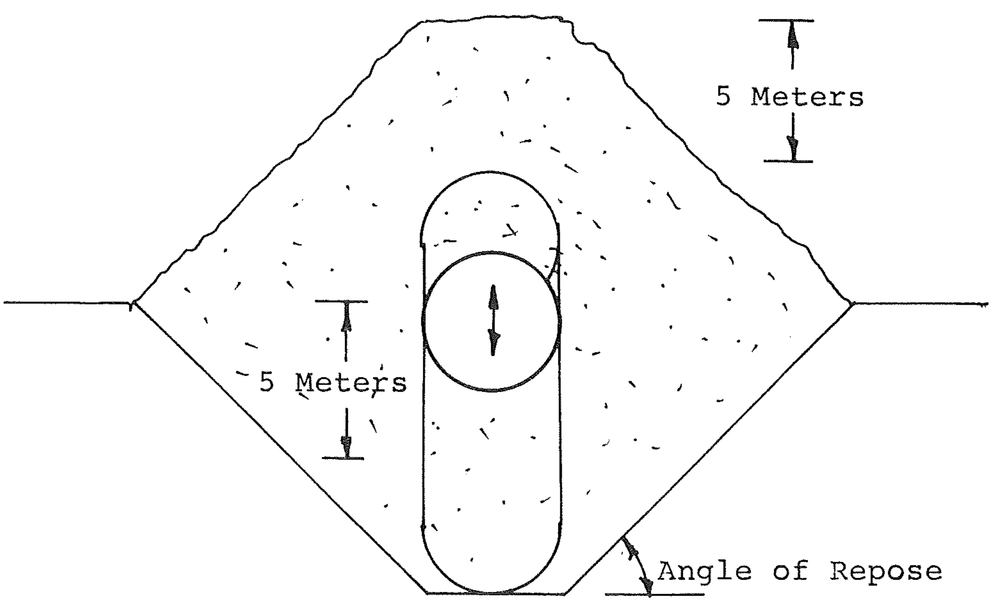


Figure 16.6-2 Soil Protection Envelope

V_o = volume of soil required above the lunar surface (overburden) to achieve the proper radiation barrier,

V_a = additional soil required for overburden (only has application when $V_e < V_b + V_o$),

V_t = total volume of soil movement required,

The terms are related as follows:

$$V_t = V_e + V_b + V_o + V_a. \qquad (16.6\text{-}1)$$

The other important consideration critical in the determination of the total volume of soil movement is the geometry of the excavation. This is illustrated in Figure 16.6-3. Notice that only the seven interior canisters are to be buried. The other two canisters are for prime-mover vehicle maintenance and the mobile warehouse storage. Both also have airlocks for personnel access to the lunar surface. An analysis of the volume of soil moved as a function of depth of excavation was performed. The results of the analysis is summarized for selected depths in Table 16.6-1.

Table 16.6-1 Depth-Volume Summary

d, ft	V_e, ft^3	$V_b + V_o$, ft^3	V_a, ft^3	V_t, ft^3
0	0	6,310	6,310	12,620
7.5	4,110	9,695	5,585	19,390
10	6,635	10,755	4,120	21,510
15	13,370	12,820	0	26,190
20	24,000	18,600	0	42,600
31	60,000	34,545	0	94,545

The V_a is a "penalty factor" which enters the analysis when the excavation does not provide enough material for backfill and overburden coverage. This is because this additional material must be scooped up and brought to the colony site from elsewhere. Presumably, this would not occur in the near vicinity of the

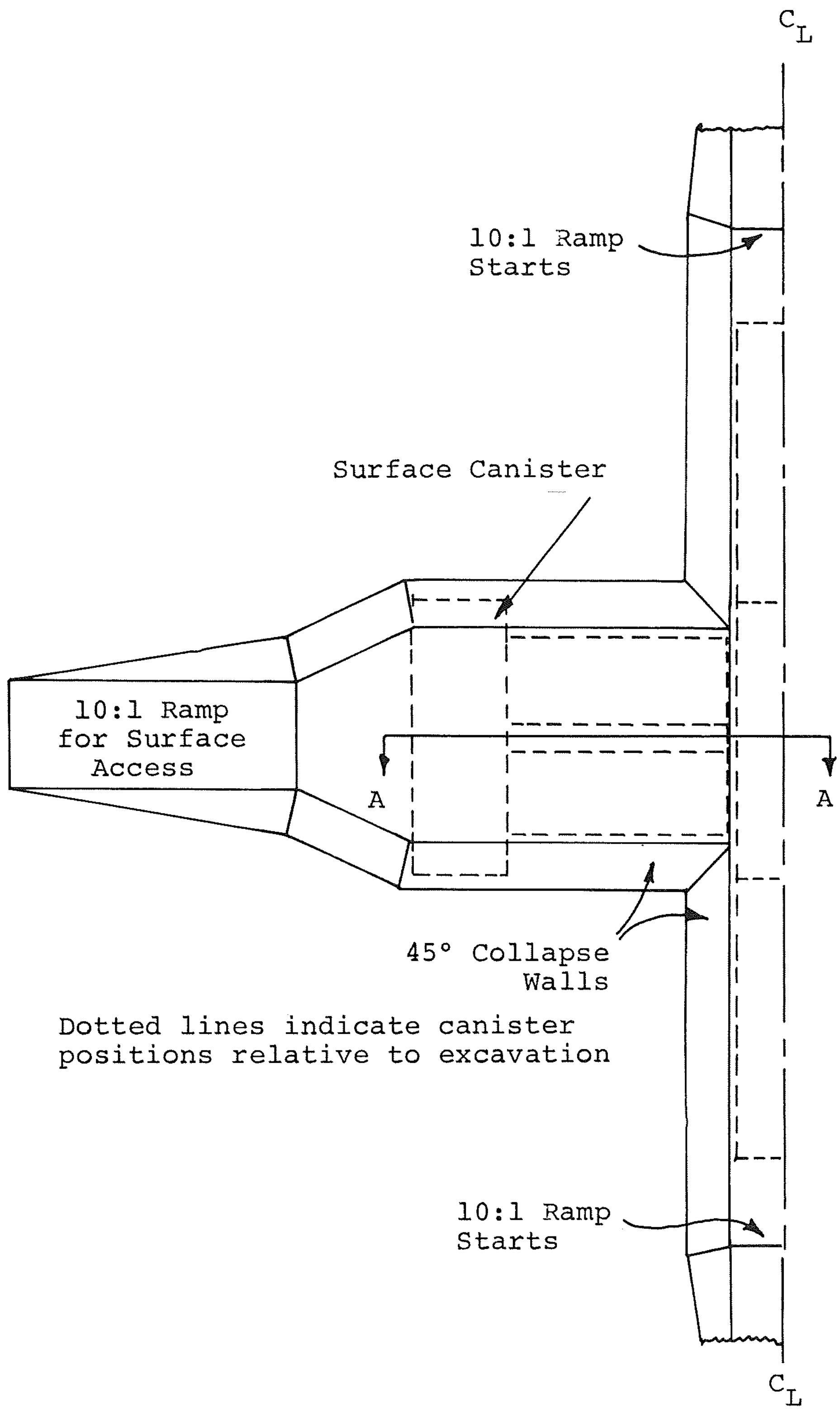


Figure 16.6-3 Plan View of Excavation

colony so as to create additional hazardous depressions. Figure 16.6-4 shows a plot of V_t as a function of depth of excavation. The effect of V_a is indicated when the depth of excavation is less than 15 feet. The depth value for which $V_e = V_b + V_o$ was 14.8 ft for this analysis.

The total movement of soil should be minimized so as to reduce the construction time required for emplacement. One might conclude from Figure 16.6-4 that the "best" procedure would be to place the canisters on the surface and pile protective soil on top. The capability of the soil-handling equipment now becomes a controlling influence. The length of the crane boom has limited the depth of excavation to a narrow range of values. This is illustrated in Figure 16.6-5. The top figure shows that the deepest excavation into which the prime mover can safely lower a canister is ten ft. It should be recalled that as excavation depth increases, the prime mover must be positioned farther from the edge of the excavation floor. This is due to the assumed angle of repose (45°) of the collapsed sidewalls. Similarly, the maximum height above the lunar surface that soil may be placed using the clamshell is 22 ft. Allowing for a 45° angle of repose, the placement of a 5-meter (16 ft) radiation barrier dictates a minimum excavation of nine ft. The analysis is not presented as rigorous or exact, but is indicative of the influence of hardware selection upon the canister burial problem.

The difference in the total volume of soil movement corresponding to nine and ten feet appears very slight from Figure 16.6-4. We would tend to select the ten-foot depth as less "extra" soil (V_a) is required.

As previously indicated, the central seven canisters are buried in the excavation, while the personnel/vehicle access canisters remain on the surface. Since the crane does not have the capability to place soil, the required 9.45 meters to provide five meters of protection, we will accept decreased protection in these special use canisters. Actually, these canisters are best

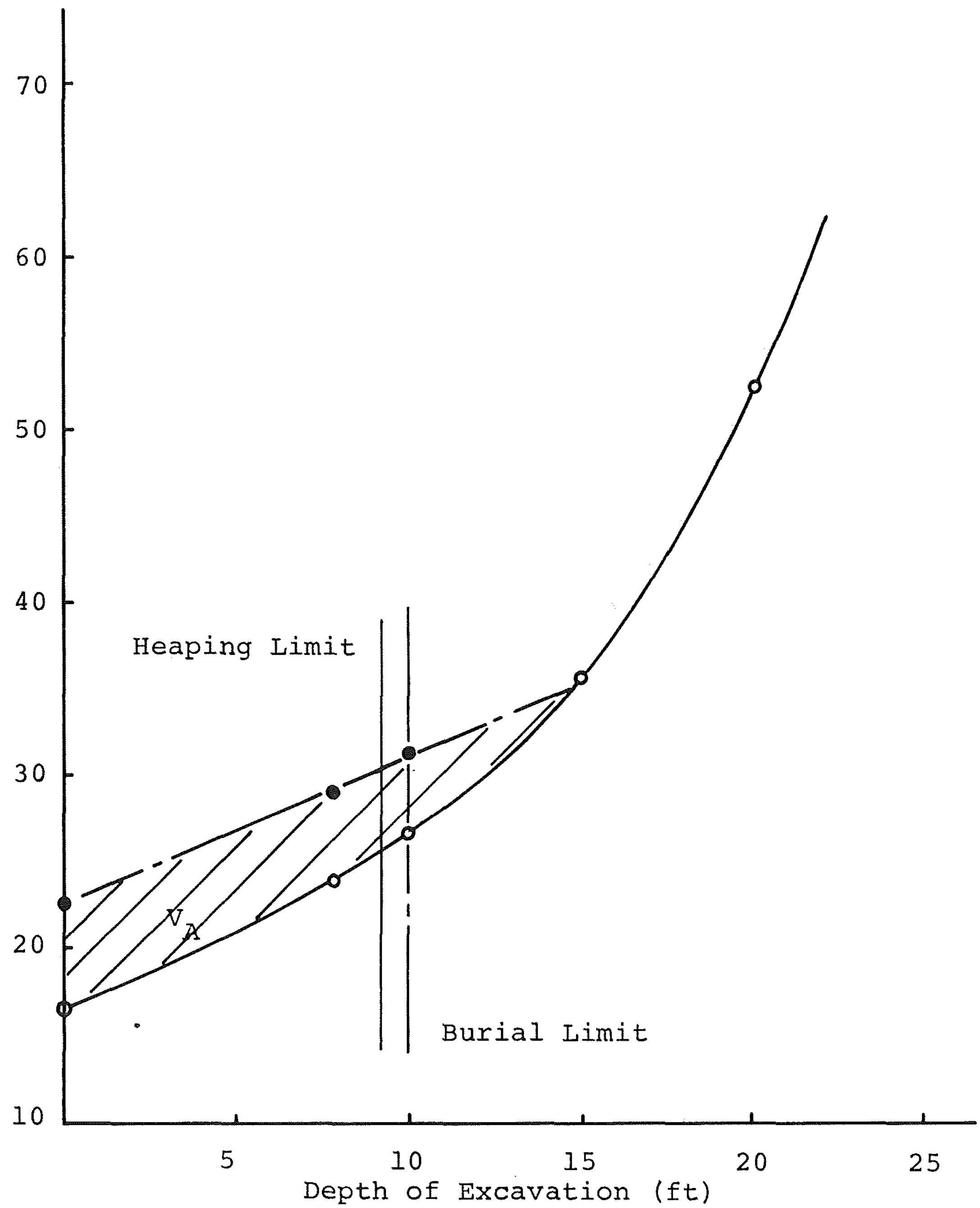


Figure 16.6-4 V_T vs Excavation Depth

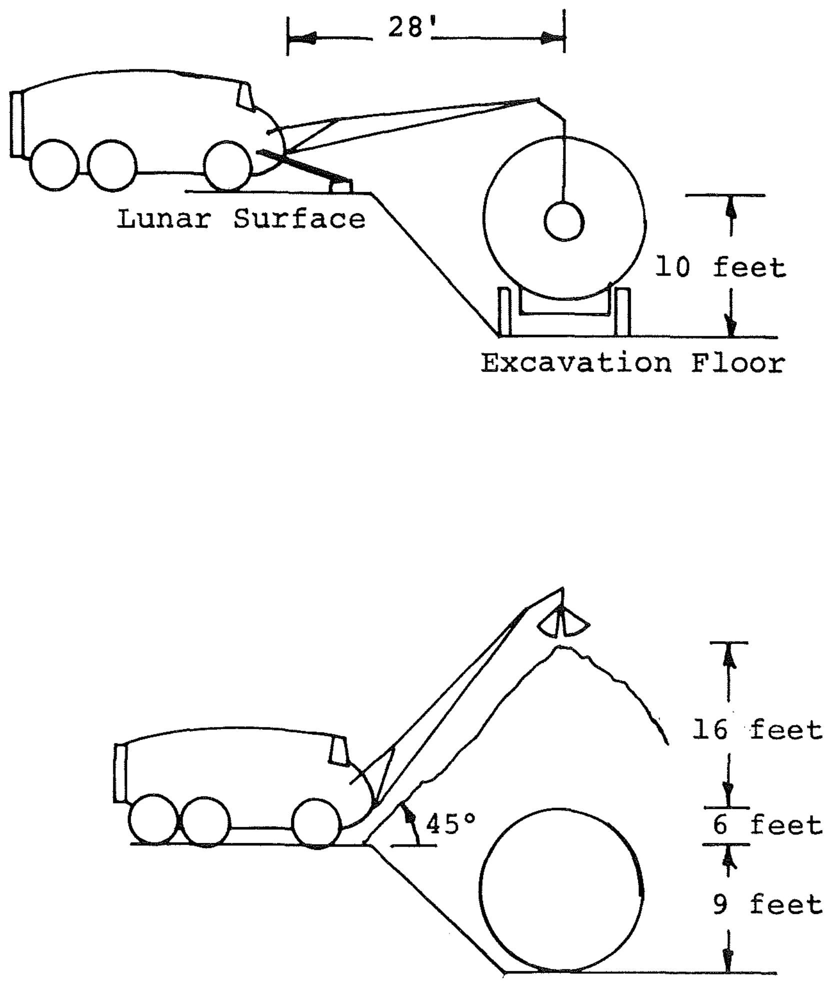


Figure 16.6-5 Crane Burial and Heaping Limits

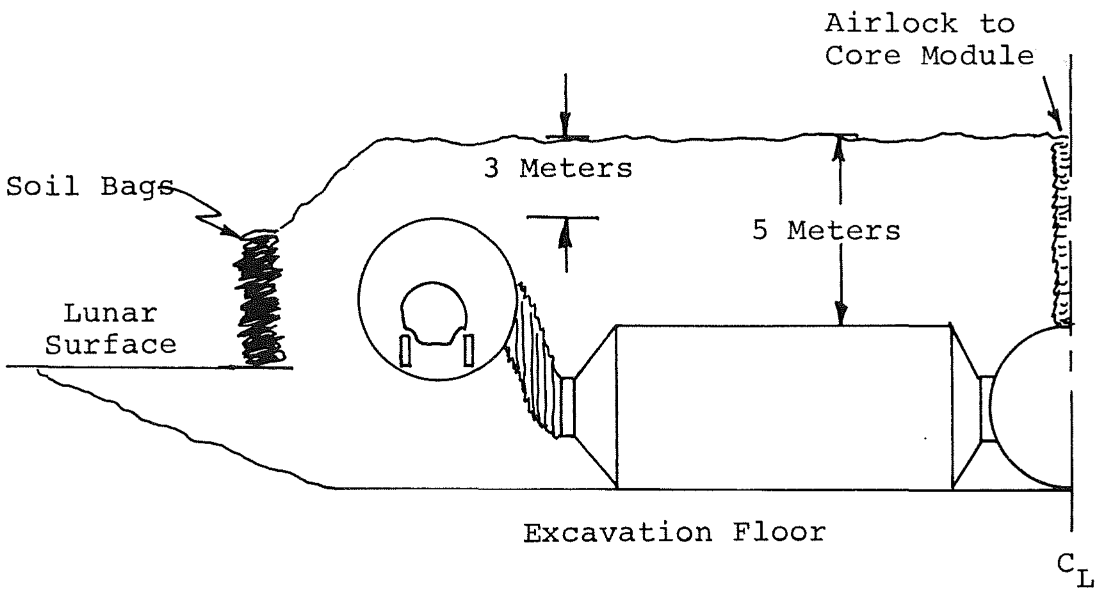


Figure 16.6-6 Subsurface Cross-Section

utilized if they are placed in a shallow (1 meter) depression. The driveway inside the canisters is 1 meter above the cylinder wall to permit vehicle maintenance access. The radiation dose in the two special-use canisters is 2 rem/yr compared with 0.13 rem/yr for the high-use areas [2]. A subsurface cross section is shown in Figure 16.6-6. Also illustrated is the use of aluminized mylar soilbags to control subsidence of the overburden soil. This is vitally important around the airlock and vehicle access areas. The soilbags may present a maintenance problem if long-term radiation degrades the mylar. A side benefit is dust control in the ingress areas.

16.6.1.2 Initial Expansion of the NASA LSB

The emplacement pattern and method is repeated until 28 canisters are connected and operating. If the materials development program shows promising construction methods utilizing lunar materials, the use of canisters for shelter will be terminated. This is projected to occur when the colony population reaches 72. If no successful lunar material construction components prove feasible, the canisters could be used to continue the growth pattern.

REFERENCES

1. Lunar Base Synthesis Study - Final Report, Volume III, "Shelter Design," Space Division of North American Rockwell Corporation, Downey, California, Contract No. NAS8-26145, May, 1971, pp. 3-2-1 through 3-2-11.

2. Lunar Colony Functional Analysis Team Meeting Minutes, Manned Spacecraft Center, Houston, Texas, February 8, 1972, pp. 20.

16.6.2 INFLATABLE STRUCTURES

In most projections, conceptions, or visualizations of a lunar colony, either in the technical or popular literature, dome-shaped structures appear without extensive explanation. In some cases, these structures can be interpreted as nonrigid bags which could be manufactured on earth and inflated at the point of installation. Such structures are presently in use on earth in several applications, such as greenhouses and temporary covers for athletic events, but in these situations the differential pressure across the membrane seldom exceeds one inch of water. In a lunar application, the differential pressure can be assumed to be equal to the internal pressure, and this valve would of necessity be large enough for the structure to serve some useful function. This pressure requirement imposes severe restrictions on the structure; materials and dimensions typical of earth applications are obviously not appropriate.

Despite the more rigorous requirements, the concept of using inflatable structures in the lunar environment suggests several desirable possibilities. Structures could be manufactured on earth, transported to the moon in a relatively small volume, and deployed with a minimum of effort. Structures with a large capacity would thus be available prior to the development of lunar building materials. It is apparent that these possibilities warrant further investigation of inflatable structures for use in the lunar environment [1].

One of the first obstacles to be overcome in the design of an inflatable structure is the selection of a material having suitable properties. Among the strongest noncomposite plastics are mylar and kapton, each of which has a tensile strength of about 1.38×10^9 dynes per square centimeter (20,000 pounds per square inch). Mylar has a demonstrated vacuum compatibility, but it is flammable; kapton is self-extinguishing. All of the desirable properties; flexibility, high strength, vacuum compatibility, and fire resistance, may be obtained through the use of a composite material such as teflon reinforced with glass cloth. The resulting film is heavier than mylar, and it is not transparent. Another property of considerable importance is sunlight resistance; this aspect has been diminished in this discussion because of the high probability that the structure would be buried in the lunar soil. In any event, the glass reinforced teflon would appear to have adequate sunlight resistance for surface installations.

A comparison between solid and flexible structures, both supplied from earth, can be made on the basis of some desired floor area. A hemispherical shelter having a diameter of 18.3 meters (60 feet) would provide a gross floor area of 262.8 square meters (2827 square feet). This gross area could also be obtained with six canister modules of the type specified for the LSB. The approximate mass of a canister module is 1800 kilograms (~ 4,000 pounds) so that, in order to be competitive, an inflatable structure should have an earth-weight less than 11,000 newtons (~ 25,000 pounds). In the case of both the canister module assembly and the inflatable structure, all accessories, including life support, are excluded from this analysis. It is also assumed that the canisters could be brought to the surface without additional tug flights solely for that purpose.

Weights for several flexible structures have been calculated on the basis of possible conditions which might exist. It was assumed that the flexible structure would take the form of a hemispherical dome, and stress equations appropriate to a sphere were used. This simplified the calculations, although a different shape, such as the isotensoid, would be a more likely choice for the real structure. Calculations were performed for structures having a floor made of the same flexible material as the dome; in this case the floor thickness was assumed to be equal to that of the dome. This configuration would require restraint at the circumference to prevent excessive bulging of the floor; such restraint could probably be provided with anchors buried in the lunar soil. In addition, results are presented for the weights of the hemispherical dome alone. This structure would require a rigid base made of lunar materials; the construction time would be longer, but the weight to be transported would be less. The weight of additional material thickness that would probably be required at the juncture of the dome and the floor was ignored in the calculations, as was the weight of the internal framework that would probably be present to delay collapse, and allow emergency egress, in the event of a puncture.

Several internal pressures were considered, from one to 0.133 atmospheres (15 to 2 pounds per square inch). The higher pressure would allow direct connection to the other elements of the environment; the lower pressure would allow utilization of the structure only as a farm or a warehouse. Intermediate pressures would allow inhabitation of the structures without special breathing equipment if the oxygen partial pressure was suitably controlled. Flexible structures pressurized to these intermediate values might be considered if the weights made them particularly desirable.

The results of the weight calculations for a 60-foot diameter hemisphere are presented in Table 16.6-2. It may be observed from the table that a flexible structure pressurized to one atmosphere is competitive with the canister modules only if a factor of safety of two can be accepted in the design. At lower pressures, however, the flexible structures become quite competitive.

It should be noted that the assumption of equality between internal pressure and differential pressure may not be entirely fair. If the structures are buried, the load provided by the soil would oppose a portion of the load due to internal pressure. A five-meter depth of lunar soil would provide a load approximately equal to an internal pressure of 0.133 atmosphere ; thus, a structure inflated to this level would be required to withstand only a small differential pressure. In a more rigorous calculation, an assumed depth should be included for each portion of the membrane.

In summary, it may be stated that inflatable structures should not

Table 16.6-2 Mass of Inflatable Structures Mass of Equal Gross Floor Area for Comparison-Six Canister Modules ≅ 11,000 kg (25,000 Pounds)

Flexible Floor	Rigid Floor	Internal Pressure ATM (PSI)	Safety Factor	Material Volume Cubic Meters (Cubic Feet)	Material Thickness Centimeters (Feet)	Material Mass Kilograms (Pounds)
		1		10.8	1.37	23,800
√		(15)	4	(383)	(.045)	(52,500)
		1		4.0	0.68	12,000
√		(15)	2	(192)	(.0225)	(26,300)
		1		7.3	1.37	16,000
	√	(15)	4	(256)	(.045)	(35,150)
		1		3.6	0.68	8,000
	√	(15)	2	(128)	(.0225)	(17,600)
		.667		7.3	0.92	16,000
√		(10)	4	(256)	(.030)	(35,000)
		.667		3.6	0.46	8,000
√		(10)	2	(129)	(.015)	(17,500)
		.667		4.9	0.92	10,600
	√	(10)	4	(171)	(.030)	(23,400)
		.667		2.4	0.46	5,300
	√	(10)	2	(86)	(.015)	(11,700)
		.333		3.6	0.46	8,000
√		(5)	4	(129)	(.015)	(17,500)
		.333		1.8	0.23	4,000
√		(5)	2	(65)	(.0075)	(8,750)
		.333		2.4	0.46	5,300
	√	(5)	4	(86)	(.015)	(11,700)
		.333		1.2	0.23	2,700
	√	(5)	2	(43)	(.0075)	(5,850)
		.133		1.4	0.18	3,200
√		(2)	4	(51)	(.006)	(7,000)
		.133		0.74	0.09	1,600
√		(2)	2	(26)	(.003)	(3,500)
		.133		0.97	0.18	2,100
	√	(2)	4	(34)	(.006)	(4,700)
		.133		0.48	0.09	1,100
	√	(2)	2	(17)	(.003)	(2,350)

Structure: 60-Foot Diameter Hemisphere

Floor: Flexible-Same Material and Thickness as Wall

Rigid-Constructed on Site from Lunar Material

Material: Teflon Reinforced with Glass Fiber

Tensile Stess of 20,000 PSI

be ignored as a possible means of achieving large volumes of habitable space in the lunar environment. Research into appropriate materials, designs, and techniques should be encouraged. The analysis included in this section was for a single structure size; a procedure could be developed for optimizing the dimensions of the structure according to specified requirements.

REFERENCES

1. Cosby, William A., and Lyle, Robert G., "The Meteoroid Environment and its Effects on Materials and Equipment", NASA SP-78, National Aeronautics and Space Administration, 1965.

16.6.3 LUNAR CONSTRUCTION CONCEPTS

Long-term growth of the lunar colony requires a maximum utilization of lunar resources for the construction of shelters as well as other products. Several lunar-shelter construction concepts have been proposed in the past, many of which have proved unrealistic from the standpoint of long-term colony growth. Unknowns concerning the long-term hazards of radiation have forced the first lunarians (lunar colonists) five meters below the surface. The shelter must be built to sustain an internal pressure of up to 14.7 psi (partial pressure of oxygen must be 3.5 psia). These very facts indicate that at least in some respects lunar construction will be different from earth construction. Nonmetallic building materials (bricks, concrete, etc.) are generally used as compression sustaining members in earth construction due to their high compressive strength and low tensile strength. Lunar-shelter structural members must sustain tensile loads due to the internal-pressure requirements. In some respects, therefore, aerospace structural design techniques must be used rather than earth-building construction techniques.

Cast lunar basalt appears to be the most likely building material as pointed out in Chapter 15. Techniques for metal extraction from lunar resources will eventually be developed, but lunar construction techniques need to be developed before metals become available. Initial utilization of lunar metals for construction will most probably be simple cast or extruded parts for attachment or possibly external reinforcement. Therefore, it seems logical to assume that cast basalt will be a primary building material for a long period of time.

Cast basalt is basically a brittle material, but it does have tensile load-carrying capability. A tensile strength of 250 kg/cm^2 (3,550 psi) to 350 kg/cm^2 (4,950 psi) has been obtained. (See Table 15.1-2 in Chapter 15.)

Prestressing or reinforcement seems at first to be a logical technique for relieving the cast basalt of tensile loads. Preliminary calculations (Section 16.6.3.1), however, indicate that this is not a viable solution. Plain cast basalt designed thick enough to withstand the tensile loads appears to be the best solution. Of course, this is not general practice in earth construction, but we are faced with a different problem on the moon. New practices must be investigated. They should, however, be thoroughly tested and proved before they are used. Cast basalt research should be initiated as soon as possible.

The real problem is joining the cast-basalt building slabs into an air-tight structure capable of withstanding the tensile stresses. The structure is only as strong as the weakest link. An inferior joining technique will produce an inferior structure. Certain techniques are discussed in this chapter (Section 16.6.3.2).

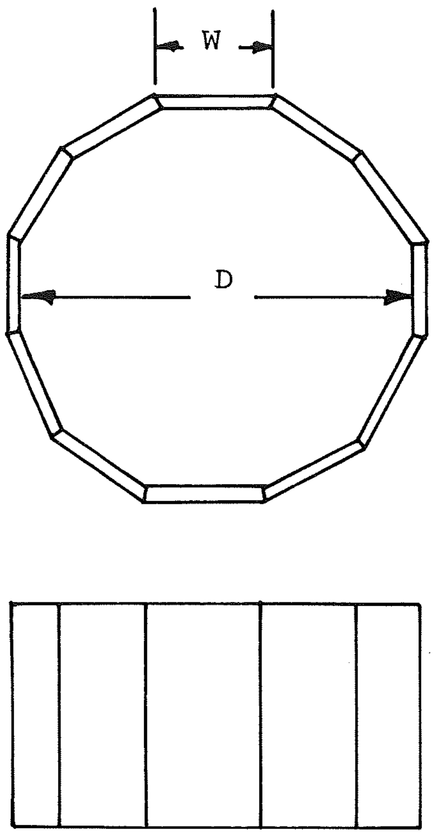
The final structural shelter is designed with a liberal safety factor of three and a redundant backup system to prevent destruction of the shelter due to initial structural failure. Details are given in the following sections.

16.6.3.1 Prestressed Cast Basalt

Prestressed cast basalt slabs appear, at first, to be a promising building block for shelter construction. The slabs can be cast into metal frames with a network of steel tendon rods or wires stressed in tension. After the basalt has solidified, the tension can be released in the tendons leaving the basalt in a state of residual compression. The metal frames can be electron beam welded together to form the walls, floors and ceilings. The concept is illustrated in Figures 16.6-7 and 16.6-8.

The equation for prestressing cast basalt is developed in Appendix D.2 and is

$$\frac{A_b}{A_{rs}} = -\left[\frac{\sigma_{rs}}{\sigma_b} + \frac{E_{rs}}{E_b}\right], \qquad (16.6\text{-}2)$$



D (ft)	W (ft)	Number of Slabs (n)
30	3	31
	6	15
60	3	63
	6	31
75	3	78
	6	39
100	3	104
	6	52

Figure 16.6-7 Assembly of Flat Slabs into Cylindrical Wall Section

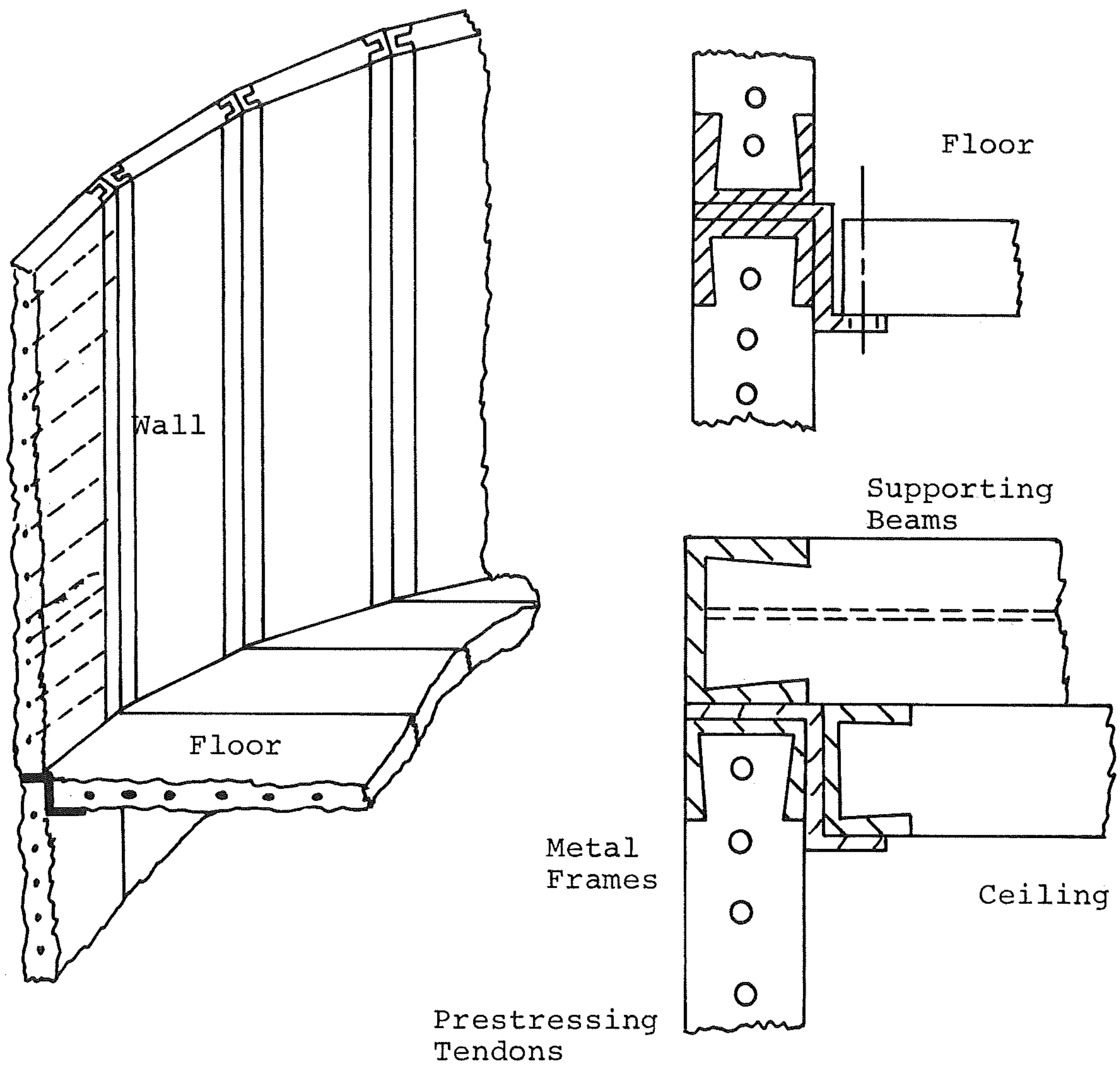


Figure 16.6-8 Wall, Floor and Ceiling Joining Techniques

where

A_b = cross-sectional area of cast basalt,
A_{rs} = cross-sectional area of reinforeement steel tendons,
σ_{rs} = tensile stress applied to tendons prior to casting,
σ_b = residual compressive stress left in cast basalt (always a negative value)
E_b = modules of elasticity of cast basalt (8×10^6 psi)
E_{rs} = modules of elasticity of reinforcement steel (30×10^6 psi)

Equation (16.6-2) plotted in graphical form is shown in Figure 16.6-9.

It is interesting to compare the amount of steel required for reinforcement versus that required to build a thin high strength steel cylindrical shell capable of withstanding an internal pressure of 14.7 psi. If, for example, the reinforcement material must be transported to the lunar surface, it might be more feasible to simply transport high strength steel cylindrical sections and weld them together rather than use the prestressed cast basalt blocks.

As a simple example, consider a cast basalt block 10 ft by 6 ft by 4 in thick (Figure 16.6-10). Assume that it is desired to prestress the cast basalt to a compressive stress of 1,000 psi with a tensile stress of 100,000 psi on the steel tendons. The stress ratio (σ_b/σ_{rs}) is therefore 100. From the curve in Figure 16.6-9, it is seen that the area ratio (A_b/A_{rs}) is equal to 96.25. The cross-sectional area of the tendon rods (A_{rs}) is 4.98 in^2. The rods are 6 ft long; therefore, the weight of reinforcement steel required per slab is approximately 107 lbs. As shown in Figure 16.6-7, fifteen slabs are required to build a thirty ft diameter cylinder. The total weight of steel rods required for a cylindrical wall section is therefore 1,605 lb. The thickness of a thin high strength (100,000 psi) steel cylinder (30 ft diameter by 10 ft long) capable of withstanding the hoop stress caused by

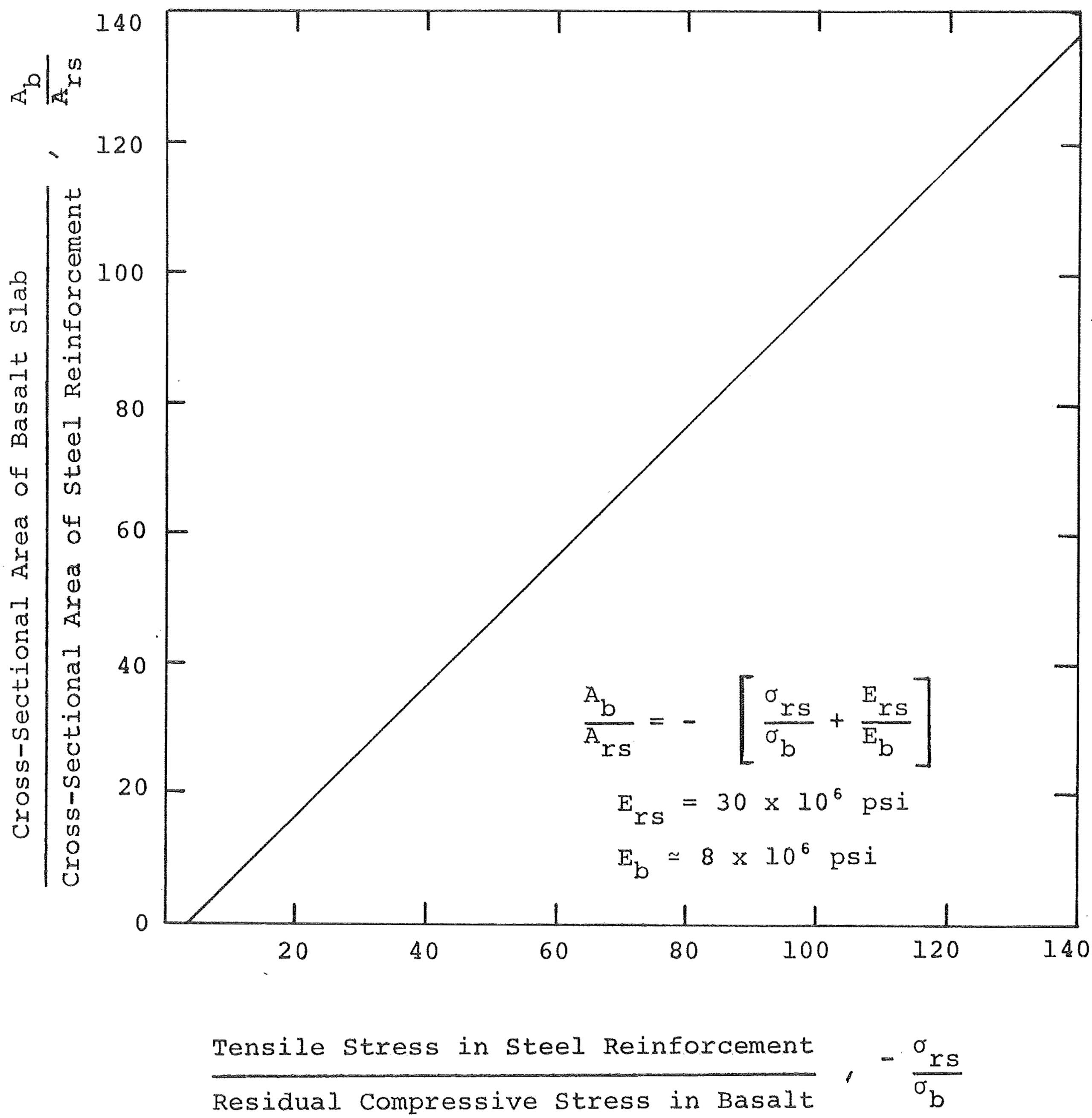


Figure 16.6-9 Prestressing of Cast Basalt

14.7 psi internal pressure was calculated to be 0.0265 in. Therefore, the weight of the cylinder is 1080 lb. Thus, the steel reinforcement (1,605 lb) weighs more than the steel cylinder. It seems more appropriate to ship steel cylindrical sections to the moon for assembly by electron beam welding than to send prestressing steel rod for use with cast basalt. Although this analysis is not rigorous, it does point out the type of analysis that must be accomplished before a particular type of construction is decided upon. Another problem with prestressing in the manner as outlined, is the fact that the basalt is cast at 1,300°C. The tensile stress in the steel tendons will be relieved by creep before prestressing can occur. The steel would also anneal in the process. The cast basalt can be post stressed, however. This would be a more complex process, but it is feasible.

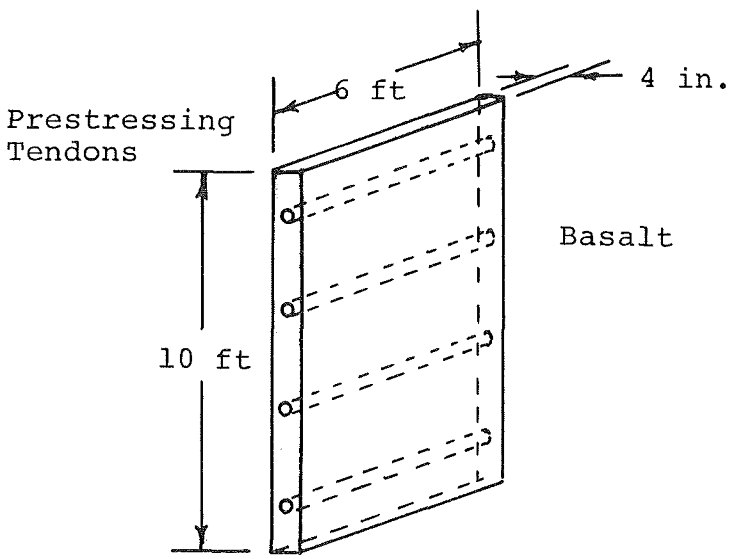


Figure 16.6-10 Prestressed Cast Basalt Slab

In the previous example, a very conservative design approach was taken. A more liberal approach indicates a possible benefit of post stressing. For example, consider the curves in Figure 16.6-11. These curves are based on standard beam and plate equations [1]. Assuming that each slab is acted upon by a uniform pressure of 14.7 psi and that the edge condition is somewhere between simply supported and fixed, the maximum bending stress versus thickness is

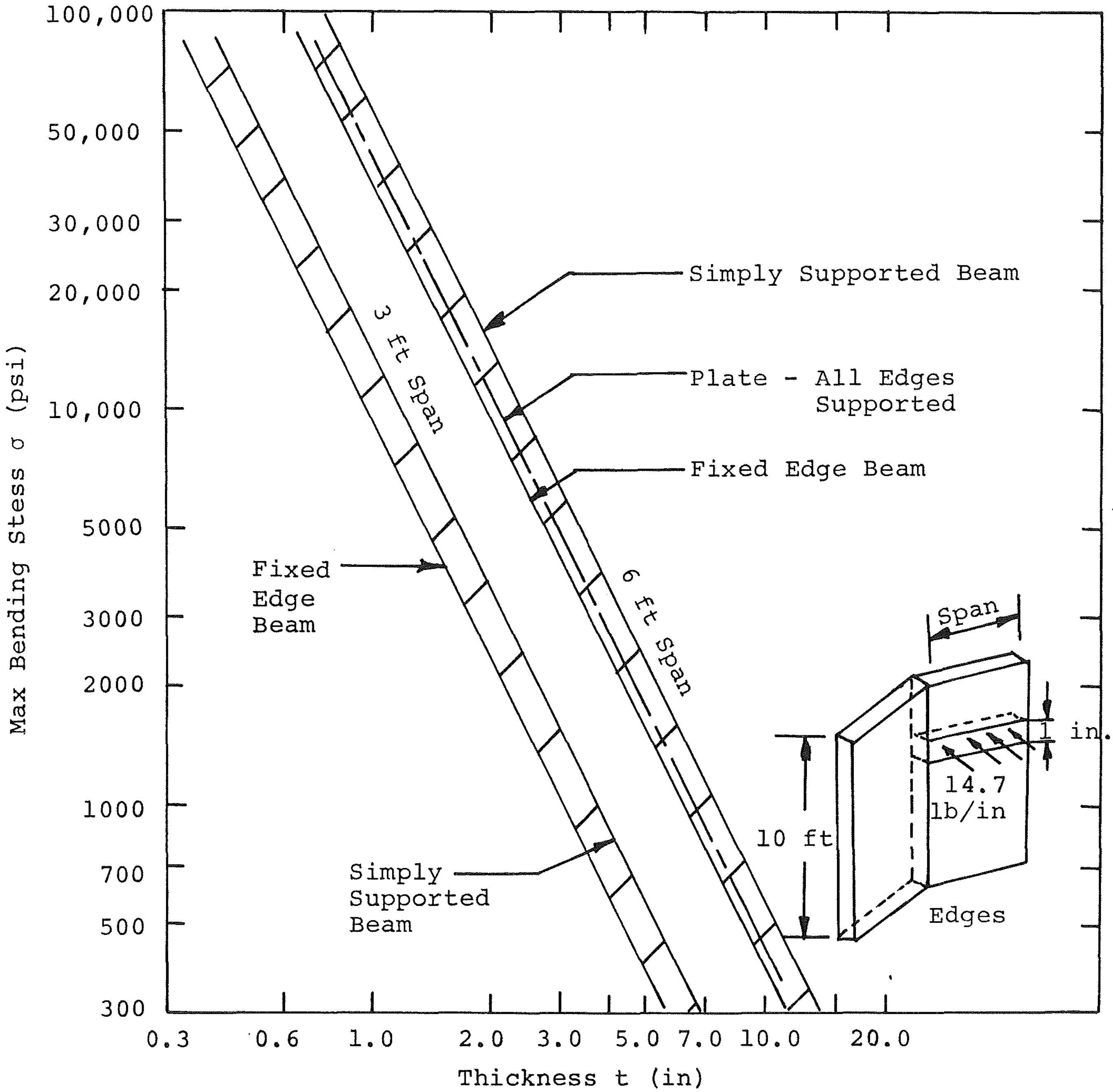


Figure 16.6-11 Maximum Bending Stress vs Thickness of Slab

plotted for span lengths of three feet and six feet. The beam curves are based on a one-inch wide section with 14.7 lb/in acting along the length. The beam equations should give a fairly reasonable nonrigorous solution for the maximum bending stress. A more rigorous approach could be taken by using folded plate analysis.

The maximum bending strength of cast basalt (Table 15.1-2) varies from 400 kg/cm^2 (5,700 lb/in^2) to 450 kg/cm^2 (6,400 lb/in^2). Using the lower value of 5,700 lb/in^2 and safety factor of 2, the maximum allowable bending stress of basalt can be estimated at 2,850 lb/in^2. If the basalt is prestressed in compression to 1,000 psi, a two-inch wall thickness will be sufficient to support the load on a three-feet wide slab (Figure 16.6-11). The cross-sectional area of the cast basalt slab is now 240 in^2. If A_b/A_{rs} is 96.25, the cross-sectional area of the tendon rods (A_{rs}) is now 2.5 in^2. The rods are three feet long; therefore, the weight of reinforcement steel required per slab is approximately 27 lb. As shown in Figure 16.6-7, thirtyone slabs are required to build a thirty-foot diameter cylinder. The total weight of prestressing steel rods required is 837 lb as compared to 1,080 lb for a thin high-strength steel cylinder. All things considered, it still does not appear to be viable to transport reinforcement rods to the lunar surface. When metal is available from lunar resources, however, post stressing should be considered.

16.6.3.2 Cast Basalt Slab Construction

Based on the previous analysis and evaluation, plain (nonprestressed) cast basalt slab construction was selected as the most viable technique for constructing the lunar shelter. The slab can be cast in a mold as illustrated in Figure 16.6-12. Techniques for controlled cooling of the cast basalt are discussed in Section 15.1. The slabs can be positioned as illustrated in Figure 16.6-13 and joined together by fusion at the interfaces using an electron-beam gun. Another possibility is a thin high-strength steel strip inserted into precast slots. An elastomer

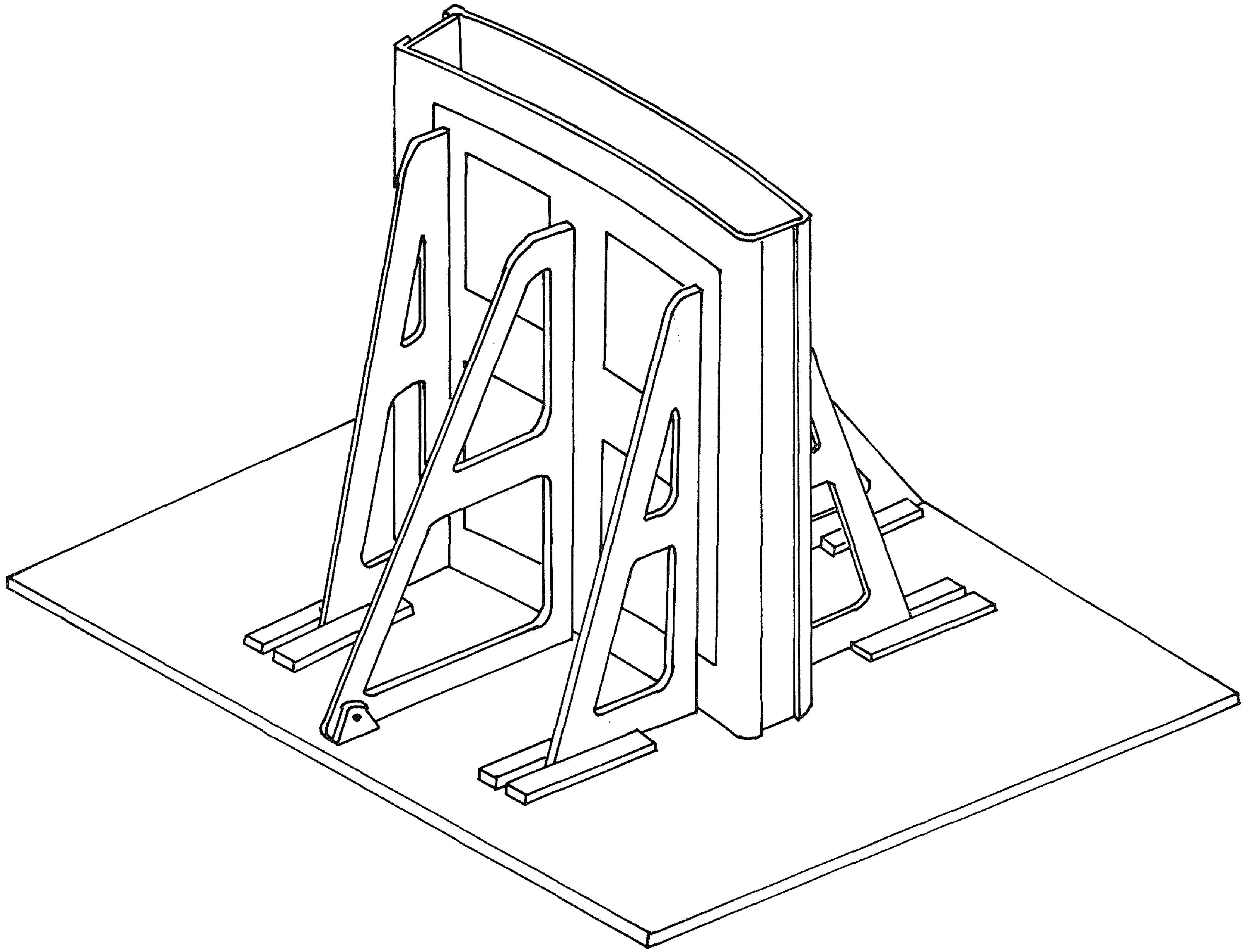


Figure 16.6-12 Mold for Casting Basalt Building Slabs

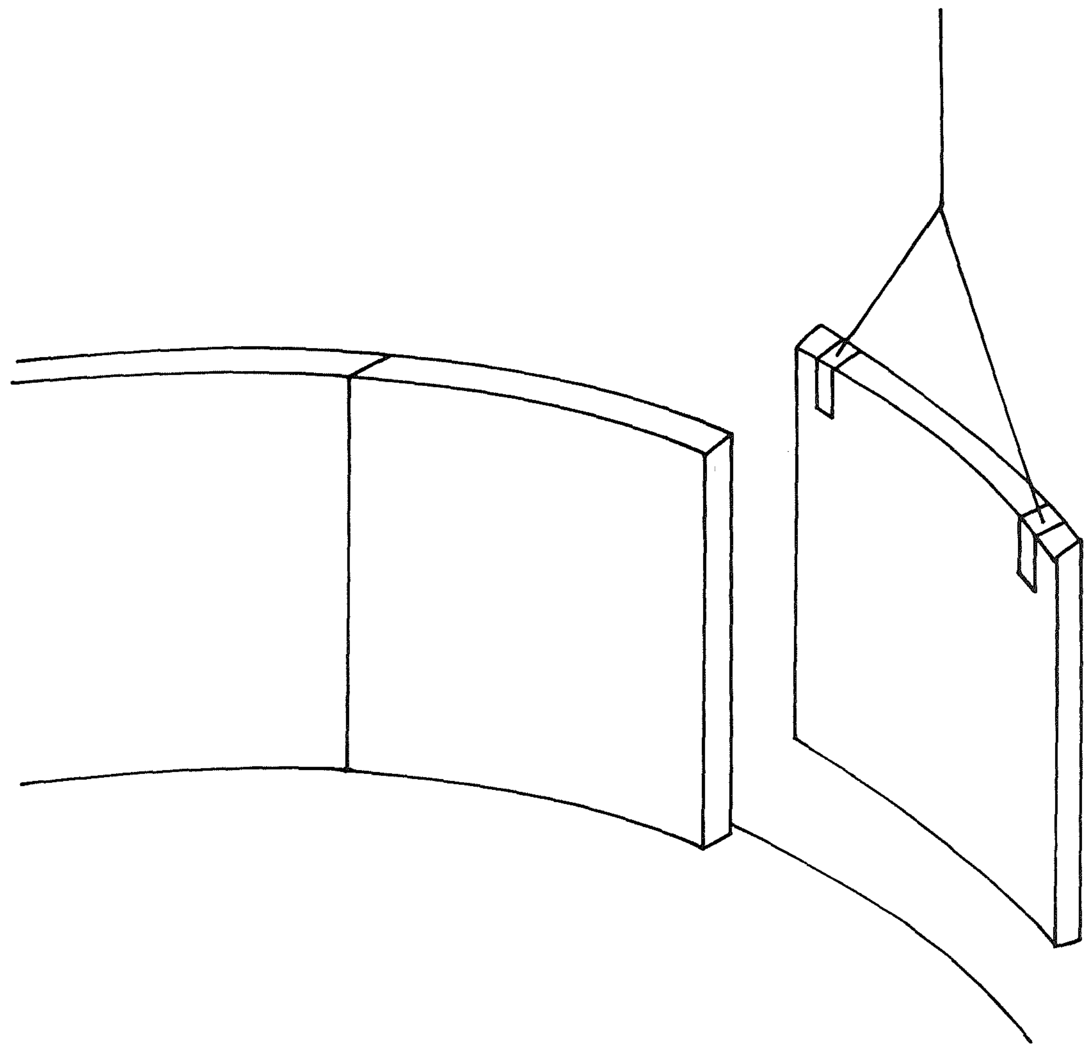


Figure 16.6-13 Positioning of Cast Basalt Building Slabs

type gasket could be inserted into the slots and, when the 14.7 psi is applied, a self-sealing effect is accomplished. These techniques are illustrated in Figure 16.6-14.

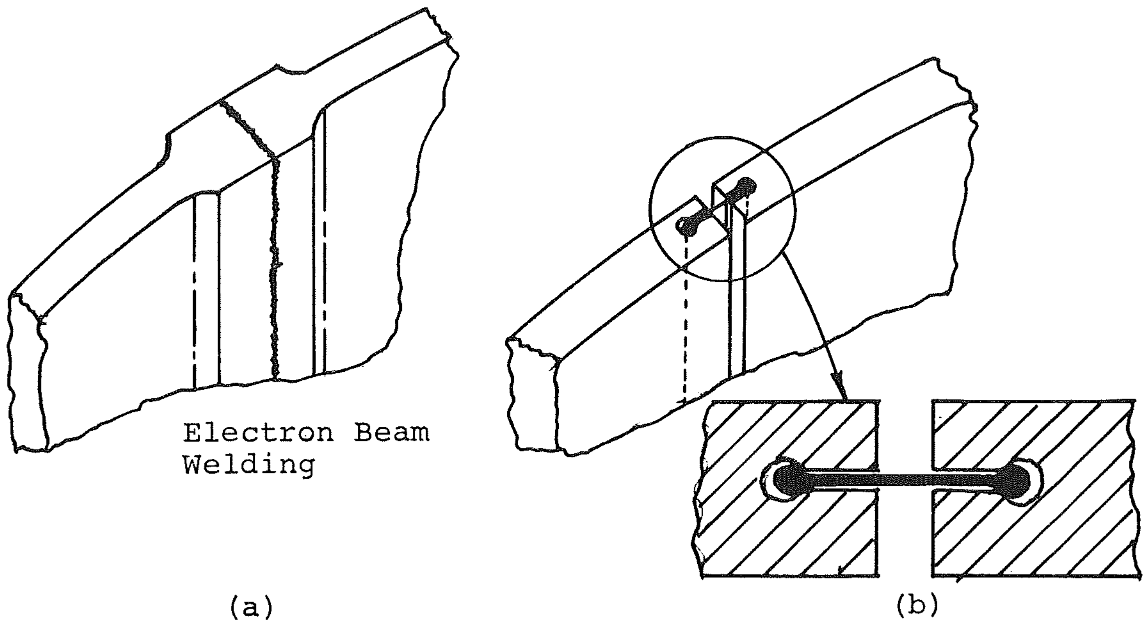


Figure 16.6-14 Joining Techniques

The lunar-colony shelter configuration is illustrated in Figure 16.6-15. The double-walled construction offers many advantages from the standpoint of safety. Consider the schematic in Figure 16.6-16 and the hoop-stress curves in Figure 16.6-17. The space between the inner and outer shell is filled with lunar fines and pressurized to 7.35 psi. This reduces the hoop stess on the inner shell by a factor of 2. The inner shell, of course, must be designed to withstand a pressure of 14.7 psi in the event of failure of the outer shell and the resultant loss of pressure between the two shells. If the inner shell fails, the total pressure within the outer shell system is equilibrated to some value less than 14.7 psi and greater than 7.35 psi. For the case of D = 30 ft and S = 1 ft, the pressure would be reduced to 13.1 psi. When the drop in pressure is detected, the oxygen partial pressure can be automatically adjusted back to 3.5 psia. Repairs can then be made.

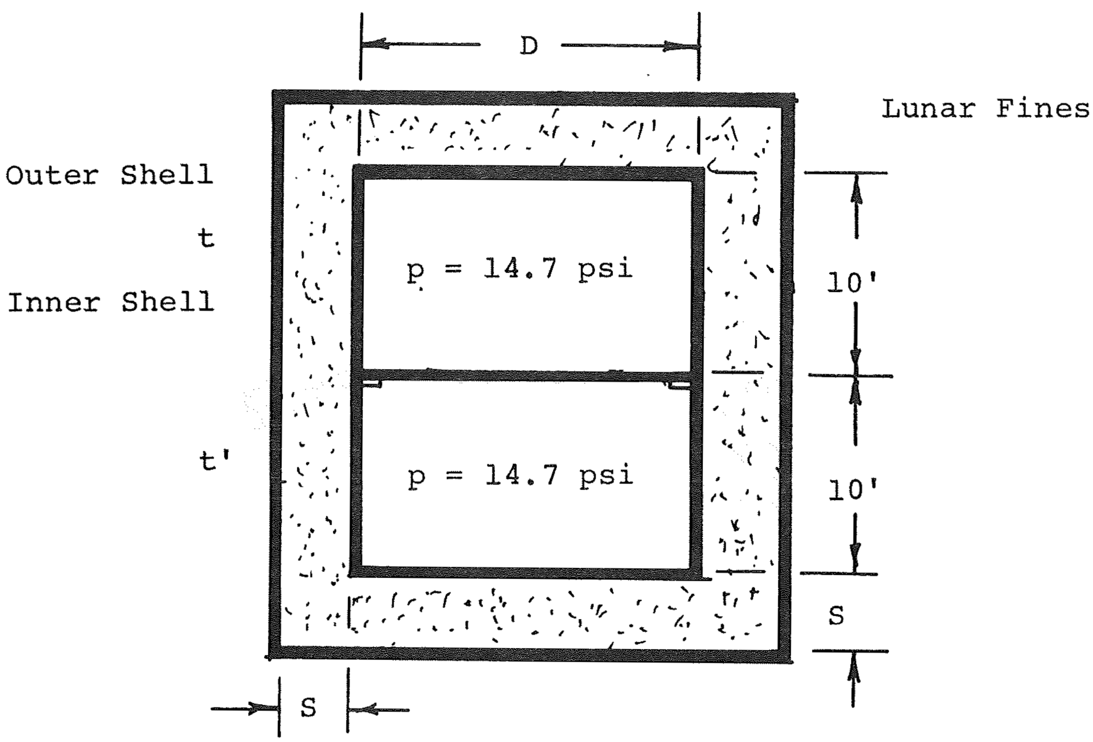


Figure 16.6-15 Cross-Section of Double Walled Shelter

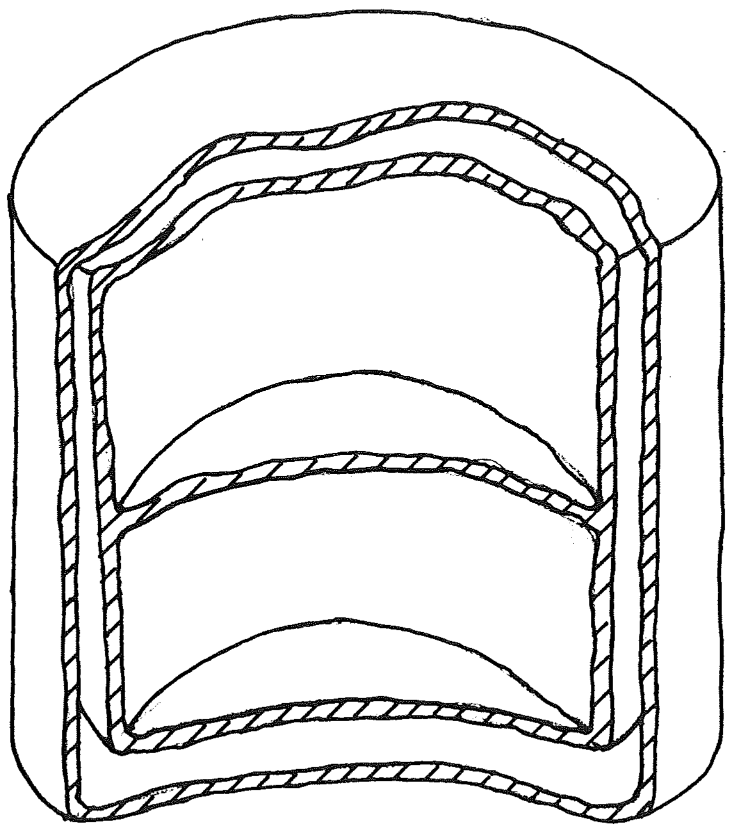


Figure 16.6-16 Shelter Module with Double Walled Cast Basalt Slab Construction

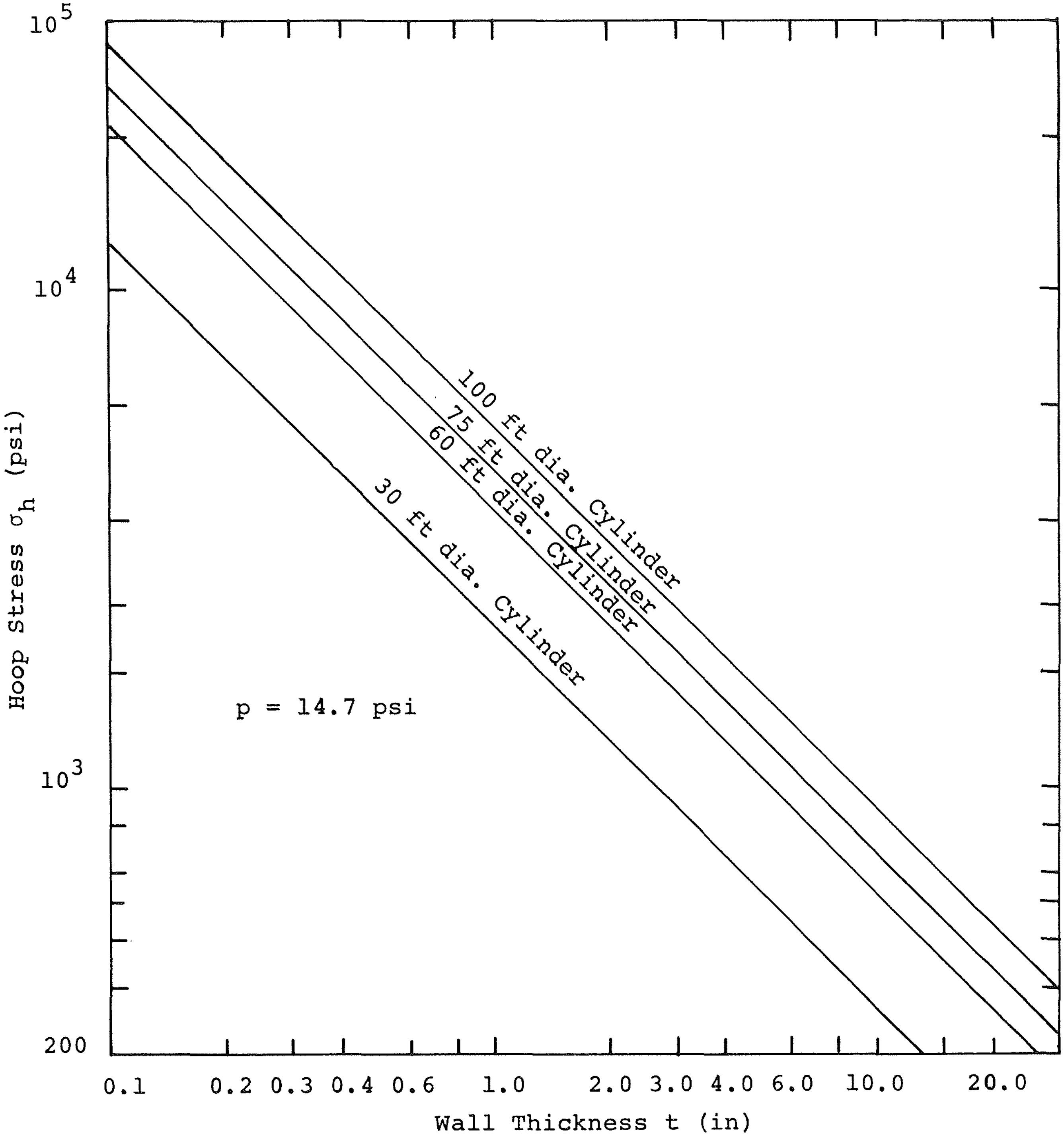


Figure 16.6-17 Hoop Stress vs Wall Thickness at 14.7 psi

The wall thicknesses required for various diameter modules can be determined from Figure 16.6-17. The tensile strength of cast basalt varies from 250 kg/cm^2 (3,550 lb/in^2) to 350 kg/cm^2 (4,950 lb/in^2). Using the smallest value and a safety factor of 3, a design tensile strength of 1,000 psi is obtained. From the curves in Figure 16.6-17, the wall thicknesses can be determined for different diameter modules. These are summarized in Table 16.6-3.

Table 16.6-3 Wall Thickness Required for Modules of Various Diameters

Diameter (ft)	Wall Thickness (in)
30	2.7
60	5.3
75	6.8
100	8.8

The actual stress condition on the wall section is biaxial. The longitudinal stress is one half the hoop stress. Since very little is known about cast basalt under these stress conditions a safety factor of 3 seems appropriate.

The bulkhead (top and bottom) portion of the cylindrical module can be either a surface of revolution (hemisphere, ellipsoid, etc.) or a flat-plate circular structure. In either case, sections will have to be joined together to form the complete structure. Although both types should be investigated in more detail, the flat circular plate structure with supporting beams was selected because the construction techniques are much simpler.

REFERENCE

1. Roark, R. J., Formulas for Stress and Strain, McGraw-Hill Book Co. Inc., 1954.

CHAPTER 17 ELECTRIC AND THERMAL POWER

17.1 POWER REQUIREMENTS

Major uses of power in the lunar colony, and approximate requirements, are shown in Table 17.1-1 below:

Table 17.1-1 Bulk Power Requirements

Use	Requires	Comment
O_2 Production	300-700 kwe 2-3 mwt	To produce 20,000 pounds with daytime production only. Requirements depend on process.
Lights and Heat for Farm	400-600 kwe	Night only
Life Support	200 kwe	
Machinery	100 kwe	Intermittant
Metals Processing	1 mwt	Later in colony life
Totals	3-4 mwt	600-1,000 kwe

From the tabulated data, it appears that a power plant capable of producing up to 1 megawatt of electricity (mwe) will be necessary. In addition, 4 megawatts of thermal (mwt) energy, at temperatures of up to 1300°K may be needed.

17.2 WAYS TO PRODUCE ELECTRIC POWER

This section contains a brief discussion of the advantages and disadvantages of various ways that might be used to generate the required electricity.

17.2.1 FISSION REACTORS

Fission reactors have been built on earth to produce 1000 mwe, so 1 mwe is no problem. It is not unreasonable to expect that power densities on the order of 75 watts/kg can be achieved, for the parts of a reactor that must be shipped from earth. The safety problems of nuclear reactors can be overcome by careful design, but their presence might boost the radiation environment at the colony by about 1 rem/year on the surface.

A more detailed discussion of a particular reactor type specifically designed for lunar colony service is in Section 17.4 below.

17.2.2 RADIOISOTOPES

Plutonium-238 powered movable generators were recommended for the 12-man base. Six generators were proposed, each with a capacity of 3.5 kwe. In general, radioisotope supplies are limited to a few tens of kilowatts. For example, Pu^{238} encapsulated as PuO^2 produces less than 500 watts of heat per kilogram. This results in about 50 electrical watts per kilogram.

Plutonium-238 is probably the best radioisotope from a physics standpoint. Its half-life is 89 years, and it emits 5.5 Mev alpha-particles, with only low-energy gamma rays. Unfortunately, it is also very expensive to make, requiring 3 successive neutron captures and a chemical separation process. Cost is on the order of $500,000/kg.

Cobalt-60 is easy to make, but its half-life is only 5.24 years and it emits 1.33 Mev gamma rays as well as 1.54 Mev beta-particles. So, it would require heavy shielding and replacement at least twice/decade.

Strontium-90 has some advantages. It is widely available as fission waste product from reactors on earth. 5.9% of the atoms produced when U^{235} splits are strontium-90. Sr^{90} has a half-life of 28 years, and emits 0.54 Mev beta-particles. However, its daughter, ytterbium-90, emits 1.75 Mev gamma rays; and its half-life is only 64 hours. Care must be exercised to assure that strontium-90 is not ingested by people, because it collects in the bones.

Samarium-151 constitutes about 0.5% of the fission products. Its half-life is 90 years, and it emits 0.74 Mev beta-particles with only small gamma rays. However, it is difficult to separate from the stable isotope Sm^{149}, which constitutes 1.1% of the fission products. Promethium-147 is another beta emitter that is a fission by-product (2.5%). It produces 0.33 Mev beta-particles and 0.12 Mev gamma rays, but its half-life is only 2.6 years.

An encapsulated mixture of fission products, that had cooled for a year or more before being shipped to the moon, might be useful as a heat source. The radioactivity in this mixture would be primarily from the isotopes in the table below, from Zysin, et al, [1].

Table 17.2.2 Radioisotopes Present in 1-Year-Old Fission Product Mixture

Isotope	% Production (U^{235} Fission)	Half-Life	Decay Mode & Energy β	γ
Sr^{90}	5.8%	28 yrs	0.54	1.75
Ru^{106}	0.4	1	0.04	
Sb^{125}	0.1	2.3	0.30	0.46
Cs^{137}	6.2	26.6	0.37	0.66
Ce^{144}	6.0	0.8	0.30	0.04
Pm^{147}	2.5	2.6	0.2	0.03
Sm^{151}	0.5	90	0.74	0.02

The heat production rate would be on the order of 0.5 watt/cm^3, or 50 watts/kg. Earth would be more than happy to ship this garbage away, and it could go far toward warming the long lunar night. Small (watts) amounts of electric power could be extracted with thermocouples.

17.2.3 FUSION

To date, man has not produced a controlled thermonuclear reactor. However, if technology forecasts come true, there may be some by the year 2000. Meanwhile, we should consider the thermonuclear power source provided by nature.

17.2.4 DIRECT CONVERSION OF SOLAR ENERGY

Semiconductor photoelectric cells have been used to provide power for many space missions. Silicon cell technology is quite well established, and gallium arsenide cells are now beginning to emerge. It appears that gallium arsenide cells have better efficiency (18% versus 11% for silicon cells), and are about equal in life expectancy [2]. Much of the discussion below was derived from a report by Electro-Optical Systems, Inc. [3] on silicon cells, but the conclusions should be valid for gallium arsenide cells also. If the quantity of solar cells being used was large enough to justify automated mass production, the cost might be expected to drop from $\$50,000/m^2$ to $\$5,000/m^2$. Both government and industry are actively researching these devices, and we can expect continuing improvement.

At earth and moon distance, the sun supplies about 1400 w/m^2. A bare, oriented silicon array can extract about 120 w/m^2 of usable electric power (200 w/m^2 for GeAs arrays). However, this power can be increased quite cheaply by using mirrors to concentrate sunlight on the array. The cells work well with photon absorbtion rates several times as high as the earth's solar flux. Their voltage is relatively constant, but the current is proportional to the number of photons. Figure 17.2.4-1 gives the voltage versus current curves for silicon and gallium arsenide solar cells.

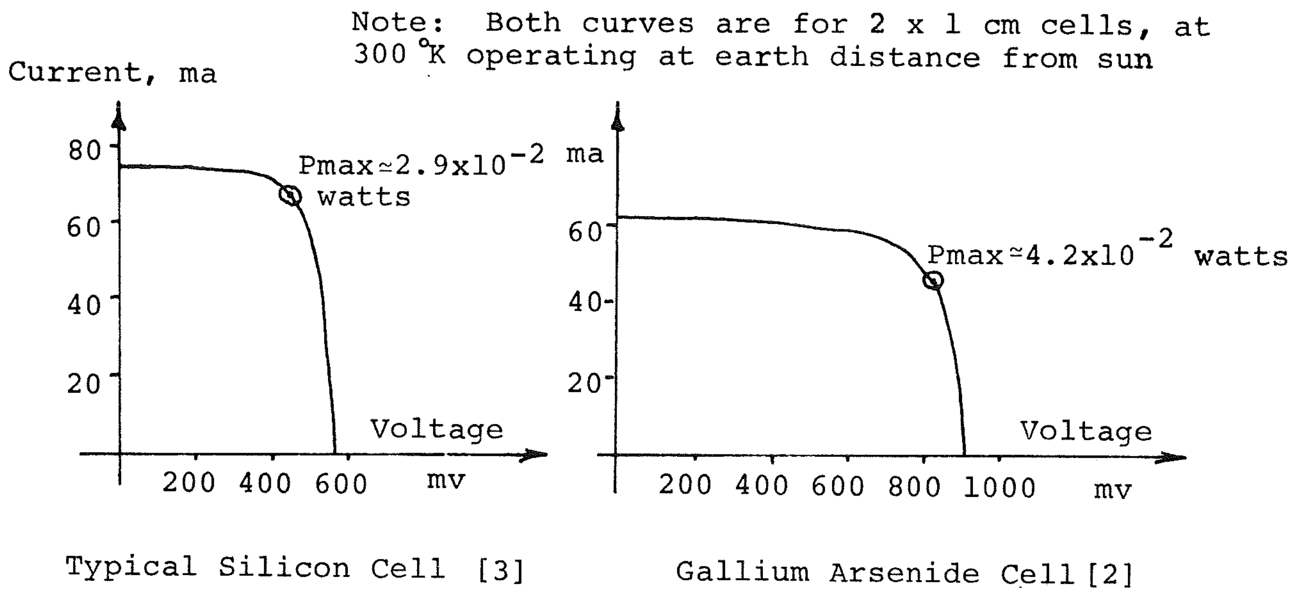


Figure 17.2.4-1 Current and Voltage Characteristics for Solar Cells

The important considerations with solar cells are the following:

1. Radiation damage. Power production in silicon cells is reduced by 25% by either an integrated dose of 3 x 10^{13} protons/cm^2 or 10^{15} electrons/cm^2. Their radiation resistance can be considerably improved by lithium doping, and the low energy protons are absorbed in the cover glass. Furthermore, the damage is logarithmic, so a flux of 10^{15} protons will reduce the efficiency of a silicon cell to 10.2% versus 12.4% efficiency when the integrated flux was 10^{14} protons [2, 3]. Taking 10^{15} as the toleration limit for protons, and using proton flux from the sun measured by the Apollo 12 and 15 solar wind instruments of 2.0 x 10^{13} protons/cm^2/yr [4], we deduce that the life expectancy of solar cells is about 50 years on the moon. Solar flares might reduce this by a few years. The cover glass will suffer ultraviolet and micro-meteorite damage. The light transmission efficiency is reduced 10 to 20% in the first few years; but this damage mode is saturation-limited, so the light transmission

through the cover glass will never be less than 80% of the incident energy.

2. Need for cooling. Silicon cells are only 60% as efficient at 375°K as they are at 300°K, so some means must be provided to cool the array.
3. Need for structural support. The cells themselves are quite fragile, and they must be mounted on a strong substitute that can hold its shape. Aluminum honeycomb makes a lightweight, stiff backing, while a flexible plastic substrate that can be stretched across a frame is even lighter and makes for easy storage. These could be used to construct the tent arrays shown in Figure 17.2.4-2.
4. Electrical connections and insulation. Most designs produce a negative potential on the illuminated side, which is gathered by metallic tines spaced a centimeter or two apart. The bottom side is the positive terminal. These must be connected together in series and/or parallel to give the desired array voltage and current. In a typical array, the electrical connections and insulation take up to 20% of the weight and reduce the effective collection area by 10%.

From the considerations above, it appears that an optimal solar array would be somewhat as shown in Figure 17.2.4-2. The backside of the solar panels could reject heat by radiation to the cooler dirt under the tent, and the frontside directly back to the black sky. Rough calculations indicate that the temperature of the panels would average about 320°K while the sun was shining on them. A tent module would produce 20 amps at 150 V dc. Estimated mass per module, using flexible teflon substrate, would be about 100 kg, including the side mirrors [5]. The cost would be about $200,000 per module.

17.2.5 ENERGY STORAGE FOR THE LUNAR NIGHT

Solar cell arrays would be very attractive if there were a good

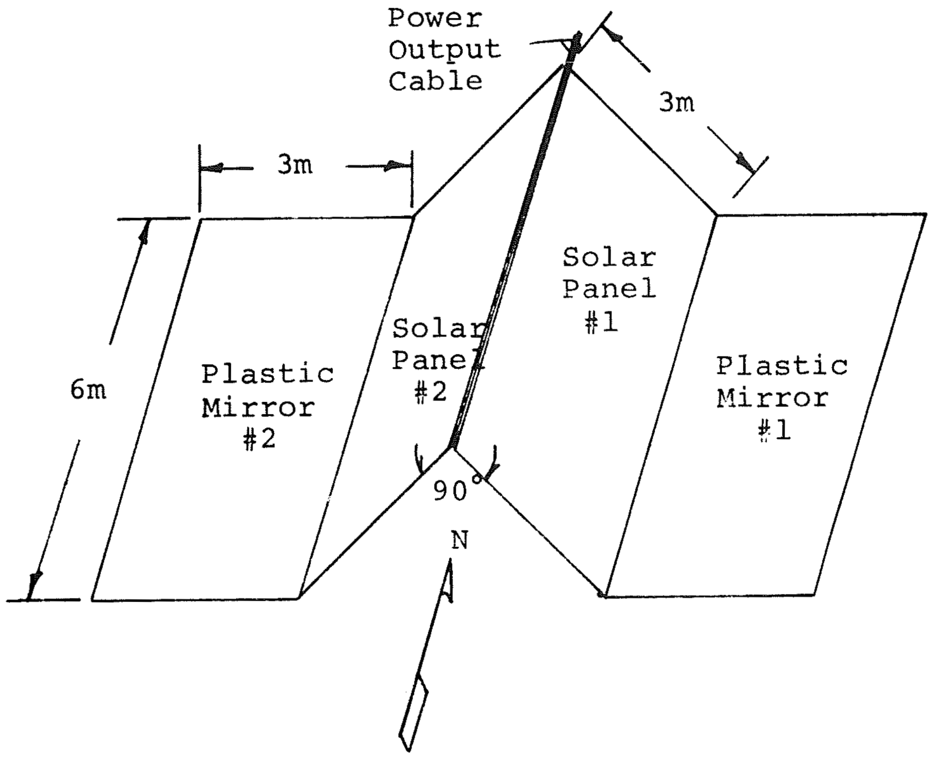


Figure 17.2.4-2a Solar Power Tent Module

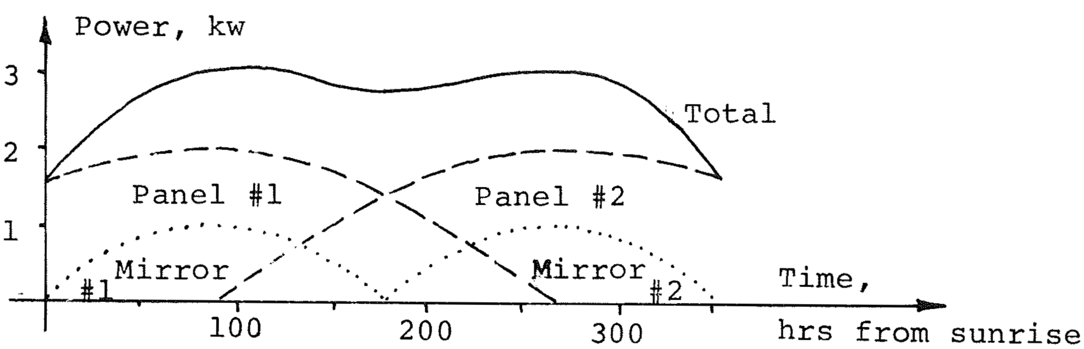


Figure 17.2.4-2b Power vs. Time for Tent Modules

way to store energy for the 350-hour lunar night. Aside from nuclear power, there appear to be only two alternatives.

17.2.5.1 Fuel Cells

For durations of more than about 10 hours, fuel cells have a weight advantage over batteries. Hydrogen-oxygen cells have been used in several space missions. The Apollo spacecraft had three fuel cell assemblies rated at 2,200 watts each. It was an explosion of a fuel cell reactant tank that aborted the Apollo-13 mission. Cryogenic storage of hydrogen and oxygen creates a significant safety hazard.

Power levels available now are in the range of hundreds of watts to a few kilowatts per module. Larger sizes could be made, but they would be probably less reliable because of the difficulty of maintaining close tolerances in larger apparatus.

Overload capability is good. A 150% load can be tolerated for several hours, and a 300% load for several minutes; the limiting factor is heat generation. Rechargeable batteries can be used to augment the overload capability.

Table 17.2.5.1-1 gives the projected power density and life expectancy of fuel cells.

Table 17.2.5.1-1 Capabilities of Fuel Cells [6]

	Apollo	1975	Ultimate
Power Density*	120 kg/kw	30 kg/kw	12 kg/kw
Life Expectancy	1,000 hr	10,000 hr	10,000+ hr

Even if the ultimate capability were realized, it would take 12,000 kg to generate a megawatt, which is about the same as the nuclear reactor's weight. Furthermore, even if the fuel cells

*Does not include the weight of regeneration equipment, which may be as much as the fuel cells themselves.

were only used at night, they would have to be replaced after three years. It is clear that fuel cells are not too attractive as a bulk power source for a long-lived colony. However, as emergency stand-by energy sources, they are probably better than Plutonium-238 isotope sources because they can be shut off, they have better overload capability, and they are considerably cheaper.

17.2.5.2 Gravitational Potential Storage

This scheme [7] is similar to the pumped storage used by earth hydroelectric facilities during the night. In Kopff crater, we could build storage bins on the rim. They would be filled with lunar fines during the day, which could be used at night to fill tramway buckets which would slowly descend to a dump at the bottom while turning a generator. The stuff in the dump would be transferred back up to the bins during the day. This scheme should give at least 70 percent efficiency, versus 25 percent regeneration efficiency for fuel cells. However, building the tramway and the bins is a monumental construction task that could not be scheduled early in the colony development. Furthermore, the weight of the components is almost prohibitive, unless they were made with lunar materials. It must be concluded that if this scheme is useful at all, it would only be as a second generation system, after about 20 years.

Estimates for a Gravitational Potential Storage System are tabulated in Table 17.2.5.2-1.

17.3 EVALUATION CRITERIA AND RECOMMENDATION

Table 17.3-1 is a comparative evaluation of the most viable candidates for the lunar colony electric power.

Table 17.2.5.2-1 Gravitational Potential Storage Estimates

Elevation difference	1,500 m
Tramway length	3 km
Stored mass	5×10^8 kg
Bins' volume	3×10^5 m^3
Power produced	700 kwe for 354 hrs
Dumping rate	2 buckets/minute
Cable speed	2 m/sec (5 mi/hr)
Mass of components:	
30 structures, 5,000 kg each	150,000 kg
Titanium cable, 4 cm dia x 6,000 m long	50,000 kg
100 buckets, $7m^3$ volume, 200 kg each	20,000 kg
Storage bins	70,000 kg
Loading equipment	10,000 kg
Slow speed motor/generator	7,000 kg
Electric Cable and switchgear	3,000 kg
	330,000 kg

17.4 POSSIBLE CONCEPTUAL REACTOR DESIGN

From the considerations previously mentioned, it appears that nuclear reactors are almost inevitable, at least during the early stages of colony development. This section describes a type of reactor designed especially for the moon or other celestial bodies with a similar gravitational field. Shielding and structural support for the reactor vessel would be provided by burying it under several meters of lunar soil. The reactor(s) would be designed with a large core and relatively low power density. The most important design consideration would be long life. We feel that refueling on the moon would be impractical because of the complex equipment and radiation hazards involved. The plan is to run a reactor until its core burns out, and then leave it buried (or bury it a little deeper) forever.

Table 17.3-1 Comparison of Power-Supply Systems

	3 Nuclear Reactors	Solar Cells with Reactor(s) at Night	Solar Cells with Fuel Cells at Night	Solar Cells with Gravity Storage	Comments
Absolute Criteria					
Performance	OK	OK	OK	OK	
Safety	OK	OK	OK	OK	
Availability	OK	OK	OK	?	Tramway will not be available during early years of colony life.
Primary Criteria					
Reliability	Good	Good	Fair		Two reactors are stand-by backup.
Flexibility & Expandability	Good	Very good	Fair		Modular solar arrays can be put up anywhere.
Resupply	Very good	Very good	Fair		20-50 year life expectancy.
Interfacing	Good	Fair	Fair		Two distribution systems required with solar cells.
Secondary Criteria					
Weight	Good	Good			About the same weight.
Volume	Good	Fair			Solar arrays are less dense.
Control Power	Fair	Good			Very dependable control power necessary for reactors.
Other Considerations					
Efficiency	Fair	Fair			
Cost	Good	Fair			
Peak-Load Capability	Good	Fair			Can start extra reactor.
Useful By-Products	Good	Fair			Waste heat from reactors radioisotopes from neutron activation.
	Preferred	Acceptable			

Figure 17.4-1 shows a possible core arrangement for a long-lived reactor. The core has three zones for power flattening and breeding. The center zone has natural uranium oxide fuel elements. It is designed to have a high epithermal neutron flux to maximize resonance capture in U^{238}, and relatively low thermal neutron flux. The cost of the fuel in the center will be minimal, since no enrichment is required. Surrounding the center zone is a seed-blanket zone [8]. The fuel elements in the seed-blanket zone are enriched UO_2 dispersed in a BeO ceramic. In the early life of the reactor, most neutrons will originate in the seed blanket. The outer zone is a thermal breeding area. The fuel elements in this area are ceramic mixtures of natural UO_2, ThO_2, and BeO. The thorium is transmuted to U^{233} by the absorption of thermal neutrons. Sketches showing the general shape of power distribution and the neutron flux spectrum for the three zones are shown in Figure 17.4-2.

During the early years, the power density is higher, and most of the power is generated in the seed blanket. Later, as the seed-blanket fuel becomes depleted, more fissions take place in the plutonium that was bred in the center and the U^{233} in the outer zone. Power density is lower, but power is spread more uniformly across the core to yield the same total power. Note that the effect of the shim rods is to confine power generation to the bottom part of the core at first. Later, as the rods are withdrawn, the center of power moves upward, and the accumulation of fission product poisons at the bottom end reduces the flux there somewhat. If flow is upward, then we get the desired condition of having the highest temperatures where the fission product inventory is lowest.

The primary coolant for the reactor should be a liquid metal, either sodium, NaK, or Li-7. NaK-78 has the advantage of remaining liquid to 262°K (-11°C), while sodium melts at 371°K and lithium at 453°K (180°C). Li-7 has a specific heat of nearly 1.0 at 910°K, versus 0.30 for sodium, and 0.21 for NaK-78; its macroscopic absorption cross section for thermal neutrons is only

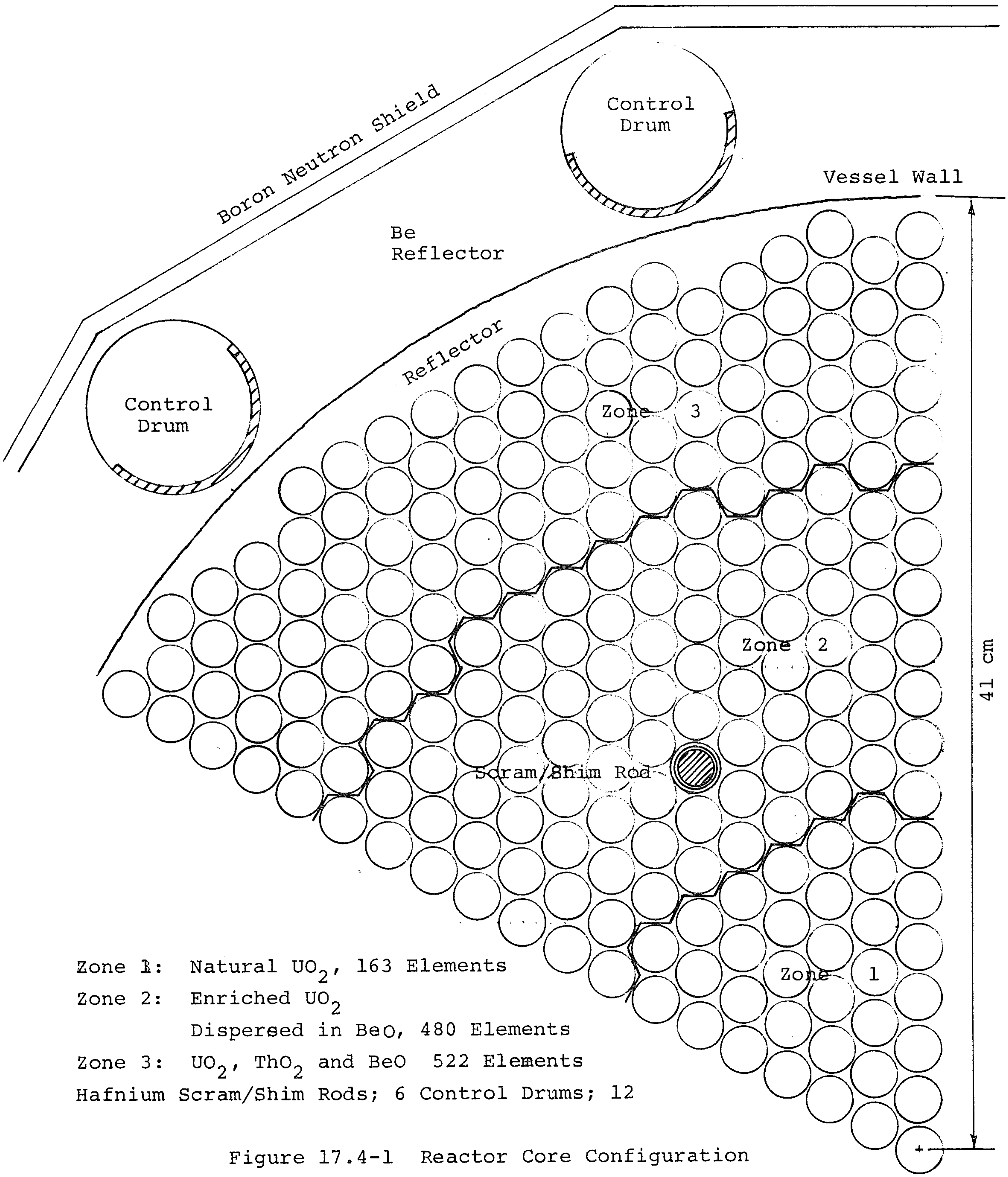
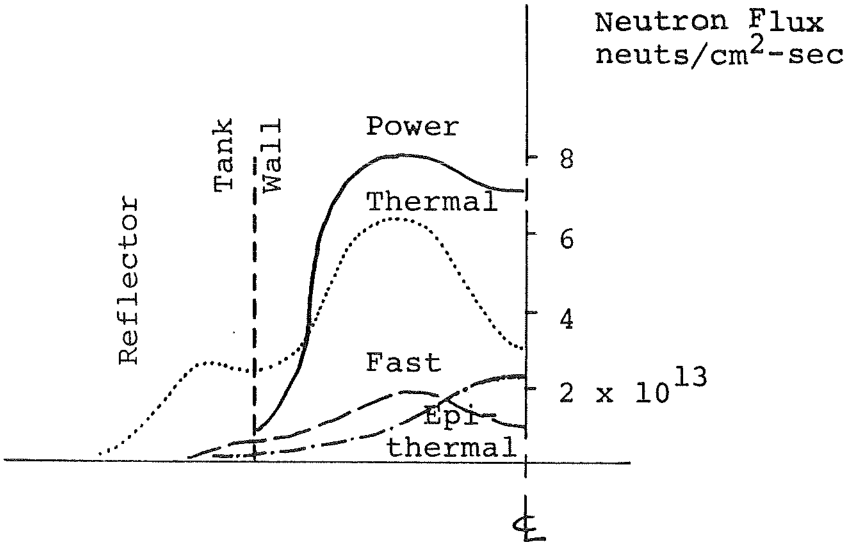
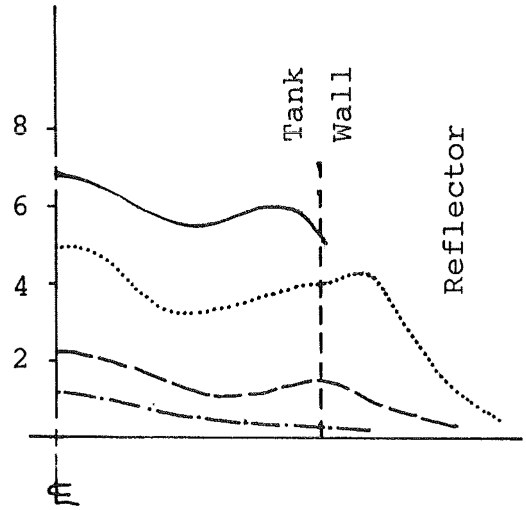


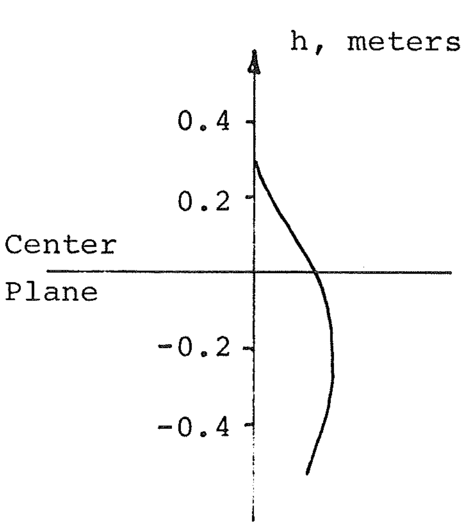
Figure 17.4-1 Reactor Core Configuration



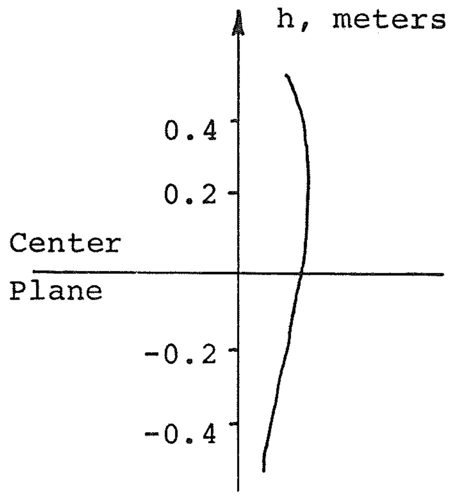
Radial Flux Distribution and
Power Early in Core Life



Flux Distribution and Power
after Fifteen Years



Axial Power Distribution
at Beginning

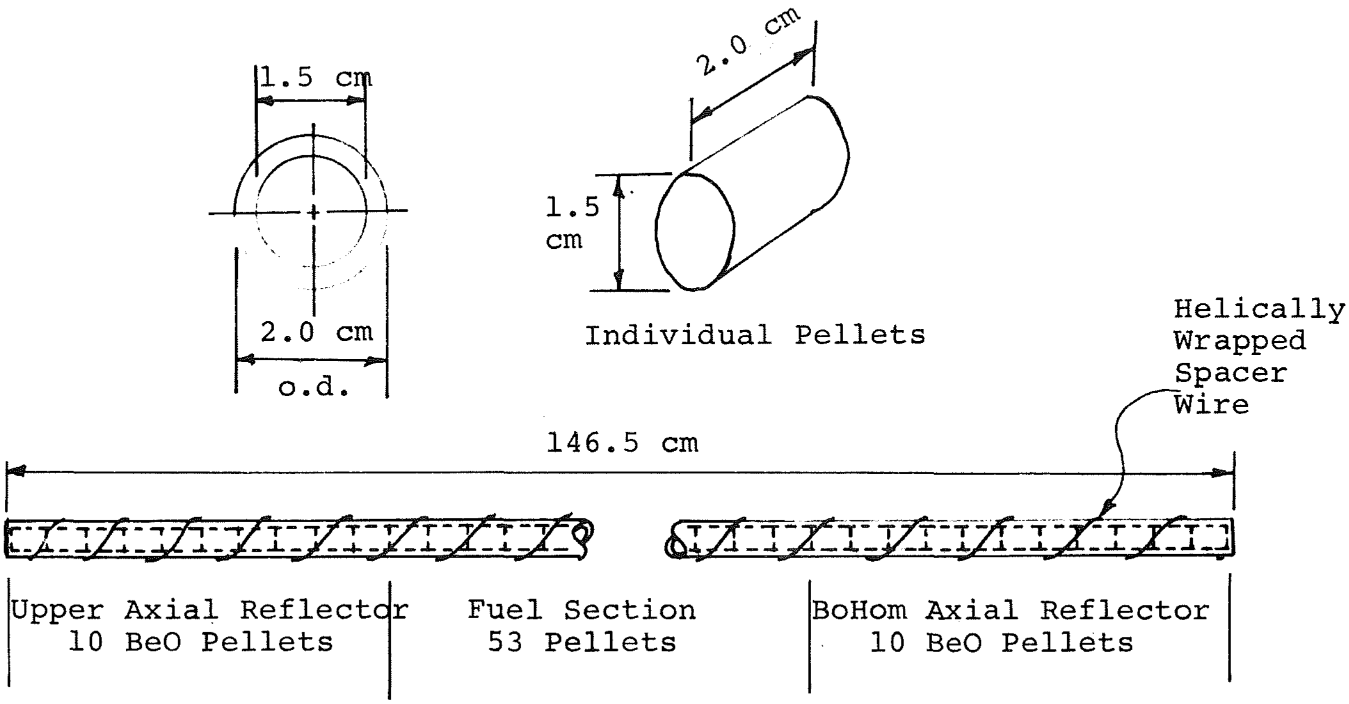


Axial Power Distribution
after Fifteen Years

Figure 17.4-2 Approximate Flux and Power Distribution in Core of Long-Lived Reactor for Lunar Colony

1.7×10^{-3} cm^{-1}, versus 1.3×10^{-2} cm^{-1} for sodium and 2.5×10^{-2} cm^{-1} for NaK-78. Lithium-7 is also a good moderator, which is advantageous in zones 2 and 3, but slightly disadvantageous in zone 1. Sodium and potassium form radioactive isotopes when they absorb neutrons. Na-24 has a half-life of 15.0 hr, and K-42 has a half-life of 12.4 hr; so personnel access to the primary coolant loop would have to be denied for at least 150 hours after shutdown. Minor fuel cladding failures might contaminate the primary loop to such an extent that personnel access could not be allowed at all.

Typical fuel elements are shown in Figure 17.4-3.



Zone 1: Natural UO_2
Zone 2: 5% Enriched UO_2 Dispersed in BeO
Zone 3: Natural UO_2 and ThO_2 Dispersed in BeO (90% BeO by weight)

Figure 17.4-3 Fuel Elements for Different Zones

If the coolant were sodium, then will it be possible to use lunar gravity to cool the core by free convection (like the earth-based "swimming pool" reactors)? The calculations follow:

Total power: 7.0 mwt

Power per coolant channel 3 kwt: 10,000 BTU/hr or 3 BTU/sec

Specific heat of sodium: 0.3 BTU/lb°F

Volume of coolant channel: 5.7×10^{-4} ft^3

Mass of coolant in channel: 0.03 lb_m Na

Temperature rise along channel: 200°F

Heat into channel column: 1.8 BTU

Velocity: 6.0 ft/sec

Equivalent diameter: 1.3×10^{-2} ft

Reynolds Number: 3,000, which is in the transition region between laminar and turbulent flow.

The heat transfer coefficient can be calculated from the Grashof Number

$$GR = L^3 \rho^2 g \beta \Delta T / N^2$$

where

L = the length of the channel

ρ = the fluid density

g = acceleration of gravity (5.2 ft/sec^2 on the moon)

β = the volumetric coefficient of expansion

ΔT = the temperature difference between the bulk fluid and the cladding

N = the fluid viscousity

ΔT = 500°F was used for Table 17.4-1.

Also needed is the Prandtl number $Pr = C_p N/K$, where C_p is the specific heat, and K is the thermal conductivity of the fluid. Then the Nussult number $= hL/K = 0.13\ (Gr\ Pr)^{0.33}$. The heat transfer coefficients for lithium, sodium, and NaK-78 were calculated at 400°F, and are given in Table 17.4-1.

Table 17.4-1 Free Convection Heat Transfer Coefficients for Liquid Metal Coolants

Lithium	Sodium	NaK-78
1,200 BTU/hr ft^2°F	2,800 BTU/hr ft^2°F	1,600 BTU/hr ft^2°F

It appears that even for the best coolant, sodium, the free-convection heat transfer coefficient is about 4 times too small.

Therefore, in order to use free convection cooling, it would be necessary to quadruple the area, which implies that the core volume would be multiplied by eight. This could be accomplished by doubling all the dimensions given in Figure 17.4-1; the larger reactor would still be operated at 7 mwt. Practically, it appears that a primary circulation pump will be necessary. However, free convection can be used for shutdown cooling.

The core pressure drop can be approximated by $\Delta P = 4f\ (L/D)(\rho V^2/2) \simeq 57\ lb/ft^2$ for sodium at 1,000°F. Pumping from bottom to top against lunar gravity adds about another 30 lb/ft^2. The flowrate is 120 lb/sec or about 1,000 gal/min. A primary circulation pump of at least 5 hp will be necessary mostly to overcome the pressure drop through the heat exchanger. This is more power than is available from the control pac, so the pumping power will have to be derived from the reactor turbine-generator. This means that full power will have to be approached gradually; it will take a few minutes to create the flowrate for full power operation.

The scram/shim rods would be in tubes which penetrate the vessel from top to bottom. Being isolated from the fluid, they would be free to fall when released. These rods would have a beryllium section at the bottom and a poison section (cadmium or hafnium) at the top. They could be occasionally lifted a few millimeters to compensate for burnup.

Automatic control would be provided by the twelve control drums outside the primary containment vessel. The moment of inertia of these drums is about $5.0 \times 10^{-2}\ kg\text{-}m^2$, so they can be accelerated fairly rapidly ($\dot{\omega} \simeq 20\ rad/sec^2$) with a small servomotor ($p<100$ watts). Twelve such motors would be powered from the Pu-238 power pac on top of the reactor. Outputs from fission chambers would be compared to the desired level and used to generate an error signal to drive the control drums. The desired level would be computed automatically at the remote monitor station.

Because the specific power is low (about 15 $watts/cm^3$), the fuel centerline temperatures can also be low. The film temperature drop between the cladding and the bulk fluid is about 5°F, which is low for a nuclear reactor.

The initial fuel inventory is tabulated in Table 17.4-2.

Table 17.4-2 Core Fuel Loading

	Zone 1	Zone 2	Zone 3
Fissile	2.6 kg U^{235}	1.2 kg U^{235}	0.1 kg U^{235}
Fertile	356 kg U^{235}	24 kg U^{238}	12.5 kg U^{238}
			20.0 kg Th^{232}

During 20 years life at 7 mwt, a total of 56 kg must be fissioned. About half of this will be plutonium formed in zone 1. This implies an average conversion efficiency for the overall reactor of about 0.95 atoms of fertile material converted to fissile for each fission.

The burnup for this reactor is about 100,000 MWD/tonne, or 2.6×10^{20} fissions/cm^3. Nearly all the fission gases would be contained in the oxide ceramic, but some pressure buildup might occur in zone 1 late in the reactor's life. The relatively low fuel temperatures will aid in retaining fission product gases.

Secondary systems would be similar to those of SNAP-8E. The primary heat exchanger would use the heat in the sodium to vaporize mercury. The mercury vapor would turn a turbine to drive a generator [9]. Since the distance from the reactor complex to most loads at the lunar colony is on the order of 100 m, a direct-current distribution system at about 240 V dc is recommended. Much of the power to the oxygen process must be direct-current for electrolysis anyway, and most other loads could be powered from a direct-current source.

The condenser on the downstream side of the Hg turbine would be pooled by an organic fluid which is circulated through a large radiator (≃ 1,600 m^2) [10]. The waste heat might also be useful as space heat or for preheating the reactants in the oxygen plant. A counterflow heat exchanger would yield a secondary discharge temperature of about 515°K (645°F). The organic circulation loops would require large pumps (≃ 20 hp), which would derive their power from the reactor.

Three reactors are recommended for redundancy and reliability.

17.5 LONG TERM PROSPECTS

The reactors may last as long as 50 years, since each one is operated only intermittantly and often at reduced power. Fifty years is also a reasonable estimate for the life expectancy of solar arrays. Beyond that, prospects are good for either thermonuclear or gravitational potential storage as second-generation power sources. The residual radioactivity from the buried reactors should be negligible compared to the background sources.

17.5.1 RADIATION DOSE FROM REACTORS TO COLONY

If the top of the reactor is buried under six meters of lunar soil, then the attenuation of neutrons and gamma rays will be approximately as shown in Table 17.5.1-1.

Most neutron absorption would be in the iron atoms which constitute 12 percent of the lunar soil. Unfortunately, when iron absorbs a neutron, it emits an 8 Mev gamma ray. The total dose rate from the reactor itself will be on the order of 20 mrem/hr. Sodium-24 (half-life, 15 hours) will exist in the primary coolant loop in an equilibrium concentration of 0.4 ppm. This means that all parts of the primary loop including the primary heat exchanger, will have to be covered by 4 m of lunar soil. A removable cover might be provided to get to the primary heat exchanger.

Access to the area on top of the reactors will have to be limited

Table 17.5.1-1 Dose Rates at Surface Due to Reactor 6 m Below Surface

	Slow Neutrons	Fast Neutrons	1 Mev γ	3 Mev γ	9 Mev γ
Relaxation Length	31 cm	10 cm	14	20	30
Buildup Factor	not applicable	Contribute Secondary Thermal Neutrons	70	15	7
Attenuation	1.2×10^{-13}				
Source Strength	2×10^{16}	$<10^{15}$	10^{16}	10^{15}	Secondary Emission from Neutron Absorption in Iron
Flux at Surface (Particles/cm^2-sec)	70*	Negligible			400
Dose Rate	10 mrem/hr	0	Negligible	Negligible	10 mrem/hr

*Based on a 1 cm thick boron shield on top half of reactor.

since the dose rate there may be around 50-100 mrem/hr. However, the dose at distances tens of meters or more from a reactor will be much less, on the order of 0.1 - 1.0 mrem/hr. Radiation from cosmic sources will be an order of magnitude more.

There is no reason that radiation should limit the staytime of persons at the colony, unless the AEC rule forbidding children under 18 to receive any occupational radiation dose at all is evoked. Such a ruling would have the effect of banning children from the colony whether reactors were there or not. See Appendix C for a further discussion of these matters.

17.6 SECONDARY POWER SOURCES

The 3.5 Kwe plutonium-238 power carts used for the 12-man base would be used as control power for the nuclear reactors. Since only one reactor would be operated at a time, only one cart would be needed. A parallel backup, such as a battery bank or another power cart, would be desirable for reliability.

Solar cell panels can be set up for use at remote locations and to power special pieces of isolated, independent apparatus such as the "Sunflowers" (Section 17.7), and the meteoritic iron "Ore Wagons" (Section 14.3.3). Use of solar panels in the vicinity of mining or construction activities is not recommended because a very small layer of dust on the cover glass will cut down the light transmission considerably. Cleaning the solar panels would be tedious.

It is to be expected that small regenerative fuel cells and rechargeable batteries will be distributed throughout the colony for emergency power. Each emergency unit should be capable of producing 100 watts for 350 hours. Solar panels could be used for emergency power during the day. A failure in the distribution system is more likely than the failure of all three reactors.

17.7 THERMAL POWER SOURCES

The waste heat from the reactors (620°K) is not hot enough to be used alone in most chemical and manufacturing processes. It might be used as a preheat step in the O_2 plant and to soften metals for ease of fabrication; but it is not hot enough to melt lunar materials.

The only other source of megawatts of heat is the sun. It is hot enough (6,000°K) to vaporize almost anything, but it is only available half the time. Furthermore, the energy density (1,400 w/m^2) requires concentration to several hundred kilowatts per square meter to be useful. A reflective solar furnace using mirrors is probably desirable. Such a furnace could be assembled in a 200 m diameter, 15 m deep crater using the "Sunflower" modules described below:

A little consideration will show the desirability of having an active solar-mirror array (as opposed to fixed mirrors) to harness thermal energy from the sun. For the amount of energy required for the oxygen plant, 1-2 mwt, a moving parabolic focus mirror would be far too cumbersome. However, it may be possible to have a couple of hundred planar mirrors made of front-aluminized mylar plastic sheet stretched over a frame, that could be individually aimed. The mirrors below have an area of 10 m^2; they are each part of a simple self-contained electromechanical sun-following mechanism. See Figure 17.7-1.

There is a ball and socket support at the center of gravity of the mirror. Radial frame spokes connect the center to the frame edge, making six equilateral triangular sections which fit together to make a hexagon. Three of the radial spokes have sliding hangers mating to vertical bars. Two of these bars are linear drive gears, which can be driven up or down to tilt the mirror in any desired direction. The third bar is there to balance the other two; it slides freely up and down through a guide bracket. In the center of the mirror is a hole about 15 cm in diameter which allows sunlight to pass through to the pedestal below.

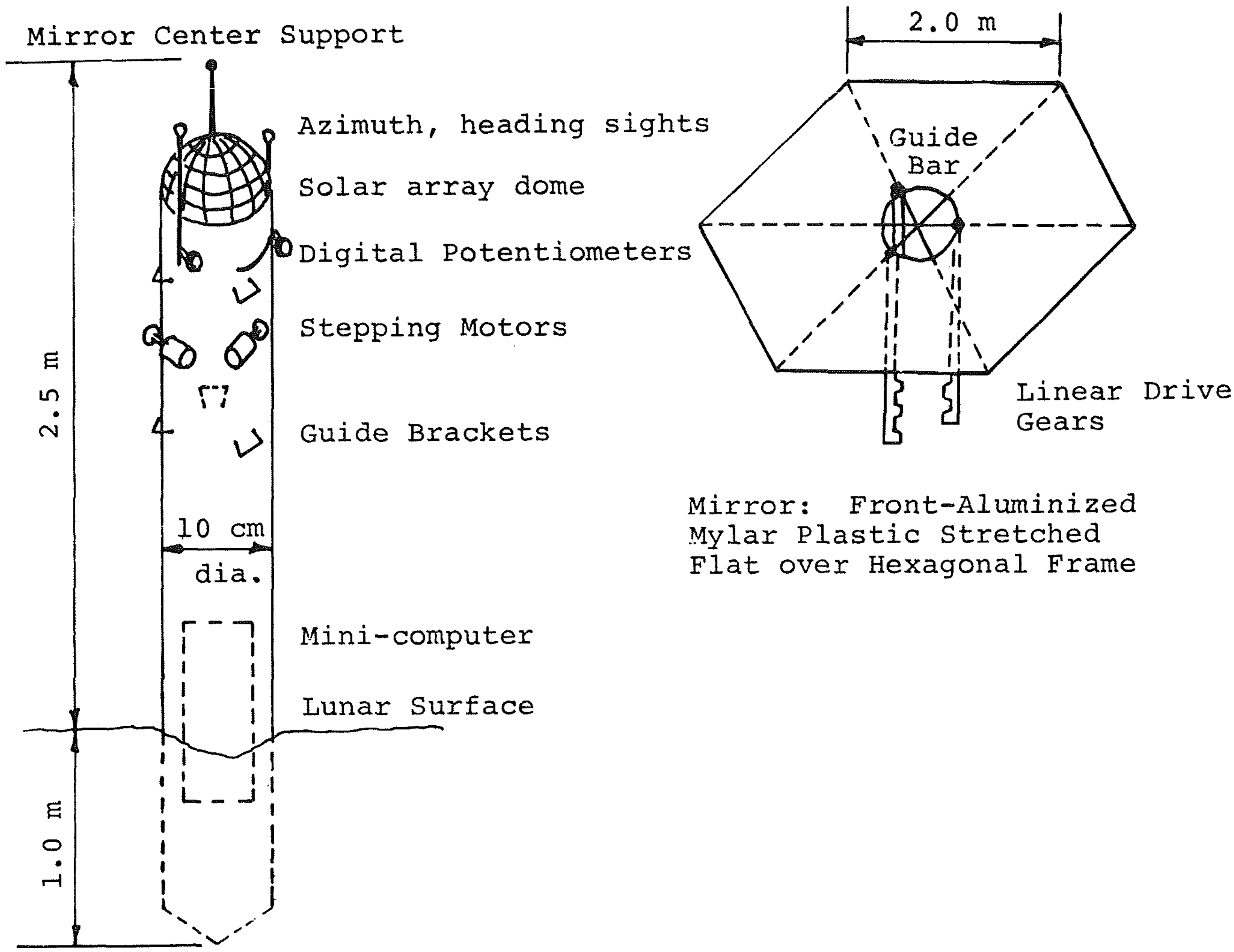


Figure 17.7-1 Solar Furnace Mirrors or "Sunflowers"

The pedestal has a peephole sight as a way for establishing the vector direction from the mirror to the reaction vessel; this vector is dialed into the pedestal minicomputer using digital potentiometers. On the top of the pedestal is a hemispherical array of solar cells. These serve the dual purpose of providing a few watts of power for the drive motors and the minicomputer, and to sense the direction to the sun. The mirror normal vector is held to be midway between the vector to the sun and the vector to the vessel. Two small step-and-latch motors are also mounted on the pedestal; they drive the linear gears on the mirror. Finally, inside the pedestal near the bottom (underground for thermal insulation) is a minicomputer, with a few hundred programmable steps and memory locations. This type of computer is expected to be widely available and quite cheap within a decade or two. Since the "sunflowers" would be within 100 m of the vessel, an accuracy of ±10 minutes would be good enough. So 10 bits, including the sign bit, would be sufficient for the computer. Each mirror would turn about 90° during the course of a day.

Optical quality of the mirrors will become degraded in about one year's time by micrometeoroids [9]. However, optical quality may not be too important in this application. Perhaps the mirrors can be periodically resurfaced or replaced.

REFERENCES

1. Zysin, Y. A., Lbox, A. A., and Sel'chenkov, L. I., Fission Product Yields and Their Mass Distribution, translated from Russian, Consultants Bureau, New York, 1964.

2. Ellis B. and Moss T. S., "Calculated Efficiencies of Practical GeAs and Si Solar Cells including the effect of Built In Electric Fields" in Solid State Electronics, January 1970, pgs. 1-24.

3. Kempt, H., "Megawatt Solar Array" report by Electro-Optical Systems Inc., August 29, 1969.

4. Clay, D. R. et al, "Solar Wind Spectrometer Experiment" in Apollo 15 Preliminary Science Report, NASA Special Publication #289.

5. Kendrick, J. B., (TRW Systems Group) "Energy Conservation Methods Applied to Lunar Surface Operations" in Intersociety Energy Conversion Engineering Conference Records, pg. 642, IEEE AES Transactions, 1968.

6. Cohn, E. M., "Primary Hydrogen-Oxygen Fuel Cells for Space", in Performance Forecast of Selected Static Energy Conversion Devices at 29th Meeting of Agard Propulsion and Energetics Panel, Liege, Belgium, June 1967.

7. Pringle, J. Kenneth, "Lunar Gravity as a Power Source", p. 117 in Report of the Fifth Annual Meeting of the Working Group on Extraterrestrial Resources, M.S.F.C. 1967.

8. Glasstone, S. and Sesonske, A., Nuclear Reactor Engineering, D. Van Nostrand Publisher, 1963.

9. Diecamp, H. M., Nuclear Space Power Systems. Booklet published by Atomics International, September 1967.

10. Dallas, T., et al, "Design Studies on the Effects of Orientation, Lunation, and Location on the Performance of Lunar Radiators", NASA N71-20092.

PART IV

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 18 CONCLUSIONS

This study of a permanent and semi-independent lunar colony has been the first effort of its kind based on real input from the lunar surface. Previous efforts were based totally on earth-reliance for their life-support needs or they were entirely speculative because they were pre-Apollo. Now that good information is available on the content of lunar materials, more definitive arguments can be made about the use of lunar resources for the life-support systems.

We have found the concept of a lunar colony to be feasible; however, much research and development work is necessary before the colony is a reality. The research and development needs are summarized in Chapter 19.

The conceptual design of the lunar colony presented here contains several important recommendations for the design of a long-term, self-sustaining facility. These recommendations pertain to the problems of sequence of growth of the colony, oxygen production, psychosocial needs and behavior, food growth, and lunar manufacturing and construction.

The sequence of growth of the colony started with the redefined LSB and detailed the development of the colony. The functions of each individual were specified as the colony developed. The rate of growth of the colony was obviously quite dependent on the capability of producing oxygen on the lunar surface.

The mineral ilmenite, found in abundance on the lunar surface, has been suggested previously as a source for oxygen. The hydrogen-reduction process seems to be the most feasible process for oxygen production. Our studies indicate that incorporation of vapor-phase electrolysis has advantages over conventional liquid-water electrolysis as both reactions (reduction and electrolysis) may be carried out at about the same temperatures. Therefore, we recommend that vapor-phase electrolysis be included in the hydrogen-reduction process for the production of oxygen.

The lunar fines are known to be sufficiently small so that no initial size reduction is necessary before most material and manufacturing use. However, size separation may be desired prior to certain specialized operations. The lunar fines, when heated, are readily processible into cast basalt which has numerous structural uses. Cast basalt has seen use on earth as a building material and as a material from which liquid-conveying pipes are made. We have suggested the means by which cast basalt can be put to use as a building material. Form, shape and size are suggested along with the procedure by which the cast basalt building blocks may be fastened and joined together.

The concept of habitability is discussed. We have tried to define the parameters affecting habitability so that the proper physical-design guidelines may be formulated. The food-energy requirements are reviewed and the types of diets necessary for the colonists to function in the lunar environment are suggested. We also have outlined a series of psychosocial factors which require extensive examination before the colony becomes a reality.

The different means of food production have been identified. Higher plants are the most likely means of providing a proper and acceptable diet. The problems of producing higher plants are reviewed and it seems that the lunar soil is well suited for plant growth except for the lack of nitrogen and several trace elements.

The possible inclusion of select small animals is discussed and the attendant problems are reviewed.

CHAPTER 19 RECOMMENDED RESEARCH AND DEVELOPMENT METHODS

We have judged the lunar colony to be a feasible project based on the subsystems and concepts selected for the various processes. There are numerous examples in the subsystem selection process where a different, and perhaps better, subsystem could have been chosen if advanced technology had been available to make certain of the subsystem functions more efficient, or even possible. Therefore, we recognize that significant research and development must be pursued before the lunar colony is a reality. Thus, the remainder of this chapter is devoted to a listing of the R & D efforts which we recommend to improve our colony design.

First, we consider some of the efforts which should be directed toward food and plant growth:

1. If only limited amounts of fresh farm foods are available, determine which crops are psychologically most valuable.
2. Establish solar radiation tolerance levels for plant life.
3. Develop electric lights that would produce only select wave-length emissions required for plant growth.
4. Develop strains of plants that could adapt to the lunar day-night cycle.
5. Grow crops to maturity in lunar soil.
6. Develop processing techniques for synthetically produced carbohydrates.
7. Determine the effects of 1/6 g and zero magnetic field on plant growth.

Secondly, we look at those factors from life support and waste control which bear further study:

1. Development of an operable water electrolysis unit.
2. Development of processes for reclamation of urine and feces, especially toward nutrient recovery.

3. Development of a nonionic detergent to insure full recycling of wash waters.
4. Development of techniques for microbiological control and detection in the life support system.

Next, those efforts associated with power-generation problems are listed:

1. Detailed design studies of long-life nuclear reactors for planetary applications.
2. Develop ways to use lunar materials to construct a gravity storage tramway.
3. Development of low cost solar cells on a lightweight structural backing.
4. Study of thermal power conservation measures; thermopiles, waste-heat use, etc.
5. Devise refurbishing techniques to restore surfaces of solar-furnace mirrors when they are degraded by meteorites.
6. Detailed design studies of the "sunflower" idea; to make them simple, rugged, and lightweight.

Fourth, we consider those areas in mining and construction which bear additional study:

1. Simulate lunar basalt and establish casting techniques to obtain maximum mechanical properties under vacuum conditions.
2. Establish effect of 1/6 g and vacuum on casting of simulated lunar basalt. Experiments should include tension studies, crack propagation, and alternating stress effects.
3. Experiment with synthetics, metals, and various fibers (boron, graphite, etc.) added to basalt matrix to establish composite material with high tensile properties.
4. Establish comprehensive design data for cast lunar basalt.
5. Conduct numerous experiments in earth-orbit workshop using centrifuge to determine effects of 1/6 g on various

manufacturing processes. Experiments should include composite casting, single crystal growth, solidification (grain structure), and alloying.

6. Study glass and ceramic technology using lunar materials to study the following:
   a. High quality optical glass (TiO_2, SiO_2, etc.)
   b. Processing to produce glass or ceramics.
   c. Transparency and strength of glass.
   d. Production of fiberglass using lunar materials.
7. Check simulated and actual lunar fines to determine effect of water addition; what, if anything, needs to be done to provide necessary hardening.
8. What is the effect of lunar vacuum on lunar-derived non-metallic building materials?
9. Test the thermal drill in simulated lunar materials under vacuum conditions to determine if penetration rate is high enough for available power supply.
10. Inflatable structures should be tested on earth to determine effects of ultraviolet and infrared radiation, light transmission, and degradation.
11. Test various alloys for effects of radiation, thermal cycles and micrometeoroid impacts.
12. Investigate the use of lunar materials for paving purposes. Paving is necessary to minimize effects of lunar fines deposits on the colony facilities.
13. Determine ways of extracting parts-per-million valuable elements such as hydrogen, nitrogen, and carbon.
14. Study the optimal design of automatic electromagnetic meteoric iron gatherers (the "Ore Wagons").

Next, we list those areas in which further study dealing with oxygen production would be useful:

1. Close examination of the fluorine and chlorine processes evaluated for oxygen production to see if the rapid kinetics of certain reactions can be slowed.

2. Electrode consumption in the electrolytic reduction process seems too rapid. Recycling of the electrodes or slower consumption rates of the electrode should be sought.
3. Develop and operate prototype hydrogen-reduction process oxygen plant including vapor phase electrolysis system.
4. Oxygen production tests should be made on simulated lunar fines for all candidate processes.

Finally, we make the following suggestions which deal with miscellaneous colony factors:

1. Topographical studies of the lunar poles. How much of a platform would have to be built to obtain perpetual sunlight?
2. How much of the natural mutation rate is attributable to radiation, and how much to temperature and chemical mutagens? What is the real radiation tolerance of man?
3. Study of possible elimination of paper and other wood products.
4. Develop ability to choose teams of individuals to live and work together for long periods of time.
5. Determine and test the multiplicity of approaches which the supporting public will accept as reasons or justification for establishing the lunar colony.

APPENDICES

APPENDIX A STATEMENT OF WORK

1.0 BACKGROUND

As a result of advanced studies for shuttle-launched space stations (SLSS), chemical and nuclear inter-orbit shuttles, space tugs, orbiting lunar stations (LS), and lunar surface bases (LSB), we are now in a position to consider utilization of lunar materials for the purpose of reducing cost of lunar operations. Such investigations are timely in view of recent presidential approval of the Space Shuttle.

2.0 OBJECTIVE

The objective of this study is to design a lunar colony at minimum cost through the utilization of lunar resources.

3.0 SCOPE

The contractor shall perform the tasks necessary to generate the study products listed in Section 4.0 in a manner that best accomplishes the study objective.

4.0 STUDY PRODUCTS

The following study products shall be generated by the members of the 1972 NASA-ASEE Summer Faculty Program in Engineering Systems Design, hereinafter designated Contractor:

a. The conceptual design of a lunar colony capable of supporting 50 to 100 men and utilizing lunar resources in an economical manner.

b. Descriptions of the lunar colony capabilities to support basic and applied science, and utilitarian ventures.

c. Description of the use of lunar materials in the following:
   - (1) food production
   - (2) building materials
   - (3) propellants
   - (4) environmental support
   - (5) natural protection
   - (6) other uses

d. Description of evolutionary steps leading from earth dependence to semi-independence. Typical of the questions to be answered are the following:
   - (1) What is needed before expansion begins?
   - (2) What skills are required?
   - (3) Should families be included and if so, when?

e. Statement of values to be derived from a lunar colony.

5.0 GUIDELINES

The Contractor shall adhere to the following guidelines unless specific deviations for changes can be substantiated:

a. Visitation to the base can be assumed to occur up to four times per year with a capability for delivering two 30,000-pound modules with no crew rotation or up to 20,000 pounds with a 6- to 12-man crew rotation capability.
b. Propellant required for the lunar landing vehicle can be assumed to be 55,000 pounds of liquid oxygen and 11,000 pounds of liquid hydrogen, either of which may be supplied from lunar resources.
c. For purposes of this study, crew staytime shall not be limited for physiological reasons.

6.0 APPROACH

The Contractor shall present a detailed description of the tasks to be accomplished in fulfillment of the study product requirements listed in Section 4.0. Tasks shall be time-phased and task interdependency shall be indicated.

The Contractor, at his option, may elect to begin his study based on Apollo results or rely on current Phase "A" definition of systems that describe a 12-man earth dependent base.

7.0 ATTACHMENTS

Attachment I, "Advanced Study Planning Data Book," presents descriptions of some hardware elements which may be available for support of a lunar colony. As Attachment I is not up-to-date, it may not represent the latest NASA planning.

Attachment II, "Lunar Surface Base Program Plans," a presentation prepared for MSC management, may be helpful in identification of areas to be investigated during this study. It should be noted that information contained in the New Lunar Era section is in general substantiated by Phase "A" study work, whereas the remainder of the document is based on very preliminary in-house work.

APPENDIX B

PROCESS DESCRIPTIONS AND SCHEMATICS FOR SELECTED SUBSYSTEMS

B.1 ATMOSPHERIC STORAGE

The selected subsystem for atmospheric storage was filament-wound high-pressure gaseous storage. Gaseous storage is inherently simple. Also, its delivery system is easy to handle. The gases for the atmosphere and the carbon dioxide reduction process will be stored at pressures of about 2.07×10^7 newton/m^2 (3,000 psia) [25].* Figure B.1-1 is a schematic of the atmospheric storage system.

B.2 ATMOSPHERIC CONTROL

B.2.1 CIRCULATION/VENTILATION

For circulation and ventilation by process fans and distribution ducts, flows of 4.6 to 30.5 m/min (15 to 100 fpm) are suggested with 15.3 m/min (50 fpm) nominal. For the modules of 4.6 m (15 ft) diameter with two-thirds assumed effective area, an approximate flow rate is 170 m^3/min (6000 cfm). The ventilation system will be shown in a later schematic (contaminant control).

B.2.2 WATER SEPARATION

B.2.2.1 Motor Driven Centrifugal

A rotating vaned drum inputs a centrifugal force to water and forces liquid against the wall where it is collected by a rotating gutter. A stationary pitot tube collects water from the rotating gutter. See Figure B.2.2.1-1 [25].

*See Chapter 13 for references

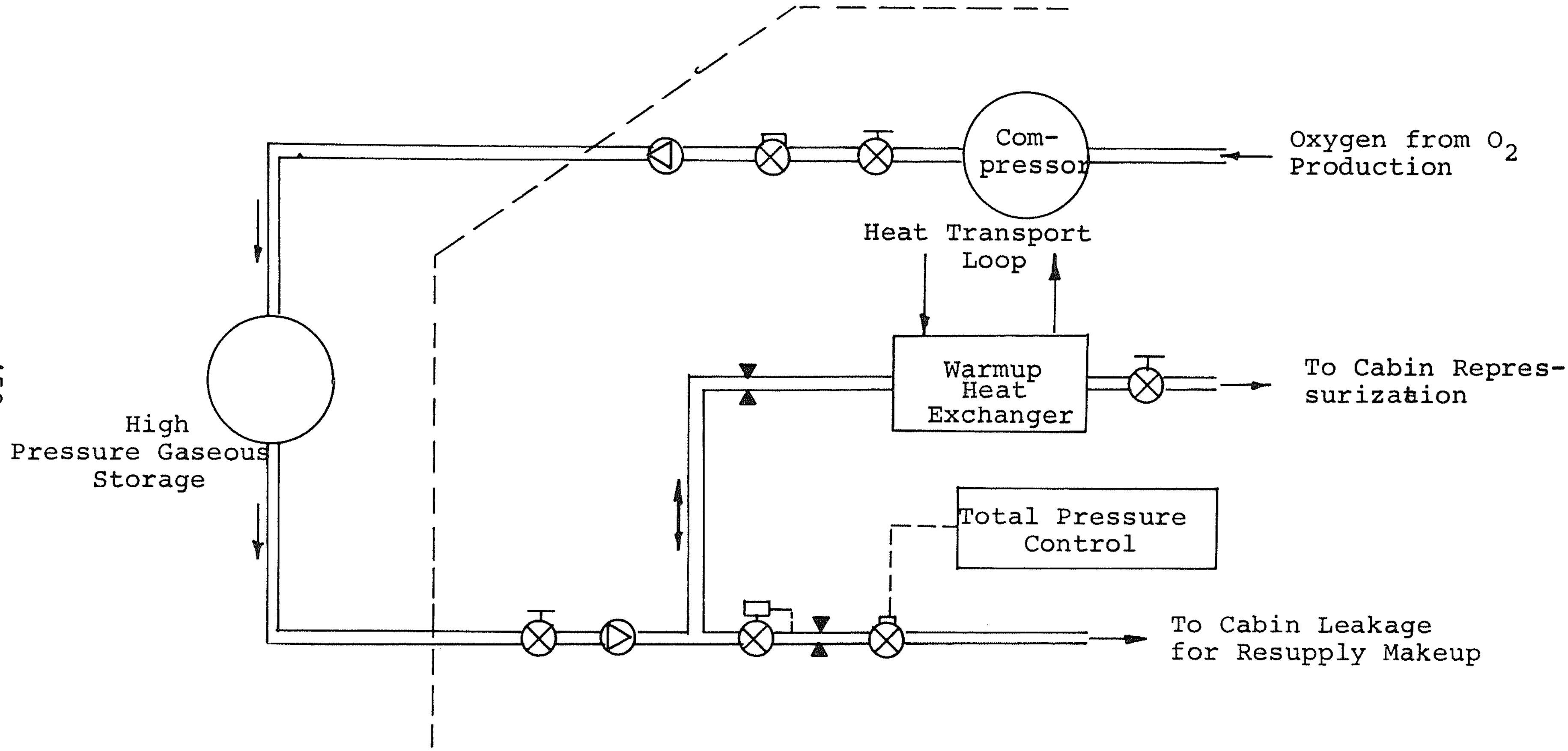


Figure B.1-1 High Pressure Gas Storage Concept [After Reference 25]

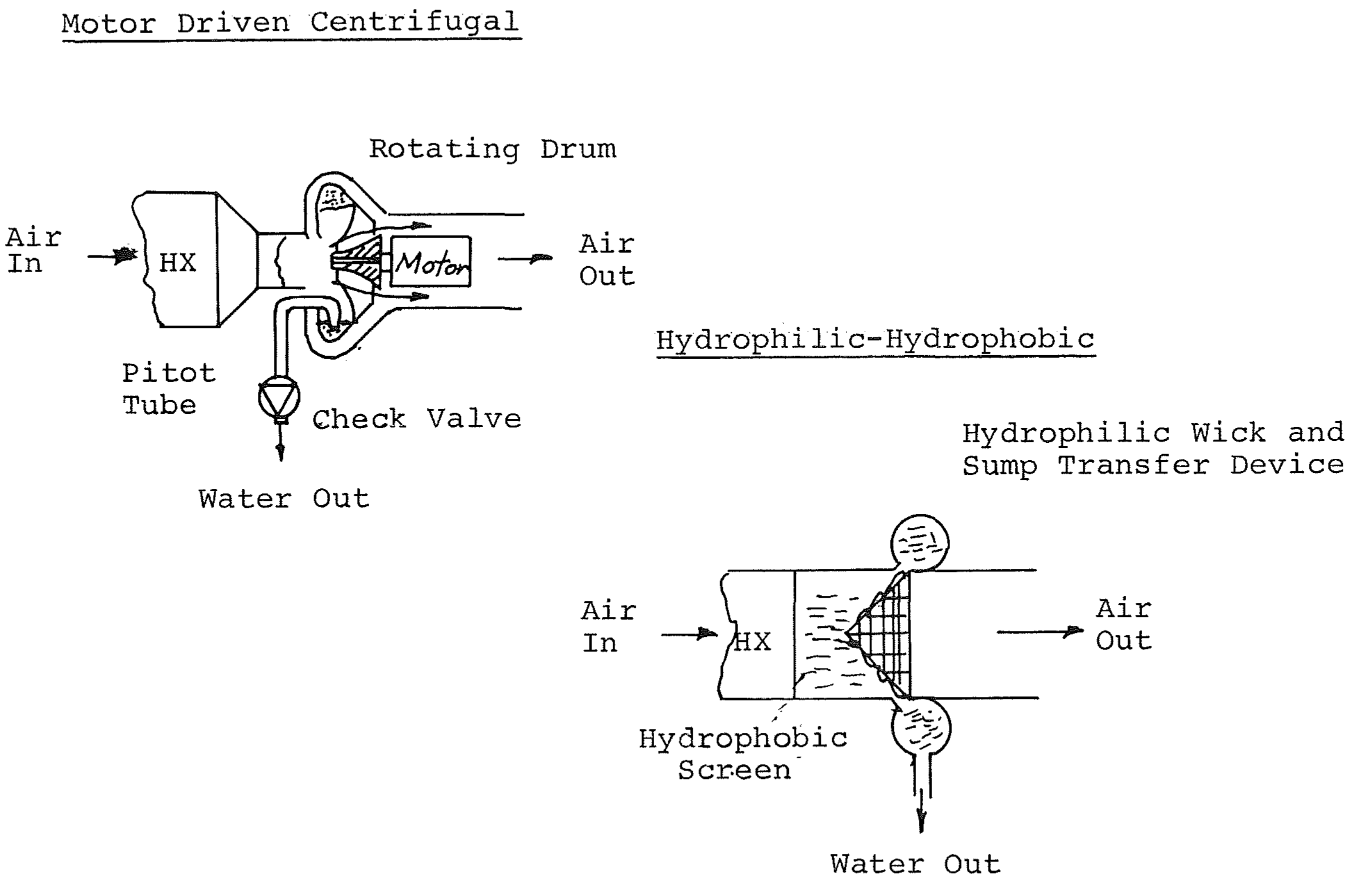


Figure B.2.2.1-1 Water Separation Techniques

B.2.2.2 Hydrophilic-Hydrophobic

The entering gas stream impinges on a conical shaped screen whose apex is oriented towards the flow. The screen is coated with a hydrophobic substance. The water droplets are deflected to the base of the screen where hydrophilic transfer discs collect the water and transfer it to water recovery. See Figure B.2.2.1-1 [25].

B.2.2.3 Porous Plate Condenser-Separator

The principle of the porous plate condenser-separator is based on the fact that when liquid droplets come into contact with an hydrophilic surface, the droplet will wet the surface. The droplets are then allowed to drop through a porous plate and be collected.

See Figure B.2.2.3-1 [25].

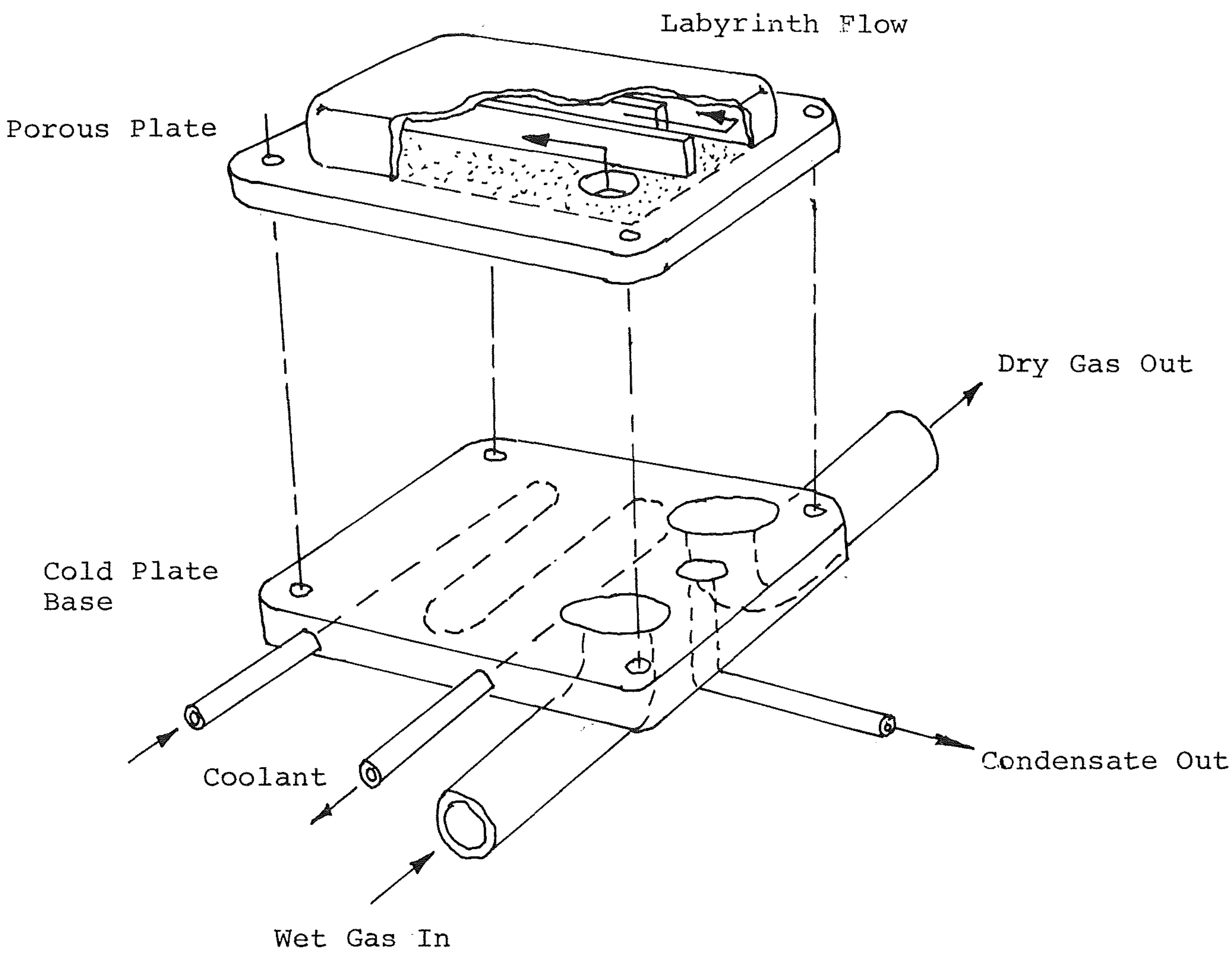


Figure B.2.2.3-1 Porous Plate Condenser-Separator

B.2.3 TEMPERATURE/HUMIDITY CONTROL

The selection subsystem concept for temperature/humidity control is a condensing heat exchanger with variable speed fan and face-wick water separator. The heat exchanger provides both temperature and humidity control. The variable speed fan is controlled by cabin temperature. The cabin temperature is controlled by varying the speed of the air flow through the heat exchanger and the humidity is controlled by varying coolant flow. A schematic of this process is shown in Figure B.2.3-1. The water separator is a face-wick device which uses capillarity as its principle. See Figure B.2.3-2 for representation [25].

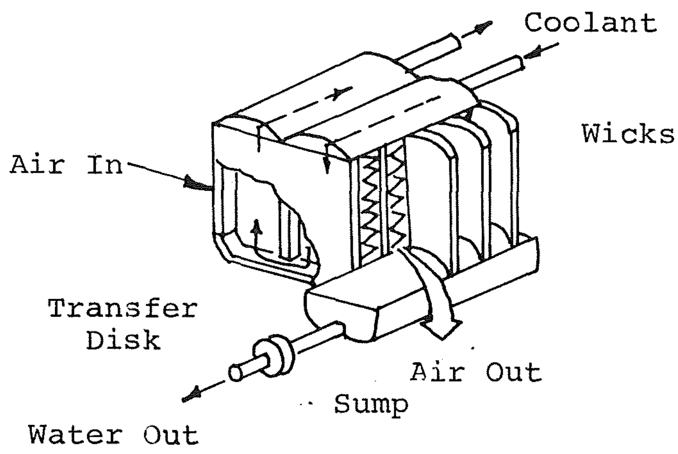


Figure B.2.3-2 Face-Wick Water Separator

B.2.4 PRESSURE CONTROL

Pressure control is provided by pressure regulators and sensors. A schematic of the pressure control concept is shown in Figure B.2.4-1.

B.2.5 CONTAMINATION CONTROL

B.2.5.1 Trace Gas Contaminant Control

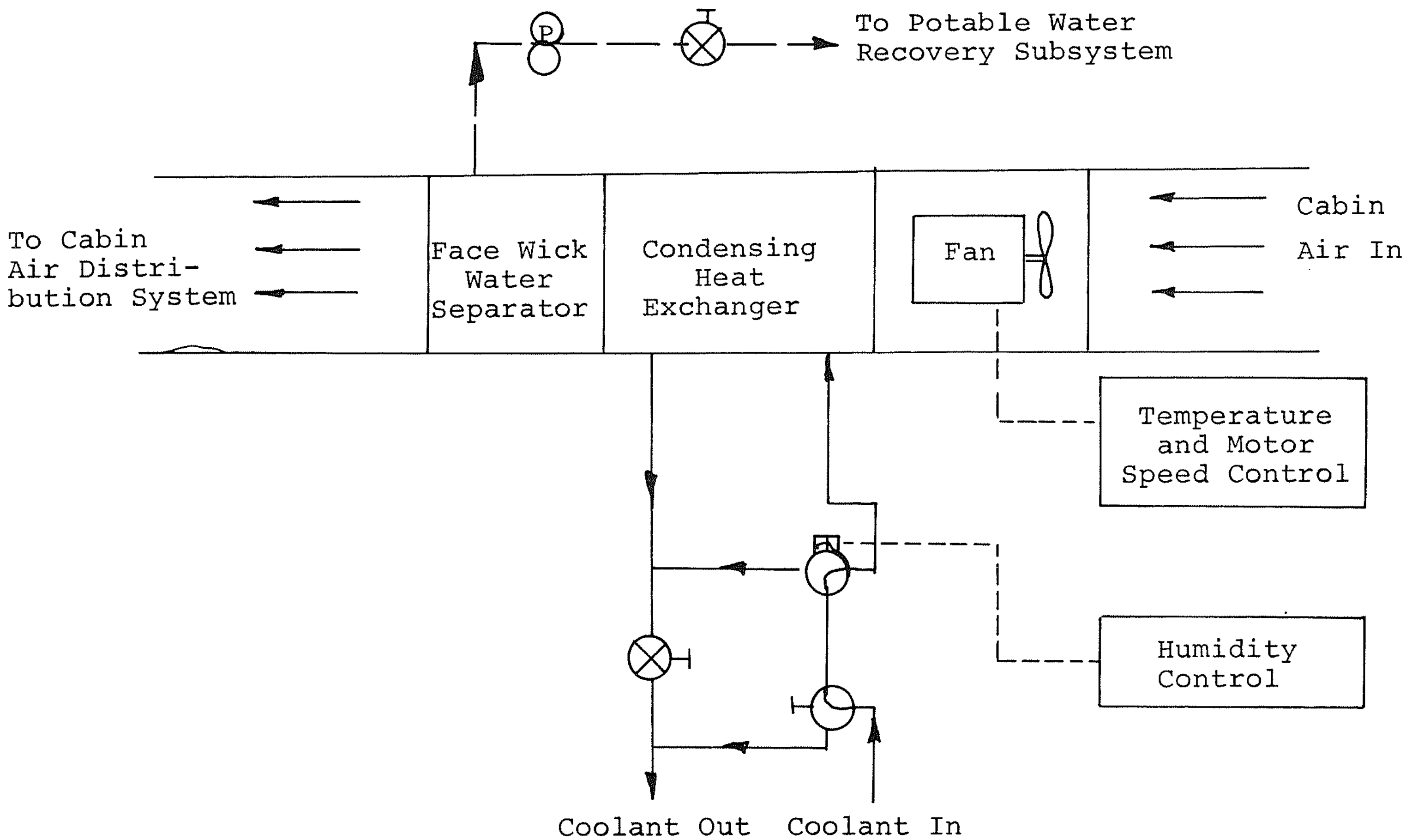


Figure B.2.3-1 Temperature/Humidity Control Concept [After Reference 25]

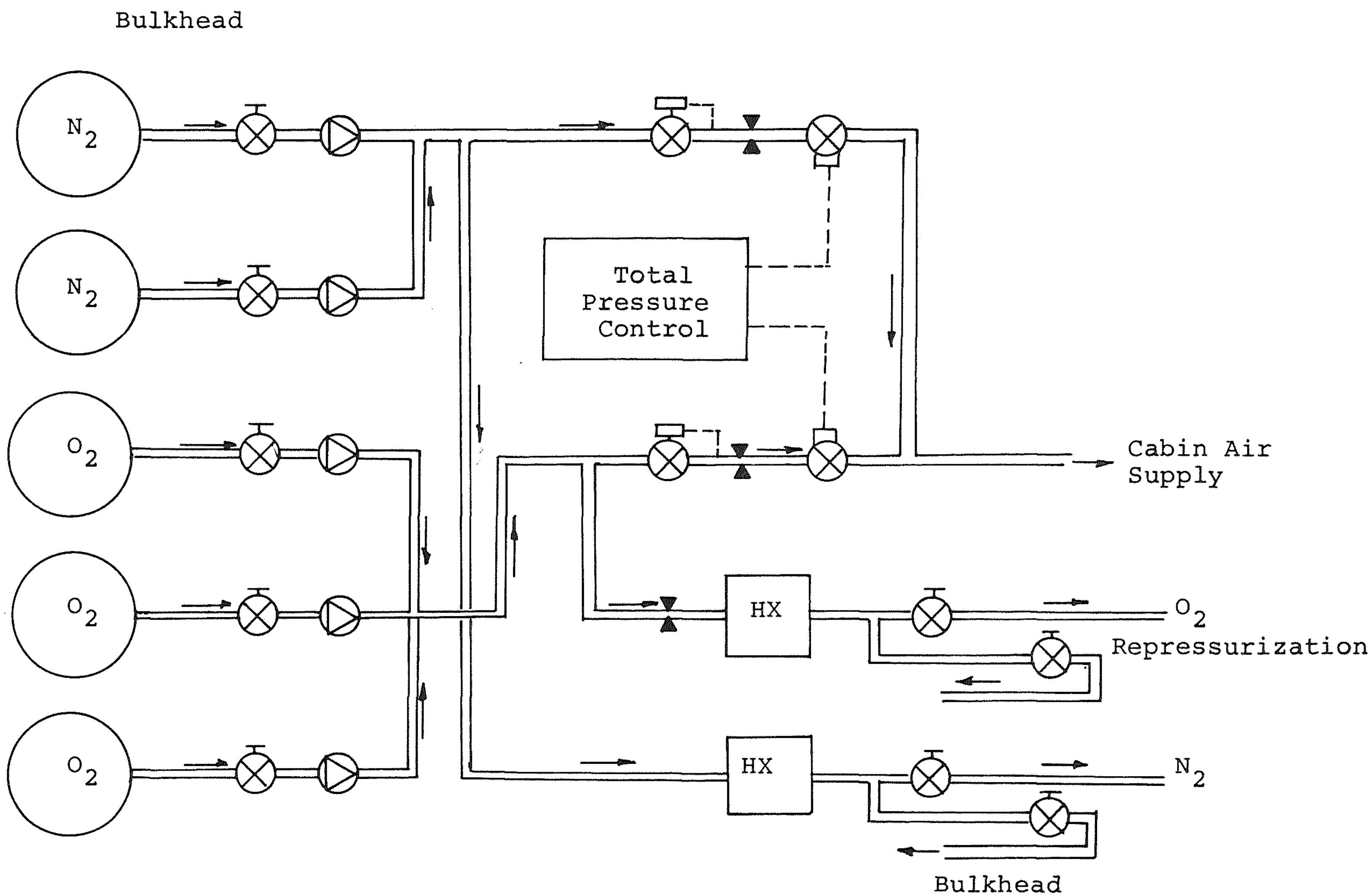


Figure B.2.4-1 Schematic of Pressure Control Subsystem [After Reference 25]

The catalytic oxidizer/sorption is the selected trace-gas control subsystem. The catalytic-oxidation portion of the system removes most acid gases. The catalytic-oxidizer presorber and main sorbent bed remove ammonia. The catalytic-oxidizer post-sorber removes acid gases. A schematic of this concept is presented in Figure B.2.5.1-1.

B.2.5.2 Bacterial Control

Bacterial control is provided by filters. Hamilton Standard recommends 95 percent efficient replaceable filters rated at 0.3 m [25]. The filters are installed in a duct with a fan used for providing flow as shown in Figure B.2.5.2-1.

B.2.5.3 Particulate Control

Particulate control (aerosols and wet and dry debris) is provided by 50 m roughing filters and a 60 mesh hydrophobic screen with hydrophilic reservoir [25]. Typical particulate-control arrangements are shown in Figure B.2.5.2-1.

B.2.5.4 Dust Control

The selected dust-control concept for ingress-egress operations is an air-jet wash with multifiltration. Prior to entry into an airlock, a preliminary brushing is made. As repressurization in the airlock is begun, the incoming air enters jets which blow the dust off the suits. The suspended particles are carried by the air flow through filters and trapped. The airlock is continuously recycled.

B.3 CARBON DIOXIDE MANAGEMENT

B.3.1 CARBON DIOXIDE REMOVAL/CONCENTRATION

In this concept two ion-exchange resin sorbent beds operate cyclically to remove CO_2 using absorption and then use steam to purge the

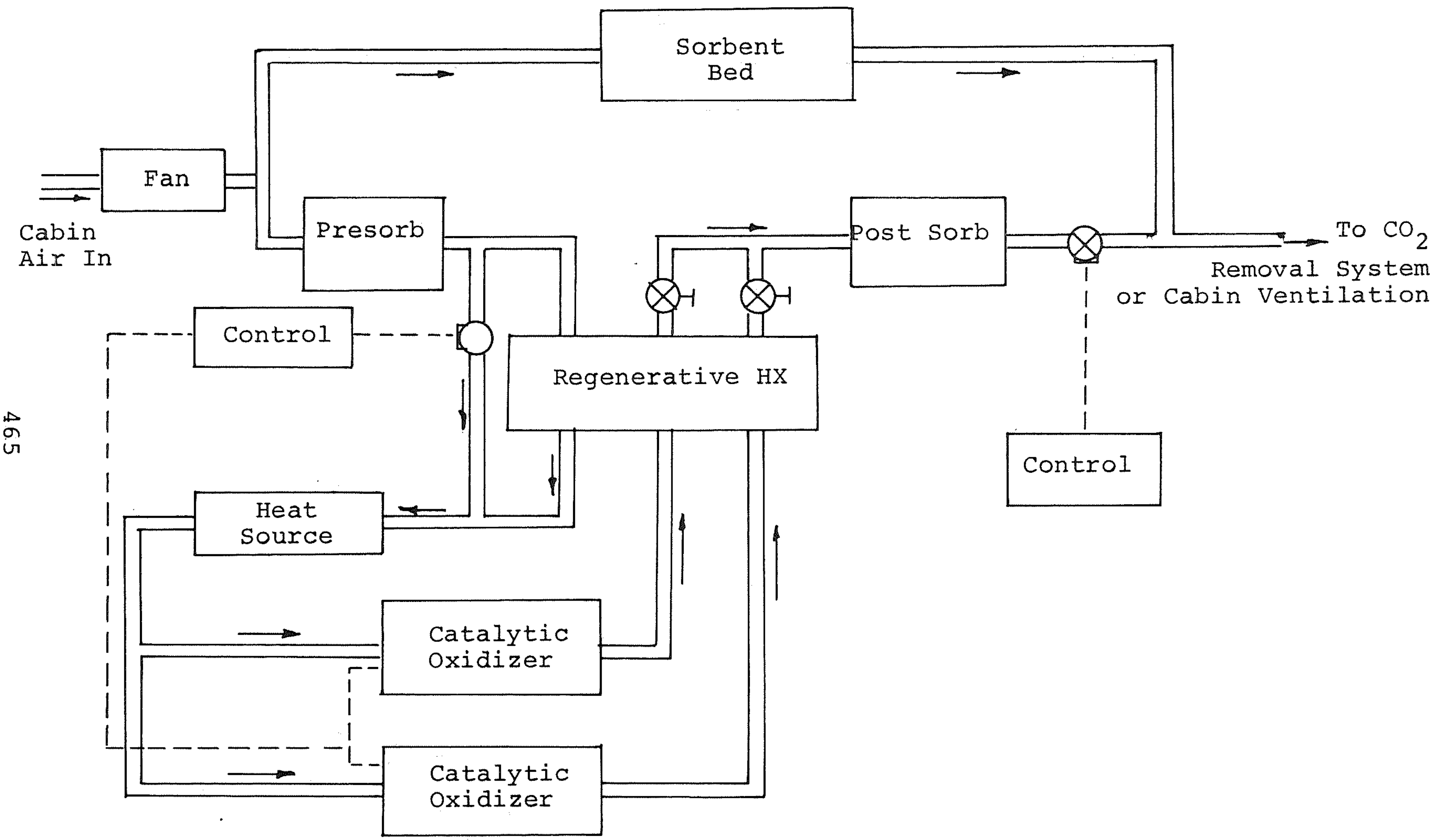


Figure B.2.5.1-1 Trace Gas Contamination Control Subsystem [After Reference 25]

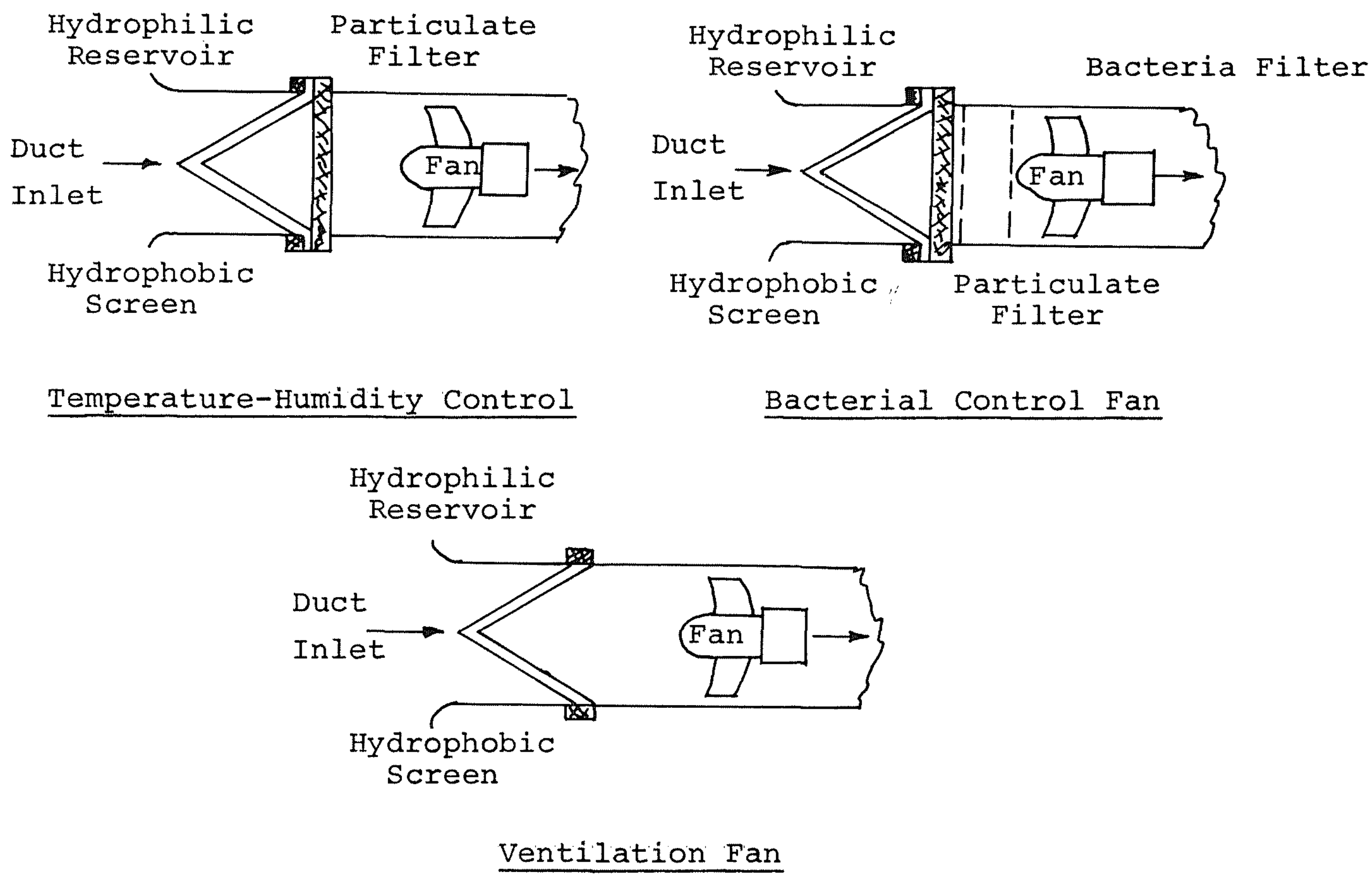


Figure B.2.5.2-1 Fan Installations for Bacterial Control, Particulate Control and Ventilation Subsystems absorbed CO_2. The two sorbents beds may both be absorbing or one may be absorbing and the other desorbing. When both are absorbing, the cabin air is directed through both beds in parallel. It is timed that each ion-exchange resin bed will continue to absorb until the outlet concentration of CO_2 in 50 percent of inlet concentration. Then the bed will enter the desorption phase and use steam to purge the pure wet CO_2 to the CO_2 reduction unit. A schematic of this process is shown in Figure B.3.1-1.

B.3.2 CARBON DIOXIDE CONCENTRATION

In the Sabatier-methane utilization process, hydrogen and carbon dioxide are fed to the hydrogenation reactor. The by-products of the hydrogenation of carbon dioxide are methane and water. The water is condensed and separated and taken to the water management system. The methane is stored for utilization. The process must be controlled to prevent excess hydrogen from entering product stream. A schematic of the process is shown in Figure B.3.2 -1.

B.3.3 WATER ELECTROLYSIS

The selected water-electrolysis concept is the gas-circulation concept. In this process water from the water-management subsystem is fed to an evaporator. Oxygen is passed over the evaporator picking up the water vapor. The water-vapor oxygen combination goes to the cell module where the water vapor is absorbed from the oxygen stream into an electrolytic matrix where it is electrolyzed to form oxygen and hydrogen. Most of the oxygen is recycled back through the system. The remaining oxygen and hydrogen are taken through a condensor-separator. Condensate extracted here is pumped to the water management subsystem. The oxygen is taken to the atmospheric control subsystem and the hydrogen is recycled to the Sabatier reactor in the carbon-dioxide reduction subsystem. Figure B.3.3-1 shows a schematic of this process.

B.4 FOOD MANAGEMENT

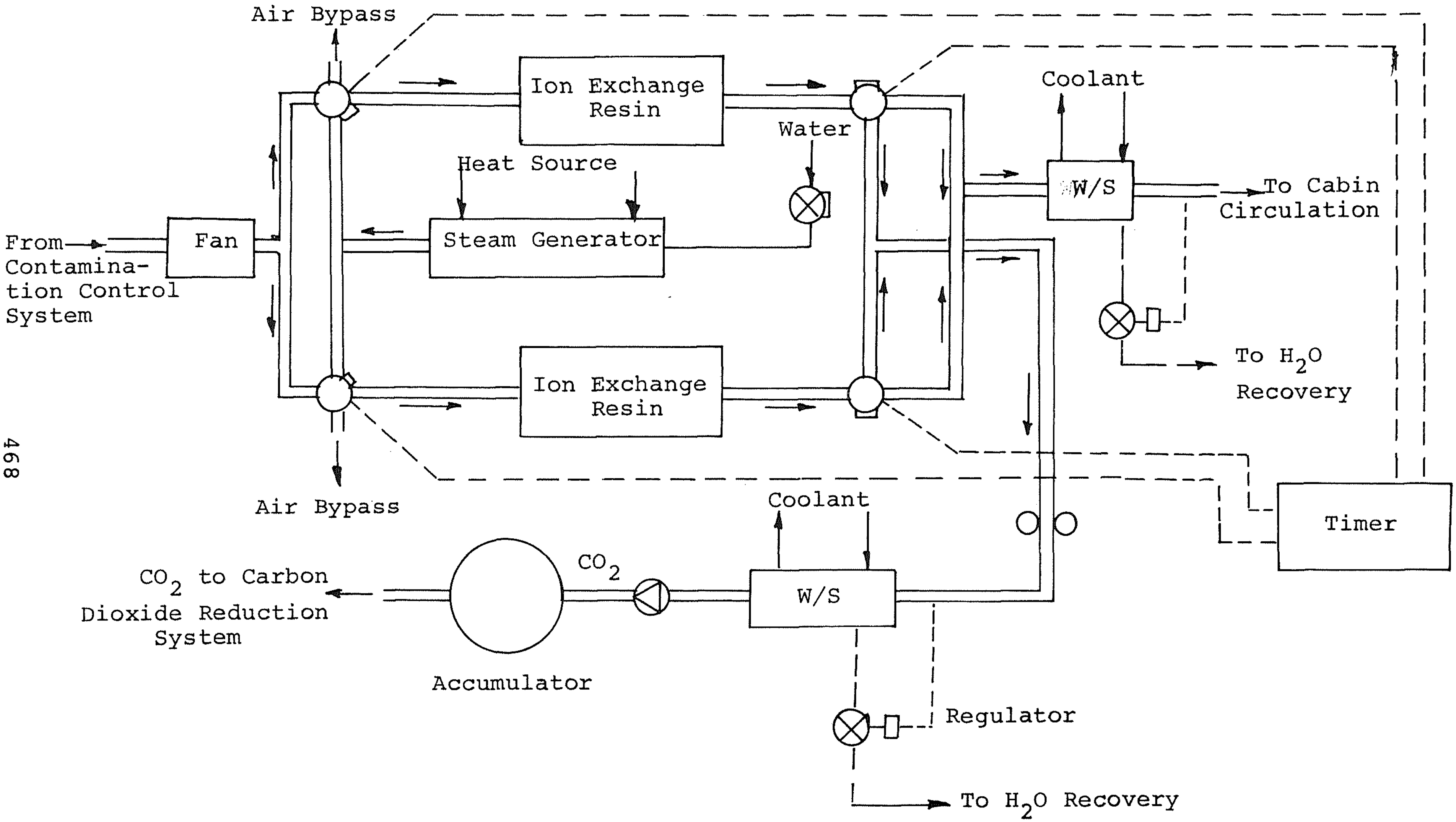


Figure B.3.1-1 Steam Desorbed Resin Schematic [After Reference 25]

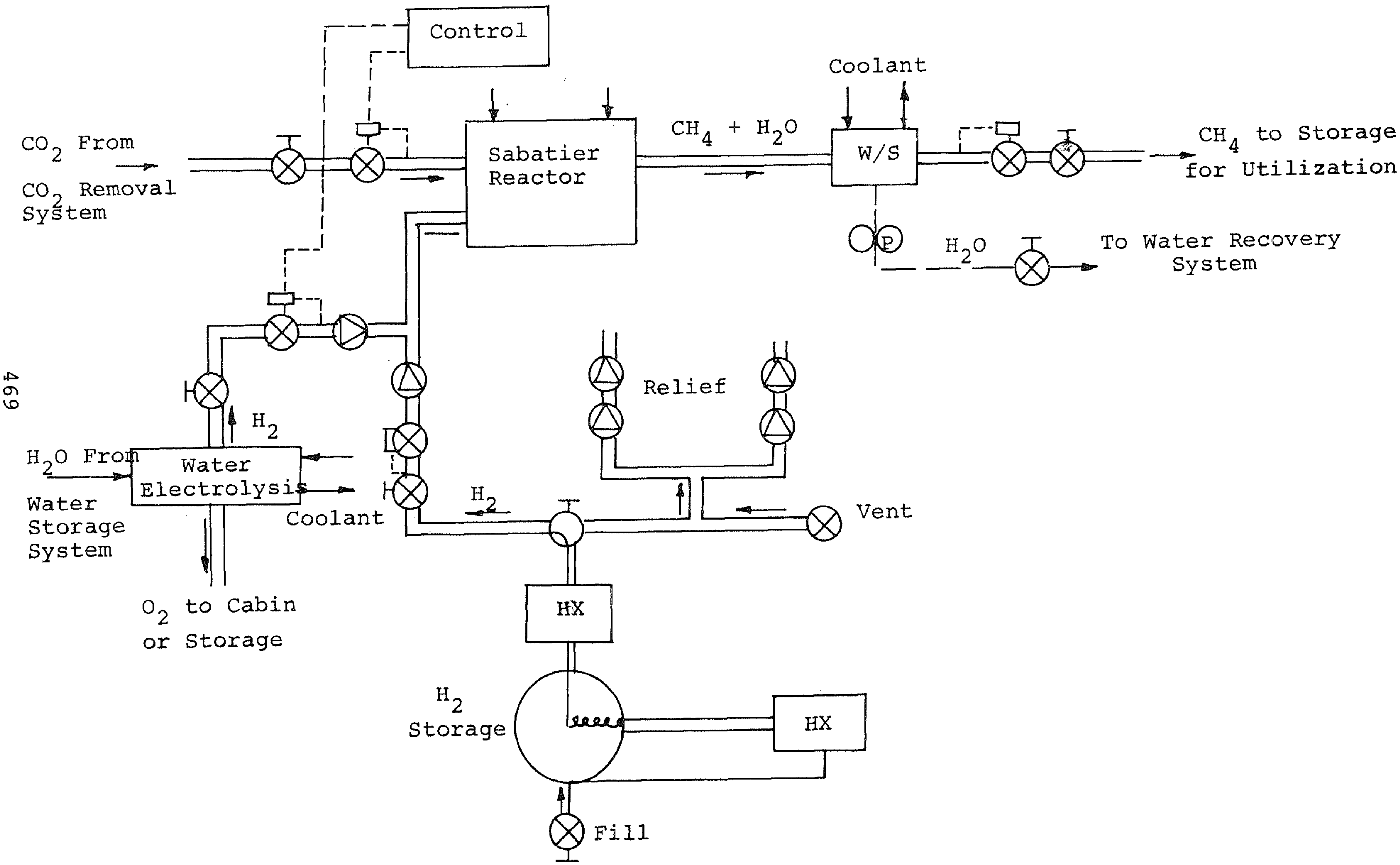


Figure B.3.2-1 Sabatier-Methane Utilization Subsystem [After Reference 25]

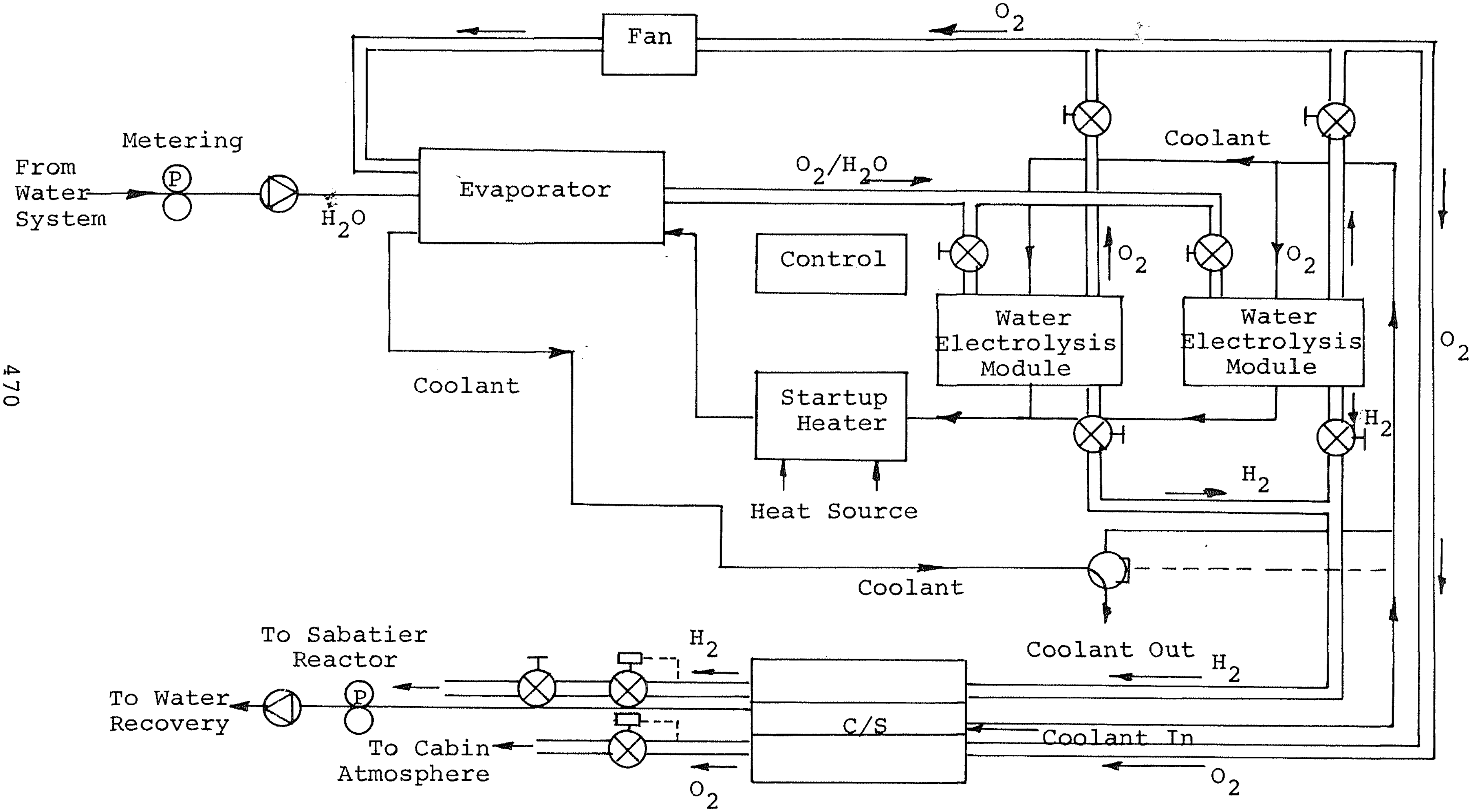


Figure B.3.3-1 Schematic of Gas Circulation Water Electrolysis Subsystem [After Reference 25]

B.4.1 FOOD PROVISION

For subsystem description see Section 13.3 in main body of report.

B.4.2 FOOD STORAGE

B.4.2.1 Refrigerator/Freeze Concept

The selected concept for refrigeration and freezing is the turbo-compressor/air-cycle concept. This concept utilizes air as the refrigerant. Air is compressed in the turbocompressor and then allowed to expand through a heat exchanger. The expanding air is taken to the insulated interior of the unit and provides cooling and circulation simultaneously. Figure B.4.2.1-1 shows a diagram of this concept [27].

B.4.2.2 Ambient Storage

Two concepts were chosen for maximum flexibility. A storage/locker room(s) is provided in the galley. Also, flexible ambient storage will be provided which consists of a membrane fastened to a bulkhead. When not in use, the flexible container can be collapsed.

B.4.2.3 Food Preparation

The microwave oven concept utilizes a magnetron tube to generate high frequency energy which penetrates and warms foods. The resistance heating oven utilizes electrically heated quartz elements to heat the food cavity. Operation is similar to broiler portion of earth-based ovens.

B.4.2.4 Food Serving

During initial stages of Phase I, the most predominant type of food serving will be self-service. The crewman will withdraw their own prepared meals from holding ovens and then transport them to a dining room. Preparation of the food will be made by a designated

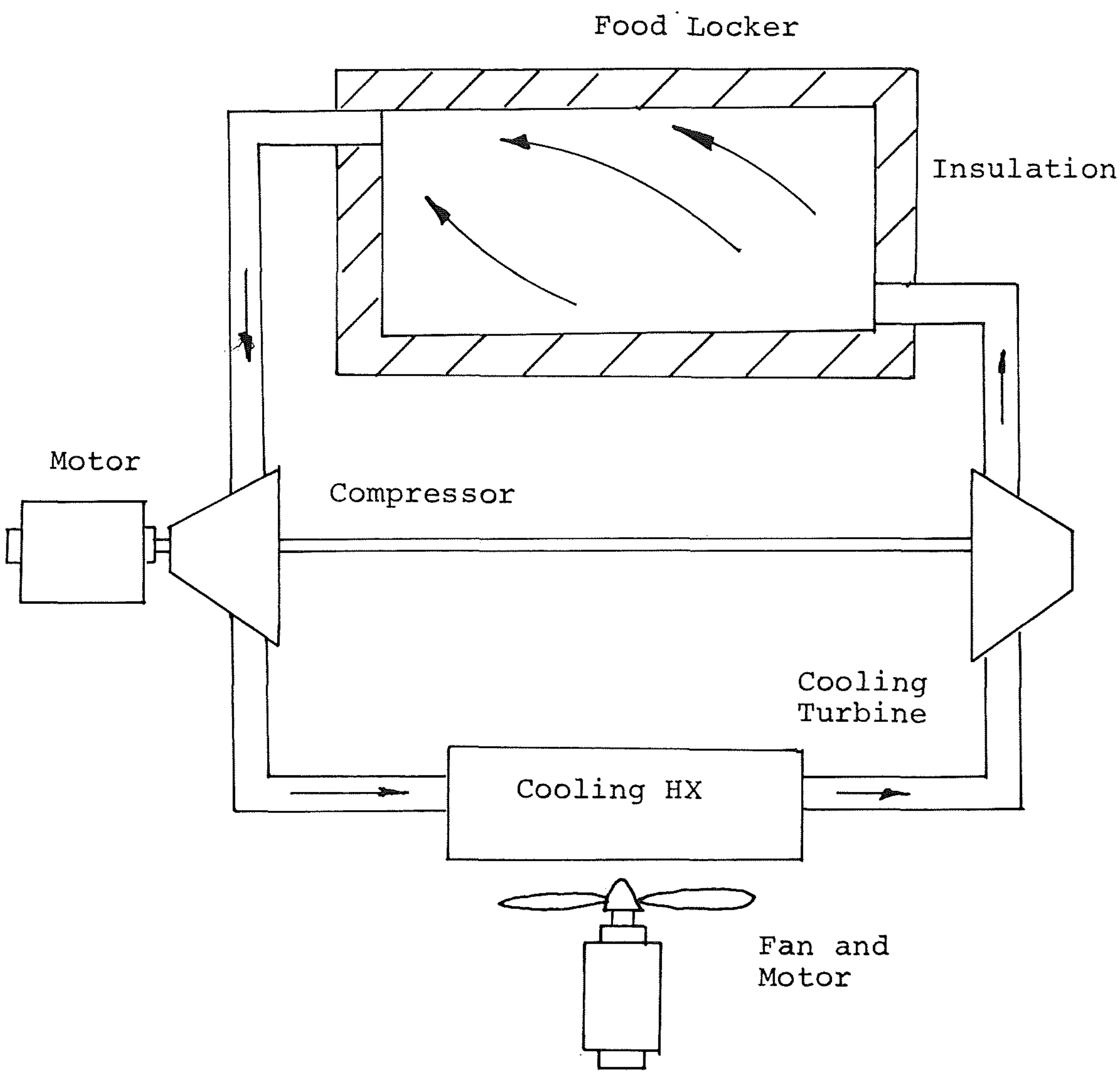


Figure B.4.2.1-1 Turbocompressor/Air Cycle Refrigerator Freezer [After Reference 27] crewman. Each crewman will return his utensils to the clean-up area where a designated crewman will do the clean-up. The duties will be rotated among the different crewmen.

During the latter stage of Phase I and during Phase II, a steward service program will be initiated. A designated portion of the crew will prepare, serve, and clean up the food.

B.4.2.5 Food Cleanup

B.4.2.5.1 Sanitary Wipe Concepts

Reusable gallery/dining area wipes offer a convenient method for washing and sanitizing work counters, food-preparation equipment, tables and other dining and galley areas. The wipes will be dampened periodically with a detergent/germicide solution for microbiological control.

Reusable hand wipes are also provided. They are wetted and soaped before usage. After usage, they are cleaned and recycled.

B.4.2.5.2 Wipe Dispenser Concept

A reusable wipe dispenser is provided for the storage of wipes which have outlived their usage due to wear.

B.4.2.5.3 Soiled Wipe Storage

Temporary storage for soiled reusable wipes before transfer to the washer/dryer is provided. Recommended as a container is a cloth bag which can be washed along with its contents. The cloth bag can also be continuously reused until it deteriorates.

Provision should also be made for temporary storage of food waste and debris before transfer to waste-management subsystem. The debris may consist of items such as deteriorated wipes, disposable utensils which should be biodegradeable.

B.4.2.5.4 Utensil Washing Concepts

An automatic washer/dryer should be provided for cleansing and sanitizing of food-preparation devices, meal trays, cups and dining utensils. Also a galley-sink, hard-utensil washer should be provided for washing hands prior to and after food preparation and for infrequent washing of utensils.

B.5 WASTE MANAGEMENT

See discussion in Section 13.3.

B.6 WATER MANAGEMENT

See discussion in Section 13.3.

B.7 HYGIENE AND CLOTHING AND LINEN MANAGEMENT

B.7.1 WHOLE BODY CLEANING

The selected subsystem concept for whole body cleaning is the shower. A schematic for the shower system is shown in Figure B.7.1-1.

B.7.2 DENTAL HYGIENE

A toothbrush and dentrifice with dental floss are the chosen hygiene techniques. See Figure B.7.1-1 for representation. As part of the dental hygiene unit is also a provision for collection of personal items such as nail clippings and hair.

B.7.3 SELECTIVE BODY CLEANING

Reusable hand wipes are used for selective body cleaning. The location of an area for this process is not defined but may be placed near dental hygiene area.

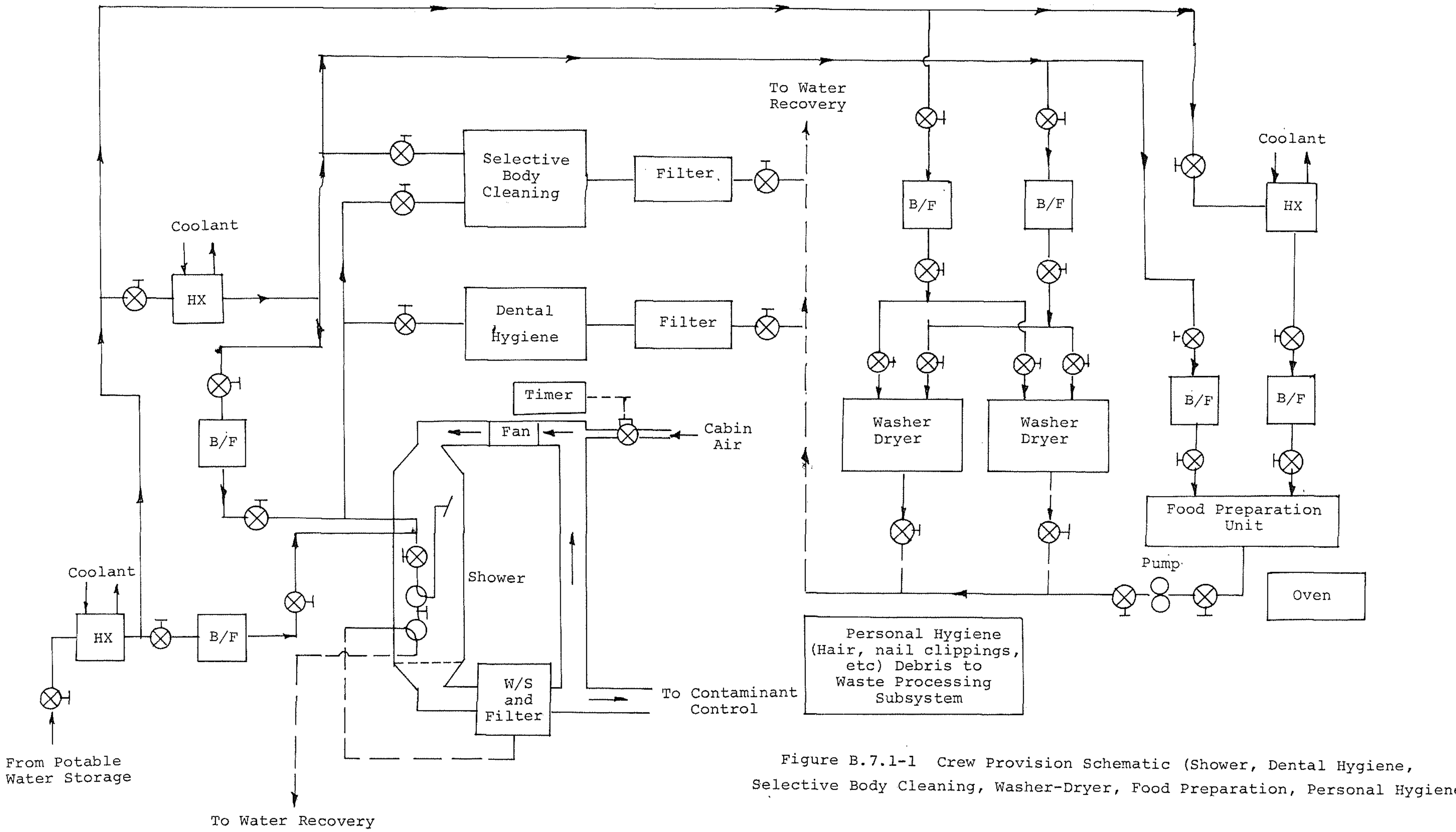


Figure B.7.1-1 Crew Provision Schematic (Shower, Dental Hygiene, Selective Body Cleaning, Washer-Dryer, Food Preparation, Personal Hygiene)

B.7.4 HOUSEKEEPING

The housekeeping concepts, oven, vacuum cleaner and reusable wet wipe, should need no description. Their location depends on where the highest degree of usage is located.

B.7.5 CLOTHING AND LINEN MANAGEMENT

Reusable clothing and linen were chosen as the clothing type. No particular style is identified. A rotary system-water solvent concept was chosen for cleansing of clothes and linens. A concept drawing is shown in Figure B.7.5-1.

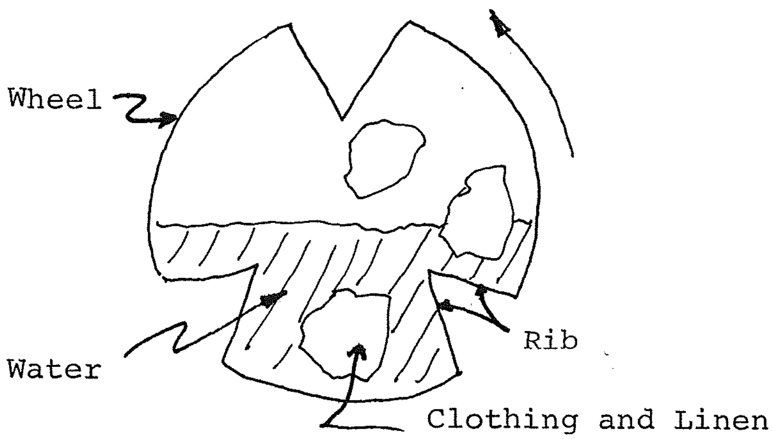


Figure B.7.5-1 Rotary Washer Concept

B.7.6 DETERGENT

A nonionic was chosen as the detergent. Associated problems with use of this detergent may be toxicity, allergenic considerations, irritability, and flammability. For the use concentrations that might be expected, an investigation of the long term effects of those parameters should be instituted.

B.7.7 ACTIVE THERMAL CONTROL

Water is used as the heat transport fluid because of its non-toxicity. The heat transport circuit should be designed to minimize flow by the use of heat cascading (waste heat of one system being used as heat source for another system). Normally a necessary part of the thermal design of a life-support system is a thermal balance. Unfortunately, time restrictions precluded a study of this nature.

B.7.8 SPECIAL PROVISIONS

No further discussion of special provisions is given here. See discussions in Section 13.3 for the subsystem microbiological control and instrumentation and control. See [25] for further discussions of fire protection control.

APPENDIX C SHOULD THE RADIATION PROTECTION GUIDES BE APPLIED TO THE MOON?

This appendix is an examination of the rationale behind the Federal Radiation Council's Radiation Protection Guides, and a critique of their applicability to the lunar colony.

C.1 THE SOMATIC EFFECTS OF RADIATION

The unit used to measure the biological effects of radiation is the rentgoen-equivalent man, abbreviated rem. For gamma rays, 1 rem is 100 ergs of energy absorbed per gram of tissue.* For other forms of ionizing radiation, such as neutrons or cosmic rays, there are conversion factors (the RBE, or Relative Biological Effectiveness) to relate the damage done by an incoming flux to gamma-ray damage. Dose rates are usually expressed in mrem/hr or rem/year. Table C.1-1 below shows the effect of large acute doses of radiation on individuals.

Table C.1-1 Somatic Effects of Acute Whole Body Radiation [1]

Instantaneous Dose (rem)	Probable Observed Effect
0-25	Nothing
25-100	Slight blood changes, but nothing else.
100-200	Vomiting by 20% within 3 hours. Fatigue and loss of appetite. Moderate blood changes. Recovery in a few weeks.
200-600	Vomiting by nearly all. Loss of hair after 2 weeks. Severe blood changes (hemorrhage and infection). 30% may die.
600-1000	Vomiting in less than 1 hour. Blood damage. 90% will die. Survivors will be convalescent for long periods.

*Note that for 1 rem absorbed in biological tissue, the probability of a given chemical bond being destroyed is about 7.0×10^{-11}.

It must be noted that Table C.1-1 is not applicable to small doses distributed over a long time. A person receiving 40 mrem/hr continuously would get 350 rem in a year, but he probably would not get sick. If there was any perceptible effect at all, it might be that his life was shortened by a few days. However, the radiation protection guide lines (see Table C.1-2 below) were not established to protect people from radiation sickness. The basic concern is for unborn generations [1] . There seems to be a deep-seated fear that in unleashing cosmic forces (e.g. nuclear energy), we may also cause cosmic side effects (e.g. evolution run amok).

Table C.1-2 Federal Radiation Council's Radiation Protection Guide for External Sources, 1967

	Atomic Workers	General Population
Cumulative Dose:	5 [Age (years)-18] rem	0.5 rem/year for any individual.
Long term dose rate:	3 rem in 13 weeks	Average for whole population should not be more than 5 rem in 30 years to the reproductive organs.
Once/lifetime emergency dose:	12 rem (planned) 25 rem (unplanned)	

C.2 THE GENETIC EFFECTS OF RADIATION

This section is a discussion of the phenomonological basis of genetic information transfer. A later section (C.3) presents some experimental data. An attempt is made to infer meanings from these scientific facts and observations.

C.2.1 THE DNA MOLECULE AND THE GENETIC CODE

Genetic information is encoded in animal cells (with the possible exception of seed cells), as long, double helical chains of deoxyribonucleic acid (DNA). The structural shape of the chain is fashioned from repeating groups of phosphate and a 5-carbon deoxyribose sugar. To this "backbone" there are special molecules attached at regular intervals. These molecules; adenine (A), cytosine (C), guanine (G), and thymine (T) constitute the four "letters" of the genetic code. A fifth base, uracil (R) is used in RNA. Each molecule or letter preferentially attracts one other base molecule because of its geometrical configuration and polarization. These mating molecules form a double helical chain, which can split and serve as a template for ribonucleic acid (RNA). The mating code between half of a DNA molecule and the RNA chain is given in Table C.2.1-1.

Table C.2.1-1 DNA to RNA Mating Code

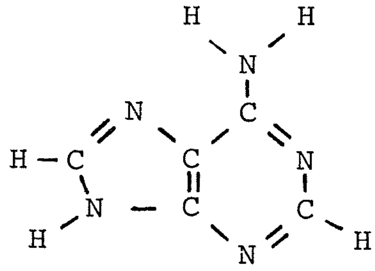
DNA	RNA	DNA	RNA
Adenine	Uracil	Thymine	Adenine
Guanine	Cytosine	Cytosine	Guanine

Symbolic chemical forms for these genetic base molecules are given in Figure C.2.1-2 [2].

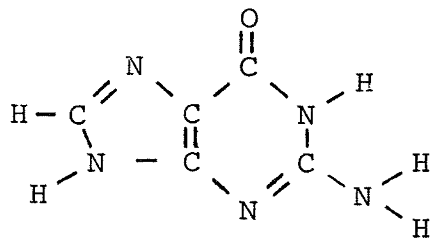
After the RNA molecule has formed, it serves as a pattern to assemble the 20 amino acids into polypeptide molecules. In reproduction, the polypeptide molecules are known as "genes", and in the human there may be more than 100,000 different genes [4]. Each gene is an assemblage of 100-300 amino acids. The amino acids are assembled using a triplet code; three adjacent bases on an RNA molecule call one amino acid. The amino acids are listed in Table C.2.1-3.

Table C.2.1-3 The Twenty Amino Acids

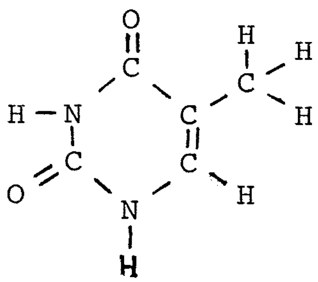
Amino Acid	Abbreviation	Amino Acid	Abbreviation
Alanine	Ala	Leucine	Leu
Arginine	Arg	Lysine	Lys
Aspargine	AspN	Methionine	Met
Aspartic Acid	Asp	Phenylalanine	Phe
Cysteine	Cys	Proline	Pro
Glutamic Acid	Glu	Serine	Ser
Glutamine	GluN	Threonine	Thr
Glycine	Gly	Tryptophan	Tryp
Histidine	His	Tyrosine	Tyr
Isoleucine	Ileu	Valine	Val



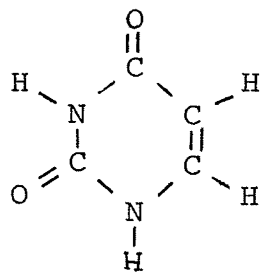
Adenine



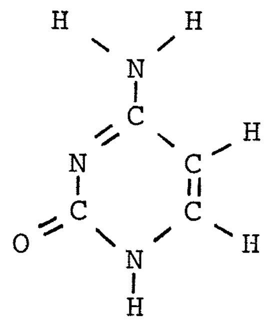
Guanine



Thymine

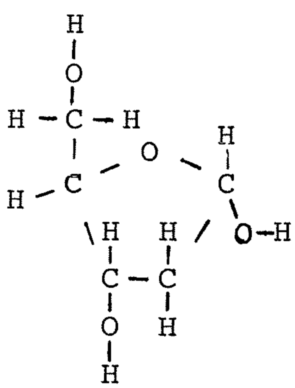


Uracil

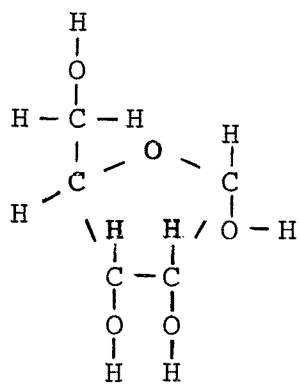


Cytosine

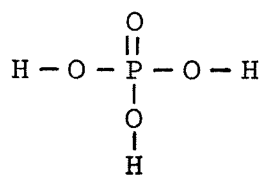
Mating Bases



Deoxyribose



Ribose
(Used in RNA)



Phosphoric Acid

Chain Backbone Molecules

Figure C.2.1-2 Genetic Molecules [2]

The correspondence between base triplets and amino acids is shown in Table C.2.1-4.

Since there are $4^3 = 64$ permutations of the four bases used in the triplet code to specify 20 amino acids, there is some redundancy in this coding scheme. Table C.2.1-4 shows that the last "letter" in the triplet set is often meaningless; and almost always there is a choice for the last letter. As will be noted below, it does not seem that replacing one base with another is a very likely mode of damage from ionizing radiation.

It is known that the seed cells (sperm and ovum) contain only half the normal complement of chromosomes. The form of the DNA molecules in these cells must be highly specialized (a single helix?) to allow reproductive joining. Thus these seed cells are quite vulnerable to damage by radiation. Fortunately, the seed cells only live for a few hours; so it is believed that most genetic damage occurs in the tissue that forms the seed cells (spermatagonia and oocytes).

If there are 150 amino acids in a typical polypeptide molecule [4], then there are $(20)^{150} = 1.472 \times 10^{185}$ different possible polypeptide chains that could conceivably be encoded in a sequence of 450 RNA bases. Of these, perhaps 10^5 are viable, and most of the others will not work. For obvious reasons, not very many polypeptide molecular structures are known with precision. But it does seem reasonable that all of the information that could be encoded in the polypeptide molecules is not used; (10^5) (1.4×10^{185}) = 632 bits long! By contrast, the human body may contain 10^{28} atoms, and exists 3.0×10^{15} microseconds from birth to death. Thus 3×10^{43} pieces of instruction would be sufficient to specify the behavior of every atom in the body for every microsecond in 95 years. How much flexibility is there in polypeptide molecules? There is some evidence that 7 amino acids can be replaced in the sequence with 7 others, and produce a nonlethal mutation [3]. However, much research will need to be done in this area.

Table C.2.1-4 RNA-to-Amino Acid Triplet Code [3]

U U U	Phe	U C U	Ser	U A U	Tyr	U G U	Cys
U U C		U C C		U A C		U G C	
U U A	Leu	U C A		U A A	Begin (?)	U G A	?
U U G		U C G		U A G	End (?)	U G G	Tryp
C U U	Leu	C C U	Pro	C A U	His	C G U	Arg
C U C		C C C		C A C		C G C	
C U A		C C A		C A A	GluN	C G A	
C U G		C C G		C A G		C G G	
A U U	Ileu	A C U	Thr	A A U	AspN	A G U	Ser
A U C		A C C		A A C		A G C	
A U A		A C A		A A A	Lys	A G A	Arg
A U G	Met	A C G		A A G		A G G	
G U U	Val	G C U	Ala	G A U	Asp	G G U	Gly
G U C		G C C		G A C		G G C	
G U A		G C A		G A A	Glu	G G A	
G U G		G C G		G A G		G G G	

C.2.2 DAMAGE FROM IONIZING RADIATION

In connection with the effect of charged particles and gamma rays in tissue, it is necessary to define Specific Ionization: the number of ion pairs produced per centimeter of path length. An ion pair is a free electron and an electron-deficient atom. The atom may be held by other electrons in a molecule (multiple bonding), or it may itself become a free positive ion. The specific ionization depends on the probability of interaction of an orbital electron with the passing particle. Since the high energy particles move faster, they spend less time in the vicinity of a given atom; so the specific ionization for high-energy particles is less than for slower particles. High-energy (3 Gev) cosmic rays have a specific ionization of about 3.0×10^4 ionizations/cm. Alpha-particles (5 Mev) have a specific ionization of 4×10^8 ions/cm in tissue. The specific ionization of a 5 mev beta particle is only about 3×10^4 ions/cm [5].

Gamma rays are degraded by the Compton effect, the photoelectric effect, and pair production to beta particles. These beta particles then produce ionization as their energy is dissipated. The energy of these beta particles varies over a wide spectrum, but in general higher energy gammas produce higher energy betas and lower specific ionization. The picture is complicated somewhat by the fact that the betas give up their energy in discrete steps which is manifested as gamma rays (Bremsstrahlung and Cerenkov radiation).

It is clear that with most forms of radiation (except alpha particles) the probability of ionizing more than one atom in a small molecule, (whose size is on the order of 10 Å (10^{-7} cm), such as those shown in Figure C.2.1-1) must be very small. Therefore we will consider only the effect of stripping a single electron from a single atom in these molecules.

Replacing one base by another requires severing more than one bond, and is highly unlikely. Breaking one electron free will either create a free hydrogen ion, or a positive charge at the bond center. With a hydrogen atom lopped off, the remaining molecule might form new bonds within itself, or acquire a new hydrogen ion or some other positive ion from the surrounding fluid. A positive charge in an area bound by other electrons might attract a stray free electron, or steal one from some nearby atom or, it might attract some negative ion such as OH^- or Cl^-, and bond to it. Thus, while there may be a large probability (almost 1.0?) that the genetic base molecules would reform themselves after ionization; it appears possible that they might be permanently altered by such action. Whether the altered molecules would be rejected from the chain depends on physical chemistry of the particular situation; but it has been speculated [6] that a repair mechanism may be at work in organisms to repair damaged links in the chain.

It should be noted that the absorption of neutrons _per se_ has no effect on most of these molecules. Hydrogen-2, carbon-13, nitrogen-15, and oxygen-17 are all stable isotopes. The damage made with neutron absorption is mostly from recoil momentum accompanying capture gamma emission. Scattering of neutrons might also be expected to sever some widely-separated chemical bonds. If the bases in DNA are equally likely, then the probability of absorption of a thermal neutron is: hydrogen, 26.2%; carbon, 0.2%; nitrogen, 73.2%; oxygen, 0.0% and phosphorus, 0.4%. Fortunately, none of the constituent atoms are very strong neutron absorbers.

The double helix configuration may well have redundancy and safety against radiation-caused damage built in. If a molecule on half of the chain is destroyed, then upon cell division, the RNA assembled by the defective half will have a base missing. This is likely to give rise to a phase-shift mutation (Fig., Pg. 59, Crick [3]), wherein every amino acid in the polypeptide chain beyond the bad spot will be wrong. Such a cell has essentially no chance of survival, and will soon be replaced by division from its healthy neighbors. If the bad base attracts a wrong mate, then the effect is to use, at most, one incorrect amino acid; which may be a very small (meaningless ?) mutation.

If the chain backbone is broken, then when the DNA molecule divides for cell replacement, there will be a long DNA template and two short ones. This may be the basis of "chromosomal aberrations" that biologists observe through the microscope. The existence of such aberrations has in some cases been correlated with specific abnormalities in the individual, but in many cases no macroscopic effect can be seen.

C.2.3 MENDELLIAN AND POPULATION GENETICS

Classical genetics is concerned with dominant and recessive genes. An offspring that inherits a dominant gene from either parent will show the characteristics associated with that gene. Recessive genes must be present in both parents before the effect shows up. If a new dominant gene is created, it takes about 15 generations for it to become established among the members of freely-breeding society. A recessive gene may take 300 generations to become established. There is a body of theory, based on diffusion and an infinite population, that defines what the equilibrium probability of benign (neither strongly favorable or unfavorable to survival; such as blue eyes or brown eyes, attached or free ear lobes, etc.) genetic variations should be. Classical evolution theory holds that if a gene is strongly favorable to survival, it will eventually become established in nearly all the population; whereas an unfavorable gene should become nearly extinct. The fact that natural populations carry a diverse mixture of genes indicates that evolution may be more complicated than simply "survival of the fittest".

Stewart Wright, professor emeritus of genetics at the University of Wisconsin, has proposed a 3-step model of evolution [7]. In his model, there are several or many local maxima in the survivability hypersurface. In the first stage, genetic drift attracts individuals to a local peak, at which a small interbreeding population called a "deme" comes into existence. The second stage, called the Intrademic Phase, occurs when individuals drift at random between nearby demes, across shallow probability saddles. The effect of the second stage is to enlarge the size of some of the demes, and to sharpen others to conform more tightly to their local environment. In the third stage, the more successful demes produce a surplus population, which emigrates or diffuses to the other deme peaks. Underlying all this are two dynamic factors: (1) The environment itself is constantly changing, so the peak loci are moving. (2) New genes are constantly being created and destroyed.

C.2.3.1 Statistical Genetics

If the population is small (say 200 individuals), then there is a substantial chance that even a favorable new gene will not get started. Random fluctuations within a small population may destroy any recessive gene. Thus, added to the genetic drift pressure is a random gene elimination probability which contributes to the variation of local populations from the universal norm. This is the significance of the demes, and it might be an important consideration for an extraterrestrial colony.

We must remember that the environment itself is changing; and sometimes quite abruptly, as geological history attests, and perhaps very rapidly now by the hand of man. It is a principle of evolution that those species have the best chance to survive which have the largest gene pools to draw on. Thus, genetic variation is desirable. As corollaries, we may venture to suggest that small isolated populations (which are rapidly disappearing among men on earth) and a means of creating new genes are, in the long run, favorable.

It has been said that the vast majority of new mutations are harmful [1,8]. This is only true if the local survival selection peak is very convex. In some dimensions, such as fingers vs. no fingers, or blindness vs. sight; this is obviously true. In other dimensions, such as freckles vs. no freckles, or shortness vs. tallness, it is less obvious. All in all, it must be admitted that while few mutations are immediately strongly favorable, many are benign. These benign mutations are the source of variability in the gene pool. Strongly deleterious mutations used to die out quickly; but medical science has recently introduced the principle of Survival of Everybody. If everybody reproduces, the effect on the quality of the gene pool is obvious.

It is conceded by most geneticists that doubling the mutation rate would not be harmful [9]. However, doubling the mutation rate combined with the survival of everybody would result in higher rates of genetic drift in all directions. In the apocalyptic view, this will result in a limiting condition where nearly all are what we would call freaks. But it seems more likely that intelligent selection will increasingly replace natural selection as an evolutionary force. The accumulation of knowledge about genetics in only two generations attests to this possibility. With a little intelligent direction (exercised not by a big brother government but by educated individuals deciding their own lives), a diverse gene pool would seem to be a positive factor for the survival of man.

C.3 EXPERIMENTAL MEASUREMENTS OF THE GENETIC EFFECTS OF RADIATION

There has been much speculation, but little real data about the effect of very low radiation rates on the order of 10 rem/year. Russell and his co-workers at Oak Ridge National Laboratories [6], have done some work with mice. Their results are presented in Table C.3-1. It appears that males are more vulnerable to genetic damage than females, and also that the extent of damage is dependent on dose rate as well as the total dose. There were only about 1/3 as many mutations when the dose rate was 0.001 rem/min, as when it was 90 rem/min, for the same integrated dose. This led Russell to suggest that some kind of repair mechanism operates to correct some of the damage; at the higher rates presumably there is multiple damage that cannot be repaired.

Table C.3-1 Effect of Radiation on Mice [6]

Type of Cell Irradiated	Radiation	Approximate Dose Rate (rem/min)	Dose (rem)	Number of Offspring	Number of Mutations at 7 Loci	Mean Number of Mutations per Gamete Locus
Spermatagonia	none	none	0	531,500	28	0.000008
	γ (C_s^{137})	0.001	86	59,810	6	0.000014
	γ (C_s^{137})	0.001	300	49,569	15	0.000043
	γ (C_s^{137})	0.001	600	31,652	13	0.000059
	γ (C_s^{137})	0.009	300	58,457	10	0.000024
	γ (C_s^{137})	0.009	516	26,325	5	0.000027
	γ (C_s^{137})	0.009	861	24,281	12	0.000071
	γ (C_s^{137})	0.80	600	28,059	10	0.000051
	X (250 KVP)	9.0	600	40,326	23	0.000081
	X (250 KVP)	90.0	300	65,548	40	0.000087
	X (250 KVP)	90.0	600	119,326	111	0.000113
Oocytes	γ (C_s^{137})	0.009	258	27,174	1	0.000005
	γ (C_s^{137})	0.009	400	37,049	2	0.000008
	γ (C_s^{137})	0.80	400	20,827	7	0.000048
	X (250 KVP)	90	400	11,124	15	0.000193

Two more things are worth noting about this experiment. First is its colossal magnitude: more than 1 million mice were involved; even so, the number of mutations observed was small, and the corresponding statistical uncertainties large. Second, from the control group data it appears that the natural mutation rate is slightly less than 1 chance in 10,000 that a given chromosomal locus will be mutated in one generation. When the mice get 86 rem of γ-radiation (which is several hundred times what they would receive in their natural lifetimes), the observed mutation frequency is only increased by 75%, to 1.4 in 10,000. This indicates that there are other causes of mutation than radiation. Two that immediately come to mind are chemical mutagens and probably most important, temperature. The state of electrons (including those involved in chemical bonds), is governed by the laws of statistical quantum mechanics. An elevated state may result in ionization and subsequent destruction of the molecule. It is known that these organic molecules are highly sensitive to temperature rises of less than 3°K. Therefore, temperature may indeed be a prominent factor in natural mutations.

It has been estimated that a dose of 30 rem to the entire population "might" (from Russell's data, it appears that the probability is less than 1%) double the mutation rate in humans [8].

Finally, the fact that the lunar colony would be only a small specialized group has some effect. Unless the colony became completely independent from earth, only certain selected persons would live there. The colony population will probably be characterized by

1. Average age >30, since it takes so long to become qualified to go. This implies that most of the people will be past their peak reproductive years.
2. Very few if any children. Expectant mothers will probably elect to return to earth. There are no plans at present to provide nurseries, schools, etc. at the colony.

The number of children born to residents or ex-residents will be on the order of 10 per year. The probability of a radiation-induced nonlethal deleterious gene (either dominant or recessive) being introduced into earth's gene pool, would be no worse than the probability of a like event occurring if the earth's population were increased by 1000. If the colony were able to live and breed in isolation for 200-300 generations, then it might become significantly different than earth's population. Then, if the populations were again brought together, there might be a marked change in the evolutionary pattern especially if the moon genes were favorable [5]. Such isolation is not in any of the current plans, and presumably the gene pool of the colony would be continually polluted by individuals from earth, and vice-versa.

C.4 SUMMARY

This appendix has examined the genetic effects of radiation. An attempt was made to explore the molecular basis of radiation damage to DNA. There was a brief discussion of what is known and not known about genes. There was also a discussion about population and statistical evolution. The important conclusions are:

1. From the known structures of genetic molecules - particularly the redundant double helix of DNA - coupled with low specific ionization, it appears that they should be quite resistant to permanent radiation damage.
2. From theoretical genetics, it appears that doubling the mutation rate would not be harmful.
3. There are other processes at work, specifically
    a. The survival of everybody
    b. Increased interdemic migration
    c. A rapidly changing environment
    d. Temperature and chemical mutagen-induced mutations

which probably will have a much greater long-term effect on evolution than a small level of radiation will.

4. Experiments indicate that mutations are rate-dependent; the effect at low dose rates is less than the same dose at higher rates.
5. The possible existence of mutants from the lunar colony is a negligible consideration for the population on earth, unless the colony existed in isolation for 300 generations.

It is concluded that the possibility of genetic mutations is not sufficient reason to drive the colony underground.

REFERENCES

1. Glasstone, Samuel, Sourcebook on Atomic Energy, 1967.

2. Nirenberg, M. W., "The Genetic Code II", Scientific American, March, 1963.

3. Crick, H. F. C., "The Genetic Code III", Scientific American, October, 1966.

4. McKusick, V. A., Mendelian Inheritance in Man (Catalogs of Autosomal Dominant, Autosomal Regressive, and X-Linked Phenotypes), 1971.

5. Glasstone and Sesonske, Nuclear Reactor Engineering, 1964.

6. Russell, W. L., "Studies in Mammalian Radiation Genetics", Nucleonics, January, 1965.

7. Wright, Stewart, "Stochastic Processes in Evolution", in Stochastic Models in Medicine and Biology. Publication No. 10 of the Mathematics Research Center, University of Wisconsin Press, Madison, Wisconsin, 1964.

8. Eisenbud, Merril, Environmental Radioactivity, 1963.

9. Davis, George E., Radiation and Life, pg. 309, 1971.

APPENDIX D CAST BASALT DESIGN FACTORS

D.1 RADIATION COOLING OF CAST BASALT [7]*

D.1.1 LUNAR NIGHT

$$t = \frac{\rho C_p V}{3\varepsilon\sigma A}\left(\frac{1}{T_f^3} - \frac{1}{T_i^3}\right) \qquad \text{(D.1.1-1)}$$

where

t = time required to cool from T_i to T_f

ρ = density of cast basalt (187.2 lb/ft^3)

C_p = specific heat (0.2 BTU/lb °R)

ε = emissivity (0.8)

V = volume of casting (30 ft^3)

σ = Stefan-Baltzman Constant

A = exposed area (136 ft^2)

T_i = initial temperature of casting (800° C)

T_f = temperature after time t

D.1.2 LUNAR DAY

$$t = \frac{\rho C_p V}{4\varepsilon A\sigma C^3}\left[\ln\left(\frac{(T_f+C)}{(T_i+C)}\,\frac{(T_f-C)}{(T_i-C)}\right) + \tan^{-1}\left(\frac{T_f}{C}\right) - \tan^{-1}\left(\frac{T_i}{C}\right)\right] \qquad \text{(D.1.2-1)}$$

where

$C = (\dot{q}_s/\sigma)\sin\beta$

$\dot{q}_s$ = solar constant (442 BTU/hr ft^2)

β = angle of incidence

*References are listed at end of Chapter 15.

All other quantities are defined in Section D.1.1.

D.2 DEVELOPMENT OF PRESTRESSING EQUATIONS

The steel tendon is placed in tension (F_{rs}) and the basalt is cast around it. After the cast basalt has solidified, the tension is released in the tendon. As a result the basalt is placed in compression (F_b) and a residual tension (F'_{rs}) remains in the tendons. Equilibrium conditions require that

$$F_b + F'_{rs} = 0 \tag{D.2-1}$$

In terms of stress and cross-sectional areas, equation (D.2-1) becomes

$$\sigma_b A_b + \sigma'_{rs} A_{rs} = 0 \tag{D.2-2}$$

where

A_b = cross-sectional area of basalt

A_{rs} = total cross-sectional area of tendon rods or wires

σ_b = compressive stress in cast basalt

σ'_{rs} = residual tensile stress left in tendons

Strain compatibility (assuming no slippage) requires that

$$\varepsilon_b + \varepsilon'_{rs} = \varepsilon'_{rs} \tag{D.2-3}$$

In terms of stress, equation (D.2-3) becomes

$$\frac{\sigma_b}{E_b} + \frac{\sigma'_{rs}}{E_{rs}} = \frac{\sigma_{rs}}{E_{rs}} \tag{D.2-4}$$

where

E_b = modules of elasticity of basalt,

E_{rs} = modules of elasticity of the reinforcement steel tendons,

Combining equations (D.2-2) and (D.2-4), we get

$$\sigma_b = \frac{E_b}{E_{rs}} \left[\sigma_{rs} + \sigma_b \left(\frac{A_b}{A_{rs}} \right) \right] , \qquad (D.2\text{-}5)$$

or

$$\frac{A_b}{A_{rs}} = - \left[\frac{\sigma_{rs}}{\sigma_b} + \frac{E_{rs}}{E_b} \right] . \qquad (D.2\text{-}6)$$

σ_b is always a negative value

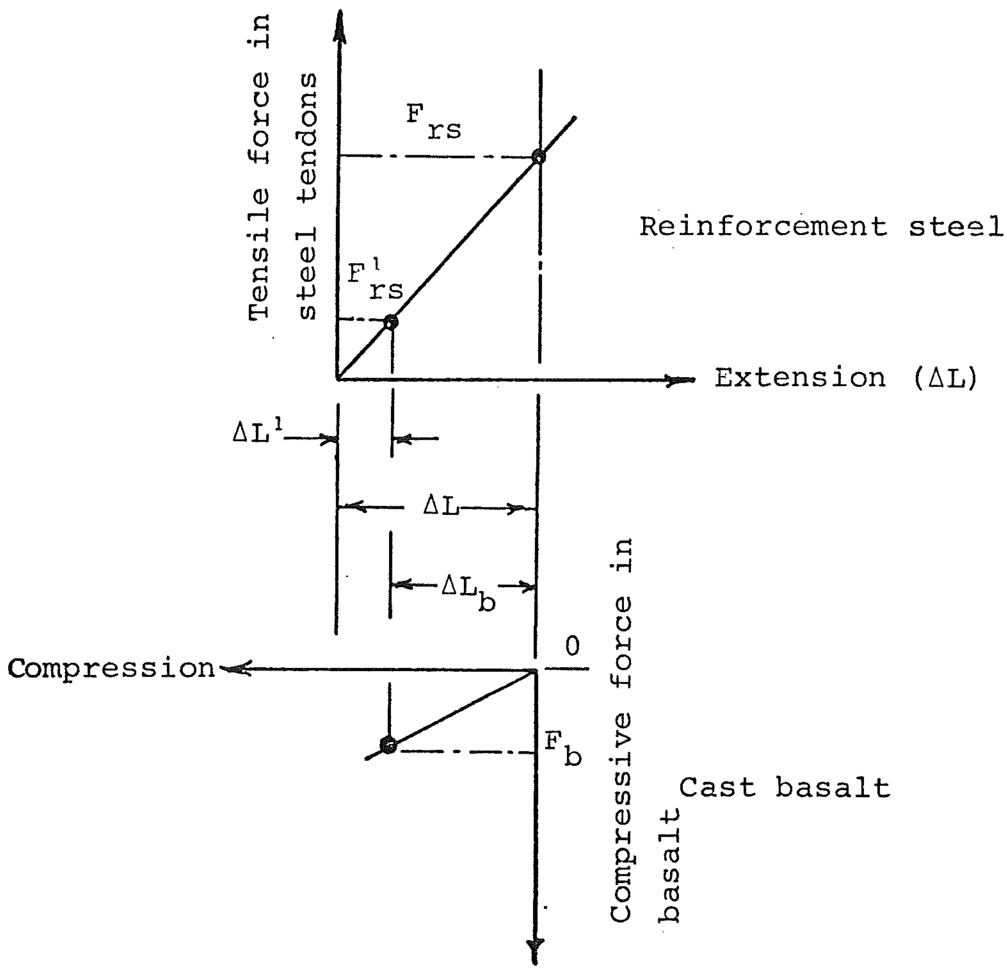


Figure D.2-1 Prestressing of cast basalt

APPENDIX E INSTITUTE STAFF

1972

NASA/ASEE ENGINEERING SYSTEMS DESIGN INSTITUTE

University of Houston - MSC

Participating Fellows

John Russell Biddle
Assistant Professor
Mechanical Engineering
California State Polytechnic University
Pomona, CA 91768

BSME, Washington University (St. Louis)
MSME, Washington University (St. Louis)
PhD, Arizona State University

Donald Albert Carey
Assistant Professor, Captain
Engineering Mechanics
DFEM USAF Academy
CO 80840

BS Engr. Sci., USAF Academy
MS Astronautics, AF Institute of Technology

Attru M. Chowdiah
Professor
General Engineering
University of Puerto Rico
Mayaguez, PR 00708

BECE, University of Madras (India)
MSCE, Michigan State College
PhD, Michigan State University

Jon A. Cole
Associate Professor
Engineering
Walla Walla College
College Place, WA 99324

BSCE, Illinois Institute of Technology
MSCE, University of Wisconsin
PhD, University of Wisconsin

Carlos Weldon Coon, Jr.
Associate Professor
Institute of Technology
Southern Methodist University
Dallas, TX 75222

BSME, Texas Tech University
MSME, Texas Tech University
PhD, University of Arizona

Ramon Earl Goforth
Instructor
Mechanical Engineering
University of Texas
Arlington, TX 76010

BSIE, Southern Methodist University
MSME, Southern Methodist University

Stephen J. Gold
Assistant Professor
Electrical Engineering
University of Southwest Louisiana
Lafayette, LA 70501

BSEE, University of Utah
MS Nu. Sci., University of Idaho
PhD, University of Utah

William Andrew Heenan
Assistant Professor
Chemical Engineering
University of Puerto Rico
Mayaguez, PR 00708

BChE, University of Detroit
MS, University of Detroit
D.ChE, University of Detroit

Dean Reese Heerwagen
Assistant Professor
of Architectural Science
Department of Architecture
Cornell University
Ithaca, NY 14850

BMetE, Cornell University
SM, MIT
BArch, MIT

Rodney Heisler
Assistant Professor
Engineering Department
Walla Walla College
College Place, WA 99324

BSEE, Walla Walla College
MSEE, Washington State University
PhD, Washington State University

Edward Charles Hohmann
Assistant Professor
Chemical Engineering
California State Polytechnic
University
Pomona, CA 91768

BS, University of Southern California
MS, Michigan State University
PhD, University of Southern California

Walter Konon
Lecturer
Civil Engineering
College of the City of New York
New York, NY 10031

BCE, CCNY
MCE, CCNY

James Giffin Seckler
Assistant Professor
Civil Engineering
and Engineering Mechanics
Bradley University
Peoria, IL 61606

BSCE, Stanford University
MSCE, New Mexico State University
ScD, New Mexico State University

Study Managers

Charles Dalton
Associate Professor
Mechanical Engineering
University of Houston
Houston, Texas 77004

BSME, University of Houston
MSME, University of Houston
PhD, University of Texas

Larry O. Degelman
Associate Professor
Architectural Engineering
Pennsylvania State University
University Park, PA 16802

BA ArchE, Pennsylvania State University
MS, Pennsylvania State University

APPENDIX F INDIVIDUAL RESPONSIBILITIES

Biddle . . . . . . Functional Analysis, Sequencing of Growth, Transportation.

Carey . . . . . . Location, Configuration, Safety.

Chowdiah . . . . . Functional Analysis, Structural Design, Excavation.

Cole . . . . Sequencing and Goals.

Coon . . . . Sequencing and Goals, Configuration, Safety, Excavation.

Goforth . . . . . Building Materials, Fabrication Methods.

Gold . . . . Location, Power Generation, Inventions.

Heenan . . . . . . Oxygen Production

Heerwagen . . . . Functional Analysis, Habitability, Life Support, Food Production.

Heisler . . . . . Sequencing and Goals, Power Generation, Communications.

Hohmann . . . . . Sequencing of Growth, Oxygen Production.

Konon . . . . . . Location, Food Production

Seckler . . . . . Evaluation Methods, Waste and Water Management, Life Support.

APPENDIX G PANEL DISCUSSION PARTICIPANTS

The people listed below are University of Houston faculty members who participated in a panel discussion held at the University of Houston. The discussion was in connection with how a lunar colony could appeal to the nontechnical professions.

Dr. Louis Alexander	Communications Department
Dr. Robert Briggs	Music Department
Dr. Michael Grimes	Sociology Department
Dr. Andrew S. Jackson	Health and Physical Education Department
Dr. Sidney Berger	Drama Department
Dr. David Jewell	Religion Center
Dr. John MacNaughton	Psychology Department
Dr. Peter Guenther	Art Department

APPENDIX H TECHNICAL CONTACTS

The following people were contacted during the course of the project in an effort to obtain the latest technical information. Their assistance and cooperation contributed significantly to the project and we acknowledge their aid.

Name	Organization
Rambaut, Paul	Preventive Medicine Division NASA-MSC, Houston, Texas
Simmonds, Richard	Preventive Medicine Division Microbiology and Environmental Biology Specialty Team NASA-MSC, Houston, Texas
Walkinshaw, Charles	Department of Agriculture on Loan to NASA-MSC Preventive Medicine Division NASA-MSC, Houston, Texas
Smith, M. C.	Preventive Medicine Division Spaceflight Biotechnology Specialty Team NASA-MSC, Houston, Texas
Sauer, R. L.	Preventive Medicine Division Spaceflight Biotechnology Specialty Team NASA-MSC, Houston, Texas
Louviere, Allen J.	Spacecraft Design Division Engineering Technology Branch NASA-MSC, Houston, Texas
Bond, Robert L.	Spacecraft Design Division NASA-MSC, Houston, Texas
Waligora, James M.	Environmental Physiology Laboratory NASA-MSC, Houston, Texas
Horrigan, David J.	Environmental Physiology Laboratory NASA-MSC, Houston, Texas
Mason, John A.	Preventive Medicine Division NASA-MSC, Houston, Texas
Feddersen, W.	Biomedical Laboratories Division Behavioral Performance Laboratory NASA-MSC, Houston, Texas

Name	Organization
Craig, Jerry W.	Systems Engineering Division Systems Integration Branch NASA-MSC, Houston, Texas
Watters, H.	Habitability Technology Section NASA-MSFC, Huntsville, Alabama
Dannenberg, J.	Process Engineering Laboratory NASA-MSFC, Huntsville, Alabama
Nishioka, K.	NASA/Ames Research Center Moffett, California
Downs, W. R.	Structures and Mechanics Division NASA-MSC, Houston, Texas
Williams, R. J.	Planetary and Earth Sciences Division Geochemistry Branch NASA-MSC, Houston, Texas
Horz, Friedrich	Planetary and Earth Sciences Division Geology Branch NASA-MSC, Houston, Texas
Pearce, G. W.	Planetary and Earth Sciences Division Geophysics Branch NASA-MSC, Houston, Texas
Kern, John	Physics Department University of Houston Houston, Texas
Kondo, Y.	Planetary and Earth Sciences Division Physics Branch NASA-MSC, Houston, Texas
Flory, Donald A.	Biophysics Department University of Houston Houston, Texas
Henny, Mary	Lunar Receiving Laboratory NASA-MSC, Houston, Texas
Rowley, J. C.	Los Alamos Scientific Laboratory Los Alamos, New Mexico
Johanson, W. G.	University of Texas Southwestern Medical School Dallas, Texas
Cross, Carleton	Electrical Engineering Oregon State University Corvallis, Oregon

Name	Organization
Kennedy, John H.	Baylor College of Medicine Houston, Texas
Potvin, A. R.	Electrical Engineering University of Texas Arlington, Texas
Brett, P. R.	Planetary and Earth Sciences Division Geochemistry Branch NASA-MSC, Houston, Texas
Johnson, Rodney W.	NASA Advanced Missions Program Office Washington, D. C.
Glaser, Peter	Arthur D. Little, Inc. Cambridge, Massachusetts
Green, Jack	Department of Geology Longbeach State University Longbeach, California
Fogelson, David E.	NASA Program Manager Twin Cities Mining Research Center Bureau of Mines Minneapolis, Minnesota

APPENDIX I COMMITTEE ASSIGNMENTS

Organization

Group I Food, Water, and Atmosphere

1. Cole
2. Heerwagen
3. Konon
4. Seckler

Group II Fuels, Transportation Power, and Energy

1. Biddle
2. Gold
3. Heenan
4. Heisler
5. Hohmann

Group III Shelter and Accomodations

1. Carey
2. Chowdiah
3. Coon
4. Goforth

Ad Hoc Committees

I. Sequencing

1. Biddle
2. Goforth
3. Hohmann
4. Seckler

II. Location

1. Carey
2. Gold
3. Konon

III. Functional Analysis

1. Biddle
2. Chowdiah
3. Heerwagen

IV. Mission and Goals Definition

1. Cole
2. Coon
3. Heisler

APPENDIX J

STAFF

Dr. C. J. Huang
Director
Asst. Vice President
University of Houston
Houston, Texas 77004

Dr. John R. Howell
Associate Director
Prof., Mech. Engr.
University of Houston
Houston, Texas 77004

Mr. Richard F. Baillie
Technical Director
Tech. Monitor of Summer
Faculty Study
NASA/MSC
Houston, Texas 77058

Prof. A. N. Paul
Assoc. Prof., Ind. Engr.
University of Houston
Houston, Texas 77004

Dr. Charles Dalton
Study Manager
Assoc. Prof., Mech. Engr.
University of Houston
Houston, Texas 77004

Prof. Larry O. Degelman
Study Manager
Assoc. Prof., Arch. Engr.
Penn. State University
University Park, Penna. 16802