GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 8.50

Microfiche (MF) 2.25

ff 653 July 65

FACILITY FORM 602

N66 35506	N66 35524
(ACCESSION NUMBER)	(THRU)
550	1
(PAGES)	(CODE)
CR-77328	30
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

UNITED STATES AIR FORCE ACADEMY

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FOREWORD

The Working Group on Extraterrestrial Resources is composed of people from the National Aeronautics and Space Administration (NASA), the U. S. Air Force, the U. S. Navy, Office of Engineers of the U. S. Army, U. S. Geological Survey, the Department of Agriculture, and the Rand Corporation. It was organized for the following function:

> "To evaluate the feasibility and usefulness of the employment of extraterrestrial resources with the objective of reducing dependence of lunar and planetary exploration on terrestrial supplies; to advise cognizant agencies on requirements pertinent to these objectives, and to point out the implications affecting these goals."

MINUTES OF THE FOURTH ANNUAL MEETING

The Fourth Annual Meeting of the Working Group on Extraterrestrial Resources was held at the Air Force Academy near Colorado Springs, Colorado 29 November - 2 December 1965. Attendees are listed in Appendix A. Condensed agenda followed was:

a. Business Session

b. Welcome Address

c. Keynote Address

d. Mars

e. Technical Papers

f. Election of Officers

g. Banquet

h. Subgroup Meetings

i. Tours

BUSINESS SESSION

At the closed session the afternoon of 29 November Dr. James B. Edson, Chairman of the WGER, introduced the following Subgroup Chairmen who reported the Subgroup progress and plans:

Dr. Paul D. Lowman, Chairman of the Subgroup on Environment & Resources;

Mr. Bruce Hall, Chairman of the Subgroup on Mining & Processing;

Mr. C. William Henderson, Chairman of the Subgroup on Logistics Requirements; and

Mr. James Malcolm, Chairman of the Subgroup on Biotechnology.

Dr. Ernst A. Steinhoff, Chairman of the Steering Committee WGER, spoke on "Plans for Next Year."

WELCOME ADDRESS

The Welcome Address was delivered to the full Working Group by Brigadier General Robert F. McDermott, USAF, Dean of the Faculty, U. S. Air Force Academy.

KEYNOTE ADDRESS

The Keynote Address was delivered by Brigadier General Andrew P. Rollins, USA, Office of the Chief of Engineers, US Army.

MARS

Dr. Edson displayed new pictures of the planet and pointed out further evidence indicating the existence of "canals."

TECHNICAL PAPERS

Technical papers presented are listed by Subgroup in Appendix B. Minor title changes may appear in the Proceedings, but papers are essentially unchanged in substance.

ELECTION OF OFFICERS

At a meeting of the Steering Committee the evening of 29 November, the following officers were elected for the coming year:

WORKING GROUP

Chairman	Dr. James B. Edson
Vice Chairman	Mr. Bruce Hall
Secretary	(To be chosen by Chairman)

STEERING COMMITTEE

Chairman	Dr. Ernst A. Steinhoff
Vice Chairman	Mr. James J. Gangler
Secretary	Mr. Ellis M. Bilbo

BANQUET

The banquet was held at 2000 hours 30 November 1965 at the Ramada Inn. Officers were introduced, and the names of officers for the coming year were announced. Dr. William Mrazek of the George C. Marshall Space Flight Center delivered the after-dinner address. He spoke on significant developments in the Saturn Program.

SUBGROUP MEETINGS

The four Subgroups assembled in separate rooms for their Fall meetings. Attendees not affiliated with a specific Subgroup were invited to attend meetings of their choice as observers.

TOURS

a. The Air Force Academy presented a briefing on and conducted a tour of Academy Facilities.

b. NORAD, with Colonel C. C. Smith, Jr., USAF, as Briefing Host, presented a briefing and conducted a tour of the Combat Operations Center at Ent AFB as follows:

Part I

Mission, Threat, Organization, and Detection System	**Flt Lt L. G. Jenks, RCAF**

Part II

Weapons Systems and Future Aerospace Defense	**Major T. H. Ball, USA**

Building P-4

Combat Operations Center	**S/L G. J. Sweanor, RCAF**

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REPORT OF THE ENVIRONMENT & RESOURCES SUBGROUP

Dr. Paul D. Lowman

Report Not Available

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MINING & PROCESSING SUBGROUP
WORKING GROUP ON EXTRATERRESTRIAL RESOURCES

SUBJECT: 1965 Annual Progress Report

A. Inclosures:

1. Subgroup Mission Statement

2. Committee Mission Statements

3. Minutes of Subgroup Meetings (2)

4. Committee Annual Reports

B. Subgroup Report:

1. In reasonable detail the Subgroup progress report consists of (a) reports of its committee activities and accomplishments, and (b) the minutes of Subgroup meetings. Committee reports and minutes of two of three meetings are included as inclosures. The third and final Subgroup meeting was held concurrently with the annual meeting on 1 December. This meeting was restricted to (a) a review of WGER organization history, (b) past and current activities of the Mining and Processing Subgroup, and (c) the interrelationships of the four Subgroups.

2. Subgroup Committees consist of:

a. Lunar Mining Procedures Committee
Wayne A. Roberts, Boeing Company, Chairman

b. Propellant Production Committee
Peter E. Glaser, Arthur D. Little Company, Chairman

c. Indigenous Lunar Power Sources Committee
Carl F. Austin, U. S. Naval Ordnance Test Station, Chairman

d. Materials Expected in Space as Related to Their Preparation, Processing and Extraction Committee
Paul G. Herold, Colorado School of Mines, Chairman

e. Intersubgroup Coordination Committee
No Committee chairman presently assigned.

3. FY 65-66 plans include:

a. Due to the importance of power sources and such concepts close relationships with propellants, it is probable that these two areas will be expanded into three committees of considerable greater scope.

SUBJECT: 1965 Annual Progress Report

b. A concerted effort will be realized to contact and recruit persons of applicable technical background for all committees.

c. For the purposes of informal papers to be presented at the spring Subgroup meeting and the more formal papers for the fall WGER annual meeting, a process of subject selected will be formulated. Based on this selective method, specific authors will be requested to prepare and present papers. Such a method will organize a body of information designed to more fully supplement the interests of the Subgroup.

d. Increased committee activity and reporting will be encouraged.

4 Inclosures
as stated

BRUCE M. HALL, Chairman
Mining & Processing Subgroup
WGER

MISSION STATEMENT
MINING & PROCESSING SUBGROUP

To evaluate feasibility and usefulness of mining and processing of local materials with the objective of reducing dependence on logistic support, to advise on ways and means for achieving this objective and to determine (1) scope of materials requirement, (2) a broad identification of materials application and (3) inherent power requirements.

COMMITTEE MISSION STATEMENTS
MINING & PROCESSING SUBGROUP

Lunar Mining Procedures Committee

It shall be the function of this Committee to (1) define the phases of the total mining operation, (2) establish the quantity and quality of mineral deposits necessarily compatible with logistics and mining procedures, (3) evaluate procedures for each operational phase relative to constraints imposed by logistics, environment, and capability, (4) examine the feasibility of existing concepts in light of the constraints, (5) determine need for unique or new concepts, (6) list areas of technology where research is necessary, (7) develop, where possible, unique concepts, (8) provide a summary of operational concepts, and (9) extrapolate where possible to other planetary surfaces.

Materials Expected in Space As Related to Their Preparation, Processing, and Extraction Committee

It shall be the function of this committee to (1) define the materials which are likely to be found on the lunar surface or within 100 feet of the surface in the light of various proposed models of lunar surface formation, (2) examine the affect of radiation on the proposed materials, (3) examine the effects and interrelations on effects of vacuum, temperature, and radiation of the proposed materials, (4) propose a model for the condition of the materials found at or near the surface of the moon, (5) examine and list the properties of materials which might be found on the moon as they affect preparation, processing and extraction, and (6) extend results of study to other planetary or space conditions.

Propellant Production Committee

It shall be the function of this committee to (1) provide guidance on the various techniques and processes required for propellant production based on the logistic requirements for different lunar exploration missions, (2) identify the various processes required for the extraction of propellants such as hydrogen and oxygen from lunar resources for either in situ or mined deposits, (3) analyze the capabilities of promising processes for the production of hydrogen and oxygen including process requirements such as nuclear or solar heat sources, electrolysis of water, liquefaction of hydrogen and oxygen, and storage of cryogenic fuels, (4) select components for extraction processes which are within the state-of-the-art and to identify those components which require further development for use in the lunar environment, and (5) make available this information to other committees and subgroups so that they can be guided in their work by the extraction process feasibility and requirements.

Indigenous Lunar Power Committee

The mission of the Ad Hoc Committee on Indigenous Lunar Power Sources is to provide advanced concepts in the field of indigenous lunar power; to encourage the establishment of supporting studies on the probable usefulness of various lunar power concepts plus the dissemination of the resulting conclusions; and to create a nucleus of personnel skilled in indigenous lunar power concepts that can act as advisors to those groups involved in advanced lunar mission planning.

Mining & Processing Subgroup
Working Group on Extraterrestrial Resources

SUBJECT: Minutes of Subgroup Meeting

TO: All Members

1. The second meeting of the Subgroup for 1965 was held in Washington, D. C. on 16 September at the Office, Chief of Engineers, DA. Roster of attendees is as listed in Inclosure 1.

2. Committee reports were rendered by:

a. Lunar Mining Procedures Committee (Incl 2)
Wayne A. Roberts, Chairman (Boeing Company)

b. Materials Expected in Space As Related to Their Preparation, Processing and Extraction.
Dr. Paul Herold, Chairman (Colorado School of Mines)

3. Committee reports were rendered in absentia by:

a. Propellant Production Committee (Incl 3)
Dr. Peter Glaser (Arthur D. Little, Co.)

b. Indigenous Lunar Power Sources (Incl 4)
Dr. Carl Austin (U. S. Naval Ordnance Test Station)

4. Informal papers on current studies having application to Subgroup interests were discussed by members.

a. Charles E. Ken Knight of Litton Industries on the effects of solar wind bombardment on mineral powders.

b. S. D. Rosenberg of Aerojet-General on their recently completed investigations of oxygen production from silicates.

c. Hoyt M. Weathers of NASA-Huntsville on the background planning for the recently awarded 100 feet lunar drill contracts. He also discussed the two alternate drilling methods proposed for development under this program.

d. Alice S. Allen, EXTERRA, Office, Chief of Engineers, DA, on current development of lunar soil simulants.

e. Bruce M. Hall, EXTERRA, Office, Chief of Engineers, DA, on a current project to investigate earthshine conditions on the lunar surface for all geographical locations and terrestrial light phases.

5. Announcements:

a. Henceforth, meetings will be confined to the WGER annual meeting in the fall and a Subgroup meeting each spring. A majority of the work will be accomplished at the committee level through meetings or by correspondence.

b. Abstracts for professional papers to be presented at the annual meeting, 30 November - 2 December, have been submitted by Peter Glaser, John Halajian, R. W. Johnson, Carl Austin, and Jon Weber. Authors selected will be notified immediately following the 27 September meeting of the Steering and Planning Committee.

Respectfully submitted,

B. M. Hall

BRUCE M. HALL, ~~Chairman~~
Mining & Processing Subgroup
WGER

4 Incl
as stated

ROSTER OF ATTENDEES

MINING AND PROCESSING SUBGROUP MEETING
WORKING GROUP ON EXTRATERRESTRIAL RESOURCES
16 SEPTEMBER 1965 -- WASHINGTON, D. C.

Alice S. Allen, Office, Chief of Engineers, DA
Leonard Aronowitz, Grumman Aircraft Engineering Corporation
Robert M. Cox, University of Alabama
Stanley A. Fields, George C. Marshall Space Flight Center, NASA
David J. Gimber, Office, Chief of Engineers, DA
Bruce M. Hall, Office, Chief of Engineers, DA
Paul G. Herold, Colorado School of Mines
Rodney W. Johnson, General Electric Company
Charles E. Ken Knight, Litton Industries, Inc.
Wayne A. Roberts, The Boeing Company
S. D. Rosenberg, Aerojet-General Corporation
Reynold Q. Shotts, University of Alabama
William L. Smith, Battelle Memorial Institute
Hoyt M. Weathers, George C. Marshall Space Flight Center, NASA
Jon N. Weber, Pennsylvania State University

Interim Report
Lunar Mining Proceedures Committee

Wayne A. Roberts

The Lunar Mining Proceedures Committee was organized in May, 1965 to delineate techniques that could properly be used in extraterrestrial environments for the extraction of necessary or desireable material from the native rocks or soils. Particular emphasis is to be placed on a lunar type environment.

The mining process consists of phases to find and define a deposit of mineral material; to develop this deposit to the extent that the economic value can be determined and an extraction method can be selected on the basis of efficiency and cost; to extract the native material and concentrate the substance of interest; and to produce a final product in useable form. The mining process is illustrated in the following Table.

Mining Process

Exploration
- Reconnaissance—definition of province or region enriched in a substance of interest.
- Location of "ore" grade material

Development
- Detailed definition of the deposit
  - Extent, shape, grade of deposit
- Development penetration of "ore" body
  - Physical characteristics of "ore" and host
  - Continuity of mineralization
  - Extractive techniques necessary
  - Economic feasibility of extraction

Extraction
- Removal of mineral bearing material
- "Up-grading"—milling, concentration
- Refining—production of "valuable" substance

Fabrication
- Useable form of "valuable" raw substance

"Ore", as used herein, is defined simply as a deposit of mineralized material that can be mined at a profit. For extraterrestrial deposits an "ore" deposit would be a mineral deposit that could yield materials more cheaply than the total cost of delivery at some extraterrestrial point such as a base and profit would be any savings realized by producing a substance from native materials. This is a complex problem and will be expanded for the final report.

The functions of the Lunar Mining Proceedures Committee are:

1. Define the phases of the total mining operation.

2. Establish the quantity and quality of mineral deposits necessarily compatible with logistics and mining proceedures.

3. Evaluate proceedures for each operational phase relative to constraints imposed by logistics, environment and capability.

4. Examine the feasibility of existing concepts relative to the constraints.

5. Determine the need for unique or new concepts.

6. Develop, where possible, unique concepts.

7. List areas of technology where research is necessary.

8. Provide a summary of operational concepts.

9. Evaluate effects of environmental factors and extrapolate techniques where possible to other planetary surfaces.

The total function of the Lunar Mining Proceedures Committee is relatively large and, since the tasks are numerous and generally laborious, considerable effort will be required to complete the assignments. The work is not funded and is generally done during spare time. With these constraints in mind it is evident that all tasks of the committee cannot be performed between inception and the annual meeting of 1965.

For the initial assessment of extraterrestrial mining to start work on the assigned tasks, the mining proceedures have been subdivided into seven different phases primarily to conform to the technical background and interests of the committee members. These phases are as follows:

1. special techniques for processing
2. rock breakage techniques
3. transportation and haulage
4. upgrading (milling) techniques
5. mining techniques
6. drilling techniques
7. sizing techniques

The feasibility of standard Earth techniques and those that have been proposed for lunar mining for each of these phases will be determined considering the constraints imposed by logistics, the environment, and the potentially limited or reduced capability of men protected from the environment. Selected proceedures, if any, may then be evaluated and the need for new concepts where required can be determined. New concepts resulting from this work will be developed in so far as possible and any detected areas of research or special problems will then be noted.

Report of

The Propellant Production Committee

of the

Mining and Processing Subgroup

of the

Working Group on Extraterrestrial Resources

At the 26 May 1965 Subgroup meeting, the Propellant Production Committee was reconstituted with Peter E. Glaser, chairman, Bruce B. Carr, Carl B. Hayward, James J. Gangler, and S. D. Rosenburg. A mission statement for the Committee was drawn up which is as follows:

The objectives of the Committee are as follows:

1. To provide guidance on the various techniques and processes required for propellant production based on the logistic requirements for different lunar exploration missions.

2. To identify the various processes required for the extraction of propellants such as hydrogen and oxygen from lunar resources for either in situ or mined deposits.

3. To analyze the capabilities of promising processes for the production of hydrogen and oxygen including process requirements such as nuclear or solar heat sources, electrolysis of water, liquefaction of hydrogen and oxygen, and storage of cryogenic fuels.

4. To select components for extraction processes which are within the state-of-the-art and to identify those components which require further development for use in the lunar environment.

5. To make available this information to other committees and subgroups so that they can be guided in their work by the extraction process feasibility and requirements.

Because of the relatively short time that the Committee has been in action, no detailed work has been as yet carried out. Committee members are planning to take part in the Annual Meeting at Colorado Springs to report on the results of work of interest to the Subgroup.

REPORT OF AD HOC COMMITTEE ON
INDIGENOUS LUNAR POWER SOURCES
Washington, D. C.

14 September 1965

T personnel changes have taken place during the reporting period immediately past. At present the active committee consists of the Chairman and five members. These are:

J. Kenneth Pringle	USNOTS, Astrophysicist and Mineralogist
Richard Fulmer	USNOTS, Chemical Engineer
Modesto Leonardi	AMPOT, Manager, Plant Production
George A. Kiersch	Cornell University, Geologist
W. J. Levedahl	The Martin Co., Power Conversion

During the past reporting period, Dr. Richard Zabelka left the committee and Dr. George Kiersch joined the group.

Although summer vacations rather fragmented our activities, there has been some modest progress during the last reporting period. Messrs. Austin, Pringle and Fulmer have been collecting data and ideas in support of their proposed paper for the Annual Meeting. Austin and Pringle have also planned one small experiment for trial in a local thermal area, which consists of a large shaped charge firing into an area of diffuse hot springs and steam emission. This test will give some indications of the ability of a shallow "bore hole" to concentrate gas emissions. Considerable data has also been gathered on the impacting rocket approach to drilling steam and/or gas wells of modest depth, although the problem of the classification of some of the data is encountered in this area and may preclude its presentation in unclassified reports. Dr. Austin has also been collecting data in support of a paper entitled "Estimating the Chemistry of Geothermal Deposits" which he will be presenting at a local AChE meeting. Much of this latter data will also be used in the analysis of the geothermal concepts which will appear in the paper for the Annual Meeting.

Mr. Fulmer has been continuing his studies of geothermal concepts and will be contributing the energy-conversion portion of the paper by Austin, Pringle and Fulmer. Mr. Pringle has continued his collection of supporting volcanic evidence from lunar observations.

Mr. Leonardi has been inactive during most of the past reporting period but will be contributing data on corrosion problems during the coming reporting period. Corrosion is a major problem whenhhandling volcanic gases, and nothing could be more frustrating than to deliver and assemble equipment at great effort and expense, only to watch it corrode and crumble as soon as it is put into service. With his vast operating experience in the chemical and brine processing industry, Mr. Leonardi should be able to make a valuable contribution.

Dr. Kiersch has just joined the group and brings a considerable fund of knowledge in the geothermal area, having prepared a rather volumnious report on geothermal power recently for AFCRL. Dr. Kiersch has already submitted a useful summary of his ideas on the lunar geothermal potential, and he too appears to be optomistic. Dr. Kiersch suggests infrared studies will be a valuable prospecting method which should then be followed up by surface observations. The other committee members heartily concur with his comments. Dr. Kiersch is a welcome addition to our deliberations.

During the coming reporting period, we plan to complete our proposed paper on geothermal concepts and to seek additional pertinent inputs from our committee cohorts. We will shortly be firming up our plans for the coming year. As we see things at present, the proposed work for the coming year will emphasize the area of gravity exploitation, using convective closed and semi-closed systems and also open systems with tramline type concept.

At the same time, a continued geothermal input will be maintained to keep our concepts up to date, and during the coming year Dr. Austin and Mr. Pringle will emphasize the problems of bore hole drilling by means of high velocity impacts. This latter subject may prove difficult to handle for reporting purposes because of the unclassified nature of our meetings and reports but we feel that the subject is quite pertinent.

Respectfully submitted

Carl F. Austin

Carl F. Austin
Chairman

LUNAR MINING PROCEDURES COMMITTEE

Wayne A. Roberts, Chairman

Introduction

The Lunar Mining Procedures Committee was organized in May 1965 to delineate techniques that could properly be used in extraterrestrial environments for the extraction of necessary or desirable materials from the native rocks or soils. Particular emphasis is to be placed on a lunar type environment. The functions of the committee are as follows:

1. Define the phases of the total mining operation.

2. Establish the quantity and quality of mineral deposits necessarily compatible with both the logistics problems related to extraterrestrial location of mining operations and the mining procedures involved in these operations.

3. Evaluate procedures for each operational phase relative to the constraints imposed by logistics, environment and capability of the men.

4. Examine the feasibility of existing concepts relative to the constraints.

5. Determine the need for unique or new concepts.

6. Develop, where possible, new concepts.

7. List areas of technology where research is necessary.

8. Provide a summary of operational concepts.

9. Evaluate effects of environmental factors and extrapolate techniques where possible to other planetary surfaces.

The total mission of the Lunar Mining Procedures Committee is relatively large -- the tasks are numerous and generally laborious. The work is not funded and must be done, generally, during spare time, resulting in a low rate of progress. The members of this committee are as follows:

1. Bruce B. Carr of Callery Chemical Company.

2. John F. Cronin of A. F. Cambridge Research Laboratories

3. Christopher Crowe of Texas Instruments, Incorporated.

4. James Paone of U. S. Bureau of Mines.

5. Sheldon Penn of Grumman Aircraft Engineering Corporation

6. Wayne A. Roberts of The Boeing Company.

7. Hoyt Weathers of George C. Marshall Space Flight Center, NASA

For the initial assessment of extraterrestrial mining processes, the mining procedures have been subdivided into eight different phases primarily to conform to the technical background and interests of the committee members. These phases and the member assigned to each phase were as follows:

1. Special Techniques for "Ore" Processing -- Bruce B. Carr

2. Rock Breakage Techniques -- John F. Cronin

3. Transportation and Haulage -- Christopher Crowe

4. Upgrading (Milling) Techniques -- James Paone

5. Mining Techniques -- Sheldon Penn

6. Exploration and Development -- Wayne A. Roberts

7. Drilling Techniques -- Hoyt Weathers

8. Sizing Techniques -- James Paone

The feasibility of standard earth techniques and those that have been proposed for lunar mining for each of these phases are to be determined considering the constraints imposed by logistics, the environment, and the potentially limited or reduced capability of men protected from the environment. Selected procedures, if any, will then be evaluated and the need for new concepts where required can be determined. New concepts resulting from this work will be developed insofar as possible and any detected areas of research or special problems will then be noted.

The mining process, as it applies to extraterrestrial bodies, has been defined and the concept of "ore" developed as the term applies to terrestrial as well as extraterrestrial deposits. All planetary environments impose constraints on all of the phases of mining. Here on earth, operations have been developed empirically to cope with the existing constraints. Extrapolation to new planets with different environments will require not only the examination of the mining problems in the light of existing methods but also consideration of techniques not used on earth due to the incompatibility or non-amenability relative to our constraints. Exploration and development of extraterrestrial mineral deposits have been initially reviewed, considering various operations costs chargeable to the mining process. Mining exploration is initiated by the decision to exploit the natural resources which may be known or suspected. The products that are useable depend not only on the stage of planetary exploration contemporaneous with this decision but also on the total projected planetary exploration and the level of technological development. The use rate as well as the total quantity needed must be considered in this decision. Mining development follows the exploration phase to define the physical and chemical characteristics of the mineralized body and the surrounding host rock to provide the basis for a new decision to choose a method to extract, refine, and fabricate the material of interest into a useable form.

THE MINING PROCESS AND THE PRELIMINARY PHASES

OF

EXPLORATION AND DEVELOPMENT

Wayne A. Roberts

THE MINING PROCESS

The mining process consists of phases to find and define a deposit of mineral material; to develop this deposit to the extent that the economic value can be determined and an extraction method or methods can be selected on the basis of efficiency and cost; to extract the native material and concentrate the substance of interest; to produce a final product in useable form. The mining process is illustrated by the following table:

Exploration

-- Reconnaissance - definition of a province or region enriched in a substance of interest.

-- Location of "ore" grade material

Development

-- Detailed definition of the deposit

-- Extent, shape, grade or content of the deposit.

-- Development penetration of the mineral deposit

-- Physical characteristics of "ore" and host or "country rock".

-- Continuity of mineralization

-- Extractive techniques necessary

-- Economic feasibility of extraction

Extraction

-- Removal of mineral bearing material

-- Milling, "up-grading" -- concentration of material of interest

-- Refining production of "valuable" substance

-- Fabrication

-- Useable form of "valuable" raw substance.

Mining is only feasible if "ore" can be found. This may seem obvious; however, this fundamental concept has not been universally understood. "Ore" is defined as a deposit of mineral material that can be mined at a profit. In the case of an extraterrestrial deposit, an ore body would be a deposit of mineral material from which a substance that is useful can be extracted and fabricated into a useable form and transported to the point of use at an overall cost less than the same material can be produced on earth and shipped to the use point. "Ore" connotes more than just the grade or useful content of the mineral body. The quantity of mineral material present as well as the quality, the dimensions and physical and chemical characteristics of the mineral deposit and the potential market or cumulative use and use rate must be considered. A market or potential use for the product must be in quantities sufficient to amortize the fixed costs of the operation. This concept holds true not only on earth but on all extraterrestrial bodies. A natural resource product must present a favorable economic aspect to compete with other substitutes. There is obviously no point in mining for mining's sake. For extraterrestrial bases, the definition of ore must be modified to some degree by the uncertainties of transportation of the earth-produced material.

Generally, costs chargeable against a mining operation include any research and development costs for equipment used in all phases of the mining operation, exploration and development of the ore bodies, extraction, upgrading, concentrating, refining, and fabrication of the substance into useable form. Equipment development costs can be applied on a unit basis to all mines that utilize the equipment. Mu ! of the research necessary for equipment design for other environments, may be done in support of other extraterrestrial operations and may not be a chargeable item "per se" against subsequent mining operations.

Preliminary exploration, or prospecting, to determine the distribution of various substances may result from early scientific exploration efforts to determine the geological and physical characteristics and areal distribution of these properties on the planetary body. This information can be utilized later for development of the natural resources and may reduce costs incurred in exploration initiated primarily for the location of potential mining.

For extraterrestrial bodies, mining will probably only be feasible after initial phases of scientific exploration and after a base or network of bases have been established. Before exploration is started, the nature of the market must be determined. The overall quantities of a substance that will be needed for the projected lifetime of the base or bases as well as potential use for exploration beyond the base planet must be estimated so that the feasibility of local mining operations can be assessed. Large monetary investments in machinery and labor for the total mining operation may be required so that any material produced, including possible by-products, must be used in large quantities commensurate with the initial and continuing investment; however, once the decision to develop certain of the natural resources has been made and any specific exploration and development expenses have been incurred, the mining property must be assessed against the extraction, concentration, refining and fabrication costs. Thus, mining may be operated at an overall loss and still be economically sound since exploration and development has already been done, and the extraction phases and beyond may recoup part of these costs.

Nature appears to be homogeneous, at least on earth, in one respect -- the heterogeneity in most of the detailed characteristics on both a local and regional scale. On earth each deposit is an individual in its physical characteristics and the general procedure is to find, develop, and actually penetrate the ore body before the details of extraction, concentration and refining are selected. The techniques chosen consider not only unit production cost but demand rate. Over production may require additional expenses for storage, interest on invested money, and administration, and a less efficient method may, in the long run, be the most economical.

Summary of Costs Applicable to Mining Process

Cost of research and development directed strictly toward any of the phases of the mining process must be absorbed by production "profits" realized in the savings by the extraction of natural resources relative to Earth-produced and shipped material. This applies to exploration or prospecting techniques and instruments as well as to actual extraction, concentrating, or refining machinery or processes. Much of the research and development for equipment or techniques for scientific exploration may apply to the mining processes thereby reducing initial fixed costs. Interest on the money invested early in the program must also be included in the overall cost of mining.

In a like manner most, or possibly all, of the expense of preliminary exploration may be applied to scientific exploration. It is conceivable that, initially, at least, deposits that were detected and mapped in as much detail as possible during the scientific exploration will be developed. Only that portion of the exploration which is directed toward exploitation of the natural resources will be part of the overall mining costs.

The development of the mineral deposits to a point where extraction and processing are feasible will be principally applicable to the mining. Again, research and development costs for such items as a surface transportation vehicle, geo-chemical field techniques, or a drill developed for the scientific work will not be included and the accidental or otherwise interesection of the mineral deposit by a drill during the scientific work or by some earth moving device may constitute a principal discovery which will be the key point for further development. Extension of the deposits through surface and subsurface work and development penetration for better defining the physical and chemical characteristics of the deposit entail direct mining costs.

The extraction, up-grading or concentrating and refining phases involve costs almost universally recognized as applicable to the cost of production. These include fixed costs of research and development for special equipment or processes, cost of this equipment delivered to the use point and the interest on money invested in these items. Production material and labor costs at the use point as well as transportation and handling costs of the "ore" between the mine and the mill will also apply to these phases.

Not all of the mining phases are necessarily applicable to all materials that could be produced. For example, ice located in a permanent shadow zones could be rapidly assessed for thickness and lateral extent. No up-grading or concentrating need be done and the raw product of the recovery, water, could be used as the fabricated product. Should H_2-O_2 be required for fuel, the water would be further processed to provide the gases. The overall costs of the total mining process include only those portions directed toward exploitation and are summarized in the following table:

Common to all phases

Research and development costs of special equipment and processes.

Production cost of material and equipment

Training costs for personnel.

Protective equipment and life support for personnel.

Labor and expendable material costs.

Transportation costs for equipment, material and personnel.

Interest on invested money.

Exploration

Geoscience exploration and mapping, sampling, analyses.

Preliminary drilling or other subsurface work.

Development

Detailed surface definition of deposit including mapping, sampling and analyses

Subsurface exploration by trenching and/or drilling also including mapping, sampling, and analyses.

Penetration of mineral deposit by trenching or tunneling including mapping, sampling and analyses to define shape, size and grade of mineable deposit.

Extraction

Production of "ore" including control sampling and mapping of headings

Transportation of ore to mill

Milling

Sizing of "ore" by crushing, screening

Upgrading or concentrating substance of interest in "ore"

Packaging and/or transportation of concentrate to refinery.

Refining

Extraction of substance of interest from concentrate

Packaging and/or transportation to a fabrication plant

Fabrication

Processing substance of interest into useable form

Transportation, packaging, storage of final product.

ENVIRONMENTAL EFFECTS

The environment at the surface of an extraterrestrial body can put different and additional constraints on surface operations. Some of the constraints or hazards present on earth will be missing on certain of our neighboring planets. For example, hazards and constraints related to possible floods or fires are not anticipated on bodies similar to the Moon and underground conditions related to the level of the watertable and conditions of ground water abundance and movement rates are not anticipated as severe. Each planetary body will probably present a different list of constraints some of which will only be known after surface exploration on the body.

A major constraint on all extraterrestrial bodies will be that imposed by shipping costs of equipment and material. Logistics problems may be somewhat affected by the planetary environment.

The lunar environment is in some respects about as severe as can be expected. The atmosphere can't apparently be much thinner even on the asteroids and, if non-existant, would not hamper man to a much greater extent. Atmospheric pressures can, of course, be higher than on earth on the surface of some of the major planets possibly requiring protection from too much atmosphere. Radiation levels at a planetary surface will depend on the thickness and density of the atmosphere as well as the proximity to the sun so that radiation levels could be both higher and lower that at the Moon.

The gravity is lower on the Moon than on earth but will be even lower on the asteroids and some of the planetary satellites. Gravity will probably be much higher on the surface of some of the outer planets. For much higher gravity, structures will need to be stronger and heavier and more energy will be needed to move and retard material. For much lower gravity, gravity feed systems could be adversely affected. Temperature extremes could be greater on the planet Mercury. Lower temperatures could occur on the outer planets. The chemical environment at the surface of extraterrestrial bodies is not known and problems of high chemical activity with earth-produced materials could be encountered, since some of the atmospheres or surficial materials could contain active chemical reactants. Adhesion of dust due to higher friction, cold welding, chemical combination could also occur in other environemnts.

In short, man will probably have to be protected on all of our neighboring planets and equipment will have to be designed to accomodate the particular environment in which it will be operated. Due to logistics costs, universal designs will probably not prove to be feasible and each piece of equipment will be optimized on a weight, volume and packaging basis for the environment at the use point.

USEFUL PRODUCTS

The precise list of products that can be considered for production from the natural resources of an extraterrestrial body will depend not only on the relative costs of logistics and production and the quantities of need, but also on the stage and purpose of planetary exploration, the total extent of exploration planned, and the level of technological development on earth.

Water, or one of its forms, appears at present to be the most useful product that could be derived from the moon. The total quantity that could be used, considering subsequent exploration as well as the rate at which it will be used, will directly affect the possibility of mining. Since there will be fixed costs related to exploration, research and development, production and delivery of equipment, the total quantity that will probably be used will directly affect the amortization costs applicable to the product. At some future date, water in large quantities for fuel may not be needed due to technological advances in propulsive systems.

EXPLORATION

The initial step in the mining process is the delineation or determination of a necessary or desirable material that occurs and can be extracted for use and a decision to exploit this resource. Commonly on Earth, deposits of mineral material are known much in advance of the development of a use or need for the substance. This will probably also be true on extraterrestrial bodies where scientific exploration precedes the establishment of a long term base or network of bases. Needs and uses of extraterrestrial resources will be based on the current technical level of development on Earth. Once a need or use is established, occurrences of the material of interest, if not already known, must be located. This is the initial or prospecting phase of exploration.

Prospecting is essentially a reconnaissance phase of exploration where a "materialiferous" province is located and crudely defined. This can include a search of accumulated, interpreted data, hypotheses, and conclusions from previous scientific exploration or a re-evaluation, re-inspection, of raw data. Actual areal reconnaissance can include the systematic or random use of geophysical, geochemical, and geological tools but on Earth has relied heavily on visual detection of anomalous material. The gradual disappearance of easily detected surficial deposits or potential subsurface occurrences detected visually by features exposed at the surface has increased the use of instruments which can detect and/or measure some physical parameter of a material. Such characteristics are then used to delimit areas of possible and probable occurrence. Important in the early or reconnaissance phase is the determination of the mode of occurrence of the substance and possible "in situ" associations of the material of interest with other materials. If these associations can be determined, the location of deposits of the material of interest may be facilitated by use of a tool for some easily detectable characteristic of the companion material.

Detection of an anomalous area by some geophysical or remote sensing tool does not necessarily mean the location of a deposit of a material of interest. For example, the location of an infra-red anomalously warm area during the umbral phase of an eclipse does not mean that surface ice or very near surface ice is present. The anomaly could be genetically related to an increase in medium fragment size exposed or nearly exposed through any surface insulating layer or to an actual source of internal heat. Spectral characteristics in the infra-red or ultra-violet may not be any more diagnostic for most minerals or materials of interest than the spectral characteristics in the visible. Color can and is commonly related to impurities and the range of color (or spectral reflectance in the visible range) of materials or minerals of widely divergent chemical compositions can be nearly identical.

The location of an anomalously radioactive area by orbital detectors can be explained by the presence of elements other than fissionable ones that may be used as nuclear fuel. A magnetic anomaly doesn't necessarily indicate the presence of say magnetite or meteoritic iron-nickel. In other words, a given anomaly detected by field tools is generally related to a property that is not a unique characteristic of a material.

When such an anomaly is detected and the most probable hypothetical cause is the presence of a needed material, the region and deposit, if located, must be studied to determine the origin of the anomalous characteristic. Further, or more detailed exploration can include visual inspection by man, areal geological mapping, areal geophysical or geochemical mapping, shallow or deep subsurface testing, and finally by chemical or spectrographic analyses. Some of the physical parameters of materials of interest can be masked by properties of associated materials so that a lack of anomaly does not always mean a lack of a particular material.

There are a host of geophysical tools which are used on Earth to aid in the determination of both structure and composition of segments of the lithosphere. Some of the categories of these tools are included, but not limited to the following list:

1. Imaging techniques of reflected electromagnetic waves of various frequencies.
2. Radioactivity detectors from total dose rate to spectral detectors of alpha, beta, and gamma rays.
3. Magnetism from total to component field strengths.
4. Gravity
5. Reflection and refraction of seismic waves
6. Specific gravity
7. Electrical conductance
8. Spontaneous electrical potential, resistivities of rocks, induced potential
9. Telluric currents

Geochemical techniques and emission and mass spectral techniques are also used for regional as well as detailed exploration. Natural phenomena, which may concentrate a material of interest, such as particular floral species, ground water, soil zones, are sampled and analyzed by rapid field techniques to localize anomalous occurrences of a substance. Even fauna may be used to detect regional positive or negative anomalies.

Geological techniques, generally visual detection of minerals, are used to determine the areal distribution of a mineral species and its association with structural, stratigraphic, topographic, or ~~floral~~ lithologic features. Commonly, a valuable substance might occur in conjunction with or in opposition to a much more abundant and prominent mineral species or other substance. Which of these tools will prove to be the most valuable can only be determined by the actual characteristics of the surficial and buried material on the outer shell of a planetary body, both generally and locally, by the nature of the material needed, and by the characteristics of occurrence. It is possible that extra-terrestrial bodies may exhibit a suite of minerals, different than, more complex than, or much simpler than that defined so far on Earth. Different chemical and physical conditions at the time of formation, for example the lack of volatile constituents such as water or carbon dioxide in mineral melts, could produce unfamiliar mineral species.

DEVELOPMENT

Once a deposit of a natural resource has been located, the next step is to determine the economic feasibility of production. This stage in the mining process is called "development" and consists of delimiting the deposit, determining the average grade of the material that can be extracted, determining the physical characteristics of the body, determining the chemical and physical characteristics of the substance of interest, and selecting the most feasible and economic technique of extraction.

The deposit is examined in detail on the surface, where possible, to determine the extent, alteration products of the ore, the presence of secondary enrichment or dilution, if possible, in the surface expression of the mineral deposit as it effects the grade, the thickness and attitude, and the potential or possible tonnage available. This is done by geological mapping, or by a combination of mapping and trenching where necessary and feasible. Geophysical and/or geochemical aids are used where feasible to postulate extensions into and through areas where trenching is not feasible and mapping strictly on surface exposures is not possible. In some cases geophysical or geochemical aids may precede actual excavation by hand or machine. At this point, the potential value of the body must be such that further exploration by subsurface techniques is encouraged.

Where the deposit appears to be suitable or amenable to extraction, concentration of the valuable material or a compound containing the valuable material, and for the refining and production of a usable product, the deposit may be tested by drilling and/or by underground tunneling. Drilling and analyses of cores or cuttings are used to further delineate the deposit laterally and vertically and to better define the shape and the grade of the body beneath the surface. Actual penetration of the body, where mechanical means are necessary to extract the usable material, is performed to determine the continuity of mineralization within the mineral deposit, to reassess the potential value with narrowing limits in the uncertainty, to determine the physical characteristics of both the mineral deposit and the host, or country rock, and to extract a sample suitable for determining potential refining techniques.

The thickness, lateral extent, attitude, continuity of mineralization and the competence, or bulk strength, of the deposit and the country rock will determine which mining or extraction methods are feasible. The most economic method will then be selected based on the possible methods, the postulated unit production cost for each method, the use rate of the material, the costs of storing or stockpiling for overproduction, and the costs for concentrating the valuable substance - providing the "ore" is amenable to concentration.

In the case of an extraterrestrial body, the weight of the machinery required for extraction as well as the weight of operation, maintenance and repair materials will be singularly important in determining unit amortization costs since the cost of production (not necessarily research and development) at Earth will probably be small relative to the delivered cost at the use point.

Material extracted from the deposit will be used to determine the milling methods and rates necessary, the amenability of the material for concentration, refining, and production of the usable material, and the unit cost necessary to process the mineral material. At this point the extraterrestrial deposit can be called either a mineral deposit or an "ore" deposit depending on the total unit production cost relative to the total unit cost of material delivered from Earth.

SUMMARY

The cost of the total mining processes is a step-like function divided into the following phases:

Exploration

Development

Extraction

Concentrating

Refining

Fabrication

Each stage in this process provides part of the base for the performance of the following stages. The total process is initiated when the decision is made to exploit those natural resources that are known to occur or believed to occur in sufficient size and grade to produce needed material at a savings relative to the delivered cost of this material in similar form at the use point.

Any mining phase can be terminated at any point if continuance appears to be uneconomical; however, the operation may be economically continued even if the total operation would appear to be at a loss. A loss, for example, may be deemed a small price to pay for insurance toward the survival of the base personnel and relative independence of the transportation umbilicals to Earth. If both the exploration and development phases have been completed and it is apparent that production of the needed substance will be at an overall loss, actual production of the substance may recoup a part of the loss. Since the deposit has been developed, these costs or a portion of these costs have already been spent and may be regained only by production. This can be true at any point within the total process.

Part of the cost of research and development of equipment and techniques that could be applicable to mining will probably not be chargeable to this process since the work will have been done in the interest of scientific planetary exploration. This will probably also be true for the exploration, and to a lesser degree, the development phases. Scientific exploration may define provinces of enrichment of a substance of interest and may even locate, explore, and map in detail individual deposits potentially exploitable. Thus, the mining process may be aided by exploration, construction of a base or network of bases, by research and development of construction and scientific equipment related to the scientific exploration program long before a decision to extract the natural resources has been made.

Those natural resources that may be usable depends on the stage of planetary exploration, the projected extent of total planetary exploration, and the level of technological development at the time a decision to "mine" is made. No decision to mine should certainly be made prior to initial exploration of a planet and, if only a few visits by a few men will be made, it would not be feasible to ship the necessary equipment and materials to the planet. Since the fixed costs of research and development, exploration, development and mining, milling, refining equipment must be amortized, a low or reasonably low amortization unit cost of these charges will be possible only for large quantities needed for future exploration. Thus, the projected exploration rate is an important factor in an exploitation decision. The level of technological development will aid in determining which of the resources can be used.

Not only the total quantity of material that can be used but also the use rate is very important in the choice of mining techniques and the feasibility of exploration.

If material is produced at a pace much more rapid than it is used, then facilities for storage or stockpiling must be provided. Interest on the money invested in mining as well as in the additional facilities may increase the unit production costs to the uneconomic point, and a low use rate may thus favor less efficient mining processes or may render exploitation uneconomical.

COMMITTEE REPORT
MATERIALS EXPECTED IN SPACE AS RELATED TO THEIR PREPARATION, PROCESSING AND EXTRACTION COMMITTEE

Paul G. Herold, Chairman

In order to get a start into the many problems involved, this report is limited to materials expected on or near the lunar surface. Later, problems of the properties of such materials will be considered and how these properties affect the preparation for processing and extraction of desired materials. Eventually consideration will need to be undertaken concerning materials on bodies other than the moon.

The problems which were considered at this time are:

1. What are the materials likely to be found on the lunar surface or within 100 feet below the surface.

2. Discussion of effect of radiation upon oxides, sulfides, hydrates, and any other materials which might occur on the lunar surface.

3. What affect will deep vacuum and temperature changes encountered in the lunar environment have on materials which might be expected to be present.

4. Review of what sort of condition might be expected of the materials on the lunar surface.

Admittedly, the committee has made only a start on the study of these problems, but we expect to delve into the problems further and report at a future date.

Problem 1. Work by Dr. R. Q. Shotts who is teaching at the School of Mines, University of Alabama, and is also working with the Marshall Space Flight Center.

Three models have been proposed to explain the conditions of the lunar surface based on different modes of formation. These are 910 Meteoritic and Planetesimal Impact Model, 920 An Intermediate Model, and 930 Outgassing of an Original Hotter Moon Model. The basic "cold-moon" model, Model 1, is least likely to have surface free-water or hydrocarbons. Due to low surface temperatures and the probability of a considerably thinner atmosphere during the Eoseline period (Bensko, 1960) Model 1 is less likely to have hydrated minerals at the surface. Abundant hydrated silicates, except those unstable in vacuum, are much more likely in Models 2 and 3, especially in the mare areas. In Model 1, hydrated silicates, other hydrated minerals, and hydrocarbons may exist at depths of 500 meters or more, although their presence is not probable at the surface. This conclusion seems reasonable because the lunar surface according to Model 1, must have always been at a low temperature (close to that of space) except for short times of higher temperature due to meteoritic impact and during the lunar day when the heat from the sun warmed it to a depth of a few centimeters. It is possible that during the cooling period which followed large impacts, some hydrated minerals might have been formed near the surface.

The following list indicates certain elements and compounds which may occur on or near the lunar surface in one or all the Models:

Water
Hydrated silicates such as serpentine, chlorite, mica, or zeolites.
Hydrocarbons
Carbon
Sulfur
Boron compounds
Nitrogen
Halides
Metallic Sulfides.

Water is certain to be present in Model 3 because of the close earth analogy. Free water is less likely on or near the surface for Model 2 than for Model 3 but both water forms should be present at moderate depths.

Kosyrev's Observations (Alter, 1958) established the presence of carbon (hydrocarbons).

In Model 3, soluble salts, sulfur gases, boron compounds and halides are quite likely to be found, as their terrestrial occurrences often accompany volcanism.

A general consideration of and extension of earth geological considerations leads to the conclusions that on the moon:

1. Large bodies of hydrous minerals are more likely to be found (a) near the edges of the maria; (b) in the vicinity of rilles and valleys on the maria; and (c) near lunar domes and wrinkle ridges, under almost all assumptions of lunar thermal history except that of early and complete melting. In the latter case, large deposits might also occur in a light, differentiated crust on the terrae.

2. If the theories of historical selenology are assumed, which rule out lava-covered maria, hydrous mineral deposits are likely to be small and irregular and to occur as entrapments in the debris of the walls and in the brecciated bottoms of the larger lunar craters, both on maria and terrae.

3. If the maria are of effusive igneous origin (ash, welded tuff, ignimbrite), mineralization in fissures, breccia, etc., from escaping volatiles should be widespread and easily found near any kind of break or disturbance in the mare surface.

Problem 2. The affect of radiation upon oxides, sulfides, hydrates and any other materials which might occur on the lunar surface. The following summary of work has been done by Charles KenKnight of the Surface Physics Laboratory of Litton Industries, Minneapolis, Minnesota.

The main result of work in the past year or so is that the optical light scattering properties of the moon can be understood to result from an under-dense powder surface that has been sputtered by the solar wind for a geologically short time on the order of 10^5 years. Both the intensity and polarization of light scattered from various test samples of terrestrial rock powders are in good agreement with lunar light-scattering if the powder particle size is about 50 to 100, if the powder is sifted for minimal compaction, and if the sample has been sputtered in a simulated solar wind. After the equivalent of about 10^5 years of solar wind at the moon, the albedo is reduced to values in the lunar range and the color is subdued to a near-grey for basalt or to a slightly more reddish hue for material richer in silica. For this amount of sputtering, the uppermost dust particles are only partially sputtered away and the visible erosion effects besides the darkening are not marked. After another order-of-magnitude increase in the sputtering, the samples are too dark and erosion effects become visibly obvious.

While the knowledge of the solar-wind fluxes at the surface of the moon, particularly in past geologic ages, might be uncertain by an order of magnitude to more and because the solar-wind should be simulated more faithfully in additional experiments, the suggested time scale of darkening in 10^5 years should not be taken too seriously. Nevertheless, it seems inescapable that the darkening effect is limited by the operation of another moon-wide erosion process whose action amounts to the uncovering of underlying, untreated lunar material. Meteoritic bombardment is the obvious candidate. The competing process should disturb, on the average, about 10^{-2} cm per 10^5 years or about 1 m/10^9 years at the current rate. There is evidence from the Ranger series of photographs of lunar maria that there is in these regions a disturbed layer about 10 m thick. The argument involves the relative absence of crisp, uneroded craters of 100-m dimension in comparison to features larger or smaller than this diameter. If a meteoritic bombardment disturbed a layer averaging 10 m thick, craters much larger than 100 m in diameter would hardly be changed in visual appearance while much smaller craters would presumably be formed in that layer. But a 100-m crater would be about 10 to 20 m deep and would be markedly rounded by a blanket of debris 10 m thick. So if maria are about 10^9 years old and if account is taken of the very likely decrease in the meteoritic bombardment rate since that epoch, then the rough estimate of a disturbed layer of 1-m thickness in the previous paragraph is in reasonable accord with an observed feature of the lunar surface.

Since a disturbed layer of 10-m thickness that might have been more or less exposed to the solar wind is by no means a trivial consideration in the availability of resources to lunar expeditions, it seems important to consider what resources might have been depleted or enriched in that layer by solar-wind sputtering. In particular, the possibility of reactive sputtering proceeding at a rate one or two orders of magnitude faster than physical sputtering of rock materials with the formation of compounds that would be vapors at 100°C would virtually assure complete depletion of those constituents from the disturbed layer. The reason is that loss of vapors from the lunar atmosphere is rapid through charge-exchange with solar-wind ions and forceful removal by the solar-wind magnetic field.

A few experiments relating to reactive sputtering have been made. In the cases of metallic Sn and free C (graphite) it has been found that "erosion" proceeds more rapidly than rock materials by several orders of magnitude. A number of metallic oxides (Al, Ti, Fe) are sputtered by either hydrogen or helium ions at a rate somewhat lower than the respective metals as though the oxygen and metallic atoms had to be dislodged separately. No data exist as to whether the hydrogen bombardment gives rise to H_2O molecules. When carbon is combined as in $MgCO_3$, no unusual erosion is obvious. ZnS is attached rapidly by hydrogen sputtering but, while H_2S was an end-product, it is not known whether H_2S was formed within the ZnS sample or secondarily within the experimental tube. Certain metallic oxides are readily reduced (Fe_2O_3, CuO, Cu_2O).

These exploratory experiments indeed suggest that chemical alteration of an important upper layer of the lunar surface might have occurred, but by no means permit an assessment of the extent of that alteration except, perhaps, in the very important case of oxygen. Oxygen should be only slightly depleted in favor of heavy metal atoms.

In conclusion, it seems probable that detectable solar-wind effects are not confined to the presently uppermost lunar surface particles, but through meteoritic mixing of the lunar surface material the solar-wind effects should be detectable to the depth of that disturbed layer. Present knowledge of solar-wind fluxes and the darkening rates for rock powders that are likely lunar surface candidates point to a turnover of the lunar surface layer many times in the lunar history. Sputtering effects are therefore probably detectable to the depth of the disturbed layer. The layer is estimated from the current darkening rate to be of the order of 1 m thick and from the Ranger photographs to be about 10 m thick. Certain elements forming volatile compounds with hydrogen, H_2O excepted, should be depleted from the disturbed layer while oxygen will be mildly depleted.

Problem 3 . What affect will deep vacuum and temperature changes encountered in the lunar environment have on materials which might be expected to be present. No work was done on this during the present period.

Problem 4. Review of what sort of condition might be expected of the materials on the lunar surface. Report by Rodney Johnson of the Valley Forge Space Technology Center, General Electric Co:

TERRAIN

A. Surface Slopes

Two types of slopes are recognized. The first type is that slope associated with the gross terrain. Previously accepted evidence for steep slopes is no longer accepted since both photographic shadow analysis and Ranger data indicate that the larger surface formations do indeed have gentle slopes seldom exceeding 10 degrees in magnitude. Smaller and more frequently encountered surface features, however, may have relatively steep slopes, in some cases greatly exceeding 15 degrees. This conclusion is supported primarily by analysis of Ranger VII photographs and the contribution which craters make to surface roughness.

Utilizing Ranger VII data, the author made a comparison of pre and post Ranger VII photographic terrain roughness. Random traverses were plotted on the lunar charts totaling some 2000 feet in length. Profiles were plotted for these traverses corresponding to the contours of the lunar charts. Using the approach followed by Mason, et al, the data were tabulated according to slope angle as a function of the total distance covered. Several conclusions are evident. One is that based on pre-Ranger data, the gross slopes of the maria and the highlands are comparatively low and that the terrain on a microscopic scale reflects slopes less than 4 degrees. When the resolution is improved from about 5000 feet to 2 or 3 feet, the slopes become steeper, the craters more numerous and the terrain on a microscopic scale increases in roughness. Caution must be exercised in interpreting these data since the small areal coverage of the Ranger VII photographs necessary to provide the fine resolution also precludes long traverse distances.

B. Crater Shapes

Baldwin has plotted crater depth versus crater diameter for lunar craters as well as some terrestrial craters and explosion pits. The data have been extrapolated to diameters less than 5000 feet (terrestrial telescopic resolution) and form the basis for the argument that steep slopes do exist on the Moon. Plotting of Ranger VII data shows slopes as steep and shapes in general agreement with those depicted by Baldwin.

It is interesting to note, and most significant to observe that Ranger VII data agree well with Baldwin's data for small crater diameters, thus Baldwin must be recognized for having performed some early work of high quality and validity.

Dust

That the Moon is covered by a deep layer of dust contributed either by cosmic depositions or crater ejectaments is disproved by Ranger data. Ranger VII photos indicate a rock mass which appears free to dust accumulation. The last Ranger IX photo from the B camera shows a number of rocks on the lunar surface having major diameters of 10 inches. Deep dust would have obscured these features had it existed, though it must be admitted that the prominence seen in the photograph may be a visible portion of a larger rock already partially obscured.

Crater Types

A. Primary Impact Craters

Kuiper indicates that the frequency of primary impact craters on the maria increases four fold each time the crater diameter is halved. Thus if craters are arranged in groups by crater diameter 1 to 2, 2 to 4, 4 to 8 meters up to 1000 to 2000 meters and so forth, each group covers roughly the same area, the total areal contributions being about 1 percent.

B. Secondary Impact Craters

These craters have diameters about one-tenth to one-twentieth the diameter of the primary and increase in number with decreasimg diameter somewhat faster than do primary craters. Secondary craters decrease in number very rapidly beyond about three crater diameters from the primary, though many isolated secondaries may occur beyond this range. Distant secondary craters are often irregular in shape due to the fragmented condition of the impacting mass.

C. Collapse Craters

Ranger IX photographs of the crater Alphonsus indicates the presence of dimple craters accounting for nearly 90 percent of the craters on the floor of Alphonsus. This confirms the conclusions reached by Kuiper after inspection of Ranger VII photographs and offers striking evidence of the existence of internal conditions leading to collapse or cave-ins of the surface material. Kuiper explains these cave-ins as post-cooling collapse of high porosity rock froth, internal drainage of magmas, low proportion of solid rock to liquid rock at time of formation or to the escape of gases leading to collapse. Kuiper considers that these cave-ins are analogous to terrestrial karst formations resulting from limestone solution-forming sink.

SURFACE COMPOSITION

Some additional light has been shed on the composition of lunar surface material by the Ranger photos. One conclusion reached by the Experiments Team is that the maria are lava flows or a succession of lava flows, each having a distinctive color.

Lunar ridges are considered to be the result of uplifting at the maria floor by dikes forming along structural planes. Kuiper believes these planes to be due to both global and regional dynamics. This action is suggestive of seismic events. Mountain ranges forming ridges of continuous extrusions or cinder-cones have been observed. Craters on the cuests are covered with a white substance, as yet unidentified. That this substance could be the residue of evaporates having very low vapor pressure at lunar temperatures (such as C_aO, M_gO) is one possibility suggested by Kuiper

SURFACE BEARING STRENGTH

Some insight into the bearing strength of the lunar surface can be derived by inspection of the photos for rock formations. That rocks are quite rarely evident is inferred as an index to possible low surface bearing strength, the impacting rocks penetrating into and below the surface. The Experimenters Team suggests that the average strength of lunar surface rock varies from about one to ten tons per square foot. The floor of Alphonsus probably averages about one ton per square foot which corresponds roughly with the unit load of an average man's foot.

Committee Members:

R. Q. Shotts
C. KenKnight
R. Johnson
P. C. Herold, Chairman

COMMITTEE
ON
INDIGENOUS LUNAR POWER SOURCES

The Indigenous Lunar Power Sources committee has had a reasonably productive year, with several committee members actively participating. The present committee membership is as follows:

Dr. Carl F. Austin, Research Geologist
Code 5007, U. S. Naval Ordnance Test Station
China Lake, California 93557

Mr. J. Kenneth Pringle, Physicist
Code 5007, U. S. Naval Ordnance Test Station
China Lake, California 93557

Mr. Richard Fulmer, Chemical Engineer
Code 4511, U. S. Naval Ordnance Test Station
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Mr. Modesto Leonardi, Manager of Plant Production
American Potash & Chemical Corporation
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Mr. Dwight Sawyer, Manager
U. S. Borax Research Corporation
Pilot Plant Research Department
Boron, California

Mr. W. J. Levedahl
Nuclear Division
Mail No. 803
The Martin Company
Middle River 3, Maryland

Dr. George A. Kiersch
Department of Geology
Cornell University
Ithaca, New York 14850

The topic of committee study for 1965 has been the consideration of the validity of the geothermal concept as a lunar power source and some of the associated problems this type of power source might encounter.

Each of the committee members has been asked to contribute not only to general discussions but also to consider specific aspects of lunar power production that falls within his own professional specialties.

The following summarizes the individual committee member assignments and the general results for the year:

1) Dr. Austin - to establish the most probable types of lunar geothermal products. During the past year Dr. Austin, with his associates, has sought to establish the most probable geothermal products and types of deposits for the lunar environment. As a part of this study he also has conferred with leaders in the geothermal and geochemical fields, in both industry and government, and in particular with Dr. Don White of the U. S. Geological Survey at Menlo Park and Dr. Edwin Roedder of the U. S. Geological Survey at Washington, D. C. Dr. White's beliefs indicate an emphasis is warranted on deliquescent salt phenomena while Dr. Roedder's work with fluid inclusions, especially from deep ultrabasic and basic rocks, indicates that more attention should be paid to CO_2 and other possible carbon-containing gases and to CO_2 utilization as a source of energy, life support chemicals and fuels.

2) Mr. Pringle - to establish the validity of the fundamental assumption that is the basis for a lunar geothermal program, i.e., that lunar vulcanism or at least lunar outgassing is a contemporary phenomenon. This work has been carried out to date as a literature study.

3) Fulmer - to consider methods of utilizing geothermal products with the present study by means of literature studies and by discussions with other technical experts in the field of energy conversion.

4) Leonardi - to consider the problems of equipment corrosion. Corrosion is a major problem when handling volcanic gases and geothermal fluids, and nothing could be more frustrating than to deliver and assemble equipment at great effort and expense only to watch it corrode and crumble as soon as it is put into service. Continued thinking in the area of corrosion control will be extremely valuable to any attempts at lunar geothermal exploitation.

5) Sawyer - to consider deliquescent salts and their utilization.

6) Levedahl - to consider the "competitive environment" in which geothermal or other indigenous power sources must operate.

7) Kiersch - to consider the overall aspects of geothermal deposit probabilities on the moon. Dr. Kiersch brings to the group a considerable fund of knowledge in the geothermal area, having prepared a rather voluminous report on geothermal power recently for AFCRL. Dr. Kiersch has already submitted a useful summary of his ideas on the lunar geothermal potential, and he too appears to be optimistic. He suggests that infrared studies will be a valuable lunar prospecting method which should then be followed up by surface observations.

The written output of the committee has been as two formal papers and one informal report. Messrs. Austin and Pringle presented a preliminary paper on the lunar geothermal concept at the American Astronautical Society meetings in Chicago in May 1965. This paper was entitled: "An Approach to Indigenous Lunar Power—The Geothermal Concept."

A final paper for this year on the geothermal subject has been prepared by Messrs. Austin, Pringle, and Fulmer. This paper, entitled: "Lunar Geothermal Power: Some Problems and Potentials", will be presented at the annual meeting in Colorado Springs by Mr. Pringle.

Mr. Leonardi, as the result of discussions with a number of corrosion control experts, prepared a brief report which indicated that in the present day brine handling and processing industry, titanium was the most universally corrosion-resistant construction material that is readily available, being better than both the common metals and the common plastics.

One area of collateral activity is worth noting at this time. A cooperative venture has been undertaken by Dr. Austin with the U. S. Geological Survey to examine and study a geothermal area that occurs primarily within the boundaries of the U. S. Naval Ordnance Test Station at China Lake. The U. S. G. S. portion of this study is being conducted by Mr. Howard H. Waldron, Geologist, Engineering Branch, U. S. G. S., Denver. These studies will initially include a remote sensing study (IR and Microwave Imagery) and air photo geology studies with both color and black and white photo runs. Dr. Austin has arranged for the use of the geothermal field area and for support by the Naval Air Facility at China Lake, and he plans to provide the ground parties for positioning the precision navigational aids. The U. S. G. S. portion of this study of a geothermal area is part of a remote sensing program being conducted by NASA, which should provide valuable data pertinent to studies of the lunar indigenous power potential.

As mentioned in the September progress report, Messrs. Austin and Pringle tried firing a large shaped charge into a patch of diffuse boiling ground in a thermally active area, in order to see whether or not a larger volume of concentrated steam flow could be obtained from the resulting crater or bore hole. The experiment gave excellent data on the structure of small boiling mudsprings but the steam emissions remained too diffuse to be of value, suggesting that shallow well boring plus adjacent surface sealing might have worked better in the loose gravel outwash through which the steam emissions were occurring. Probably a "gathering tent" placed over the area of steaming mud would have been equally successful and much simpler from the standpoint of low pressure gas collection. However, the resulting crater did give a rapid temporary outgassing of the immediate crater walls and the explosion and resulting shock wave caused a very marked increase in the rate of gas emission in adjacent boiling mud springs over a radius of approximately 100 yards and also resulted in new steam eruptions scattered throughout previously quiescent ground that had been safe to walk upon. The scattered new points of steam emission have persisted for several weeks now, while the formerly increased activity has died off to a "normal" rate of activity.

For Next Year

During the coming year, the committee on Indigenous Lunar Power will emphasize the potentials of gravity-based power schemes. Gravity-based indigenous power studies will emphasize the use of convective closed and semi-closed systems and also the use of open systems such as downhill tram lines.

Some continuing effort will also be maintained in the geothermal area.

Depending upon the individual interests expressed by present and future committee members, areas of possible study include bore hole formation by various systems including impacting missiles, deliquescent salts' behavior, attempts to further delineate specific lunar areas of geothermal interest, and studies of ways to use potential geothermal products.

The progress of the thermal area study now underway at the U. S. Naval Ordnance Test Station will be reported to the working group by Dr. Austin or by others working on the project to the extent that the results pertain directly to the problem of establishing geothermal power on the moon.

Respectfully submitted,

CARL F. AUSTIN
Chairman

1965 ANNUAL REPORT

SUBGROUP ON LOGISTICS REQUIREMENTS

by

C. William Henderson - Chairman

During the course of the last year the Logistics Requirements Subgroup has undergone considerable reorganization and consolidation. Because of our organizational turmoil, we have had no subgroup meetings this year, but rather have relied heavily upon the committee chairmen to arrange for the inputs to this year's working group meeting. Unfortunately, the lack of any meetings has resulted in a temporary loss of rapport with the membership. However, some of the members have corresponded with each other or have met with one another, the results of which have been very gratifying. I am sure that you will be pleased with the three papers which will be presented by the Logistics Requirements Subgroup during this meeting.

In brief, the Logistics Requirements Subgroup was formed to determine the potential desirability for extraterrestrial resources and to establish the practicability of their use. We were organized within the framework of five committees, three of which were to establish reference models of logistic burdens imposed by the equipment and facilities required to locate, extract and process resources. The remaining two committees were to assign scaling factors to the logistic burden models, estimate the potential logistics demand and compare the costs of delivering the resources from earth to the cost of manufacturing the resources on the moon or planets.

The five committees were entitled:

Logistics Burden for Propellant Production
Logistics Burden for Power Production
Logistics Burden for Facility Materials
Estimated Resource Demand
Comparison of Extraterrestrial Resources vs.
Earth Resources

Early in the year Dr. Gordon Hammer suggested that his added responsibilities at the Rand Corporation severely penalized the adequate chairmanship of the Resources Demand Committee. Consequently, he requested that his participation be less active. Due to the close interrelationship between his committee and that for Comparison of Extraterrestrial Resources vs. Earth Resources, it was decided to consolidate the two committees under the leadership of David Paul. The new consolidation is now called the Logistics and Resource Demand Committee.

Shortly after the creation of our new committee, we determined that the Committee for Logistics Burden for Propellant Production overlapped the interests of the Mining and Processing Subgroup. In order to avoid any duplication of future efforts, and to provide a closer relationship with the Mining and Processing Subgroup, the committee was transferred to this subgroup. Consequently, Mr. Bruce Hall can now take advantage of the able talents of Messrs. Barney, Gangler, Glaser, Hayward, and Rosenberg.

Despite loss of people to Mr. Hall, we were very fortunate in adding to the subgroup, prior to and following last year's meeting, Messrs. Fulmer, Larson, Jonah, McKaig, Richardson, Sevin, Smith, Woo and Zahn. These members will work with Don Butler on the Committee on Logistics Burden for Facilities Materials. Mr. Howard Segal has joined the subgroup to work with Dave Paul.

We have dropped the efforts of the committee on Logistics Burden for Power Production. This was justified on the grounds that the committee's functions also overlapped those of the subgroup on Mining and Processing and that the committee has not been very responsive. So now we are reduced to two committees, Logistics and Resources Demand and Logistics Burden for Facilities Materials.

I am sorry to announce that Dr. H. Herman Koelle, of our subgroup, elected to leave MSFC and accept the Chair of Astronautics at the Technical University of Berlin in West Germany, which was recently vacated by the untimely death of Dr. Eugen Saenger. Dr. Koeller has long supported the search for cost-effective approaches to space exploration and has actively considered the applicability of lunar resources. The subgroup membe ship will miss his personal guidance. Also we suffered a great loss la month as did, in fact, the entire space program, with the death of our esteemed member, Dandridge Cole. Mr. Cole has made a great contribution to the field of advanced concepts, and is perhaps best remembered for his Panama theory, his concept of macrolife, and his recommendations for capturing the planetoids. You may recall his excellent paper on the latter subject at the last annual meeting at Cape Kennedy. I am sure that the entire membership of the Working Group shares with us our deep regret at the loss of Dan Cole, not only as an ardent proponent for the use of extraterrestrial resources, but, for those who knew him personally, as a warm and engaging friend. Mr. Cole was able to look farther into the future than most men and cannot be replaced.

Despite our setbacks and reorganization during the past year, the Logistics Requirements Subgroup has, in most cases, achieved a first order answer to the questions which the subgroup posed to itself in defining its charter and its direction. It must be reiterated, however, that we depend heavily upon individual membership participation outside of their normal professional endeavors, since there is virtually no government or company sponsored effort relating to the economic and practical uses of extraterrestrial resources.

The Committee on Logistics Burden for Facility Materials, chaired by Don

Butler, was organized within the subgroup to determine the potential desirability for use of extraterrestrial resources as material for facilities construction and to establish the logistics burden imposed by their use. The last annual report contained the outline of a program to be attempted on a year-to-year continuing basis. It was to be concerned with lunar exploration systems and their facility requirements and the material requirements for these facilities which might be satisfied by lunar material.

It was pointed out in the last annual report that some indefinite period of time would be required before a group was organized and functioning on a continuing basis. The personnel of the committee have now been recruited from industrial corporations, university research institutes and government agencies. The number of persons now totals ten. We have a capable group experienced in various aspects of lunar exploration systems and with a good spectrum of background experience.

Identification by the committee of programmed, proposed and projected lunar exploration systems has been started. Projections are being attempted based upon mission requirements outlined in the LESA, and identification of the facility requirements for each of these lunar exploration and scientific mission systems has been started. Once this work has been completed, the requirements for both terrestrially supplied and lunar material will be catalogued.

From this cataloguing, work by the committee can begin on 1) the engineering implications of processing designated lunar materials; 2) a search for possible lunar materials, which by processing, can be substituted for terrestrial material; and 3) a search for possible lunar materials which can be utilized in new and novel applications for advanced facility systems.

Any material application which is feasible can then be subjected to analysis to identify the associated logistics burden and can be evaluated as to its effectiveness and cost savings.

I am especially pleased with the results of the Logistics and Resource Demand Committee, chaired by David Paul. Mr. Paul has devoted considerable amount of his personal time to his committee duties, which almost solely accounts for the results of our subgroup this year. In addition to Mr. Paul, two other members of his committee have evidenced the personal motivation to the working group's cause, so necessary if we are to achieve the goals we so nobly set for ourselves at the beginning of each year.

The Logistics and Resource Demand Committee has dedicated itself to a study of the potential desirability and the practicability of the utilization of extraterrestrial resources in the accomplishment of future space efforts. The committee chose economics as the primary measure of desirability and set out to define those factors which influenced the desirability of various resource development concepts and resource utilization modes. At the annual Working Group meeting of last year it was reported that the problem had been adequately defined and that a methodology had been established which could assess the "break-even" resource production rate requirements for various resource utilization schemes. Application of such a technique to a variety of concepts for resource utilization would allow the identification of those concepts which show the most promise for the enhancement of a future space flight capability and likewise the identification of those concepts which intrinsically cannot be economically exploited and should be dropped from further consideration.

Mr. Rollin Gillespie, who has long been interested in planetary flights, has labored during the year on a mission planner's handbook for the utilization of extraterrestrial resources in the accomplishment of planetary space flight. Mr. Gillespie's paper, which will be presented at this annual meeting and be published in the Proceedings, is entitled "Impulse Propulsion Gains Resulting From 'Free' Retanking of Propellants on Various Orbits and Stations at the Earth, the Moon, Mars, and Venus". It is presented in a format which will permit rapid evaluation of the desirability of many possible resource utilization schemes associated with planetary flights. The use of Mr. Gillespie's charts will establish the zones of interest wherein more detailed analysis should delineate the conditions necessary for an effective exploitation of lunar and planetary resources. Of special significance, was the discovery that lunar resources could substantially decrease the earth launched propellant requirements for low velocity planetary missions if refueling were accomplished at a lunar libration point. This approach, coupled with refueling in the vicinity of the planets, would make major manned planetary missions an economic reality.

Mr. Howard Segal who is also a proponent of extraterrestrial resources, has devoted his time to an effort which will also be published in the annual meeting proceedings, entitled "The Role of Lunar Resources in post-Apollo Missions". Mr. Segal considers the optimistic situation of discovering a deposit of lunar ice and applies the processed LOX and LH_2 propellants to the crew rotation problem of lunar operations. Mr. Segal's results are somewhat pessimistic for the case of a lunar orbital rendezvous mode of crew delivery. Since the resource assumption (ice) was most optimistic, Mr. Segal implies that application of lunar manufactured propellants in a realistic situation to an LOR crew rotation mode will be extremely problematical.

We are fortunate in having a report by Messrs. R. A. Gorrell and J. B. Decdati reflecting the results of an inhouse effort by General Dynamics - Ft. Worth concerning the system requirements for utilizing lunar propellant resources. It is most gratifying to see one of the aerospace companies looking at this problem. The paper to be presented here and published in the Proceedings is entitled "Space Transportation Logistics Requirements Comparison Utilizing Lunar Manufactured Propellants". Major conclusions are that a 12 to 24 man base could economically utilize lunar manufactured propellants for earth return capability; and given a sufficient number of launches, a saving of 40% in launch vehicles could be effected.

Mr. Paul, the chairman, reports that development has been continued and some progress can be reported on the establishment of manufacturing cost burden relationships which are essential to the analysis of economic desirability. Also, a space activities calendar for the lunar program has been postulated. Such a calendar aids the assessment by establishing the resource demand estimates for lunar resource production plants. Since the future of large super rockets is uncertain, the impact of post-Saturn launch vehicles upon resource utilization economics has not been considered. The results of this work will also be presented here by Mr. Paul and will be published in the Proceedings under the title "Economic Analysis of Extraterrestrial Propellant Manufacture in Support of Lunar Exploration". The paper considers application of lunar oxygen production to Earth-Moon crew transport operations, and establishes certain prerequisites for economic justification of this concept. In general, the paper concludes that electrical power production is the prime factor dictating the feasibility of any scheme for resource production. Only when the substantial power requirements can be met with a limited transportation burden can desirability be predicted. Economic desirability is especially sensitive to power plant lifetime and this technology should receive considerable attention if extraterrestrial processing is to become a practical reality.

In summary, the Logistics and Resources Demand Committee has established first-order answers to the question of resource feasibility (or has delineated a methodology which can produce the desired answer) as it applies to lunar exploration operations or to the application to planetary space flight missions. As a Committee the self-imposed goals have been, at least moderately, achieved.

As a goal for next year's effort, in addition to a refinement of the techniques and analyses, it is suggested that the development of specific systems and operational concepts requiring the use of extraterrestrial resources seems appropriate. Systems, operations, and flight modes could be suggested which would effectively utilize space resources to enhance mission performance. It should be possible to suggest space exploration concepts built expressly upon the utilization of extraterrestrial resources as an inherent feature of the scheme rather than as an unorganized afterthought.

It is hoped that the Working Group and this Subgroup can continue to dedicate their efforts to our original cause and vigorously pursue this important challenge during the coming year. I also strongly urge that each of us in the Working Group continue to encourage both government and industry sponsorship of studies relating to the exploitation of extraterrestrial resources, with special emphasis on how and WHY such exploitation can advance man's conquest of space.

Mr. Chairman and Fellow Participants:

The Biotechnology and Human Factors Subgroup has initiated its expanded activities somewhat cautiously. In the papers to be presented at this session of the Working Group, cost consciousness or realistic evaluation of man's capabilities in extraterrestrial environments provide the underlying theme. This is following the guidance expressed last year by our Group chairman.

Our chief concern has been in the past year, how the Biotechnology Group may more closely support the other groups, and how its services could be unique, that is not duplicating work of other similar groups.

In our summer meeting we undertook to expand the experience base of our group, and I am happy to report that we have been successful in adding about 15 new participants of a wide variety of specialties, most of whom will be with us at this meeting, and in consequence we will be better able to assist in other Subgroups on problems of special interest to them.

We are currently investigating the activities of similar groups associated with our technical societies, so that we will not needlessly duplicate their efforts.

As a group we are investigating the special group studies which may be undertaken, particularly with respect to the support of the other Subgroups.

An interim evaluation of our current position, vis à vis extraterrestrial resource exploitation, points out need for study in the areas of:

1. variation of metabolic rate with environment and activity.

2. dexterity in protecting garments

3. effective materials balances in closed systems

4. Leakage parameters as functions of systems design, activities and materials

5. Minimum ecologies

In our coming year we plan to organize for specific group studies, and we envision about two formal meetings per year, one in the spring at a laboratory or operational facility critically engaged in biotechnological development or application, and the other meeting will be in connection with the annual group meeting.

Though, we have not generated the progress hoped for at the last annual meeting and have had only one subgroup meeting, we have maintained member contact through correspondence, work sheets and the "autovon system". With our enlargened participation, we will strive for greater support for the other subgroup activities in the coming year, and will work toward fulfilling more specific working group goals.

PLANS FOR 1966 - by Dr. E. A. Steinhoff, Chairman, Steering Committee

During the past year, the lack of accepted space mission models, describing space flight modes using extraterrestrial resources, has become more and more obvious. While many studies presented during this meeting give very good answers to approaches to use extraterrestrial resources, the analysis of missions including these has not kept step. However, recognizing this problem, the papers to be presented by Rollins Gillespie and Dave Paul, using extraterrestrial mission modules, give examples of what I mean and point in the right direction towards more critical evaluation of the cost effectiveness of such approaches and of their operational pay-offs. It is recognized that the availability of a mere comprehensive picture of the economic use of extraterrestrial resources not only would focus the work of our Working Group towards the more promising solutions, but also help to weed out those techniques which could lead to blind alleys.

Another problem area is the need for common reference data, permitting each worker in the field to use the same reference data. It has been therefore proposed to prepare a common source book on extraterrestrial resources for use by all members of the Working Group and beyond this, by anyone who has an interest in the use of extraterrestrial resources. Beyond that, it has been proposed that the individual subgroups address themselves to the following four broad areas during 1966:

A. Extraterrestrial Environment and Resources

1. Present methods for determining resources

2. Potential extraterrestrial resources

3. Probability of resources

B. Mining and Processing of Resources

1. Types of resources and how to use them

2. Resources processing techniques

3. Resources mining and transportation techniques

C. Human Factors, Biotechnology and Life Support Aspects

1. Types of human support required

2. Human capabilities to process resources

D. Resource requirements and cost effectiveness

1. System requirements to manufacture resources

2. System concepts to utilize resources

3. Cost effectiveness and practicability of utilizing resources

Furthermore, it has been proposed that the history, aims and objectives of the Working Group be formulated by the subgroup chairmen in cooperation with the chairman of the Steering Committee to provide a prospective to be available to those who formulate our national spaceflight objectives.

In order to improve focusing of 1967 work to a more comprehensive effort towards those solutions which would permit utilization of extraterrestrial resources, beginning the second half of the 1970 era, a determined effort will be made in the second through fourth quarter of 1966 to improve our model use and begin optimization of spaceflight models using extraterrestrial resources, and study to what extent spaceflight missions can be based on fully reusable spacecraft models. This appears to be a difficult objective and it will not be easy to forecast how far we can proceed in 1966. However, it will be certain that we can continue to focus suggested work assignments such that the most promising avenues of approach be used and a more concerted effort towards a common goal is possible.

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TRANSIENT LUNAR EVENTS: POSSIBLE CAUSES

B. M. Middlehurst and J. Burley

Abstract

A literature survey has produced records of 200 sightings of apparent activity on the moon; of these, 145 were dated. Analyses of the dates of occurrence were made. It was found that a large proportion occurred within a few days of mean perigee or mean apogee, and this suggests a relation with tidal effects due to the earth's gravitational pull. Work on this aspect is continuing. A negative correlation with sunspot numbers as a measure of solar activity suggested earlier by other workers is not supported by our evidence.

Survey of the Material

This paper reviews records of observations relating to apparent lunar activity over a period of nearly four centuries. The earliest record which we have found refers to a naked-eye observation of an event in March 1587, and records are continuing. About 145 records appear to refer to real events and these are analyzed below.

In about half of the cases considered we have been able to consult the original reference; and of the other half only those events have been included that appear to have been reliably reported. The new edition of Houzeau and Lancaster's Bibliographie General d'Astronomie, edited by David Dewhirst (1964) was extremely useful. This lists all papers known to the compilers up to 1880 on every subject considered by them to be important astronomically. It is a very valuable collection since at least one of the authors, Houzeau, traveled extensively in many countries and was able to consult a large number of libraries and private book collections. J. H. Schroeter, an enthusiastic and careful German amateur astronomer of the eighteenth century and friend of William Herschel also contributed contemporary reports of many observations between 1780 and 1790 in his Selenotopographische Fragmente (1791).

We have included observations of temporary bright spots, as well as veils, obscurations, and brightening of crater floors and other small areas. Most of these occurred in Alphonsus, Aristarchus and the surrounding area, Plato, Mare Crisium, and Theophilus. Many other phenomena were recorded as bright spots, without reference to their location on the moon. The various types of phenomena seem likely to be closely related since many records of veils and/or bright areas are available for Aristarchus and also for Alphonsus and other areas where bright spots have been recorded; the report by G. A. Alter of obscuration of details in the floor of Alphonsus noted in the UV relative to the red from photographs led Kozyrev to watch the behavior of Alphonsus and later to obtain the only spectral evidence of an apparent lunar eruption or exhalation of gas which has been recorded up to the time of writing. In assessing the value of Alter's photographic records of an

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apparent event in Alphonsus, attention must be paid to the fact that seeing is always poorer in blue light than in red, and the details of Alter's blue photograph are more blurred over the whole blue plate as far as can be told from the reproduction. Nevertheless, Kozyrev's spectral record of an event on November 3, 1958, is now accepted as genuine. The reports from Flagstaff of events seen in 1963 by Greenacre and other observers are without question the result of observing real changes in the appearance of the Aristarchus region (Greenacre 1964). In other cases, however, it was not always clear that a report represented a real event rather than a record of a difference in albedo, but in such cases which were relatively few, if any doubt remained, the record was omitted. We did not include reports of changes in shadows, dark or bright areas or the morphology of craters or rays; this was partly because there was some uncertainty as to whether the changes were recorded at their first appearance so that the date of the record might lack significance. Reports of changes in such features as Messier and Linné have been so much disputed that it was decided to exclude these altogether. Many of the observations used in our survey were made by Argelander, Bode, W. Herschel, Olbers, Piazzi, F. G. W. Struve and others of integrity. We feel that independent observations by such respected observers could hardly be dismissed en bloc and, though over a number of years records of similar phenomena have repeatedly been discounted one by one, we believe that they now amount to a significant body of information even though details, as always with visual observation, may be subjective.

We have compiled a listing of 145 observations starting with a report in Harrison's Description of England (see Lowes, 1927). This refers to an event in March 1587: a bright spot on the dark side of the moon "directly between the pointes of her hornes, the mone being chaunged not passing five or six daies before." We have found records of two events in the seventeenth century, twenty-seven in the eighteenth, and thirty in the nineteenth. In this century around eighty-five events have been reported up to the present date.

By far the largest number (about 40) of lunar events was reported in or near Aristarchus. Plato was second with twelve reports; however, several other Plato reports have been rejected by reason of the topography of the region which leads to peculiar effects at sunrise. The location of an event was not always stated in the reports.

Some descriptions follow. J. H. Schroeter wrote in the Astronomische Jahrbuch for 1792 that he observed on September 26, 1788, "a whitish bright spot shining somewhat hazily and 4" to 5" of arc in diameter, as bright as a star of 5th magnitude, about 1' 18" southwest of Plato and in the bright mountainous region bounding Mare Imbrium." It was visible for 15 minutes.

A more recent example is contained in a report by G. Jackson in the Bulletin du Societé Astronomique Français describing the lunar eclipse of March 21, 1913: "During totality there remained visible to the northeast only a luminous point, not much larger than the planet Mars, and of the same color."

Most of the observations are described as a "bright spot" or a "brilliant point," but twenty state that the color was red or reddish. Color determination is a particular problem with visual observations, and must be regarded as subjective.

The data remaining after the deletions mentioned above are analyzed below from two points of view: (1) possible relation with solar activity as measured by monthly sunspot numbers, and (2) tidal action.

Possible Correlation with Sunspot Numbers

In a recent letter to Nature, Drs. Flamm and Lingenfelter (1965) considered the possibility of a relation between the number of occurrences of transient lunar events in the vicinity of Aristarchus and the yearly mean sunspot relative numbers. They deduced a negative (or inverse) correlation with solar activity. However, they did not analyze the general distribution of sunspot relative numbers.

We made a more detailed statistical investigation using all possible observations of transient lunar events using monthly rather than yearly sunspot numbers. These were available from January 1749 until June 1964, covering 2586 months (Waldmeier, 1961 and Quarterly Bulletins). In comparing our results with those derived from the data used by Flamm and Lingenfelter, the number of events considered by them was increased to twenty-two to include the observations by Bode from March-May 1789 which they counted as one as three events and by Kozyrev in November-December, 1961 similarly as two.

Table 1

Records of Lunar Events According to Monthly Sunspot Relative Numbers

Monthly Mean Sunspot No.	(Aristarchus F & L)		(All Available, J.B. & B.M.)		Total	
	No. of Events	%	No. of Events	%	No. of Months	%
0 to 30.0	13	59.1	37	35.9	1064	41.1
30+ to 60.0	4	18.2	26	25.2	691	26.7
60+ to 90.0	1	4.5	20	19.4	423	16.4
90+ to 120.0	1	4.5	8	7.8	220	8.5
120+ to 150.0	3	13.6	3	2.9	109	4.2
150+ to 180.0	0	0	5	4.8	52	2.0
180+ to 210.0	0	0	2	1.9	21	<1
210+ to 240.0	0	0	1	<1	5	<1
240+ to 270.0	0	0	1	<1	1	<1
Total	22	99.9	103	100	2586	100

In Table 1, the percentages of entries in each of the Flamm and Lingenfelter groups is shown, together with the total number of events considered by us up to the middle of October, 1965. We consider that no correlation with sunspot number is shown, but that the differences in the

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various columns are due to statistical fluctuation. The data of Table 1 appear to be consistent with a random distribution of events superimposed on an asymmetric distribution of sunspot numbers with respect to time. The conclusion was drawn that no correlation has been shown to exist between solar activity as measured by sunspot number and the lunar events.

Possible Correlation with Tidal Effects

Another possible cause of the lunar phenomena is change in the tidal stresses set up in the body of the moon due to change in the distance of the principal attracting bodies, the earth and the sun. Differential solar effects are small and changes caused by the librations of the moon are even smaller, but variations in tidal forces due to the attraction of the earth are much more significant. At a distance R, the earth, of mass M_E, exerts a maximum tidal stress per unit mass between neighboring (mutual distance dR along the vector to the earth's center) portions of the moon equal to $\frac{2GM_E}{R^3}\,dR$*. Like the gravitational force, this is maximum at perigee and minimum at apogee. Further, it should be pointed out that the stress at apogee and at perigee deviates by the greatest amounts from the mean value. The eccentricity of the moon's orbit is 0.055, so that the change in the tidal force from maximum to minimum is thus of the order of 30 percent. At the same time it may be noted that both the force of terrestrial gravitation and the tide-raising stress are eighty times the corresponding forces on the earth produced by the moon. Moreover, lunar gravity is less than terrestrial gravity by a factor of six and the cohesive forces of the lunar surface layers are still unknown. It was thought worthwhile to calculate orbital positions with respect to the anomalistic month, perigee being taken as zero phase, and apogee as 0.5 phase.

Figure 1 shows a histogram in which the location in the lunar orbit relative to mean perigee of 145 events for which the exact date is recorded are plotted for each 0.1 of the period, or 2.75 days. Mean perigee is shown as P, apogee as A. These data are also given in Table 2. The events were dated to the nearest whole Julian Day and the actual time of day was neglected. Julian Days begin at noon so that all observations have here been assumed to take place at noon. However, the average error in the time of most observations is approximately +9 hours, i.e., +.013 period, which is much less than the error introduced by the use of mean perigee and mean apogee. The results of Table 2 can only be considered as a first approximation since periodic terms in the lunar theory were not included in the calculation of mean perigee. True perigee can differ from the mean by as much as three days, so that our approximation has lost some resolution. Exact dates of perigee and apogee will be available shortly for comparison with the earlier reports through the kind cooperation of Dr. Duncombe,

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* In a detailed discussion, a harmonic analysis would be needed. However, in the present paper this would be out of place. It is sufficient here to consider maximum stresses which are given by the formula in the text.

Director of the Nautical Almanac Office, and this should improve our statistics.

Table 2

Frequency of Lunar Events with Respect to Anomalistic (Orbital) Phase

Fraction of Period+	Number of Events
.05-.14	16
.15-.24	14
.25-.34	6
.35-.44	5
.45-.54	21
.55-.64	9
.65-.74	11
.75-.84	18
.85-.94	18
.95-.04	27

+ Phase = 0.00 at perigee, 0.5 at apogee.

Nevertheless, the excess of events near perigee and apogee is greater than could be expected as a result of chance and seems to indicate a causal relation with tidal stresses. At or near perigee maximum cracking could be expected; at apogee, the point of maximum relaxation of the crust, a "squeeze" might result and at each of these points, one might expect relatively favorable conditions leading to the release of gases. A similar excess of events near apogee and perigee was found by Dr. Jack Green (1965) who considered fifty events. The nature of a mechanism which might produce a bright spot on the dark side is not at present clear to us. However, whatever the mechanism, tidal forces are probably significant in relation to at least some of the events.

We also computed the age of the moon for all the events considered. Up to 1900, there is a large concentration of observations of such spots in the period before first quarter, the majority being three to six days after new moon; the concentration is not so pronounced for recent observations. This is probably an observational selection effect because the three to six day moon is convenient to observe due to its visibility in the early part of the evening.

Nearly all of the early observations are of points of light on the dark side of the moon. Only when telescopes of larger aperture became more common among moon watchers, that is, after about 1930, did observations of changes on the bright side of the moon become possible for most observers.

Summary

It appears that most of the records of events discussed in this paper

represent some real activity which may be due to endogenous causes. Our findings do not support correlation with sunspot activity as suggested by earlier workers, but the excess of events recorded within a few days of mean perigee and apogee suggest a correlation with tidal forces. It may be that tidal cracking causes release of volatile material from subsurface layers. Various mechanisms are under consideration, but we feel that discussion of these would be premature at the present time.

References

Fisher, W. J. (1924) Harvard Reprint No. 7.

Flamm, E. J., and Lingenfelter, R. E. (1965) Nature, 205: 1301.

Green, J. (1965) Ann. N. Y. Acad. Sci., 123: 403.

Greenacre, J. C. (1963) Sky and Telescope, 26: 316; (1964) Sky and Telescope, 27: 3.

Herschel, W. (1912) Collected Works, ed. J. Dreyer, London, Royal Soceity.

Houzeau, J. C., and Lancaster, A. (1881) Bibliographie General d'Astronomie, 2nd edition (1964) ed. D. Dewhirst, London, Holland Press Ltd.

Klado, T. N. (1965) NASA Technical Translation F-310.

Lowes, J. L. (1927) The Road to Xanadu, London, Cambridge Press.

Moore, P. (1953) A Guide to the Moon.

______. (1965) Private communication.

Schroeter, J. H. (1791) Selenotopographische Fragmente, Göttingen, Joh. Georg Rosenbusch.

______. (1792) Astr. Jahr.

Waldmeier, M. (1961) The Sunspot-Activity in the Years 1610-1960, Zürich, Schulthess and Co.

Wilkins, H. P., and Moore, P. (1955) The Moon, London, Faber and Faber Ltd.

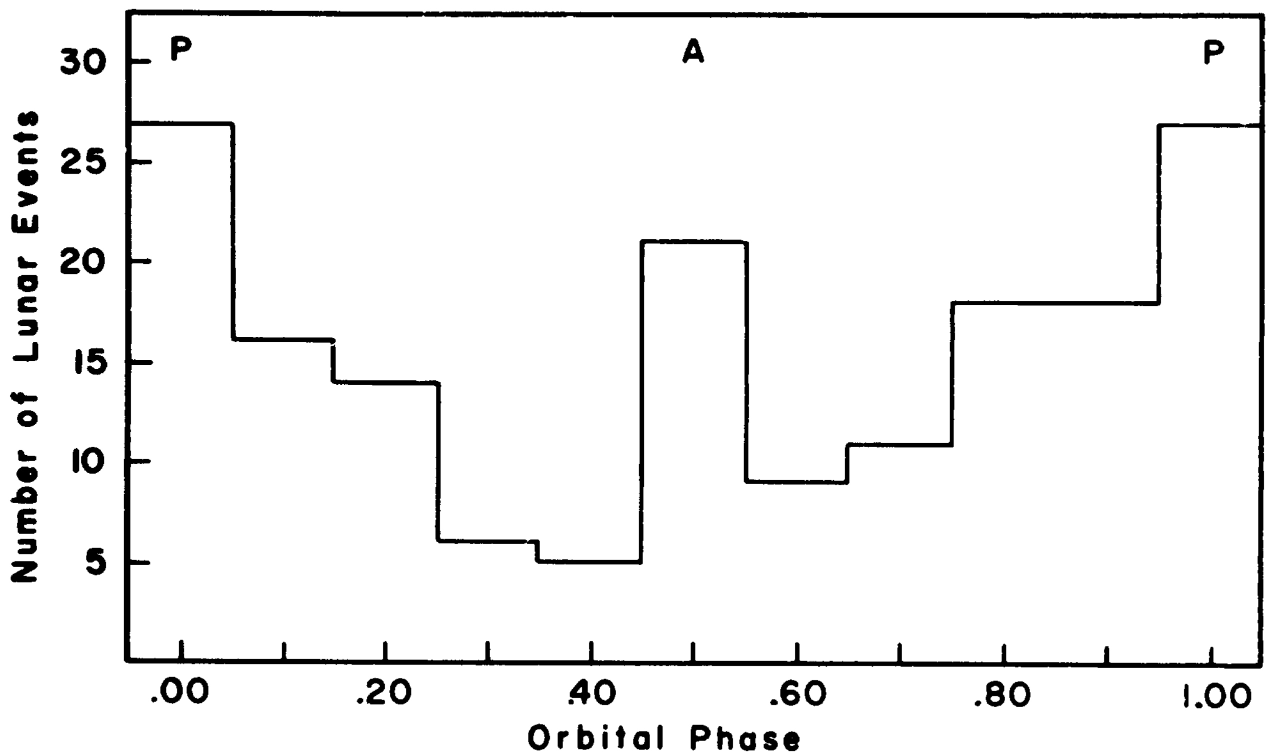

P
A
P
30
25
20
15
10
5
Number of Lunar Events
.00
.20
.40
.60
.80
1.00
Orbital Phase

Figure 1

GEOMETRY OF BACKSCATTERING SURFACES AS APPLIED TO THE MOON*

J. D. Halajian

ABSTRACT

The relationship between the photometric and geometric properties of the lunar surface is studied by means of "artificial" models that, unlike previously investigated natural specimens, lend themselves readily to controlled manipulation and analysis.

"Composite" models consisting of dust covered geometric solids permit the study of the relative contribution of micro and macro-roughnesses (including the effect of slopes) on the total backscatter. A "simple," i.e., dust-free, model built by means of thumb tacks helps to demonstrate that shadowing on and within a dark, porous structure can primarily be responsible for the backscattering exhibited by the lunar surface and that both quasi-horizontal and quasi-vertical members having a well-defined proportion and spacing appear to be necessary components of a lunar photometric model.

"Simple" models of the "thumb tacks" variety help the experimenter to interpret the lunar data or their terrestrial analogs in terms of relevant properties rather than in terms of generic names (i.e., dust, cinder, slag, etc.) that often confuse the issue. These models appear also to be convenient tools for the simulation and study of some recently observed lunar photometric phenomena as well as for the study of other reflecting celestial bodies of known photometry.

*Performed under NASA Contract No. NAS 9-3182

INTRODUCTION

The lunar photometric data are currently gaining increasing recognition as a useful source of information about the detailed structure of the lunar surface (Refs. 4 and 6)* as well as about visibility conditions that will be encountered during lunar landing and surface operations (Ref. 9). Essentially, these data are a measure of the change in brightness of the lunar surface as seen by an observer on the earth during a full lunation and are characterized by a sharp backscatter peak at zero phase angle corresponding nearly to full moon. This peak appears to be independent of location on the lunar disc or of the type of terrain.

An improved photometer recently built at Grumman, capable of viewing areas 3 inches in diameter (about an order of magnitude larger than previously examined), has made it possible to discover a number of "natural" and "artificial" models that reproduce the known photometric properties of the moon at representative longitudes. The "natural" specimens, including fine dust (originally discovered by Hapke), volcanic cinders, furnace slags, sea corals, metallic meteorites, etc., were reported in a previous publication (Ref. 4), and the "artificial" or contrived models are discussed herein. The purpose of these models is not merely to proliferate the number of lunar photometric models for their own sake but to help assess the natural specimens that reproduce or fail to reproduce the lunation curves of the moon.

It was pointed out in Ref. 4 that physical analogs of the lunar photometric function can be useful when interpreted in terms of "relevant" properties. However, these analogs, particularly when they consist of natural specimens, often lead to unnecessary disagreements about the nature of the lunar surface when they are described by their generic names (i.e., dust, slag, meteorite, etc.). The natural specimens that we have investigated suggest that changes in material composition, strength, consistency, depth, grain size, etc., do not affect significantly the photometry of a surface but changes in albedo, porosity, relative micro and macroroughness, slope orientation, etc. do. In this study, an attempt is made to incorporate the relevant photometric properties in contrived models and to investigate their relative contribution to the observed backscatter by varying each variable more or less independently of the other. As with macrorough natural specimens,

*References are listed at the end of this paper with authors names in alphabetical order and are numbered accordingly.

the experiments with the artificial models have been made possible by the large area viewing capability of our photometric analyzer. A detailed description of this instrument is given in Ref. 4.

TEST SPECIMENS

Two types of models designated as "composite" and "simple" have been used in these experiments. The "composite" models consist of simple, wooden or metallic, geometrical solids of varying dimensions and slopes covered by a veneer of loosely sprinkled CuO and/or SiC (carborundum) powders of known albedo and photometric quality. The geometrical solids used were as follows: prisms, pyramids, cups and domes, and hexagonal depressions.

In the composite models, the CuO cover simulates the albedo and microroughness of the lunar surface, and the geometric shapes simulate the gross topographic features of the moon such as craterlets, bumps, ridges, and depressions. These models serve two distinct purposes. One of them is to determine the contribution of the gross features of the lunar surface to its photometric function. This is accomplished by changing the dimensions, slopes and location of the solids while keeping their albedo and microstructure unchanged. The other purpose these models serve is to provide the experience that is needed to create a contrived geometrical model that will match the lunar curves without the help of a backscattering powder veneer. It is desirable to eliminate the dust cover (without compromising the backscatter) because the "fairy castle" structures built by fine powders are too small and complex for detailed scrutiny, whereas those built by geometric, "macro" (i.e., visible to the naked eye) elements could lend themselves to quantitative analysis and could illustrate graphically the relationship of the changes of light and shadow on and within a porous model to their photometric signature.

As was anticipated, the knowledge acquired from the measurement and analysis of a sufficient number of composite models led to the creation of a simpler, more basic model essentially consisting of centimeter-size horizontal and vertical elements. This model is described and discussed in a succeeding section.

Experiments

Brightness vs. phase measurements were performed on various combinations of "simple" and "composite" models. Model geometry, albedo, viewing angle, and condition of illumination (i.e., relative position of the intensity equator with respect to model axis) during each measurement are listed next.

I. The following CuO-covered models were measured at 0°, 30°, and 60° viewing angles:

1. 60° pyramids, 1" high (Fig. 2a).
2. Hemispheric cups and domes, 3/4" in diameter, (Fig. 3a).
3. Hexagonal depressions, about 1/2" across (Fig. 3b).

II. The prismatic solids, covered with CuO powder, were examined at 0° viewing angle under the following conditions:

1. One to five 45°-prisms, 3rd column in Fig. 4.
   a. Intensity equator parallel to ridges, Fig. 5.
   b. Intensity equator perpendicular to ridges, Fig. 6.

2. 5-prism assemblies with 30°, 45°, and 60° base angles, fifth row in Fig. 4.
   a. Intensity equator parallel to ridges, Fig. 7.
   b. Intensity equator perpendicular to ridges, Fig. 8.

III. Mixtures of CuO and SiC powders in various proportions have been sprinkled on a 5-prism assembly and a flat plate. The results at 0° viewing angle are shown in Figs. 4 and 5.

IV. The "thumb tacks" model with and without vertical strips were measured at 0°, 30°, and 60° viewing angles. The results are shown in Fig. 15.

The specimens described in Parts I, II, and III above are termed "composite" models; those in Part IV are termed "simple" models, and are discussed in a separate section.

STANDARD LUNATION CURVES AND DATA PRESENTATION

Brightness averages for a representative number of crater floors, maria, and continents distributed widely over the lunar disk, have been derived by Orlova and van Diggelen. These averages are shown as brightness vs. phase curves in Figs. 1a, b, and c for 0°, 30°, and 60° longitudes (or viewing angles). The Orlova and van Diggelen curves, based on data by Fedoretz and Minnaert respectively, are in fair agreement with one another and support the view expressed by many authors that the moon is nearly, photometrically homogeneous. The gray band enclosed by these curves may be considered as the data scatter for the entire lunar disk; it is adopted as the lunar standard and is used as a basis for comparison with all our test curves. For the sake of clarity, the lines delimiting the band are omitted in the figures containing the test curves.

In plotting the curves in Fig. 1, the individual albedo differences of the crater floors, maria, and continents have been eliminated by normalizing the brightness of each area to a value of 1.00 at about 4° phase angle. This point represents approximately the smallest phase angle at full moon in the Fedoretz-Minnaert observations. The brightness values of the moon at smaller phase angles are extrapolated beyond this point, and hence are unreliable. It was decided, therefore, to normalize the test curves at this point, rather than at 0° phase angle. In our photometric setup, this point corresponds to the position of the sun-source when the frame of the beam splitter obscures the sample. Beyond this position the beam splitter is used (between +4° and -4° phases), and the actual plot is shown by the solid, "dipped" curve which peaks between 0.5 and 0.75 units. This peak represents the brightness of the sample as seen through the beam splitter. The actual brightness of the sample near 0° phase (shown in dotted line) is obtained by multiplying the "dipped" peak value by a factor of 1.66 which represents the correction for the attenuation of light coming through the beam splitter.

Of course, the brightness of the moon at 0° phase, unlike that of our test specimens, is not known, since this position of the moon corresponds to total eclipse, but Gehrels' recent measurements (Ref. 3) taken before an actual eclipse come as close as 0.8° to totality, and reveal a much sharper rise in brightness in this previously unexplored region than indicated by the extrapolations on the lunar standards in Fig. 1. This fact, which Gehrels calls the "opposition effect," may be quite significant and will be considered when evaluating the test results.

Discussion of Test Results of "Composite" Models

I. CuO-covered geometric solids examined at 0°, 30° and 60° viewing angles. The albedo of all these models, regardless of the number of the gross features or viewing position, is the same, and is equal to that of the CuO powder on a flat surface.

1. 60°-pyramids, Fig. 2a. Four test curves are shown in Fig. 2b, taken at 0° viewing angle, representing the photometric properties of a CuO-covered flat surface occupied by one, five, and nine pyramids respectively. Notice that the addition of pyramids progressively increases the slope of the backscatter curve from a value less than the lunar backscatter to one slightly greater. Figures 2c and d show the test results at 30° and 60° viewing angles for the five and nine pyramid patterns. At these viewing angles the 9-pyramid pattern shows a larger deviation from the lunar data than at 0°. These curves clearly indicate that gross features do contribute to the backscattering of light from a surface, but, under the conditions of this experiment, this contribution is negligible compared to that of the microstructure and is within the lunar data scatter band, particularly at 0° viewing positions. It is interesting to note that the best fit is not given by the model "saturated" with pyramids, but by the checkered pattern in which the pyramids are interspaced by flat areas.

2. Hexagonal pits and hemispherical pits and domes. These models, shown in Figs. 3a and b, are made up of stamped metal plates covered with a thin layer of CuO powder. The photometric measurements at the three viewing angles are shown in Figs. 3c, d, and e. The curves for a flat surface covered with CuO are also shown in these figures for comparison. As in the case of the pyramids, there is an increase in the backscatter, but it is noticeably smaller probably due to the fact that the shadow casting pits and domes are not so deep (or high) and so sharp in outline as the pyramids. The increase in backscatter is larger for the hemispheric shapes than for the hexagonal shapes, but the difference is not large enough to warrant further analysis at present.

II. CuO-covered prismatic solids at normal viewing angle. The photometric properties of these models depend upon the position of the intensity equator with respect to the prism ridges. The intensity equator is determined by the motion of the sun-source; the equator is located in the plane of vision which contains the specimen and viewer. Both directions of sun-source travel, i.e., parallel and perpendicular to the prism ridges, have been investigated, both analytically and experimentally. The discussion of test results is presented in terms of model combinations and lighting geometry.

Condition No. 1: One to five prisms, constant 45° base angle (column 3, Fig. 4); intensity equator parallel to the prism ridges.

The photometric properties of the CuO-covered 45° prisms at normal viewing angle are shown in Figs. 5a and b for one to five prisms. The test curves are all nearly identical, indicating that the number of prisms does not affect the photometry of the surface under this particular set of conditions; this set is, in effect, equivalent to a flat surface inclined to the horizontal at the same angle as the base angle of the prism as shown in Fig. 44c. The test curve in this figure does not differ noticeably from the curve obtained from the CuO powder on a horizontal surface, shown in Figs. 2b and 3c. Thus, it is not necessary to measure the photometric properties of the other prisms in Fig. 4 under this particular condition of illumination.

Condition No. 2: Same as Condition No. 1 except that intensity equator is perpendicular to the prism ridges.

The photometric properties of the CuO-covered 45° prisms at normal viewing angle are shown in Figs. 6a to e for one to five prisms respectively. In general, the test curves have a slightly sharper backscatter than measered in the previous condition, because under transverse lighting the prism ridges are in a position to cast shadows. The test curves differ from one another only to the extent that the "bend" at 45° phase shown by the single-prism curve, Fig. 6a, becomes gradually smoother with each additional prism, Figs. 6b to e. A typical analysis of the one-prism and three-prism configuration is presented in Ref. 5. This analysis confirms the experimental curves, as indicated by the plotted points in Figs. 6a and c, and shows that the subsequent blending of the "bend" in the one-prism curve is due to the presence of shadows in the trough of the prisms at phase angles larger than 45°. Since the single-prism configuration does not have any troughs, the entire face remains exposed to light beyond 45° phase and, consequently, registers a brighter signature.

The close fit between the analytical and test curves indicates that, in general, it is possible to predict the photometric behavior of a surface of known geometry, like the geometry of the prisms shown in Fig. 4, if the photometric function of an individual element, such as the face of a prism, is known. It is thus possible to derive analytically the photometric curve of the other models in Fig. 4, on the basis of a single measurement of a flat surface with the same composition as the prisms inclined to the horizontal at the same angle as the base angle of the prisms. Conversely, it may be possible to reconstruct a surface or surfaces to correspond to a known photometric function. The analytical technique developed for the purpose of verifying the prism curves might be used to build a physical photometric model that will obey the peculiar reflection laws of the moon. Past attempts by Barabashev, Bennett, and van Diggelen to build such an artificial model have not been very successful.

Condition No. 3: Five prisms, base angle 0°, 30°, 45°, 60°, (row 5 in Fig. 4); intensity equator parallel to the ridges.

In this condition and the following conditions, the number of prisms under observation remains constant, but the base angle of the prisms varies from 0° (a horizontal plane) to 60°. Under this condition the sun-source travels parallel to the prism ridges. In lunar terms, this particular combination of model and lighting is equivalent to increasing the latitude of the observed lunar areas at a given longitude. The lunar observational data shown in Fig. 7 indicates that the photometric properties of individual areas on the lunar surface are nearly independent of latitude. The test results shown in Fig. 8 agree with the lunar data. Both sets of curves show only a slight increase in backscatter with increasing latitude or base angle. It is believed that no useful additional knowledge will be gained by investigating the other models in Fig. 4 under this condition of illumination.

Condition No. 4: Same as Condition No. 3, except that the intensity equator is perpendicular to the prism ridges.

The photometric properties of the set of five prisms with varying base angles are shown in Fig. 9. The test curves reveal a progressive sharpening of the backscatter curves as a result of increasing base angle or decreasing ridge angle of the prisms. The over-all increase in backscatter is more pronounced under the transverse mode than under the parallel mode of illumination. Since the albedo and the surface compositions of these models remain constant, the sharper backscatter could be attributed mostly to the shadows cast by the large scale features (i.e., prism ridges) at large phase angles under the transverse mode of illumination. It should be noted that the prisms cannot reproduce the lunar curve without the help of the CuO cover. However, these experiments indicate that it may be possible to achieve a match with the lunar curve using lambertian, centimeter-size elements alone, provided these elements have sharp edges and are arranged in the proper order -- which is, as yet, unknown. It is apparent that the investigation of prisms, pyramids, hemispheric, conical, or ellipsoidal pits and domes alone will not lead to this pattern, but sufficient knowledge has been gained from these experiments to explore other, less conventional geometries. The "Thumb Tack" model described below is an attempt in this direction and appears to be more rewarding than other similar attempts.

III. Models sprinkled with mixtures of CuO and SiC powders. In these experiments an attempt is made to keep the roughness or geometry of the model unchanged and to vary its albedo within the range of lunar albedo values. Copper oxide and silicon carbide powders (having albedos of 0.06 and 0.15, respectively) are mixed in various proportions and sprinkled over a surface of known geometry. Both powders have about the same grain size, less than 0.037 mm. (passing through a 400 mesh screen).

The albedos of these mixtures were first measured at 0°, 30°, and 60° viewing angles. The result plotted in Fig. 10 show that silicon carbide, unlike copper oxide or the surface of the moon, does not have a constant albedo independent of viewing angle.

The photometric curves (at normal viewing angle) of a flat plate and a 5-prism assembly on which some of these mixtures are sprinkled, are shown in Figs. 11 and 12. The results indicate that the match with the lunar curve, or band, deteriorates with increasing albedo or SiC content. These results are somewhat similar to those obtained with natural specimens (Ref. 4, Fig. 35), in which sea coral No. 1 was progressively darkened by a spray of paint. In this case, however, it is debatable whether the loss of backscatter can be caused entirely by an increase of albedo. The loss could also be attributed to the inability of the SiC particles to fluff up and form "fairy castles." An examination of the constituent powders with a stereoscopic microscope revealed that this is indeed the case. The SiC particles, unlike the CuO particles, do not agglomerate to form intricate labyrinthine structures. In addition, the shiny, specular surfaces that they contain could also be responsible for their relatively high albedo and poor backscatter.

It may be concluded that the flattening of the photometric curve due to the addition of SiC powder could be due to a combination of albedo (i.e., multiple scattering) and geometry effects.

Microscopic examination suggests evidence of both effects and indicates that the technique of mixing powders is not necessarily conducive to a meaningful study of these effects on the photometric function, since it is difficult to separate them and measure or compute their individual contributions. For this and other reasons mentioned above, it was found more desirable to deal with "simple" models having one order of roughness instead of two, i.e., "micro" and "macro," as represented by the dust cover and geometric solids respectively. However, the experiments with the composite models were useful in revealing the type of geometry that may be needed in order to backscatter light in the same manner as the moon without a cover of fine dust; this cover, as we have seen, is expedient to give a good match with the lunar data, but is not very helpful, other than in a qualitative sense, in giving an insight into the physics of the phenomenon.

An Analysis of the Basic Geometry of Backscattering Surfaces

It can be stated on the basis of the previous experiments that a "surface," which backscatters light like the moon, could have a pronounced tridimensional structure composed of opaque elements larger than the wavelength of visible light and arranged in such a manner that whatever light leaves by reflection through their interstices, must leave more or less in the direction of the source. These surfaces are sometimes said to have "negative gloss." The "natural" and "artificial" models that we have investigated thus far exhibit this tridimensional structure, but to a degree too complicated to be subject to a useful analysis on the basis of the actual shape and contour of the surface. To overcome this difficulty, an attempt is made in this section to build a tridimensional structure composed of elements of known geometry and albedo, arranged in a series of patterns, all of which are photometrically similar to the moon or to the natural specimens examined previously. These patterns may not necessarily conform to the random geometry of the natural specimen or lunar surface, but they may be considered as geometrically analogous to them in terms of relative roughness and, possibly, actual porosity.

The search for a lunar photometric model made up exclusively of "macrorough" features, which, unlike microscopic dust particles, lend themselves to easy manipulation and analysis, may begin with centimeter-size "lambertian" elements that are horizontal and/or vertical to the viewed area and are oriented in a direction perpendicular to the plane of vision including the intensity equator, as shown in Fig. 13.

To begin, consider the simplest possible tridimensional model composed of equal width opaque, horizontal strips of negligible thickness "suspended" over a flat surface, as shown in Fig. 14a. Assume all surfaces have the same albedo and that all scatter light according to Lambert's law. Let an observer or a photometer view this model at an angle, E, from the normal to the surface.

The following discussion is highly qualitative and ignores the fact that the flux projected on the surface varies with the angle between the local normal and the incident beam. The discussion is meant to provide a general feeling for what may be the behavior of these models; detailed quantitative analysis will be completed in subsequent work.

At zero phase angle, when the directions of sight and illumination coincide, the brightness of this model is at its maximum because the photometer sees 100% of the illuminated area, half of which consists of the top of the suspended strips and the other half consists of the AB-type areas on the base, as seen through the openings of the suspended strips, Fig. 14a. As the light moves counterclockwise along the intensity equator, area AB will be progressively darkened by the shadow of the upper element. The rate of change of the brightness vs. phase angle will depend of course upon the phase angle, the vertical distance between the base and the upper element and the width and spacing of the elements.

Neglecting multiple reflections, the brightness of this particular model will reach a minimum at phase angle α_1 corresponding to the position where a suspended element casts its full shadow over area AB. At larger phase angles the shadow will move away, the brightness of the model as seen by the photometer will increase, and, unlike the geometry of the lunar surface, it will reach a second maximum at a phase angle α_2 which (as it can be seen in Fig. 14a) corresponds to the position where the light source, the next opening between the suspended strips and area AB are on a straight line. The height of the second brightness peak depends upon the angle of incidence, i, and the geometry and nature (or finish) of the surfaces. It is clear that a tridimensional model made up of suspended elements only could give the peculiar "opposition effect" Ref. (3) exhibited by the moon at small phase angles; however, the match with the lunar curve is very likely to deteriorate at larger phase angles.

Another tridimensional model, as simple as the preceding one, can be made up of equal height vertical elements only, as shown in Fig. 14b. This model, unlike the preceding one, will not behave, photometrically speaking, the same way at all viewing angles. For instance, at normal viewing, its brightness is expected to drop sharply (depending on the height and spacing of these elements) as the light moves away from a zero phase position, but at off-normal viewing angles, the drop in brightness near zero phase may follow a "cosine type" curve rather than a backscattering type curve, as shown in Fig. 14b. At larger phase angles, the vertical strips start casting their shadow over area AB, the brightness will drop at a faster rate; unlike the case of the previous model, no second brightness peak will appear. However, the vertical strips are equally unsatisfactory as a lunar model because they will not obey the reflection laws of the moon at all viewing angles. It would be interesting to verify this conjecture by experiments and/or analyses.

From the above discussion and sketches in Figs. 14a and b, it can be anticipated that a model consisting of a combination of horizontal and vertical elements as shown in Fig. 14c, may be free of the shortcomings of its constituents, namely, the second brightness peak exhibited by the horizontal strips and the "cosine type" curve at small phase and large viewing angles exhibited by the vertical strips. In the "T" model, shown in Fig. 14c, the vertical strips eliminate the second peak by preventing the light rays from reaching area AB for a second time during the same lunation, and the horizontal elements eliminate the "cosine type" curve by casting their shadow over area AB at all viewing angles. In the T-model, a slight, undesirable "bulge" is anticipated on the lower portions of the brightness-phase curve due to the Lambertian behavior of the exposed top of the horizontal strips being the only remaining illuminated elements of the model beyond phase angle α_1. This portion of the curve could be improved easily by superimposing a "second order" roughness on top of the horizontal strips. This may be accomplished by adding a small vertical element or elements in the middle of the horizontal strip or two vertical elements or "lips" on the edges.

In the following section, an experimental account of the T-model is given. The results are preliminary, but they essentially bear out the validity of the approach.

Discussion of Test Results of "Simple" Models

The T-model discussed in the previous section was built in the following manner. The horizontal suspended elements were simulated by the heads of thumb tacks pinned in parallel rows into a flat base, the vertical elements consisted of two strips of blotting paper, each one fixed between two rows of thumb tacks as shown in Fig. 15a. It is safe to assume for the purpose of this investigation that the shadow cast by the stems of the thumb tacks is negligible. The entire model, excluding the vertical strips, was sprayed with a gray nonglossy paint. The results of albedo and photometric measurements at 0°, 30°, and 60° viewing angles, with and without the vertical strips, are shown in Figs. 15b, c, and d. The light source was moved in a direction perpendicular to the alignment of the thumb tacks.

The thumb tacks model in its present configuration is not photometrically homogeneous like the lunar surface or the natural specimens when examined under both directions ofthe intensity equator with regard to the alignment of the tacks. This, however, is not a serious shortcoming, since such a condition could be satisfied by arranging the tacks and the vertical elements in a checkered symmetrical pattern. Hence, by using the "aligned," nonsymmetrical pattern as a preliminary step, we do not depart as far from a realistic model as it would appear at first sight.

The experimental results, presented in Figs. 15b through d show, as predicted, that the model with vertical and horizontal strips is in better agreement with the lunar data than the model with only horizontal elements. For convenience, these models will be referred to as the "T" and the "suspended" models. The difference between these models is particularly noticeable at the 60° viewing position, Fig. 15d, where three points located at or near the inflection points of the photometric curves have been singled out for further scrutiny. Points 1, 2, and 3 are located on the suspended model curve, and points 1', 2', and 3' are located on the T-model curve. Scaled cross sections of both models indicating the illuminated and shadowed areas seen by the photometer at phase angles 45°, 60°, and 100° are shown in Fig. 16. These sketches reveal the following points of interest:

1. In Fig. 16, the illuminated areas seen by the photometer on the T-model are smaller than those on the suspended model. This accounts for the fact that in Fig. 15d, points 1', 2', and 3' are lower on the scale of brightness than points 1, 2, and 3.

2. Unlike the lunar or the T-model curves, the curve for the suspended model ascends between points 1 and 3, indicating increasing brightness. This behavior is adequately explained by the increasing width of the illuminated areas

in Fig. 16, that is,

$$C_1D_1 < C_2D_2 < C_3D_3 \quad .$$

3. The second brightness peak anticipated in the discussion of the suspended model is confirmed by the test curve at 60° viewing angle. The illumination geometry drawn for this point in Fig. 16 does indeed show that area C_3D_3 on the base of the model, in full view of the photometer, is almost fully illuminated, whereas the same area in the corresponding cross section of the T-model is in the shadow of the vertical strip. The presence of this element is largely responsible for the better match with the lunar data at these critical phase angles. It is easy to see why the curve of the suspended model dips sharply past point 3, because area C_3D_3 in Fig. 16 is progressively shadowed by element F_3F_3 with increasing phase angles.

It is not necessary to discuss all the peculiarities of the test curves in Figs. 15b through d. Most of these could be reasonably accounted for by the surface and illumination geometries of the individual points as illustrated previously. It is important to point out that these experiments are preliminary, but they nevertheless, provide sufficient knowledge and confidence to enable one to improve the thumb tacks model or to create other contrived models so as to yield an improved match with the lunar data.

Significance of the Thumb Tacks Model

The dust-covered solids that we have thus far investigated suggest that the contribution of gross lunar features (within telescopic resolution) to the observed backscatter is less important than the contribution of innumerable irregularities which, could be of the order of meters but are probably less than some centimeters in size. The partial failure of the composite models to provide a deeper insight into the geometric and photometric relationships of backscattering "surfaces," has made it necessary to build and investigate dust-free, though contrived, lunar photometric models. The Thumb Tacks model is a crude example of such models, but it marks a new departure toward the solution of the lunar photometric puzzle. It promises to be a valuable tool which allows one to see and follow the sequence of shadowing, on and within a backscattering-type structure, with greater convenience and accuracy than would be possible with dust-covered and other complex natural specimens.

The Thumb Tacks model has confirmed that <u>shadowing</u> within a porous structure, more than any other optical phenomenon, is probably primarily responsible for the peculiar photometric properties of the lunar surface. The albedo of the surface and the subsurface (visible through the pores), particularly when uniform, appears to play a minor role in the backscattering process. In addition, the Thumb Tacks model has revealed that the shadow-casting elements in the porous crust (which appears to cover uniformly the entire visible surface of the moon) are made up predominantly of sharp edges and overhanging horizontal members. No conclusions can be reached, based on this model, about the actual scale of and the interfacial bond between these elements. It appears, however, that both quasi-horizontal and quasi-vertical members are necessary and that neither set of members is sufficient by itself to account for the reflection of the lunar surface at all phase and viewing angles. The horizontal or "suspended" elements, if properly arranged, could reproduce the unusual lunar "opposition effect" at very small phase angles, and fail to reproduce the rest of the lunar curves at larger angles. Vertical elements were introduced in the Thumb Tacks model in order to improve its backscattering property; this addition to the model may be very significant since such elements render the model less tenuous and could possibly lend to it the stability and strength that is not associated with "suspended" models. However, this conclusion must remain tentative until further investigations of various "suspended geometries" are conducted.

An equally significant aspect of the Thumb Tacks model and its future derivatives is that such models lend themselves more readily to an analytical formulation of the photometric function in terms of the illumination angles and the tridimensional geometry of the surface. Such a relationship is of more than academic interest. The porosity of the lunar surface, or a relatively narrow range of porosities dictated by the lunar photometric data, may be quantitatively assessed. This information could, under certain conditions, complement the lunar radiothermal data in estimating the internal consistency, bearing strength, insulating, and other engineering properties of the lunar surface material.

A shortcoming of the Thumb Tacks and perhaps other "simple" models is the fact that such models, unlike the lunar surface or most of the natural specimens we have examined, do not or are not likely to exhibit a constant albedo at all viewing angles. This fact could be attributed mostly to the mathematical idealization of the shadow-casting elements. In the case of the terrestrial specimens, or the lunar surface, there is sufficient randomness in the distribution and orientation of the reflecting surfaces to minimize the variation of albedo with change in viewing angle. In the case of the contrived models, this difficulty could possibly be overcome (without compromising the integrity or realism of the model) by rounding off sharp corners, so that incident light could strike the surfaces at a more or less equal angle with respect to the local normal, and consequently, according to the principle of Lambertain reflection, yield a more uniform brightness or albedo at all viewing angles.

Contrived models like the Thumb Tacks, unlike the composite, dust-covered models, offer the advantage of enabling the experimenter to vary the albedo of a given model without incurring the risk of changing its structure (as we did when we mixed SiC and CuO powders). Specifically, varying the albedo within a given model would consist in painting the uppermost layer of the tridimensional model with a paint of different brightness than that in the interior of the pores. It is surprising that composite-albedo models, theoretical or experimental, have not been considered by previous investigators. Such models appear to be quite realistic in view of the possibility that the outermost surfaces on the moon could be darkened (or reddened) more extensively by radiation and other mechanisms than the interior of the pores. The latest observational data by Gehrels et al. could be interpreted as lending support to this view. Thus it may not be necessary to postulate a tenuous cloud of particles in order to account, photometrically speaking, for the "opposition effect" at small phase angles. This particular phenomenon might be explained by the increased brightness of the interior of the pores which come into view at very small phase angles. In addition, the composite-albedo, tridimensional model might explain the "reddening" of the lunar surface at increasing phase angles (again reported by Gehrels), when we consider that the bright interiors of the pores (which could tend mostly toward the blue) become less and less visible at these angles, while the duller, "weathered" outermost surfaces, (likely to be darker or red), will contribute more and more to the observed color. This newly-discovered peculiarity of the lunar surface imposes an additional constraint on model-matching experiments in lunar photometry. It would be very desirable to look for evidence of "red shift" in the natural specimens reported in Ref. 4 that have passed the photometric test under integrated visible lighting. This may be accomplished by measuring the brightness vs. phase relationship of these specimens at discrete wavelengths in the visible spectrum. The reddening effect may conceivably affect the estimate of the porosity of the lunar surface material from the photometric data. This is because increasing the volume by undercutting the sides of the cavities between the shadow-casting elements has an effect on the backscatter curve similar to increasing the albedo of the interior of the cavities that come into view at small phase angles. Thus, a composite-albedo model exhibiting the reddening effect is likely to be less porous than one which has a uniform albedo. "Simple" models of the Thumb Tacks variety lend themselves very conveniently to the simulation and study of this newly observed lunar phenomenon.

CONCLUSIONS

"Artificial" lunar photometric models investigated in this paper included "composite" and "simple" models. "Composite" models consist of centimeter-size conventional geometric solids (such as prisms, pyramids, cusps, and domes, etc.) covered with a backscattering powder. These models fulfill two useful purposes; they provide a means of evaluating the relative contribution of "first" and "second" order roughness to the photometric function, and they lead to the discovery of unconventional, "simple" (i.e., dust-free) models which promise to offer an intuitive and mathematical basis for the study of the backscattering phenomenon in general and the reflection laws of the moon in particular.

In the study of the "composite" models, the dimensions, slopes, distribution, and orientation of the geometric solids were changed while keeping the microstructure and albedo of their surfaces the same. A useful analytical technique was developed to check and confirm the test results. It was found that the conventional geometric solids do contribute to the backscatter when they have steep slopes and sharp edges, and when they are oriented in a direction perpendicular to the intensity equator. However, they are unable to reproduce by themselves the lunation curves of the moon without a complex microstructure, which in these models is simulated by a veneer of CuO powder. If we assume that the geometric solids simulate relatively large lunar features such as craterlets, ridges, and rills, (visible by telescope) we may tentatively conclude that these features play a minor role in the over-all change of brightness of the lunar surface during a lunation, and that the lunar backscatter is predominantly due to the shadow-casting characteristic of innumerable small surface irregularities. The wellknown photometric similarity of the seemingly smooth maria and the obviously rugged highlands of the moon lend some weight to this view and suggest that the outermost layer of the moon, regardless of the origin and nature of the underlaying layer, is nearly uniformly covered by a dark, porous material to an unknown depth in which the shadow casting, solid elements are arranged in an "underdense" pattern separated by a complex array of cavities which might be interconnected. Since for each photometric function there corresponds an infinite variety of geometric reliefs, it would seem difficult to give a more reliable description of this layer in terms of the actual dimension and spatial arrangement of its constituent elements. The "first" order irregularities are likely to be no larger than a few milimeters or centimeters. However, considering the size of lunar areas that are involved in photometric measurements, one cannot rule out at this state of our knowledge the possibility that meter-scale roughnesses on the lunar surface contribute to the observed backscatter. Measurements of the photometric properties of terrestrial formations on a topographic scale could shed some light on this question. Some insight was gained into the spatial arrangement of the small solid elements constituting the outermost layer of the moon, when a successful attempt was made to simulate the microscopic complexity of "fairy castle" structures by means of dust-free, contrived models made up of centimeter-size elements arranged in such a manner as to present sharp vertical edges and overhanging horizontal members.

The "simple" models and their future derivatives have many advantages. They reveal the relevant photometric parameters, and help to establish, quantitatively, the proper value of these parameters. A preliminary model built by means of thumb tacks has shown that shadowing on and within such a porous structure, more than any other optical phenomenon, can be primarily responsible for the peculiar photometric properties of the lunar surface, and that both quasi-horizontal and quasi-vertical elements having a well-defined proportion and spacing appear to be necessary components of a lunar photometric model because neither set of members is sufficient by itself to account for the reflection of the moon at all viewing and phase angles. This preliminary conclusion is significant but must remain tentative until a number of "suspended geometries," devoid of vertical elements, are studied. Additional advantages of "simple" models of the "Thumb Tacks" variety include the convenient simulation and study of newly observed lunar phenomena such as the "opposition effect," "reddening with phase," etc. The technique could apply equally to the study of other reflecting celestial bodies whose photometric properties are known.

The photometric variables discussed in this paper included distribution of micro and macroroughnesses, slope and slope orientation albedo and relative spacing of shadow casting elements. The important effect of porosity on the photometric function will be the subject of a future communication.

ACKNOWLEDGMENTS

I am indebted to H.B. Hallock, T. Grusauskas, and D.R. Lamberty of Servo Engineering at Grumman, for building and operating the photometric analyzer and for making the measurements.

REFERENCES

1. Barabashev, N.P., and Garazha, V.I., Soviet Astronomy, Vol. VI, No. 2, September-October 1962.

2. Bennett, A.L., Astro. Jour., Vol. 88, No. 1, 1938.

3. Gehrels, T., Coffeen, T., and Owings, D., Astro. Jour., Vol. 69, No. 10, December 1964.

4. Halajian, J.D., Grumman Research Department Report RE-219, Phase I, July 1965.

5. Hallock, H.B., and Lamberty, D., Grumman Research Department Report RE-219, Appendix A, July 1965.

6. Hapke, B.W., and van Horn, H., J. Geophysics Res. 68:4545-457 , 1963.

7. Orlova, N.S., Astron. Zhurnal, Akad. Nauk, SSSR, Vol. 33, No. 1, 1956, NASA TTF-75, 1962.

8. Van Diggelen, L., Recherche Astronomique de l'Observatoire d'Utrecht, Vol. XIV, No. 2, 1959.

9. Willingham, D.E., Technical Report No. 32-664, Jet Propulsion Lab., Pasadena, California, November 1964.

FIGURE CAPTIONS

Figure Captions (Cont.)

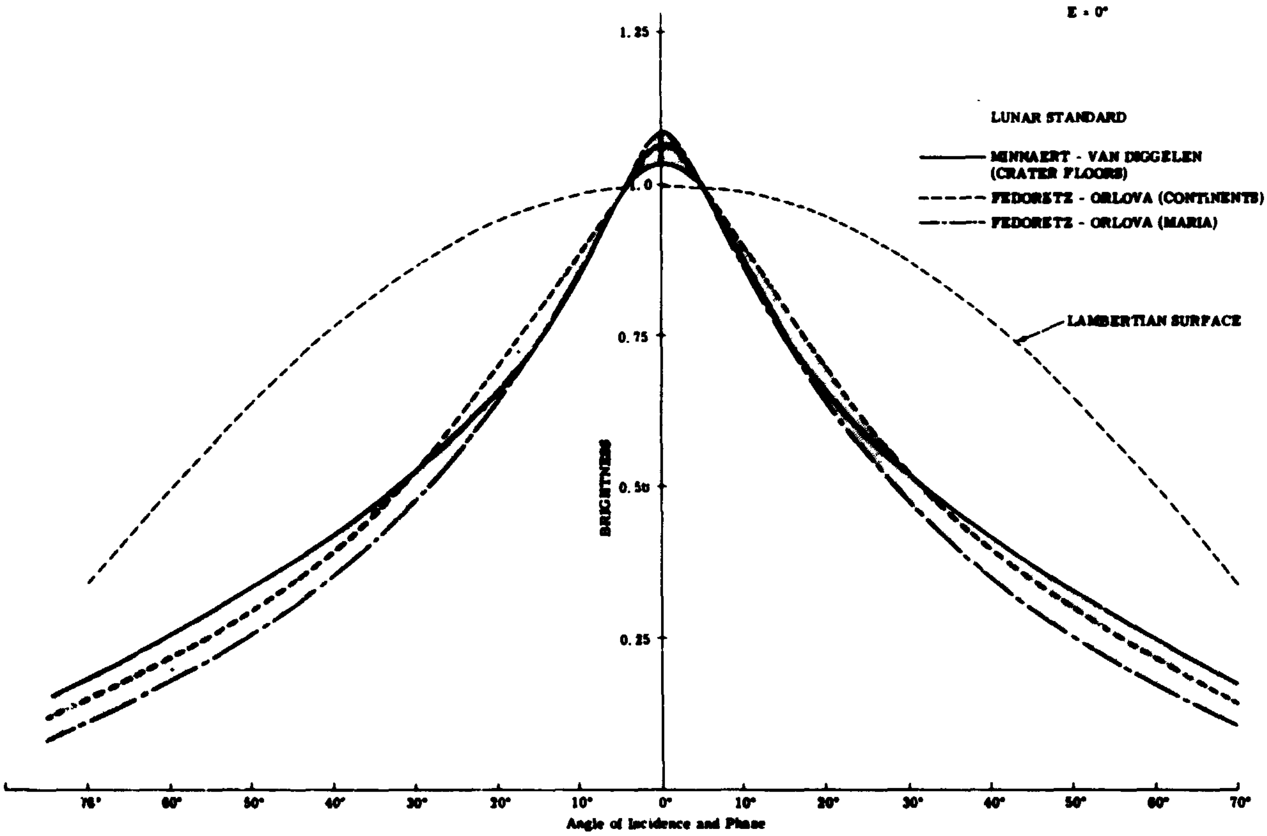


Figure 1a. Standard Lunar Photometric Curve

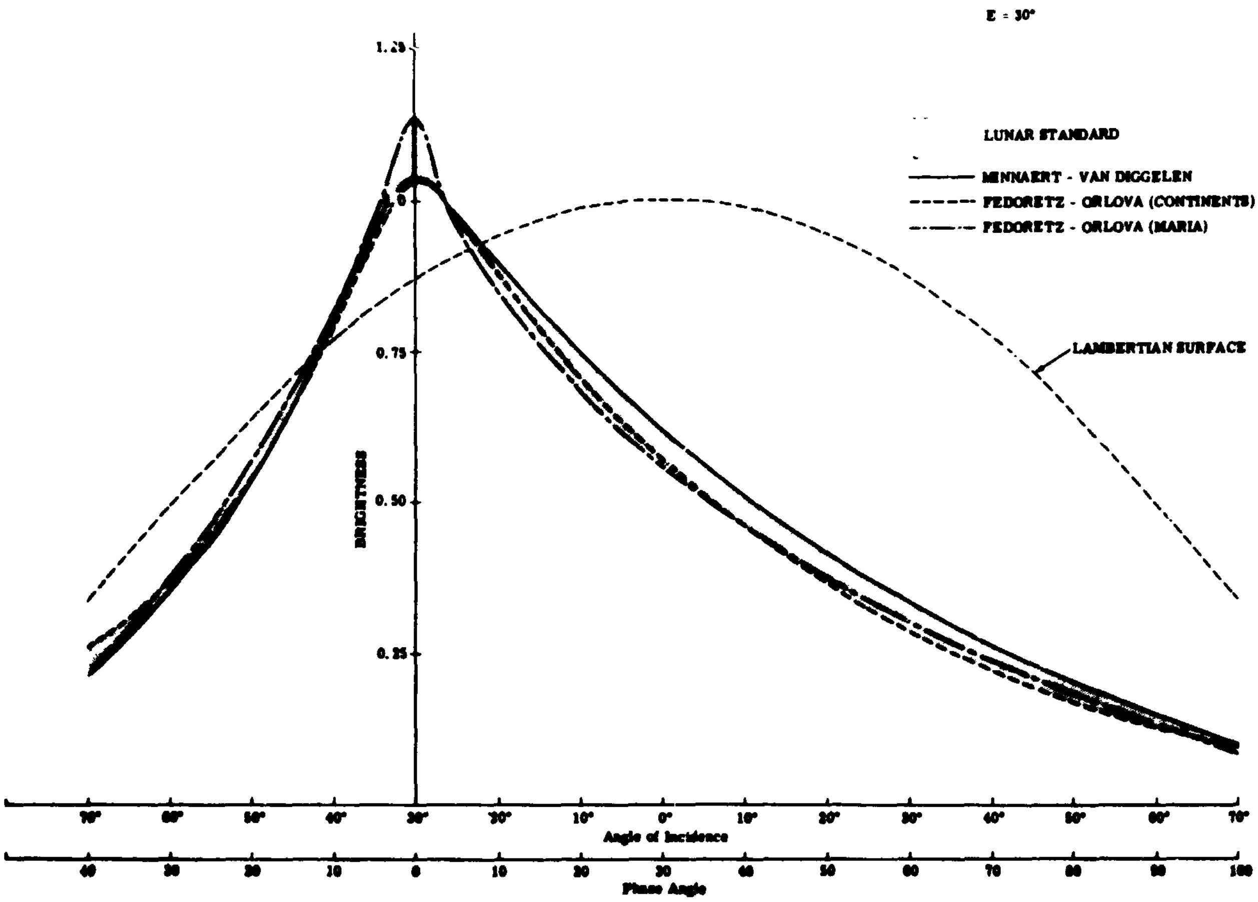


Figure 1b. Standard Lunar Photometric Curve

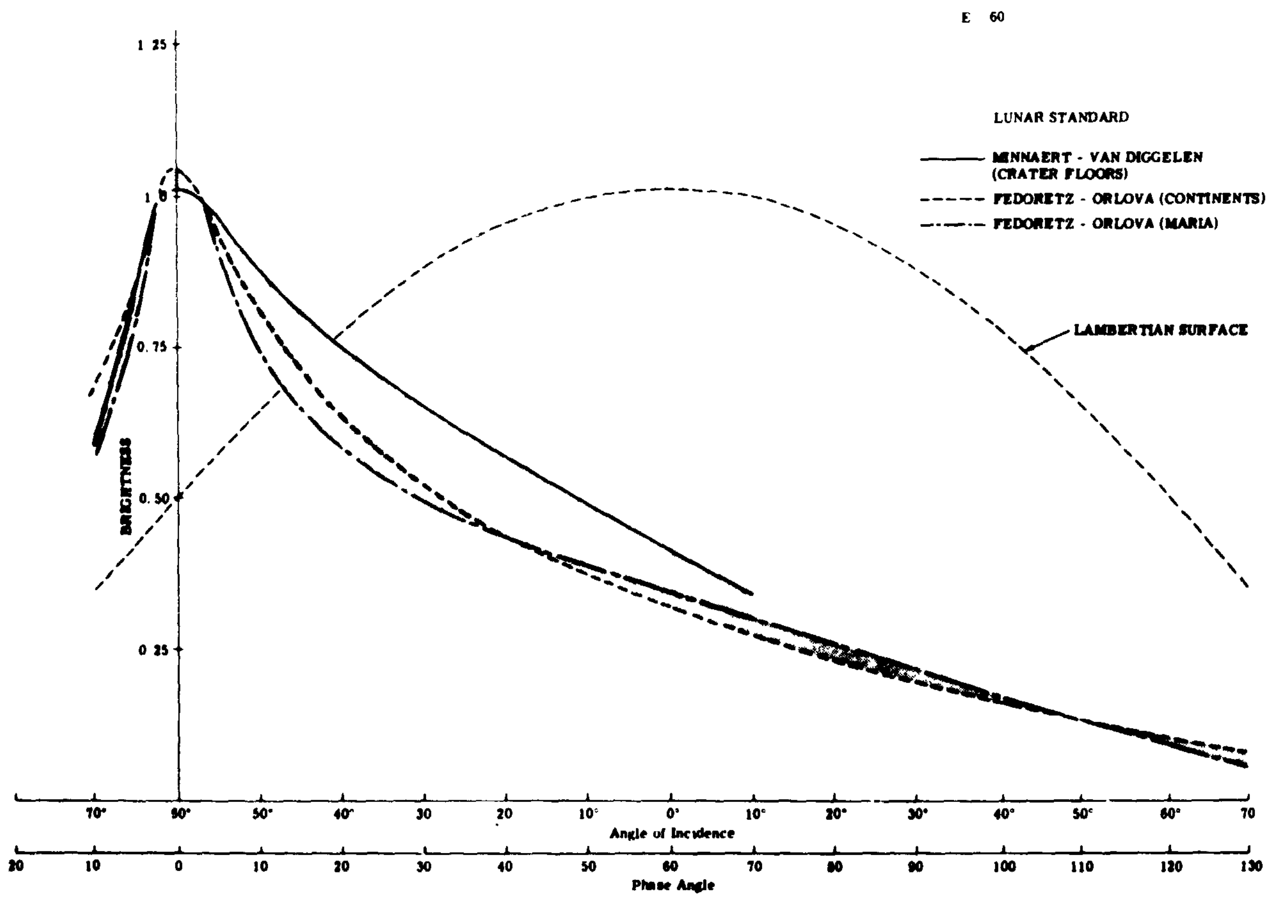
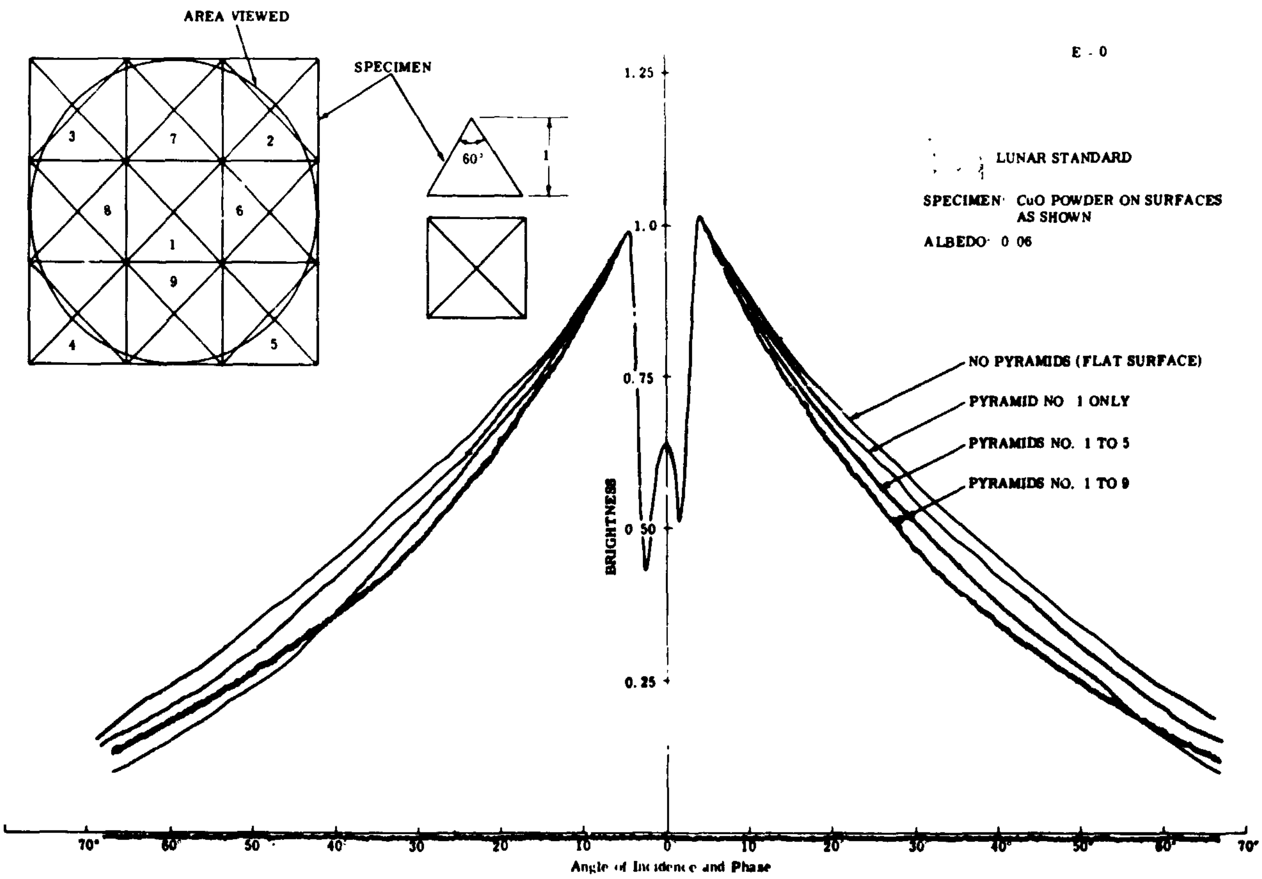


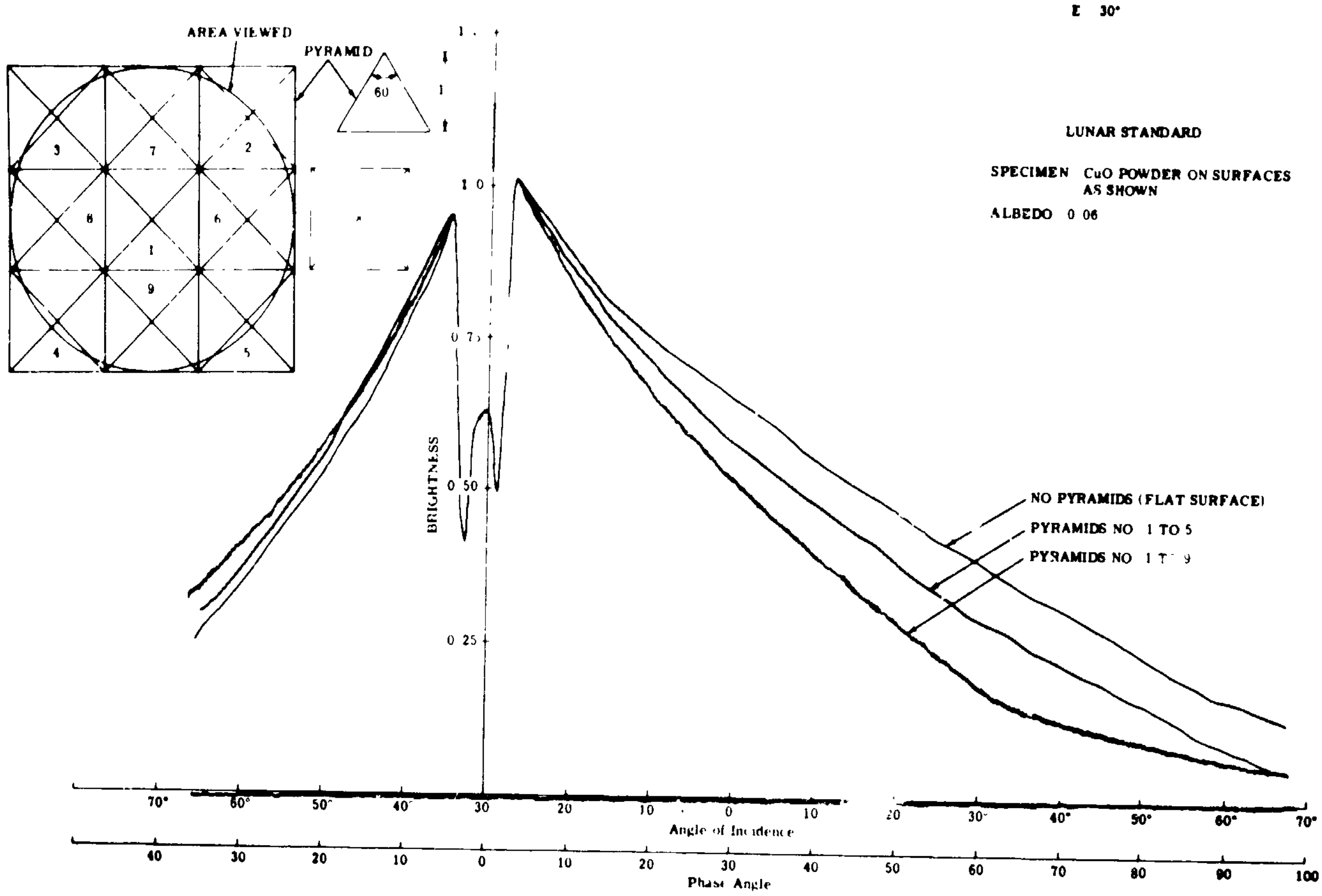
Figure 1c. Standard Lunar Photometric Curve

(a)

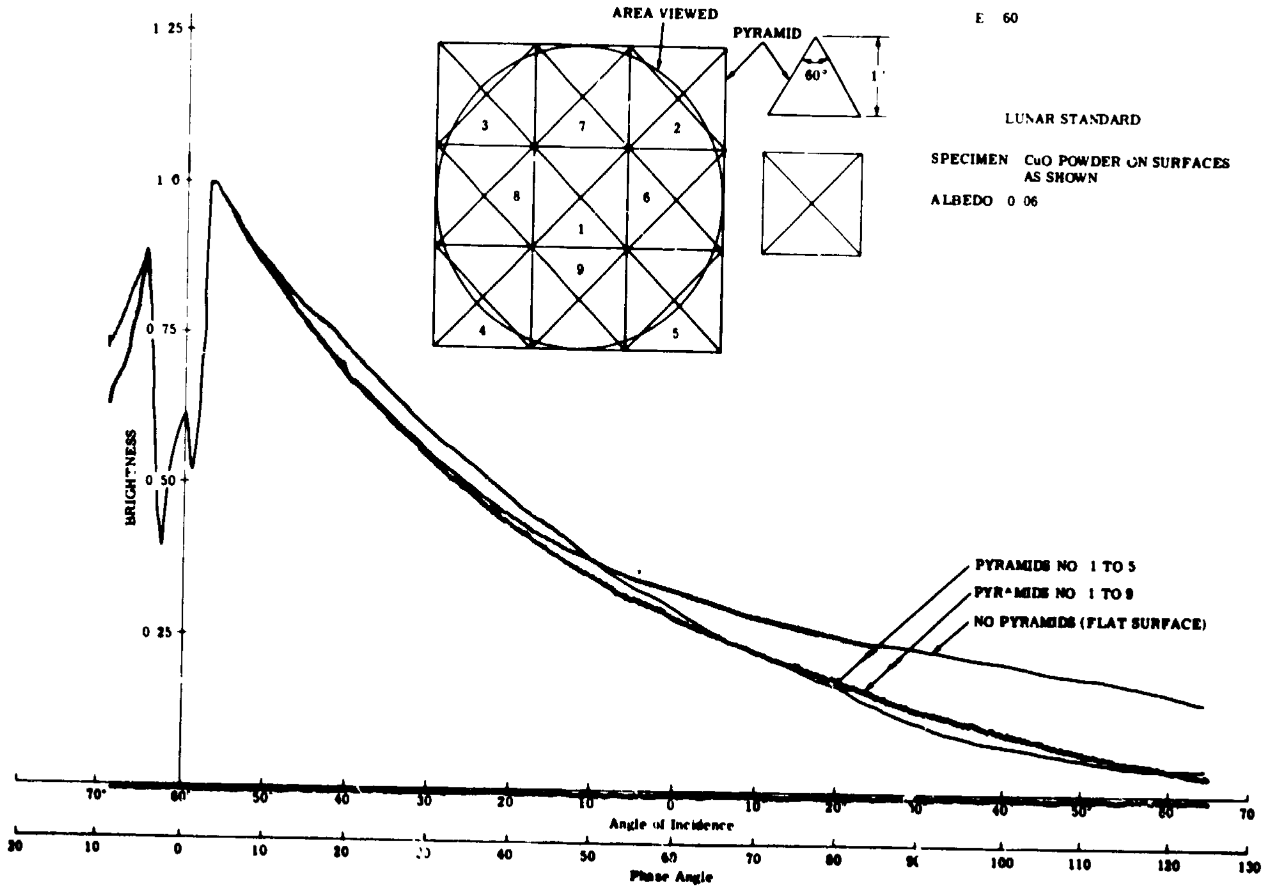


(b)

Figure CuO Powder on Pyramids (Sheet 1 of 2)



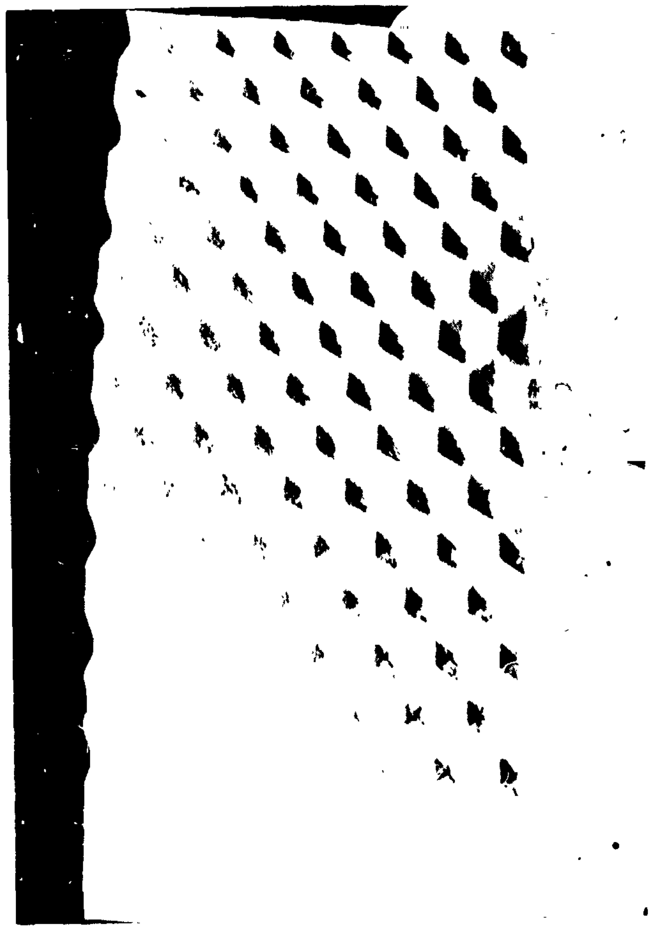
(c)



(d)

Figure CuO Powder on Pyramids (Sheet 2 of 2)

(a)



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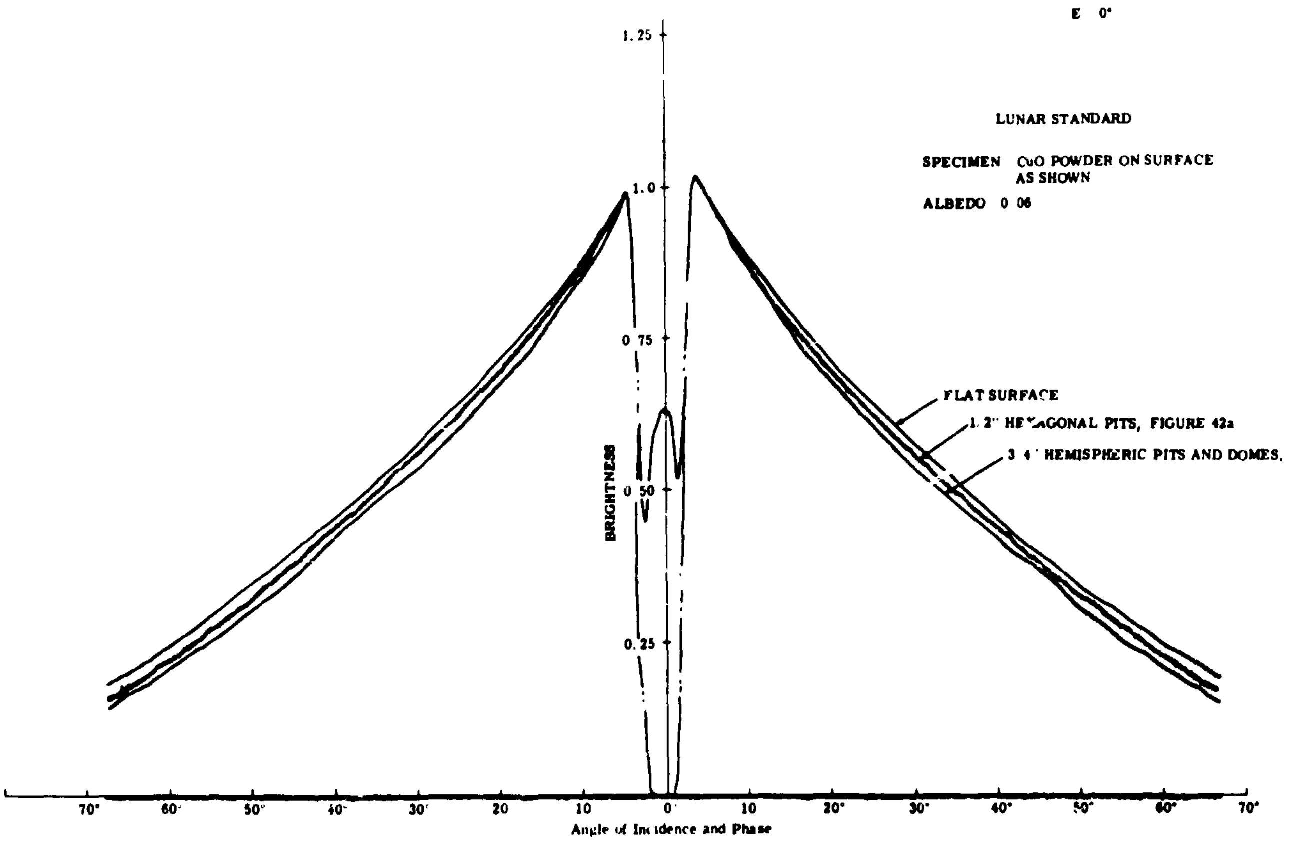
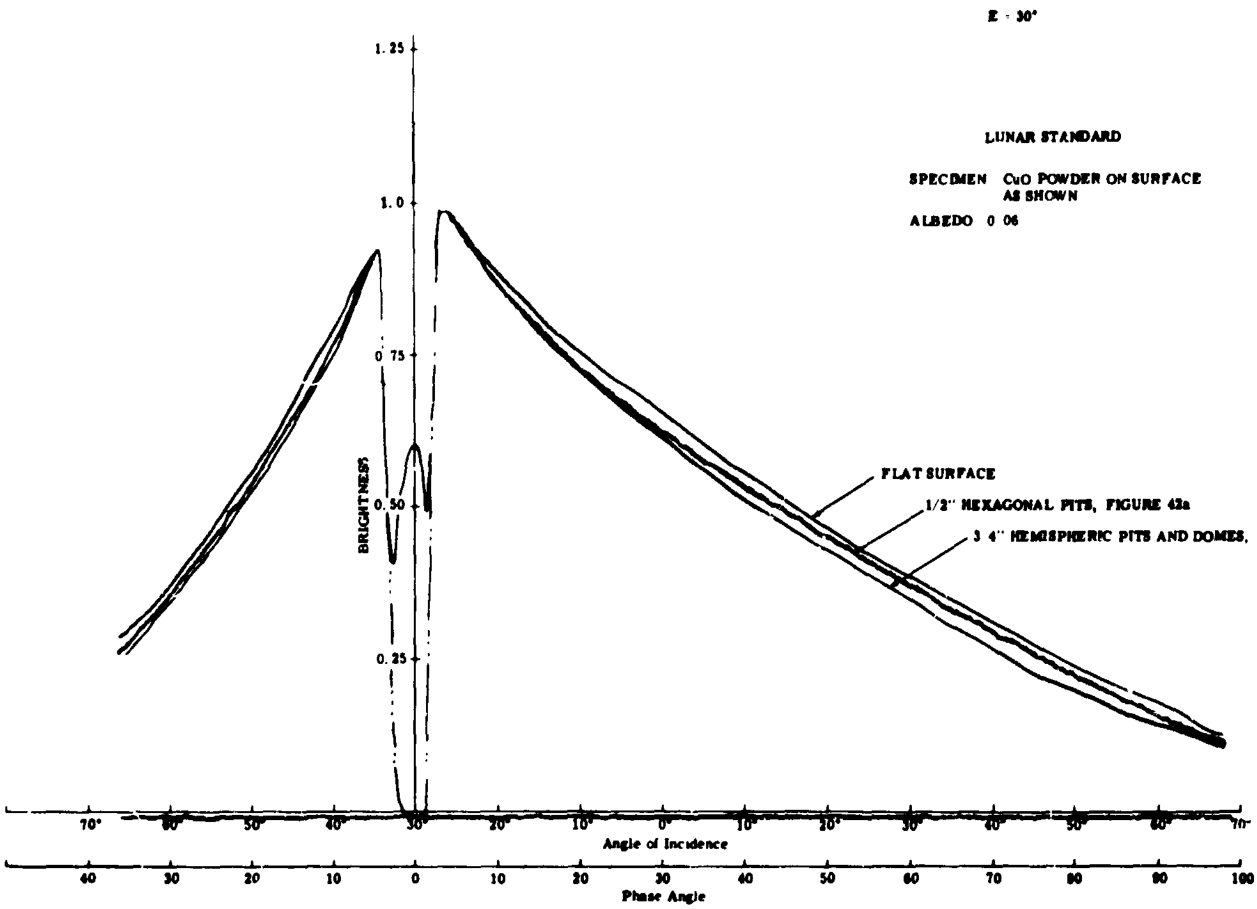
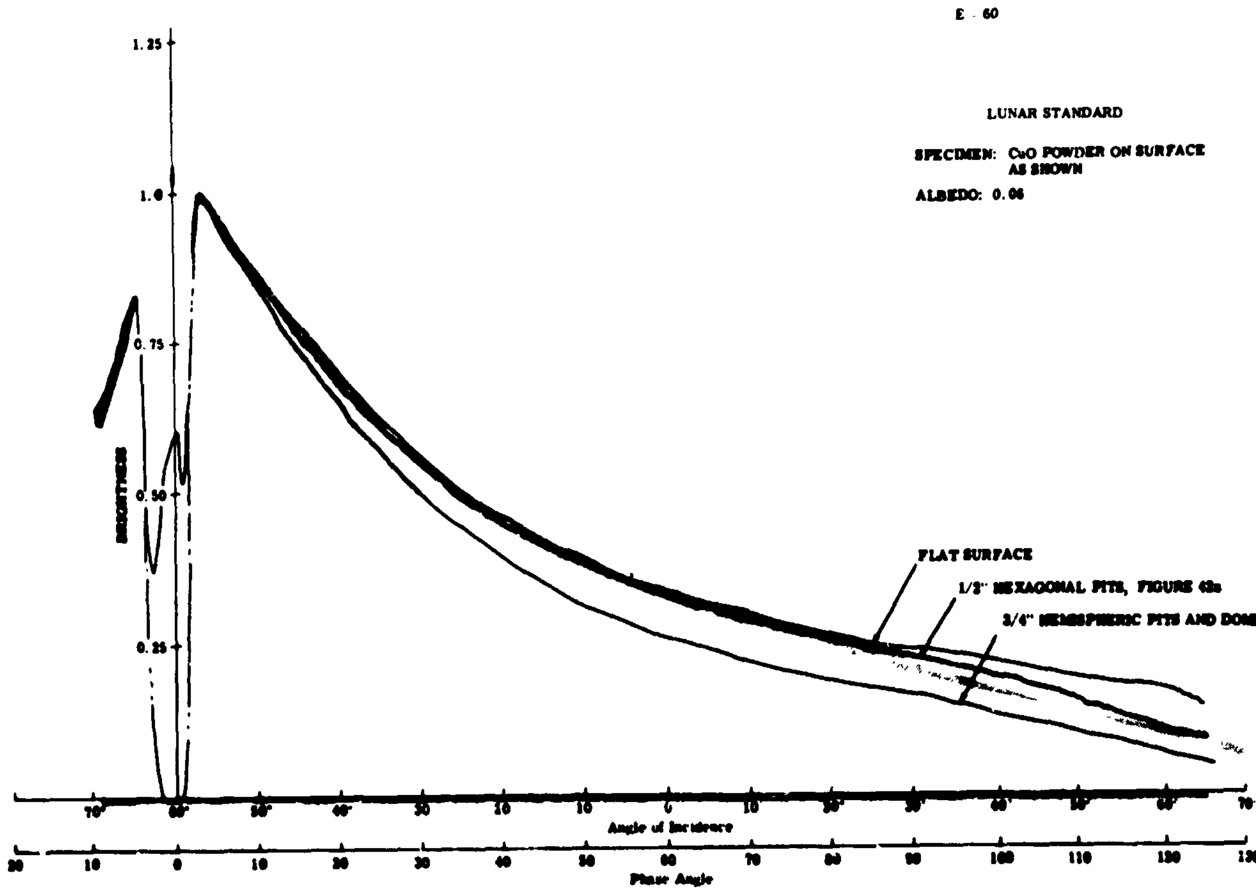


(c)

Figure CuO Powder on Surface as Shown (Sheet 1 of 2)



(d)



(e)

Figure CuO Powder on Surface as Shown (Sheet 2 of 2)

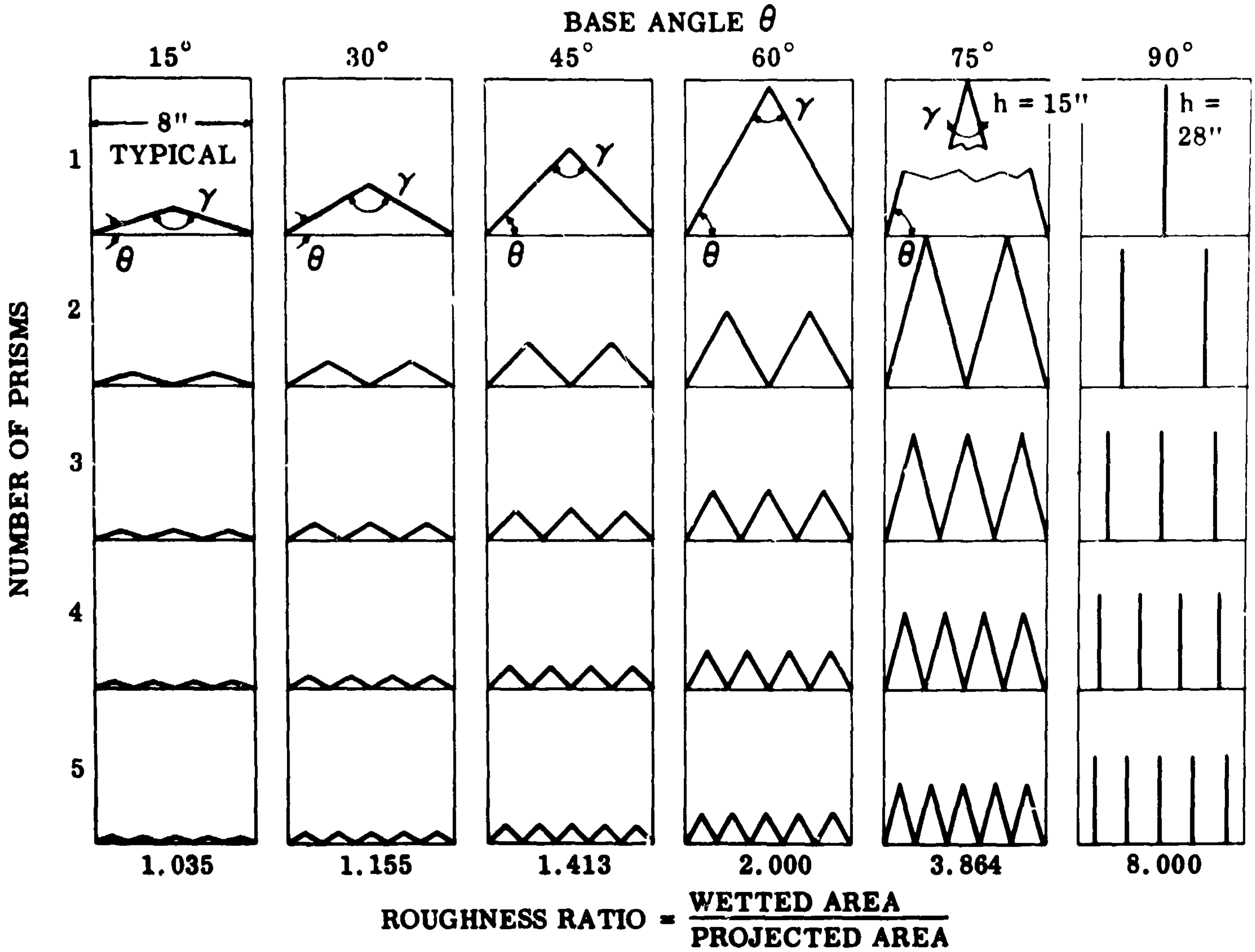


Figure Cross Section of Prismatic Ridges

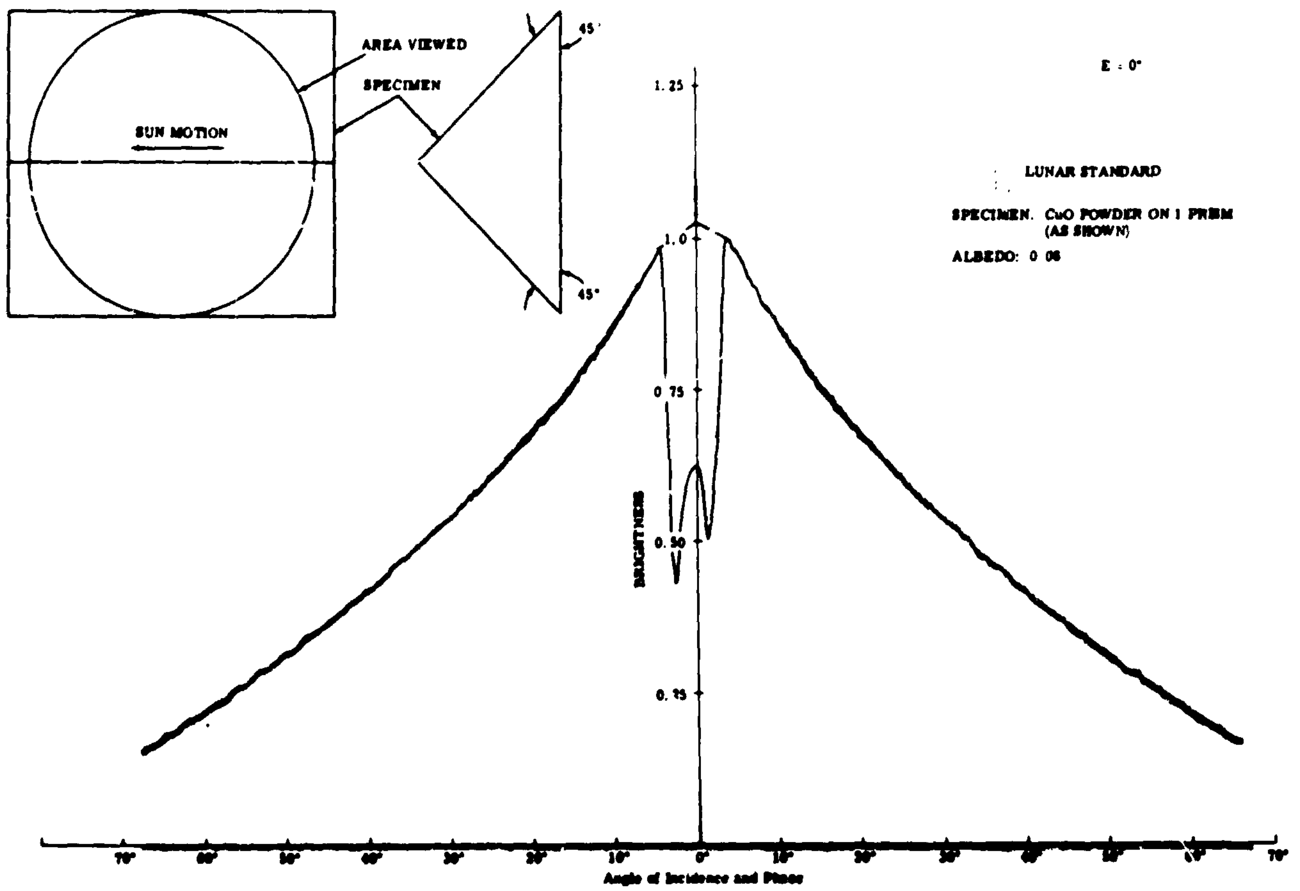


Figure 108 CuO Powder on One Prism

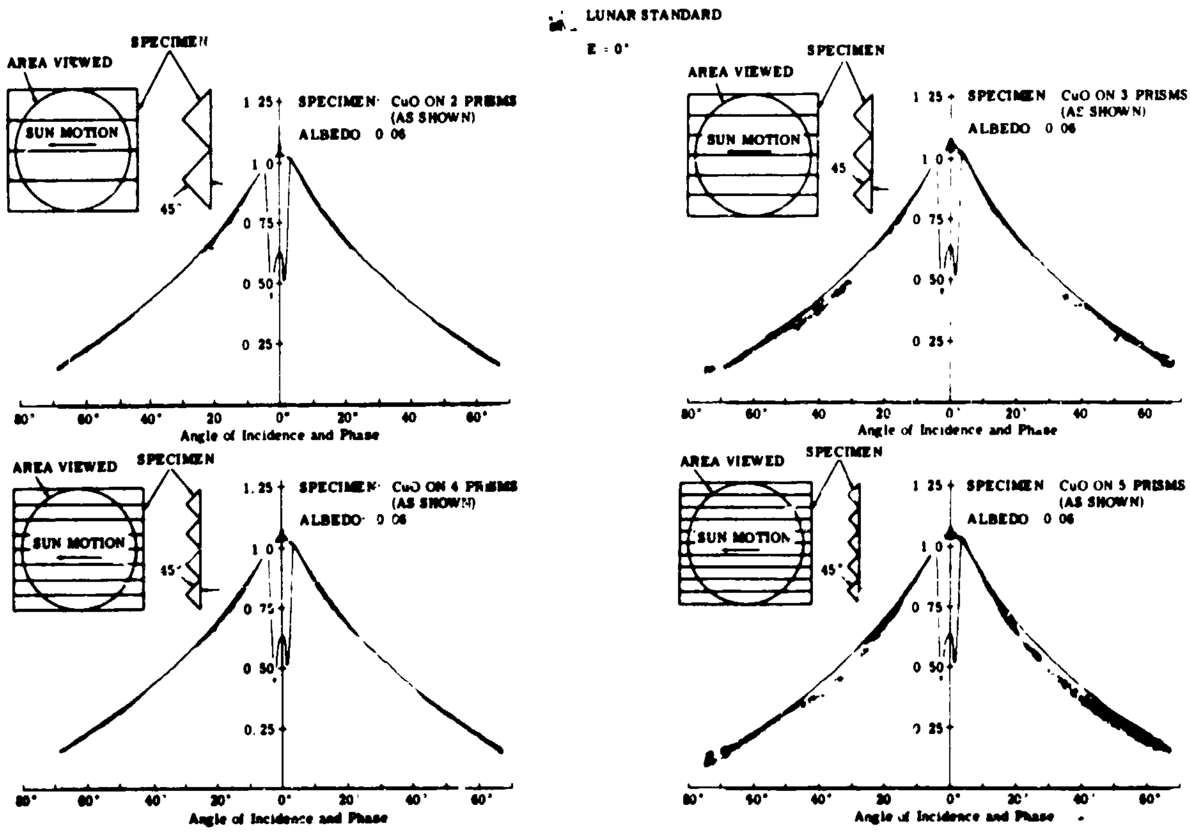


Figure CuO Powder on Two to Five Prisms

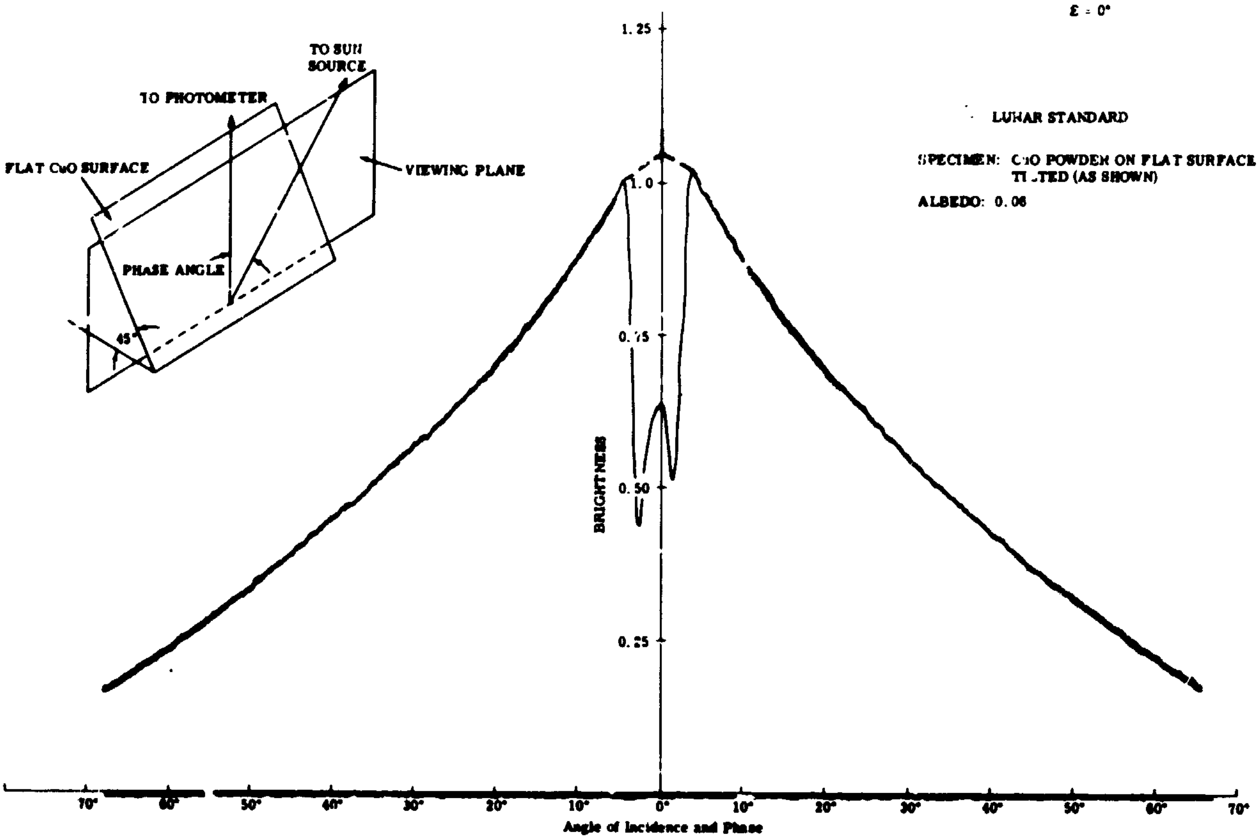
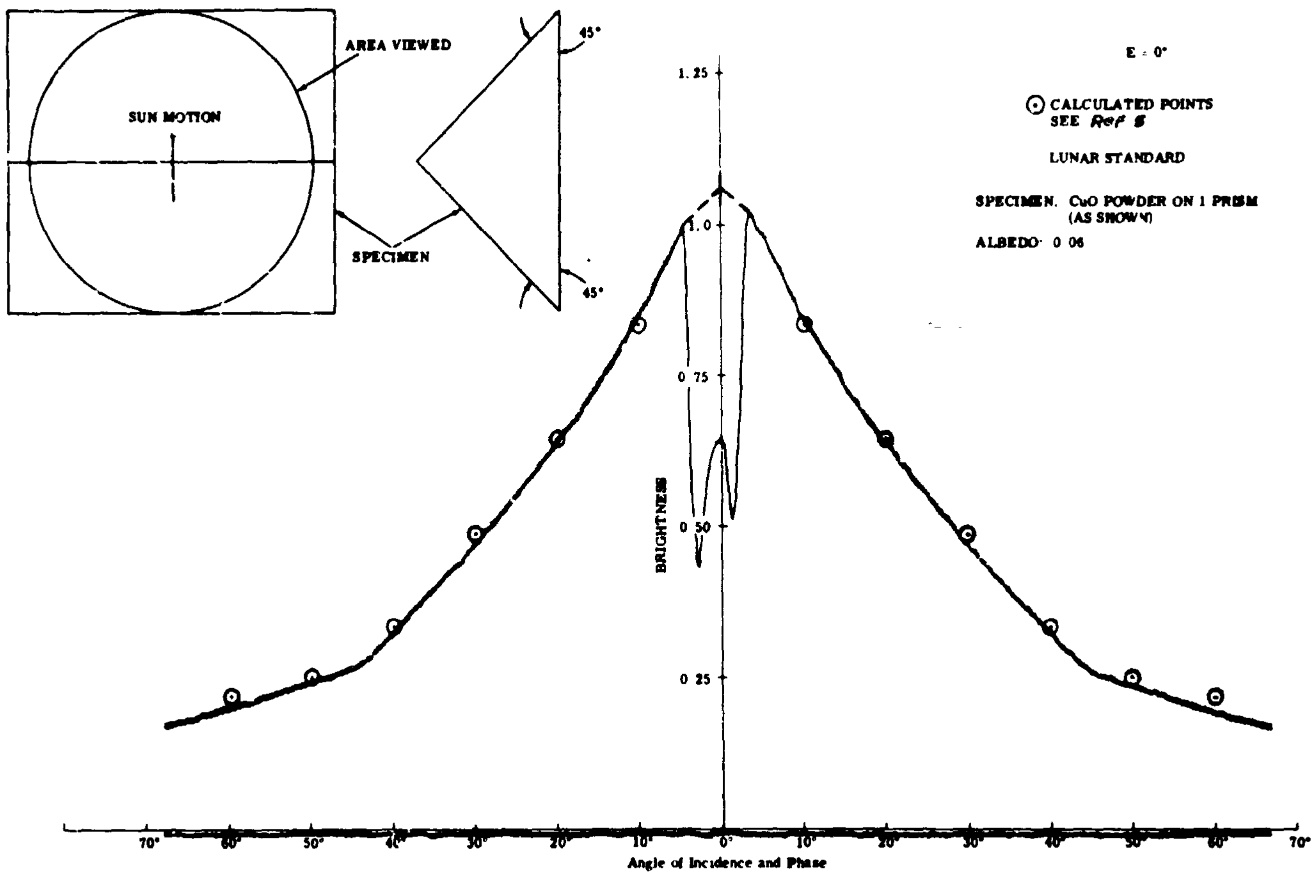
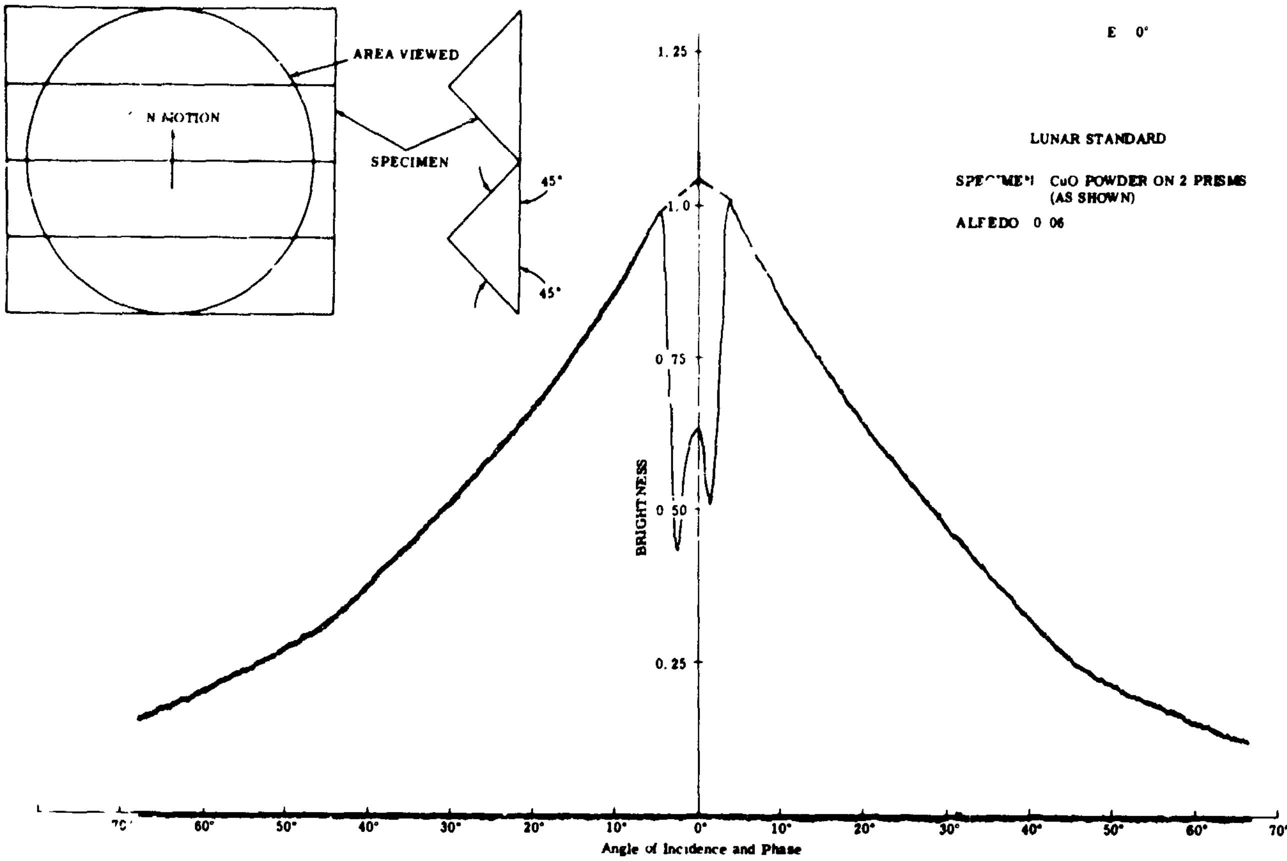


Figure 110 CuO Powder on Flat Tilted Surface



(a)

Figure CuO Powder on Prisms (Sheet 1 of 3)



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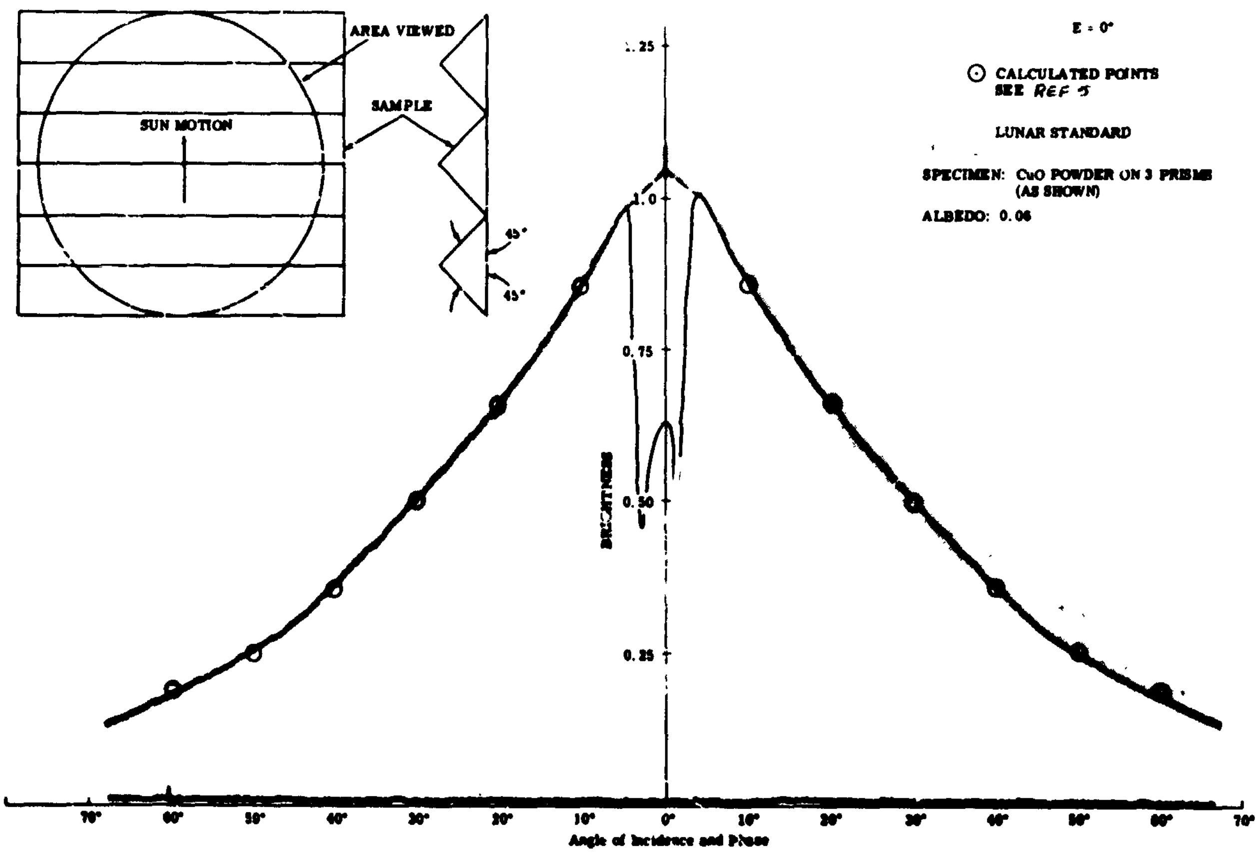
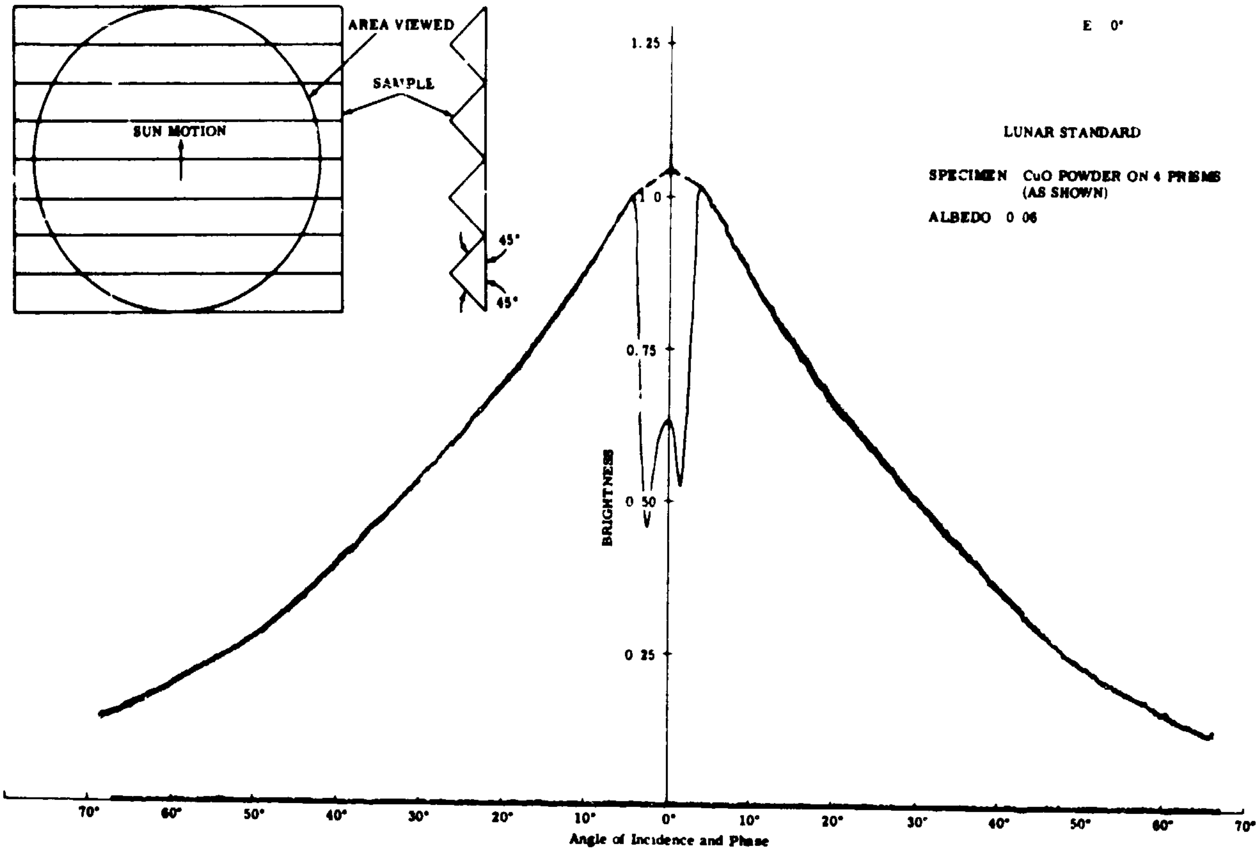
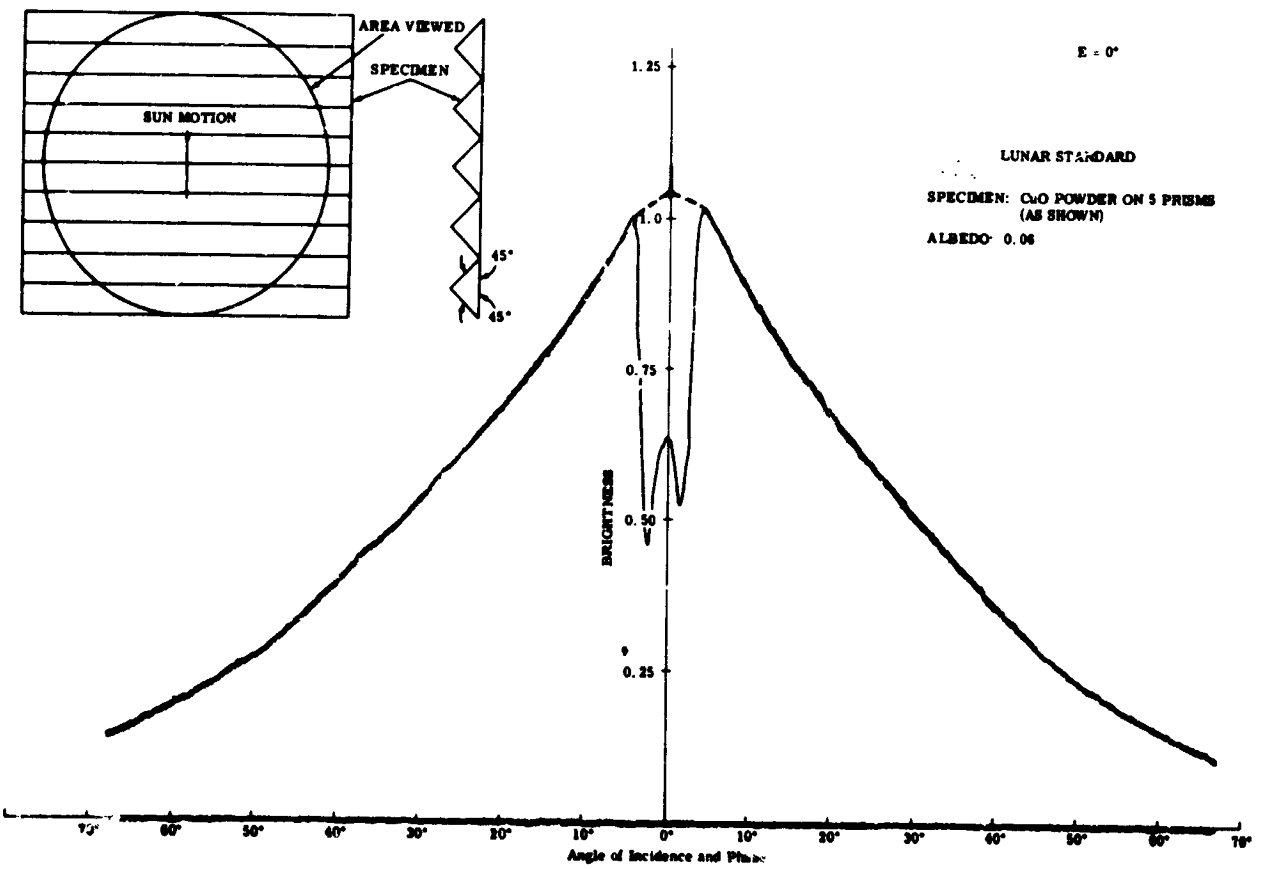


(c)

Figure CuO Powder on Prisms (Sheet 2 of 3)



(d)



(e)

Figure CuO Powder on Prisms (Sheet 3 of 3)

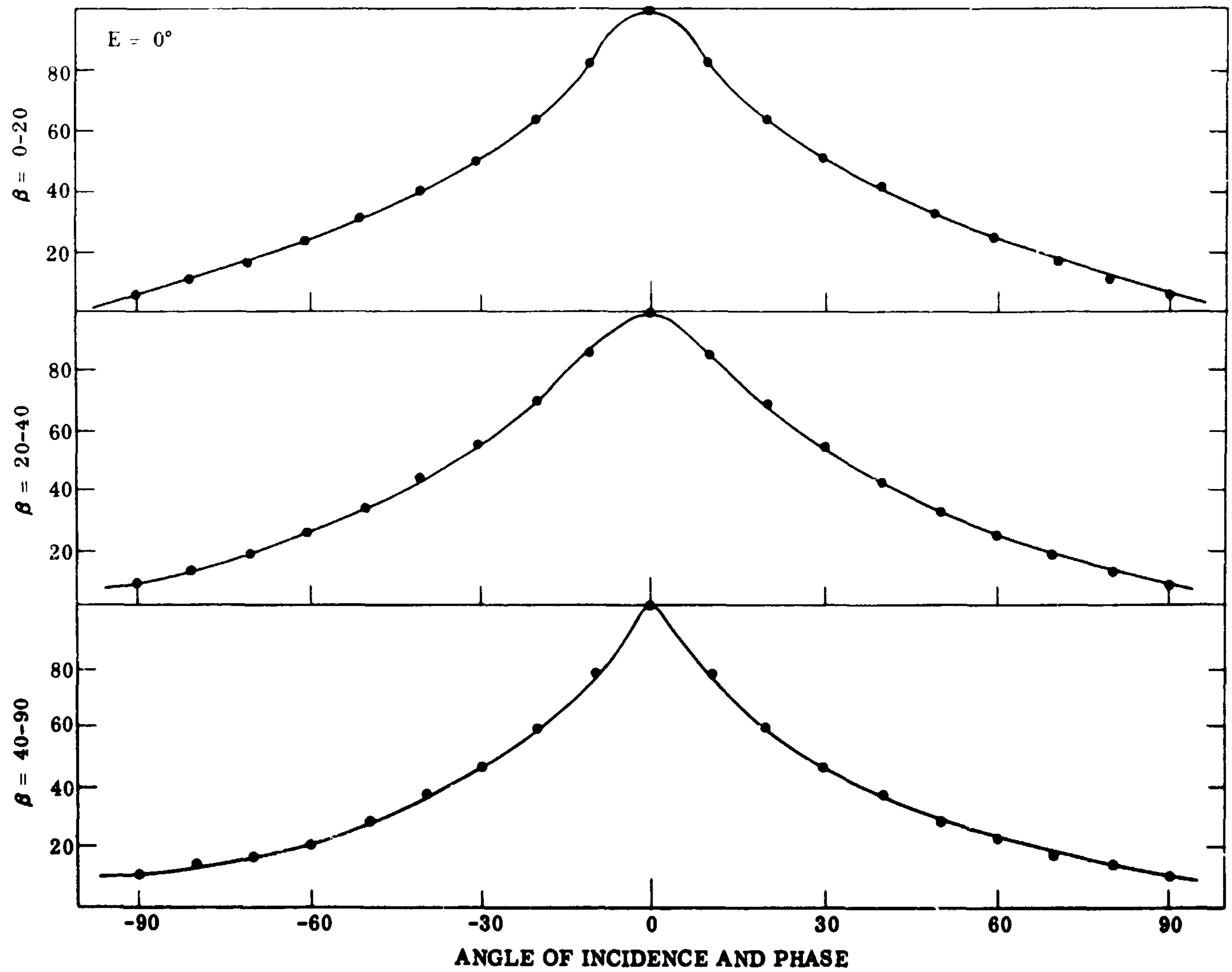


Figure Lunation Curves of 0° to 10° Longitude Crescent; β = Latitude (Ref 8)

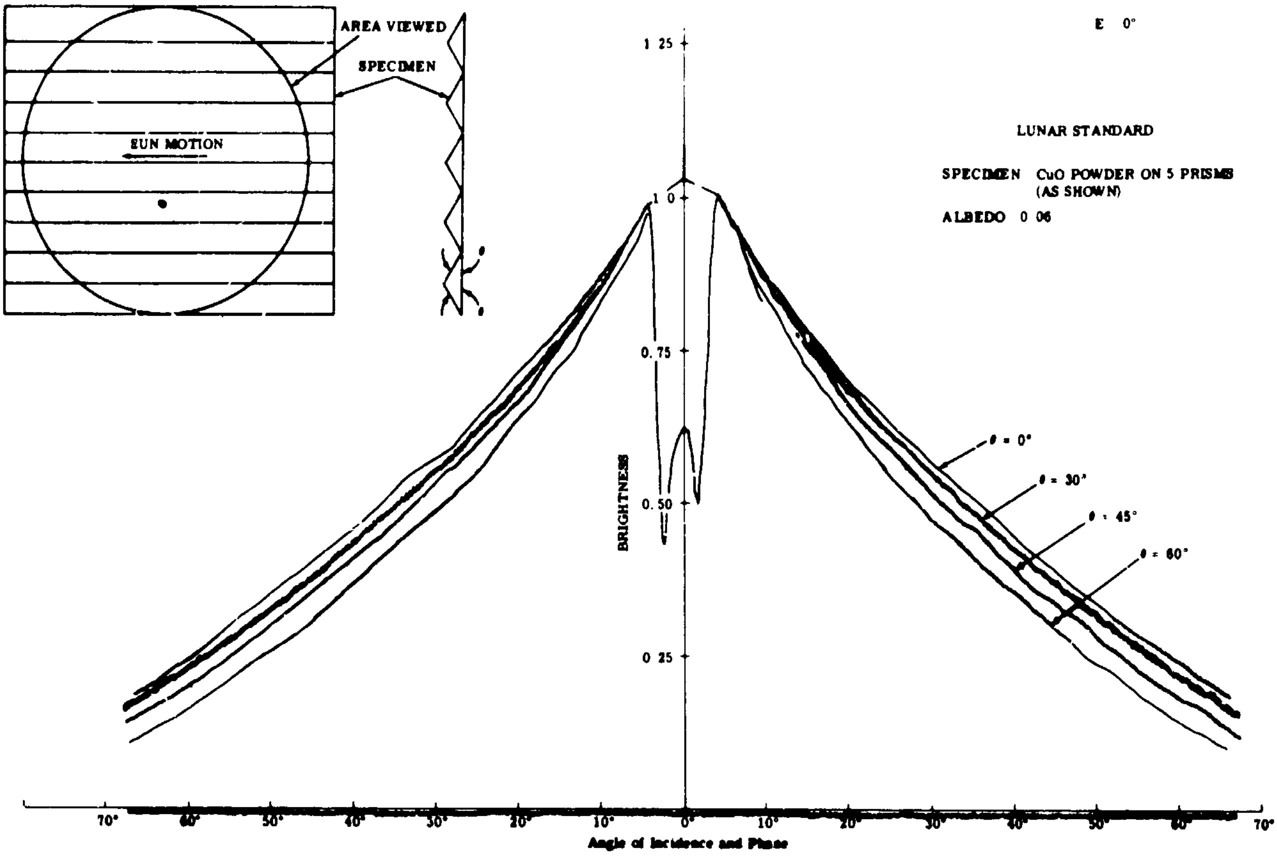


Figure CuO Powder on Five Prisms Intensity Equator Parallel to Ridges

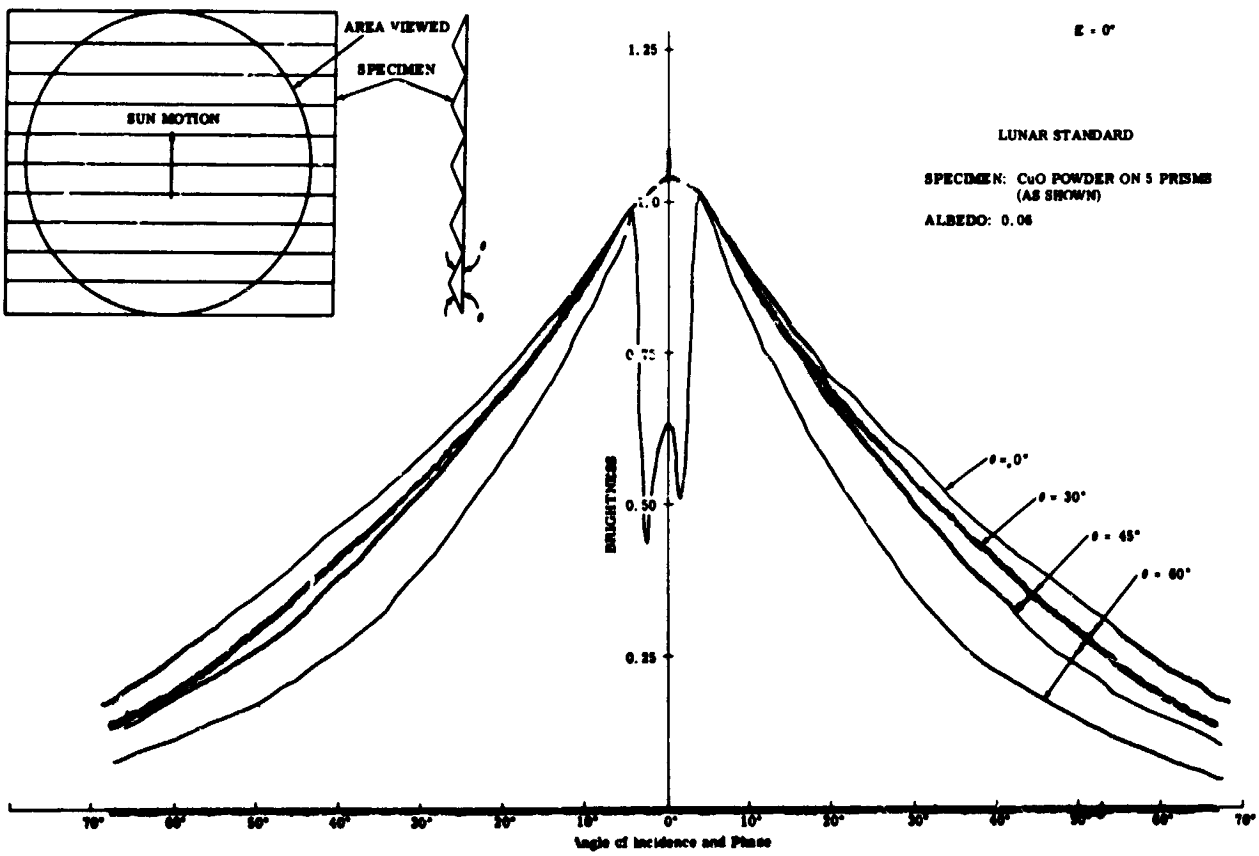
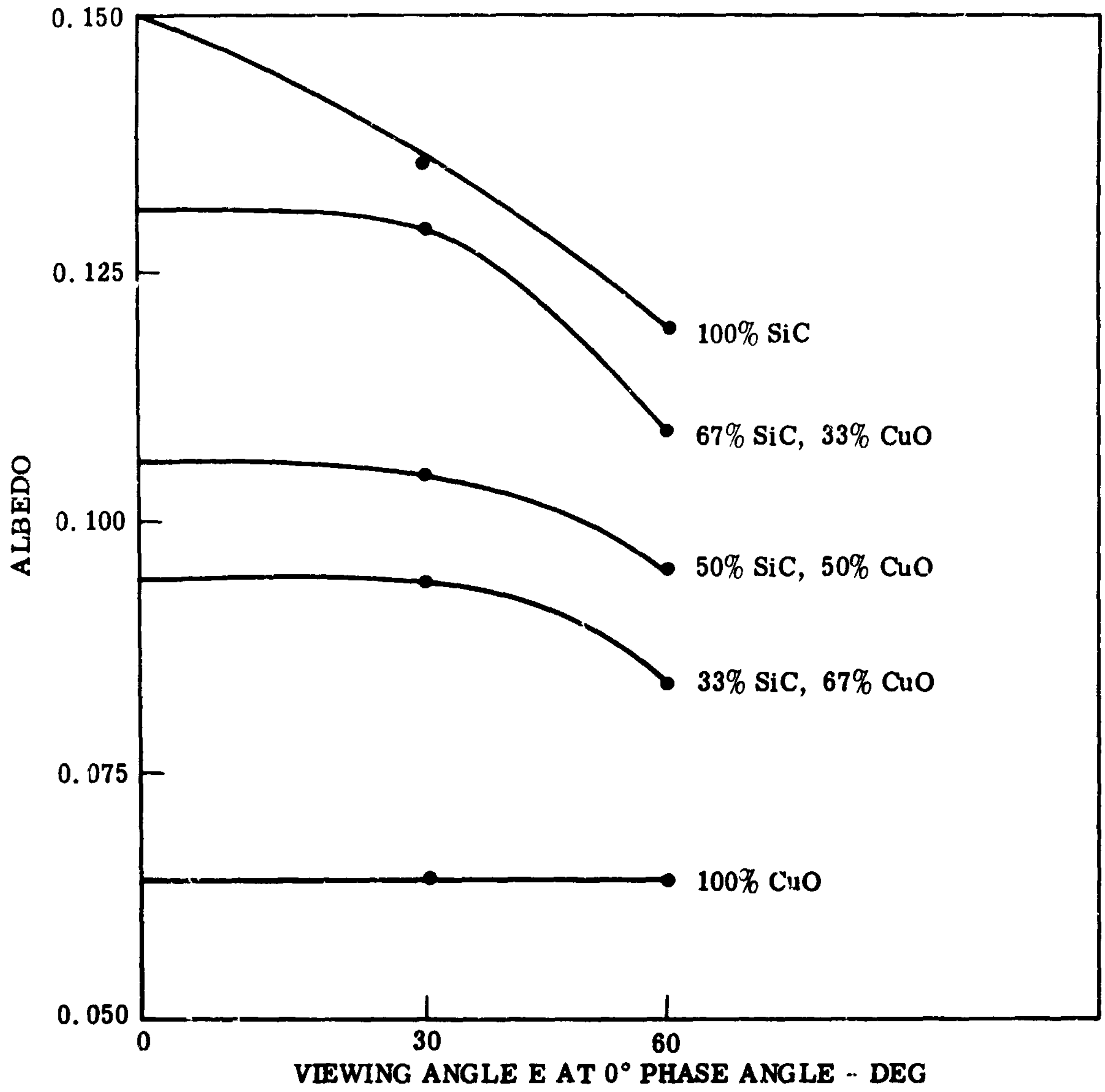


Figure CuO Powder on Five Prisms Intensity Equator Perpendicular to Ridges



NOTE: PERCENTAGES GIVEN BY VOLUME

Figure Albedo vs Viewing Angle of CuO and/or SiC Powders.

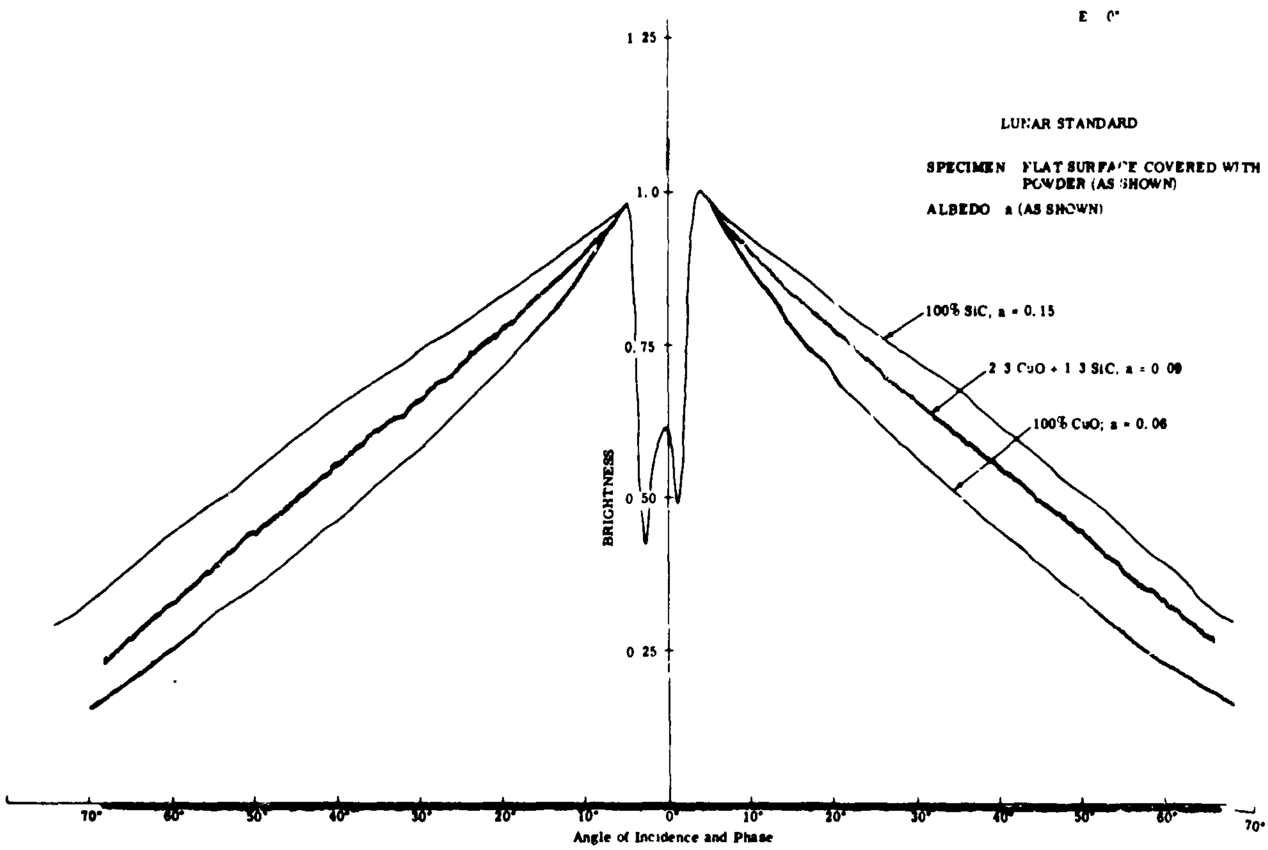


Figure Mixed Powders on Flat Surface

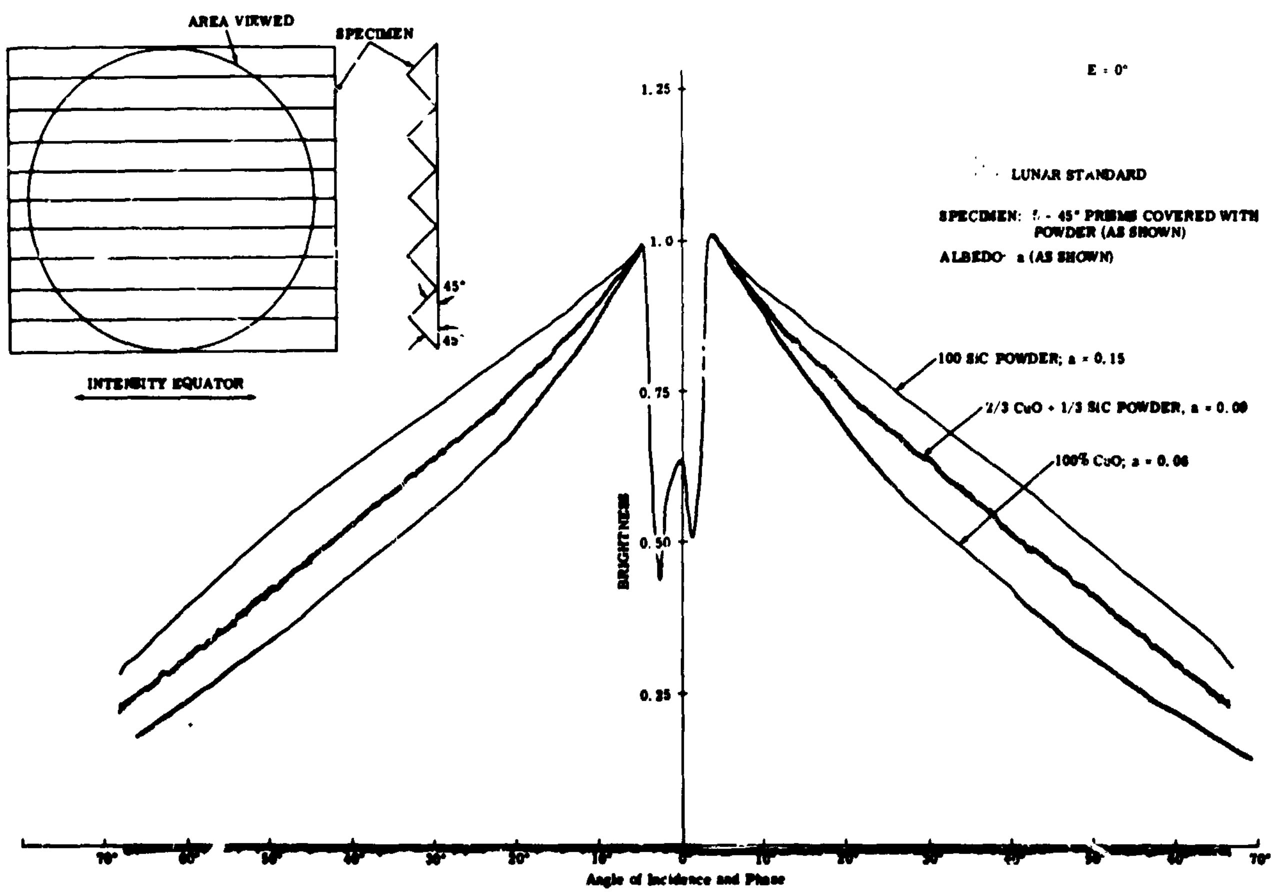


Figure Mixed Powders on Prisms

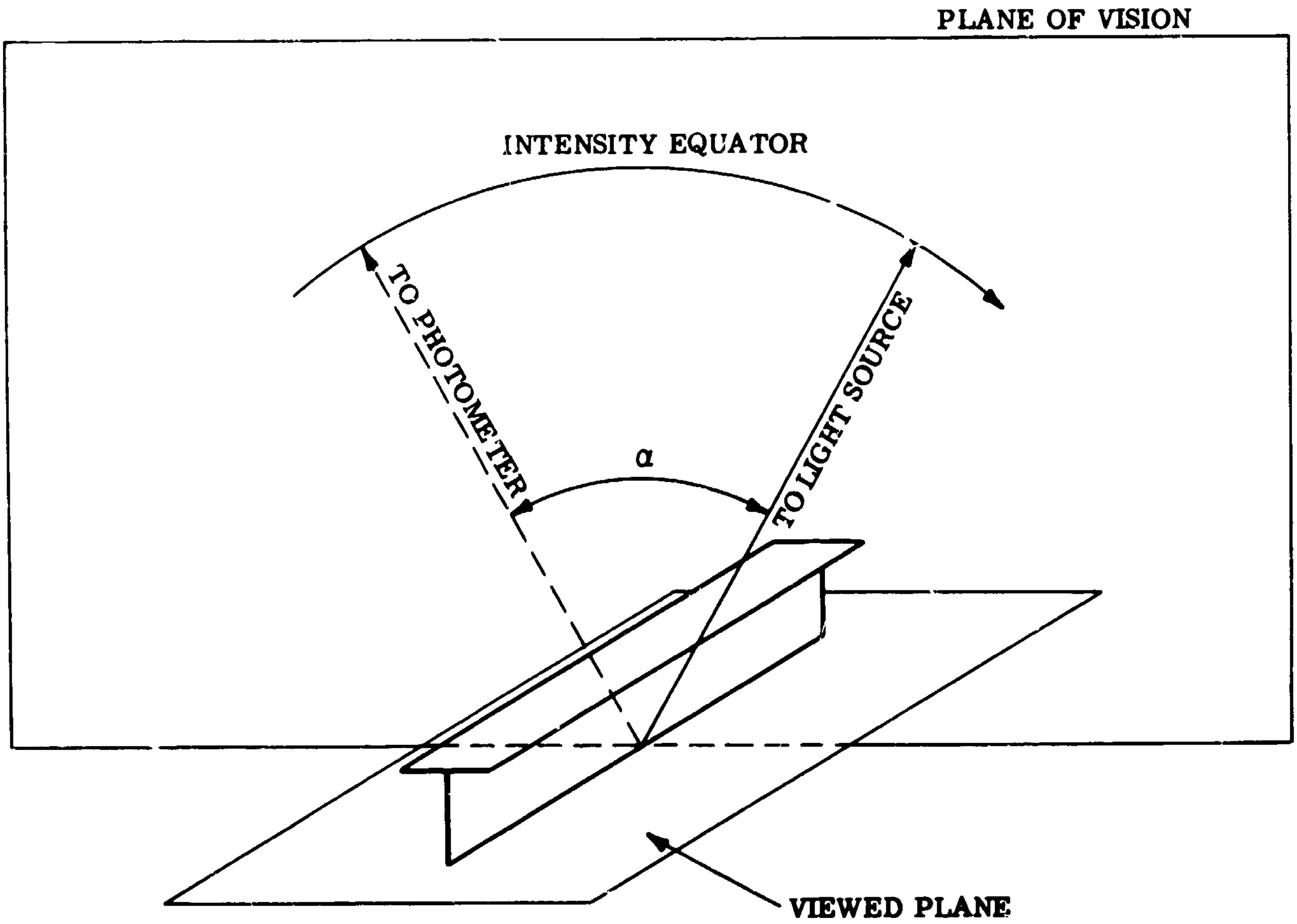
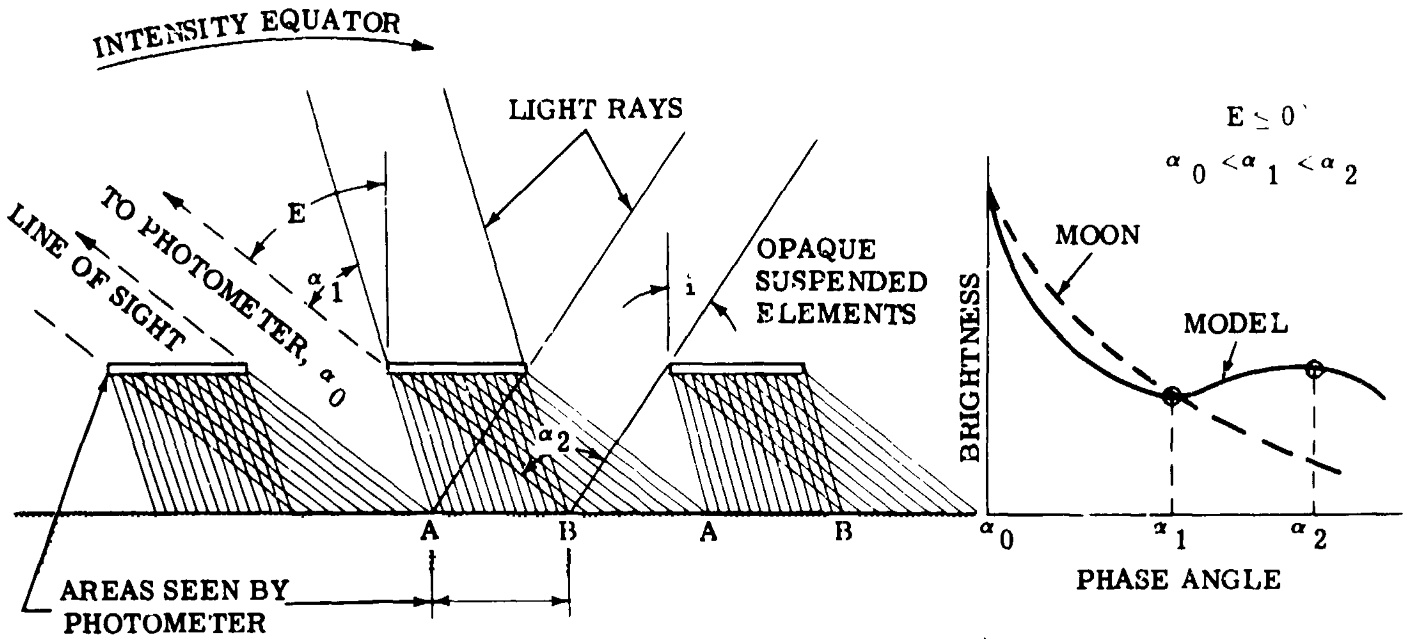
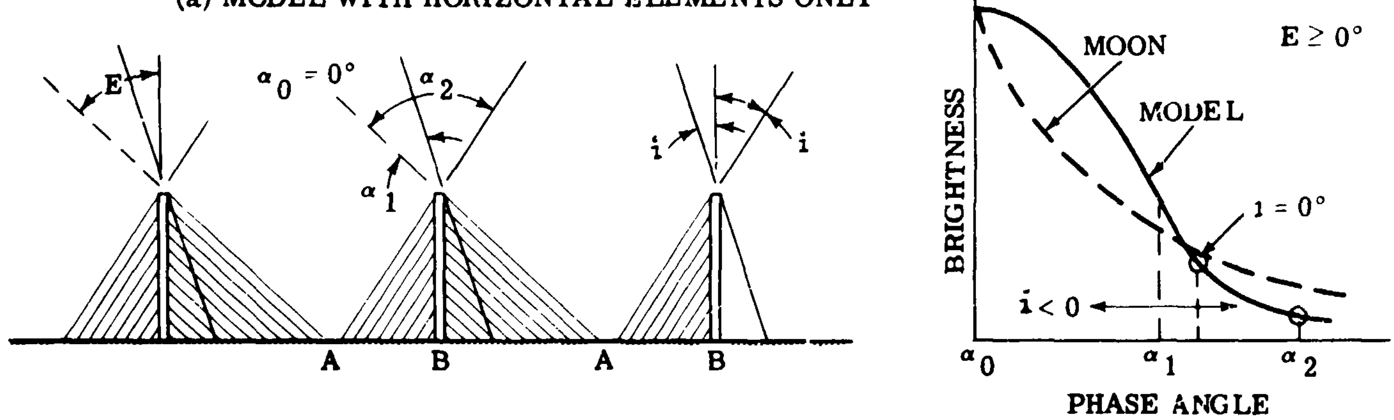


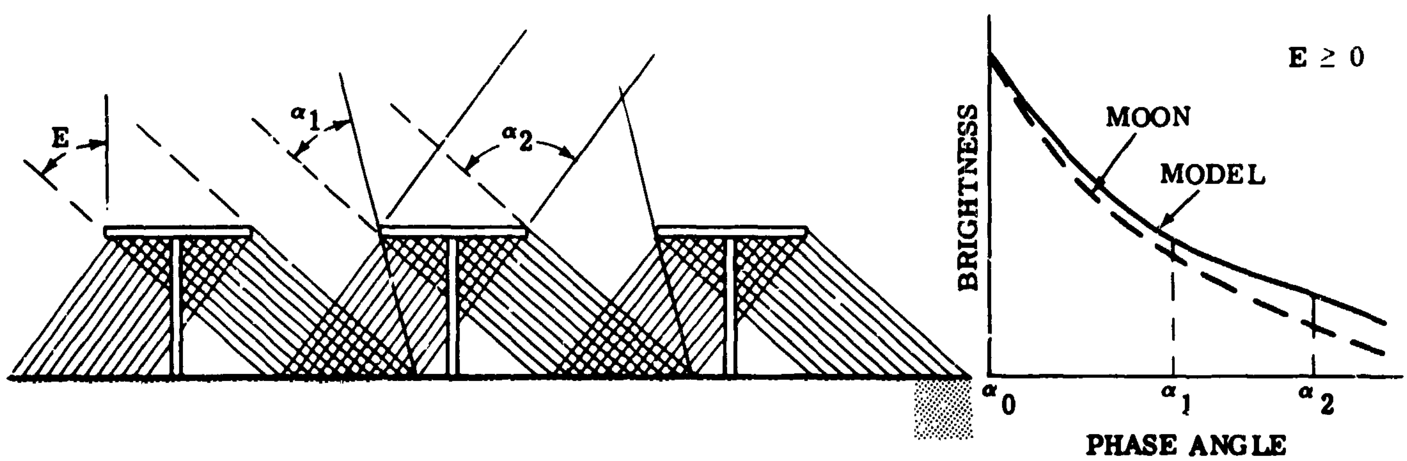
Figure Intensity Equator and Model Orientation.



(a) MODEL WITH HORIZONTAL ELEMENTS ONLY



(b) MODEL WITH VERTICAL ELEMENTS ONLY

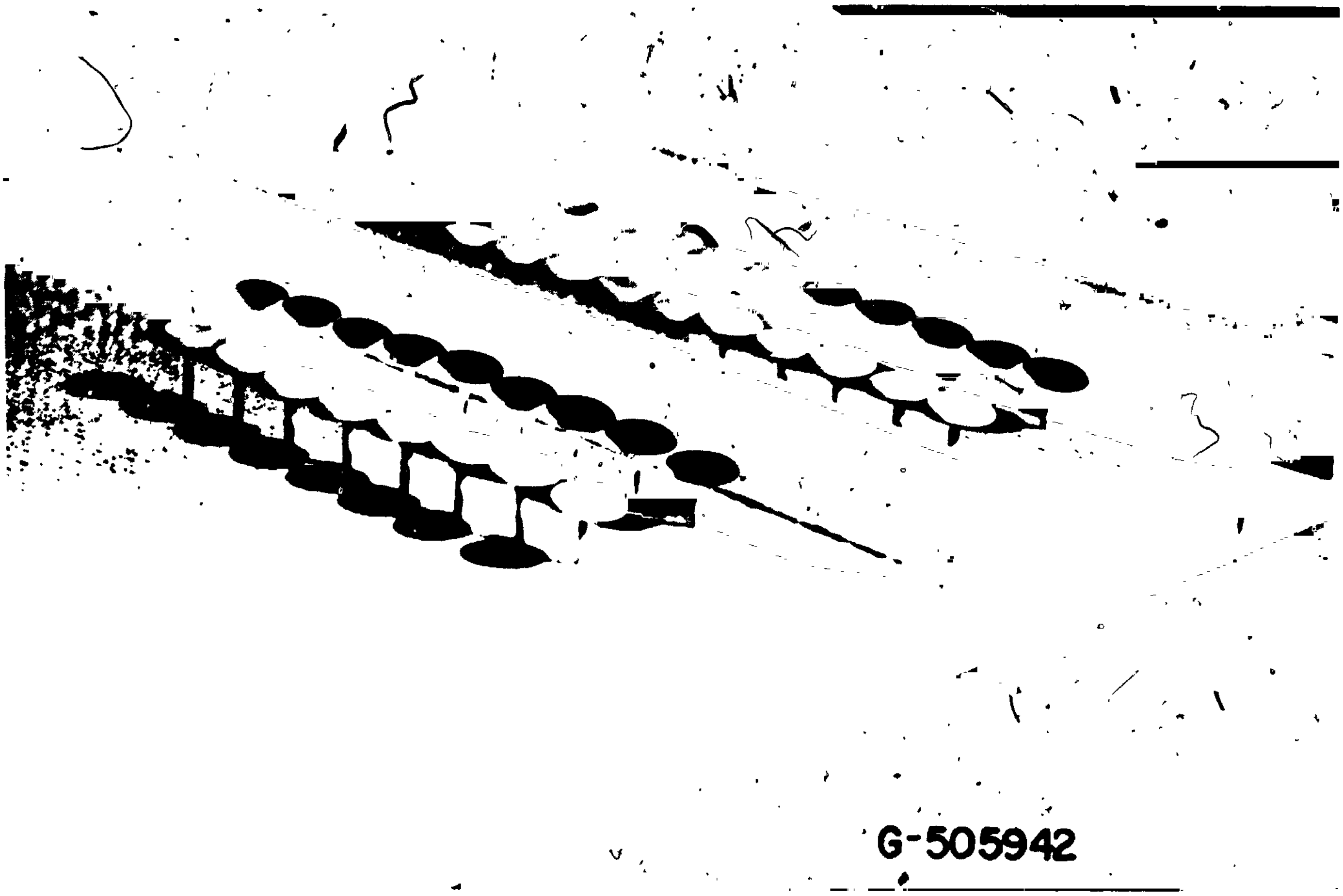


(c) MODEL "T": HORIZONTAL + VERTICAL ELEMENTS

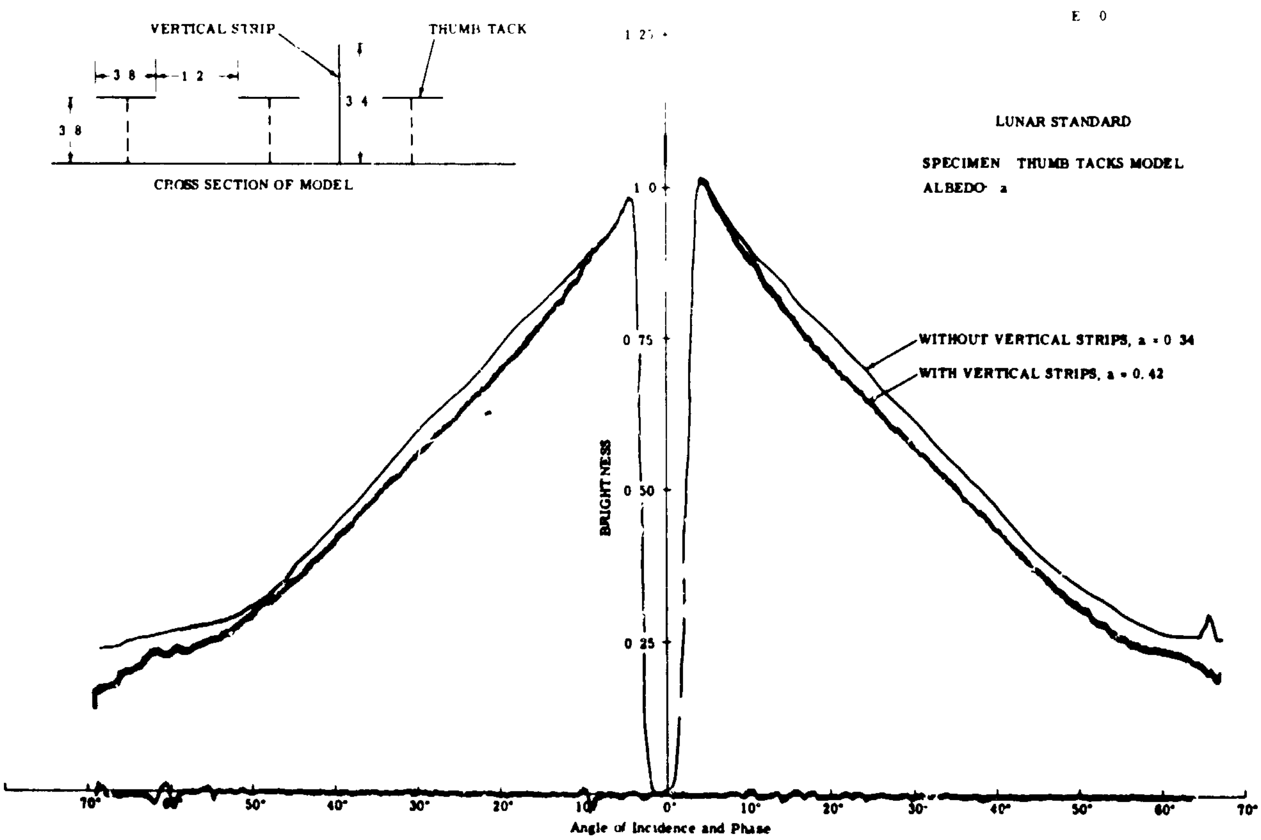
Note:

All Surfaces Assumed Lambertian and Cross Sections in Plane of Vision

Figure "Simple" Models and Their Photometric Function

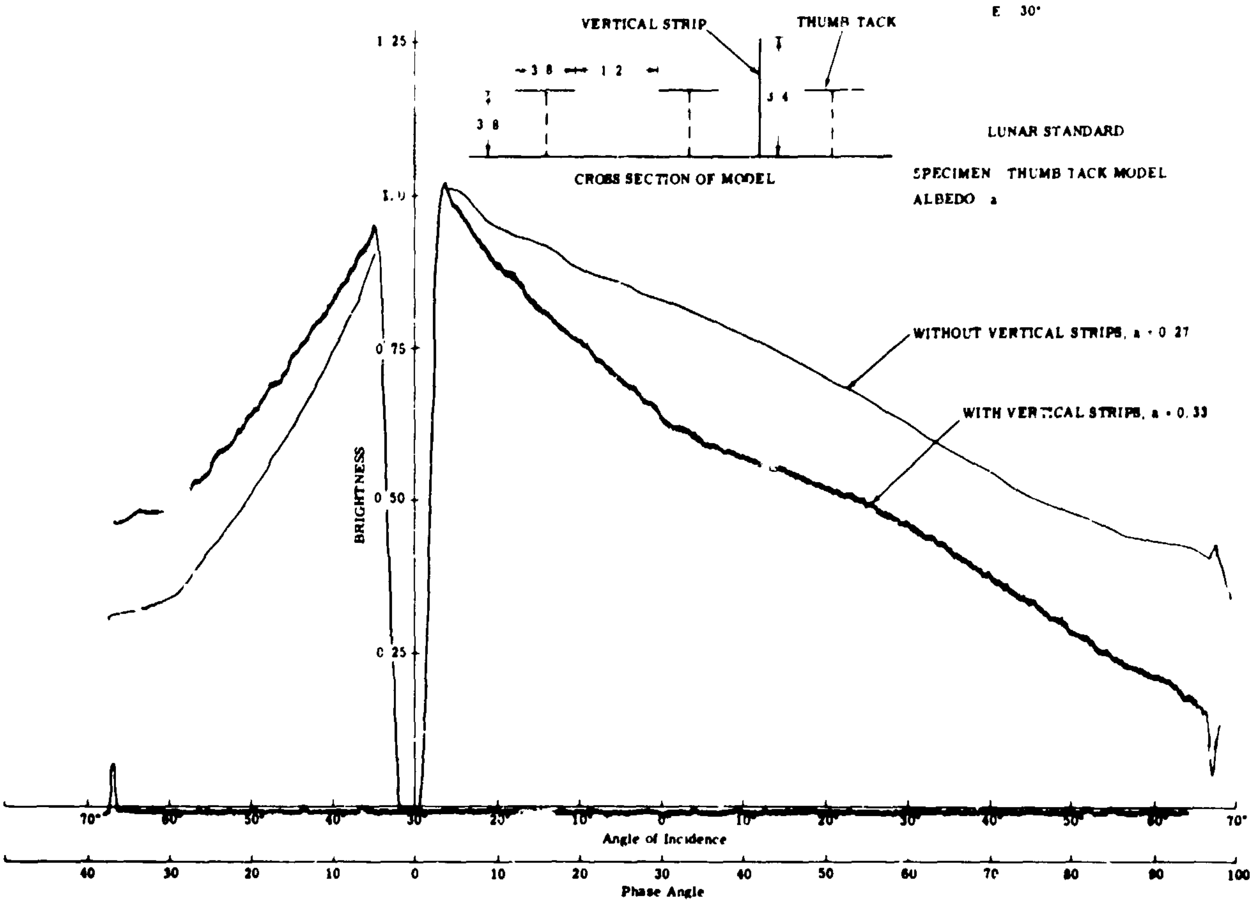


(a)

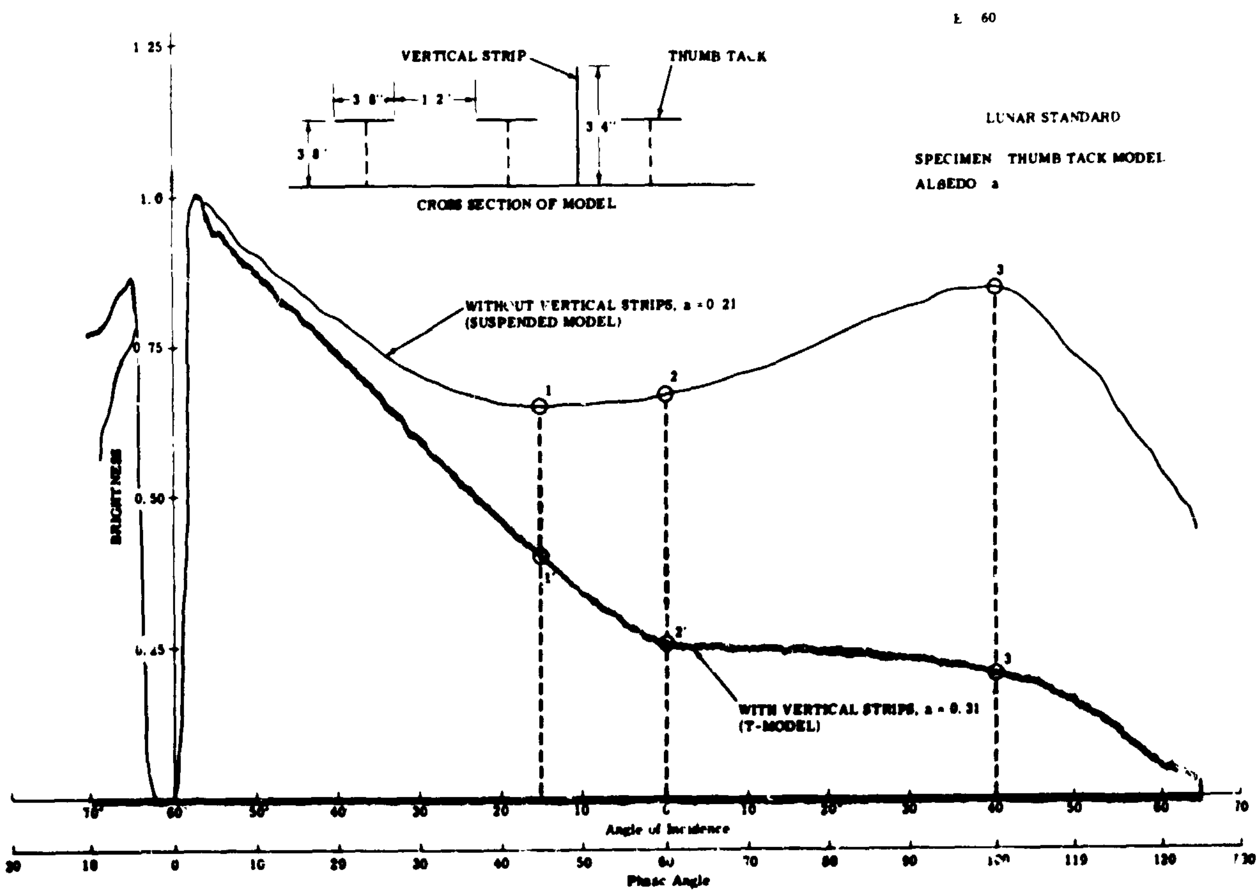


(b)

Figure Thumb-Tacks Model (Sheet 1 of 2)

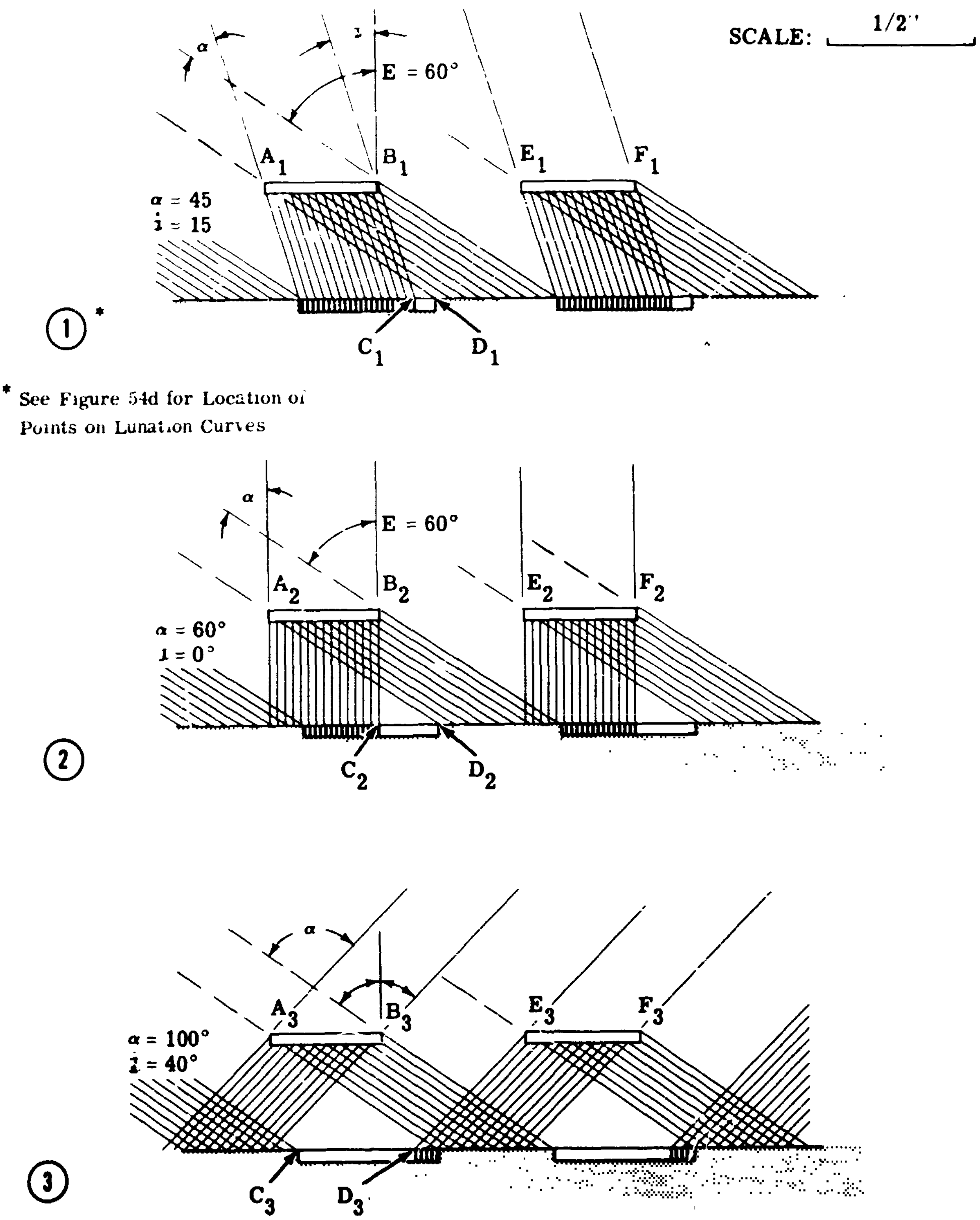


(c)



(d)

Figure Thumb-Tacks Model. (Sheet 2 of 2)



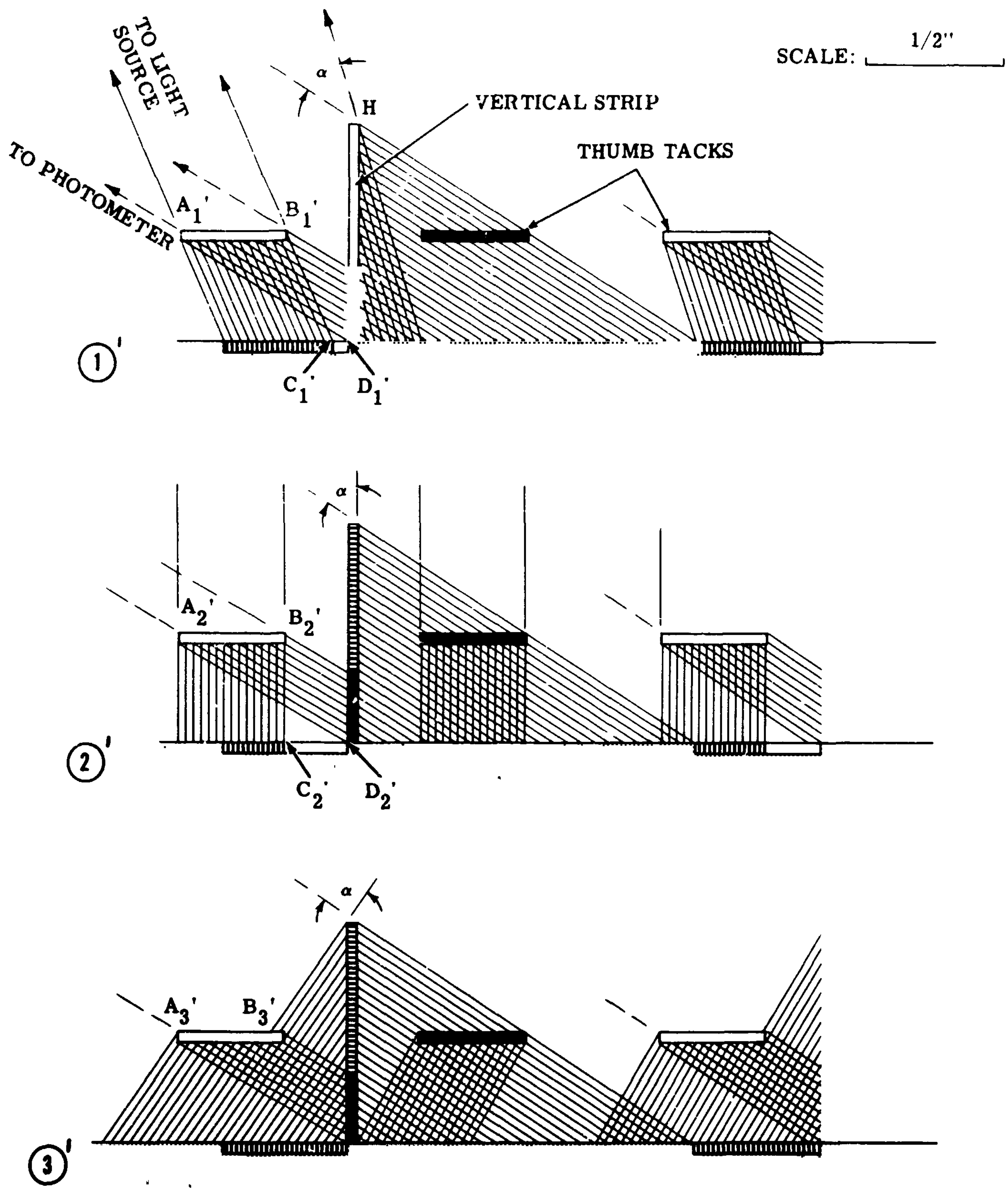
* See Figure 54d for Location of Points on Lunation Curves

(a) WITHOUT VERTICAL STRIP

LEGEND

- Illuminated Areas Seen by Photometer
- Shadowed Areas Seen by Photometer
- Areas Not Seen by Photometer
- — — — Line of Sight
- ——— Ray of Light

Figure **Cross Sections of and Shadowing Sequence in Thumb-Tack Model**



(b) WITH VERTICAL STRIP

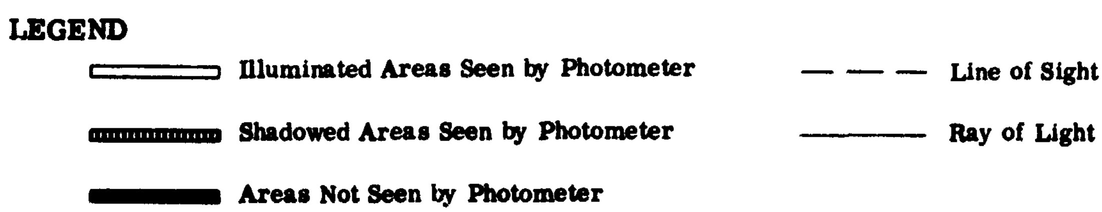


Figure Cross Sections of and Shadowing Sequence in Thumb-Tack Model

ABSTRACT

EVIDENCE FOR LUNAR IGNIMBRITES

Paul D. Lowman, Jr.

The theory that ignimbrites (stratiform deposits of partly-welded volcanic ash deposited by avalanche-like eruptions) are common on the moon has been supported by recent research. This paper summarizes the properties of terrestrial ignimbrites, compares them with the inferred properties of the lunar surface, and briefly discusses the engineering importance of lunar ignimbrites.

Ignimbrites (roughly synonomous with "welded tuffs" and "ash-flow tuffs" are heterogeneous aggregations of volcanic glass, crystals, and rock fragments, usually with overall compositions corresponding to rhyolites, dacites, and andesites. They occur, in regions such as Indonesia, New Zealand, and the western United States as blanket-like deposits up to several thousand feet thick covering originally more than 10,000 square miles in some instances. Studies of ancient and recent ignimbrite deposits (the Mt. Katmai eruption of 1912 is the best known modern ash flow) indicate that the original surfaces, before erosion, consisted of unconsolidated volcanic ash forming a smooth, essentially horizontal surface. Differential compaction tends to produce a subdued replica of the buried topography. Ignimbrites on the earth have been discovered to be much more common in continental regions than formerly realized; Mackin estimates, for example, that such rocks in the Great Basin have a volume on the order of 50,000 cubic miles.

Properties of the lunar surface explainable by the presence of ignimbrite deposits include:

1. Topography:

    Telescopic and Ranger photographs of the mare surfaces reveal a relatively smooth terrain modified chiefly by what appear to be impact craters. Very few fragments of solid rock have been identified to date. The subdued shapes of craters with diameters of hundreds of meters suggest deposition of a blanket of unconsolidated material. Gault interprets the circularity of secondary impact craters photographed by Ranger VII as indicating a non-cohesive material some tens of meters in depth.

2. Radar Reflections:

At wavelengths down to about 10 centimeters, the moon is essentially a specular reflector. The radar reflections are believed to indicate a relatively smooth surface, with average slopes of 10%, consisting of material with a porosity on the order of 40%. The diffuse component of the reflection indicates that about 10% of the surface is covered with small objects below the limit of optical resolution. The dielectric constant inferred from radar returns is between 2 and 3, similar to that of dry sand. The radar returns from ray craters are anomalous, indicating material much more like solid rock.

3. Thermal Properties

Temperature measurements of the lunar surface indicate a highly insulating material at least 1 meter and possibly several meters deep, covering much of the moon with the exception of ray craters and other localized sites. The latter have measurably higher conductivity, and are apparently underlain by denser material. Measurements of the thermal properties of powders in vacuum give values similar to those estimated for the lunar surface.

4. Chemical Composition:

Although there is yet no reliable information on the chemical composition of the lunar surface, several lines of evidence are consistent with a granitic or rhyolitic composition. Luminescence of the surface, such as observed by Kozyrev and Kopal, indicates a low iron content, since iron tends to damp luminescence. The low dielectric constant suggests a very small proportion of metallic iron. The polarization studies of F. E. Wright point to a scarcity of exposed ultrabasic and basic rocks, but instead to a surface covered with powders of siliceous rocks such as quartz porphyry, trachytes, and tranites. Finally, a lunar origin for tektites, supported by much recent research, requires large areas to be covered with rock of granitic composition; certain tektites retain textures suggestive of derivation from a pyroclastic rock.

These properties of the lunar surface, taken together, strongly suggest that ignimbrites are a common lunar rock type. This would have major implications for manned lunar operations in the following areas:

1. Trafficability:

   Ignimbrite terrains on the earth present little difficulty in helicopter landing and surface travel by wheeled vehicles or on foot. Although the trafficability of lunar volcanic ash cannot be predicted with certainty, various experimental studies of powders in vacuum contradict the probability of extremely soft material.

2. Construction and Excavation:

   Unconsolidated volcanic ash would clearly facilitate excavation for foundations or underground construction, while possibly presenting some difficulties in erection of large telescopes or other structures requiring solid footing.

3. Raw Materials:

   If the maria are the site of relatively recent ash flow eruptions, there might be active fumarole and hot springs, which would be an invaluable source of water (and possibly power). Even in older deposits, hydrous materials, such as the tuff itself and hydrous minerals (e.g., clays, zeolites, opal) formed by hydrothermal alteration of tuff might be found.

References

1. Boyd, F. R., 1961, Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming, Bull. Geol. Soc. America, 72, pp. 387-426.

2. Cook, E. F., 1958, Stratigraphic study of eastern Nevada Tertiary volcanic rocks (abstract), Geol. Soc. Am. Bull., 58, pp. 1548-1549.

3. Evans, J. V., 1962, Radio echo studies of the moon, in Physics and Astronomy of the Moon, ed. by Z. Kopal, Academic Press, New York.

4. Glasstone, S., 1965, Sourcebook on the Space Sciences, Van Nostrand, Princeton, N. J.

5. Green, J., 1964, A study of the feasibility of using nuclear versus solar power in water extraction from rocks, AFCRL-62-733, Air Force Cambridge Research Laboratories, Bedford, Mass.

6. Lowman, P. D., Jr., The relation of tektites to lunar igneous activity, Icarus, 2, pp. 35-48.

7. Lowman, P. D., Jr. and D. A. Beattie, 1965, Lunar scientific operations, paper presented at the 10th Annual Meeting of the American Astronautical Society, May 4-7, 1964, New York City.

8. O'Keefe, J. A., and W. S. Cameron, 1962, Evidence from the moon's surface features for the production of lunar granites, Icarus, 1, pp. 271-285.

9. Ross, C. S., and R. L. Smith, 1961, Ash flow tuffs, their origin, geologic relations, and identification: U. S. Geological Survey Prof. Paper 366.

10. Salisbury, J. W., and P. E. Glaser, 1964, The Lunar Surface Layer, Academic Press, New York.

11. Smith, R. L., 1960, Ash flows, Bull. Geol. Soc. America, 71, pp. 795-842.

ABSTRACT

SCIENTIFIC MISSIONS FOR A LUNAR BASE

Paul D. Lowman, Jr.

This paper summarizes the scientific value of the moon as an object of study and as a site for research, and suggests specific scientific missions for a lunar base such as the Lunar Exploration System for Apollo (LESA).

As an object of study, the moon is of scientific interest primarily because of its lack of atmosphere, a condition believed to have existed throughout most of the moon's history. This leads to two general scientific benefits. First, the moon's geologic record is probably more complete, and extends back much further in time, than does that of the earth. Second, it presents in principle a control in comparative planetology, in that its evolution has not involved air and water, factors which have dominated the development of terrestrial topography and geology. Detailed exploration of the moon, taking advantage of these characteristics, may shed decisive light on such problems as the origin and age of the earth-moon system, evolution of the solar system, composition of non-volatile solar matter, the origin of continents, and numerous others. It is stressed that the history of the solar system can be studied only through solid bodies such as the moon, because only solids retain a memory of their development; space-borne measurements tell us essentially the condition of the solar system now.

The moon as a site for research offers several unique advantages. First, it is close to the earth in terms of travel time and data transmittal. However, it is at the same time far enough away to be beyond the effects of the earth's magnetosphere (except for occasions when it may pass through the geomagnetic tail). This distance, coupled with the absence of an appreciable atmosphere, should make it possible to study primary cosmic radiation, and undeflected solar radiation, from the moon. The moon's estimated atmospheric density is orders of magnitude less than that of the earth at 200 miles altitude (a likely altitude for a manned space station), further adding to its value as an observation point.

Perhaps the moon's greatest advantage over earth-orbiting space stations lies in the probability that manned operations will be easier on the moon. This stems from the moon's gravity field, which should prevent the physiological degeneration and operational difficulties (such as dispersed liquids in free

fall) foreseen under prolonged weightlessness. Furthermore, the moon furnishes, in principal, material resources; only energy is available to a space station. Finally, the moon provides a stable platform for the construction of, for example, radio telescopes, thus avoiding problems of reactive motion and momentum conservation.

These considerations strongly suggest the great value of a lunar research station as a major manned space flight project in the post-Apollo period.

Specific missions suggested for the LESA, a conceptual design for a modular lunar base transportable for the Saturn V, include:

1. Extensive geological and geophysical exploration

2. Operation of optical telescopes of various sizes

3. Operation of radio telescopes, preferably on the far side of the moon

4. Studies of primary cosmic radiation

5. Physiological studies of man and other organisms under reduced gravity

6. Synoptic observation of the earth by astronomical techniques.

References

1. The Boeing Company, Aero-Space Division, 1963, Initial Concept of Lunar Exploration Systems for Apollo, D2-100057-1, Seattle, Washington.

2. Glasstone, S., 1965, Source Book on the Space Sciences, Van Nostrand, New York.

3. Henderson, C. W., 1965, Extended lunar exploration, presented at the 11th Annual Meeting of the American Astronautical Society, Chicago, May 5, 1965.

4. Hess, W. N., (Editor), 1965, Introduction to Space Science, Gordon and Breach, New York.

5. Lowman, P. D., Jr., and D. A. Beattie, 1964, Lunar scientific operations, presented at the 10th Annual Meeting of the American Astronautical Society, New York, May 4-7, 1964.

6. North American Aviation, Inc., Space and Information Systems Division, 1965, A Study of Scientific Mission Support for the Lunar Exploration System for Apollo, SID 65-289-3, Downey, California.

7. Smith, R. E., 1965, Space environment criteria guidelines for use in space vehicle development (1965 revision), NASA Technical Memorandum, TM X-53273, George C. Marshall Space Flight Center.

N66 23309

CHEMICAL BONDING AND SHEAR STRENGTH
OF SILICATE SYSTEMS UNDER LUNAR CONDITIONS

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INTRODUCTION

Models of the structure of the lunar surface vary from a rock froth to a dust layer, the bonding characteristics of the latter having been hypothesized to range from loose particles to welded crust. Experimental studies, however, have been so incomplete and information so lacking that no definitive conclusions regarding strength of the lunar soil have been reached. In this report, an attempt has been made to show that experimental evidence exists to support the conclusion that chemical bonding and interparticle force effects are exhibited by particles of the dust layer and to discuss some physical properties of simulated dust models reflecting these bonding and force effects.

The simulation problem is comprised of two main elements. The first part is definition of the soil model and the performance of tests to verify the model and to establish and correct discontinuities with known data regarding the lunar surface properties. The second part is definition of the space environment and identification of the processes governing the environmental interactions. Of these two considerations, the prime requirement for study of the lunar soil is proper simulation of the lunar environment. Tests conducted during the research program (Johnson and Griffin, 1965) have considered both the lunar vacuum and the solar wind bombardment of the Moon. Under these conditions, it was possible to study the microscopic structures of the lunar surface and to observe the physical properties of these structures. Since in this environment the particle surfaces were cleaned of contaminants, the only forces present were those arising from the particles themselves. The strength of these forces should permit the determination of the physical characteristics of the surface.

The objective of this research program is to develop an understanding of the nature of the lunar dust, primarily its probable particle size distribution, porosity, and related physical properties. This will be achieved by matching the results of tests on simulated dusts with data from lunar observations. From the data derived by these studies, engineering strength properties and chemical compositions can be calculated or inferred. With both an experimental and theoretical model available, some conclusions regarding the structure of the Moon's surface are possible.

RESEARCH PROGRAM

The program of research designed to provide data in support of existing concepts and defense of new hypotheses was envisioned as a three phase sequence of research as shown in Figure 1, each phase representing approximately one year of effort.

The first phase was envisioned as reflecting major emphasis on verification of the soil model. Particle size and grain size distribution as well as chemical composition dominated the variables of interest, although the photometric properties also were of interest. Radiation effects were investigated by electron irradiation. Though many researchers have investigated grain size and composition of simulated lunar surface materials, little definitive research has been performed in support of lunar surface model hypotheses and the assumptions on which they are based. During this phase, therefore, soil particles were dropped in an ultra-high vacuum in such a manner that a loose, porous structure could be formed. The particle sizes ranged from 1 to 50 microns in diameter. Coincident with the particle fall, the grains were irradiated by electrons from an electron gun source. Comparison between the bonding behavior of irradiated and non-irradiated particles was determined from these test conditions. By varying the chemical composition of the soil samples, the structure produced by the falling particles was investigated and could be compared with lunar surface models.

The second phase reflects concern with the engineering strength properties of the structural model. A program of engineering tests and experiments was designed to develop surface strength data and design-load parameters. At the present time, some work has been done on investigation of developed bond strengths and these have been compared with calculated values. Cohesion and adhesion phenomena have been investigated as well, and some distinctions between the two types of behavior have been noted. It is anticipated that shear strength parameters will be determined by applying vertical loads to the soil and recording the variation of strength with increasing load in accordance with the Coulomb equation of soil strength. It is hoped that significant bearing strength data can be obtained by a test involving the application of known static loads to round bearing plates of varying diameter. The ability to accomplish this is a function of the vacuum capacity of the system and its ability to maintain the desired environmental conditions for a significantly large soil mass.

During the third and last phase it is expected that additional tests will be run on the soil structure developed and verified in earlier phases to determine methods and techniques for stabilizing the dust particles to produce improved bearing strength. Chemical additives will be applied to the soil in vacuum to determine sublimation rates and activity as well as the amount of additive required to produce a finite, known strength gain. Techniques of chemical application will be investigated extending earlier work by Winterkorn and Johnson, (1964).

The research reported upon in this paper includes essentially only that work accomplished during the first and second phase and reflecting effort applied during two years of activity. Though this work has been directed at verification of a soil model, it became apparent quite early in the program that certain iterative procedures were involved in which permutations of equipment modification, soil models, and soil structure were varied. In this way, the influence of the test variable could be determined. Early tests demonstrated that sufficiently low vacuum levels could not be obtained by the system as originally conceived and, for this reason, modifications were made during the experimental program. This was true for the granular particles also, when it became apparent that behavioral characteristics at very low vacuum levels were a function of particle size and composition.

MODES OF BONDING

The characteristics of any material are highly dependent upon the bonding forces active in the substance. The chemical, molecular, and inter-particle bonds which may exist will determine the physical properties of that system, and the surrounding environment will dictate which of these possible bonding modes are most important. Thus, the presence of high vacuum, intense radiation fields, wide temperature fluctuations, and a steady influx of micro-meteorites argues for the existence of a lunar surface structure which has no analogy on Earth. The greatest variety of bonding modes which might be influenced by lunar surface conditions is presented by a granular surface layer system. For experimental purposes, such a covering will be postulated to exist on the Moon, as this assumption involves the most unknowns and hence the greatest hazard for lunar missions. It is further assumed that the surface layer is comprised largely of silica or silicates as has been proposed by many researchers. The bonding properties of granular silicate systems under lunar conditions must, therefore, be considered.

The atomic or chemical bonds are the strongest of the bonding modes. These forces, however, are of short range and become active only on close juxtaposition of the atoms to be bonded (on the order of angstroms). In the absence of driving energy, clean, uncontaminated surfaces with unsaturated bonds are necessary for the activation of chemical bonding.

The major types of atomic bonding forces and their distinguishing characteristics are summarized in Figure 2. All but the metallic bond are important in silicates. Ionic bonding arises from electrostatic forces while covalent bonds result from the sharing of electrons. Although both are strong bonding forces (30-200 kcal/mole), the major distinction between the two is the directionality of the covalent bond: this bond requires specific inter-atomic angles for development of maximum strength whereas purely ionic forces are isotropic. The hydrogen bond is basically electrostatic in origin, arising from the attraction of a bare proton for highly electro-negative atoms. This bond (Pauling, 1960) is far weaker than the primary (ionic and covalent) bonds (2 - 10 kcal/mole), but it is important in determining the properties of some silicates (Means and Parcher, 1963), especially certain clays (e.g. kaolinite).

Most actual atomic bonds are mixtures of ionic and covalent modes known as resonance. An increase in bond energy from 5 to 110 kcal/mole (Pauling, 1960) is often achieved by mixing several bond types and configurations. The wave function of such a system may be written as that linear combination of ionic and covalent states which minimizes the system energy. The silicon-oxygen bond, of importance to the silicates, is a resonance structure having 51% ionic and 49% covalent character (Pauling, 1960). The basic SiO_4 unit is a tetrahedron whose properties are summarized in Figure 3. Note that the covalent bond character is exhibited through the precisely determined O-Si-O angles, while the presence of partial ionic bonding produces a charge of +0.96 on the central silicon atom.

The silicate tetrahedra can combine in a variety of ways to form many silicate structures. These structures are determined by the atomic radii, the nature of the Si-O bond, and the electrostatic valence rule (Pauling, 1960). The ratio of the Si^{+4} radius to that of O^{-2} is such as to permit coordination of four oxygen atoms, yielding the tetrahedral SiO_4 unit. Due to the large residual charge on the central silicon atom, the tetrahedra tend to repel one another and thus do not share edges. This is evident from the more common silicate structures (Kraus, Hunt, and Ramsdell, 1951) depicted in Figure 4. The electrostatic valence rule for oxygen anions is given by the relation

$$\sum_i \frac{z_i}{v_i} = 2$$

where z_i is the number of electronic charges on the i^{th} cation, v_i is the coordination number of the i^{th} cation, and the summation includes the central cations of all polyhedra of which the oxygen anion forms a corner. Thus, an oxygen may share two tetrahedral silicon bonds, a silicon plus two octahedral aluminum bonds, and so forth. The great variety of substitutions possible gives rise to many silicate structures found in nature.

The importance of the silicate atomic bond for the lunar surface lies in its highly directional character. The complicated nature of silicate configurations will inhibit spontaneous bond formation between particles. The involved structure should also inhibit vacancy migration and thereby impair sintering (Smoluchowski, 1965). And finally, the strong, symmetric bonds are responsible for the hard, brittle nature of the silicates, a property which influences inter-particle contacts.

Of the three major molecular or van der Waals forces listed in Figure 5, only the dispersion force is important for silicate molecules. The alignment and induction forces require the presence of permanent dipole moments. Dispersion, however, is active between all molecules, including the silicates, and arises from a consideration of the polarization of a molecule by the instantaneous dipole moment of another. These dipoles arise from momentary fluctuations in the molecular charge distributions. Note that these are short-range forces, the energy decreasing as r^{-6}, where r is the intermolecular distance. In the energy expressions given in Figure 5, μ is the permanent dipole moment, α is the polarizability, T is the absolute temperature, k is Boltzmann's constant, and $h\nu_0$ is the zero point energy (Day and Selbin, 1962). The molecular forces are very weak, with energies ranging from 0.5 to 5 kcal/mole (Pauling, 1960).

The dominant interactions between particles are frequently long-range forces, some of which are listed in Figure 5. In such systems, contaminants often prevent activation of strong, short-range bonds by limiting the minimum inter-particle separations. Furthermore, the small particle mass and high surface to volume ratio of granular systems reduce gravitational effects and permit the weak long-range forces to become dominant.

Of the many types of long-range forces which have been observed or hypothesized, probably the most important one for silicate systems is the integrated dispersion force. This interaction may be derived by assuming that the molecular dispersion forces described above are additive. By summing the dispersion force contributions between all molecules of two separated particles, an attractive, long-range force is obtained. This force is dependent upon the polarizability of the constituent molecules and the geometry of the interacting surfaces. Early calculations (de Boer, 1936; Hamaker, 1937) yielded an attractive force which varied as d^{-2} for two spheres of minimum separation d, while for flat, parallel plates, the force per unit area varied as d^{-3}, with d defined as the separation of the surfaces. Detailed consideration (Derjaguin et al, 1956) of retardation effects associated with the finite time required for propagation of force fields over distances greater than a characteristic wavelength (Overbeek and Sparnaay, 1954) associated with the materials yielded a force per unit area between flat, parallel plates which varied as d^{-4}. A macroscopic treatment (Lifshitz, 1955) yielded essentially the same results through consideration of fluctuations of electromagnetic fields in continuous media. Experimental evidence seems to verify these predictions (Kitchener and Prosser, 1957, Sparnaay, 1957).

The presence of dispersion forces in granular silicates under lunar conditions is to be expected. Several authors (Salisbury and Glaser, 1964; Ryan, 1965) have apparently observed experimentally such interactions in both granular and bulk silicates under vacuum. Ryan, for example, has attributed certain adhesive phenomena between silicate surfaces to integrated dispersion forces. The bulk adhesive forces generated were on the order of 1 to 10 dynes/cm^2.

Double layer forces arise from the presence of contaminants adsorbed by soil particles. Such layers may exist in both liquid, gaseous, and moderate vacuum environments. The structure of the double layers can be quite complicated. Adamson (1960) has proposed a double layer system in electrolytic solutions consisting of three regions: a chemically adsorbed "potential-determining" layer, the Stern layer of immobile, electrostatically adsorbed atoms, and a diffuse layer consisting of a mobile cloud of charged, weakly-bound particles. The associated potentials, being electrostatic in origin, are of very long range.

An excellent example of the double layer forces active in granular systems is found in clay water. Small clay particles exhibit a large surface to volume ratio and, as a result, adsorbed water is crucial in determining the properties of a clay. Water bound to clay particles forms two poorly-defined regions (Johnson, 1964): (1) a strongly adsorbed layer (5-10 Å) of solid water bound by the electrostatic charges on the clay particle and by the dipole moments of the water molecules and (2) a region (200-400 Å) known as "double layer" water which is weakly bonded by induction forces. Such layers will be present in simulated lunar soils, and great care must be exercised in their re-

removal. Although most double layer water can be removed by moderate heating (100° C), it has been established that adsorbed water is driven off only at temperatures on the order of 300° C (Grim, 1953.)

The importance of the removal of double layer forces from simulated lunar soils lies in their probable absence on the lunar surface. Ultra-high vacuum in conjunction with the incident radiation flux and high temperature extremes will clean all exposed lunar surfaces of foreign substances. Of course, some contaminating phenomena will exist on the moon. A lunar atmosphere with a maximum pressure of about 10^{-13} earth atmospheres may be present, but such gas densities still represent a hard vacuum. Number density estimates range from 5×10^5 molecules/cm^3, mostly H_2O, H_2, and CO_2 (Öpik, 1962) to 5.5×10^4 molecules/cm^3, primarily He, Ar, H_2, and H_2O (NASA, 1965). The low chemical activity of most of these substances and of silicate surfaces in general precludes chemical adsorption except possibly for hydrogen. Low gas densities and high surface temperatures imply that formation of an effective physically adsorbed double layer will be difficult.

The water present in the lunar atmosphere would most likely be generated by proton sputtering of oxygen from the silicate lattice (Öpik, 1962). Using an empirical sputtering rate (Öpik, 1958) in conjunction with estimates of gas occlusion in lunar rock, meteorite outgassing, and possible plutonic activity, Öpik arrived at a water density of 1.4×10^5 molecules/cm^3 in the lunar atmosphere. This yields a surface density of 2700 molecules/cm^2, far too few for development of double layer effects under lunar conditions. Thus, the removal of double layer and adsorbed water from simulated lunar soil samples is imperative.

A third long-range interaction which could be important in granular systems is the elastic force. The hard, brittle silicates will probably react elastically to stress introduced by surfaces, dislocations, or external mechanisms. These forces are essentially averages of atomic reactions throughout the lattice, reflecting the properties of the constituent bonds, crystal structure, and dislocation state. Although of long range, they require the presence of an energy transmitting medium, unlike the other forces which have been considered. The nature of the inter-particle contact area under ultra-clean conditions however, is very likely a function of the elastic properties of the constituent silicates.

The remaining three long-range forces listed in Figure 5 have little importance in granular silicate systems. Shiller-layer ordering (Adamson, 1960) is active in fluid systems only. A long-wave dispersion force was hypothesized by London (1941) to arise from the interaction of small particles with long-wave electrical oscillations present in large molecules. Although the silicates include many appropriate chain structures, the absence of double bonds would greatly reduce the magnitude of the effect. Charged dislocations (Friedel, 1964) are only important in ionic crystals; the highly covalent silicate bond and the low atomic mobilities present in silicate structures should eliminate these phenomena and their associated long-range electrostatic fields.

There are several other bonding mechanisms for granular systems which should be mentioned. Sputtering can create free, active atoms which chemically bond surfaces in mechanical contact. Such bonding could be accomplished by the water, hydroge. , and oxygen sputtered in the Öpik (1.'62) model of the lunar atmosphere or by the enrichment in sputtered metal atoms suggested by Wehner (1964). However, the low chemical activity of the silicates would tend to inhibit this. Creation of lattice vacancies by sputtering could enhance sintering (the transformation of mechanical contact to chemical bonding) which requires the presence of mobile lattice vacancies and inclusions (Smoluchowski, 1965). The incident flux necessary for sputtering effects to become important is probably far greater than that available on the lunar surface, as illustrated by the data of Wehner (1964).

Electrostatic charging of soil particles can give rise to mutual attraction or repulsion, depending upon whether adjacent particles have acquired like or unlike charges. Electrostatic forces have a very long range and hence could influence the initial contact between loose or falling grains. Such effects would be expected to modify adhesion phenomena: attractive static charges could provide a mechanism for bringing particles near enough for short-range forces to be activated, whereas repulsive charging could inhibit close-packing, yielding porous, flocculent structures. Temporal effects on the nature of a surface dominated by electrostatic charging effects will depend upon interparticle contacts, particle conductivity, and the nature of external discharging mechanisms (gaseous atmospheres, radiation fields, solar wind, etc.).

The possible effects of electrostatic charging on the lunar surface layer are numerous. The lunar surface potential of 20-40 volts proposed by Öpik and Singer (1960) could give rise to a lunar ionosphere and high field intensities several centimeters from the surface. Static charging of the surface layer due to the solar wind, impact phenomena, and radiation has been hypothesized to cause erosion of the soil (Gold, 1955; Grannis, 1961). Others (Singer and Walker, 1962) have proposed that static charging by the lunar ionosphere of impact-ejected dust could contribute to fluidization of the particles and dust transport. In any case, the effects of electrostatic charging of lunar surface soils must not be overlooked in simulation experiments.

One might consider surface tension as a possible bonding mechanism. Water present in soils derives some of its bonding characteristics from the effects of surface tension. This mechanism becomes increasingly important in more porous structures. However, the absence of adsorbed water layers on the lunar surface coupled with the hard, brittle nature of the silicates should eliminate the possibility of surface tension effects either within or between the soil particles.

The bonding effects of the intense radiation field present on the lunar surfaces must also be considered. Ryan (1964) has proposed that radiation damage is limited to a depth of about $2 g/cm^2$, though for granular layers, the damage might exist throughout the soil region. The significance of any radiation damage present as regards modification of strength through dislocation formation is also questioned by Ryan. However, recent work by Smoluchowski (1965) indicates that vacancies and interstitials produced by solar wind protons could cause sintering of lunar dust. Electrostatic effects might be enhanced by radiation-produced dislocations in the more ionic lunar surface materials, if such substances are present. These defects can become electrically charged (Friedel, 1964) especially in ionic crystals. And finally, the physical effects of atomic recoils caused by the passage of radiation through solids have not been investigated, although the presence of fission tracks due to radiation recoil are well-known (Fleischer et al., 1965).

THEORETICAL SHEAR STRENGTH OF IDEAL GRANULAR SYSTEMS

The contributions of the interactions discussed above to the engineering properties of granular materials are not very well understood at present. Most engineering characteristics of soil systems rely upon generalized friction parameters which are at best crude averages of many inter-atomic and inter-particle phenomena. Before a theoretical treatment of one of these quantities, shear strength, is presented, several engineering characterizations of frictional phenomena will be outlined.

The coefficient of friction between two solid surfaces, μ, is defined as the ratio of the frictional force to the force normal to the surfaces. According to Amontons' Law, μ is independent of the apparent area of contact (Adamson, 1960) and hence is independent of the load. The explanation, as proposed by Bowden and Tabor (1950), is that the surfaces touch only at a few asperities. Since the initial actual area of contact is very small, the pressure at these asperities is high, and they yield in plastic flow. The actual area of contact thus increases until the contact pressure falls to the characteristic yield pressure of the softer material. The actual contact area, A, is

$$A = \frac{N}{P_Y}$$

where N is the normal load and P_Y is the yield pressure. To shear the contact area requires a force

$$S = As$$

where s is the bulk shear strength of the material. Substituting for A,

$$S = \frac{s}{P_Y} N = \mu N .$$

This is simply Amontons' Law, with μ equal to s/P_Y and hence independent of the normal load.

The shear strength of soils is usually described by the Coulomb equation (Terzaghi, 1943):

$$S = N \tan \varphi + C$$

where S is the shear strength, N is the normal load, C is the cohesion, and φ is a constant known as the angle of internal friction. This phenomenological relation gives reasonable agreement with experiment for many types of soil. The constants C and φ depend on a variety of factors: soil type, particle size, kind and amount of contaminents, porosity, water content, and frequently the stress history of the soil. Hence, C and φ represent macroscopic averages of many atomic and inter-particle forces.

Granular systems are frequently characterized by the angle of repose, the angle between the horizontal and the slope of a pile of dry soil poured from a low elevation (Halajian, 1964). While not directly related to the shear properties of a soil, in some cases the angle of repose may be associated with other frictional parameters (Halajian, 1964).

Bearing strength is defined as the normal load which can be imposed upon the surface of a soil before the system fails in shear. Terzaghi (1943) has calculated theoretical expressions for this parameter in terms of the angle of internal friction of the soil. As a rough estimate of the bearing capacity for a strip load, Winterkorn (1963) uses the expression $2\pi S$, where S is the shear strength of the soil.

Adhesion, the tendency of a particle to cling to another surface, may frequently be described in terms of more basic concepts than is possible with the other soil parameters. Adhesion is frequently related to double layer and surface tension forces; under some conditions, the other long and short-range forces mentioned in the previous section may become active. The distinction between adhesion and cohesion should be noted: adhesion refers to the bonding of two surfaces whereas cohesion denotes the homogeneous intergranular bonding active throughout the mass of a soil system (Johnson, 1964).

The microscopic phenomena associated with friction in soils or solids are only slightly understood. Motion can be inhibited by both the geometric configuration and the interparticle forces. Grain shape, packing configuration, the direction of the shearing force, and the orientation of the failure plane will be important geometric factors determining soil shear strength. In addition, asperities on sliding surfaces could possibly produce locking effects. The difference between chemical and mechanical contact must be stressed. The lattice refers to the mere juxtaposition of two surfaces, often with intervening oxide or other contaminating layers. Chemical contact, however, requires the presence of clean surfaces and small surface separations to permit activation of chemical bonds. Furthermore, chemical bonding of surfaces will often require precise inter-molecular angles between the two surfaces to permit formation of directional covalent bonds.

Shearing of granular systems will also be a function of the gross physical characteristics of the constituent particles. Elastic properties will become important in reaction to stresses in hard materials. Plastic flow may also take place during shear and hence, the plastic properties could very likely influence soil strengths.

To estimate the relative importance of these many factors, a model of a granular system is required. Such a model should compromise continuum and atomic treatments while emphasizing the effects of lunar surface conditions such as vacuum and radiation. With these considerations in mind, the following model has been developed by extending the early work of Winterkorn (1963).

A theory of the shear strength of a system of spherical particles is outlined in Figures 6 and 7. It is assumed for this model that the contacting grains deform to produce flat inter-particle surfaces. This deformation is assumed to be small; the geometry of the particles is unchanged except at the interface. The contact area, A_{12}, between particles of radii R_1 and R_2 (cf. Figure 8), is given by

$$\begin{aligned} A_{12} &= \pi a_{12}^2 \\ &= \pi\left[R_1^2 - (R_1 - h_1)^2\right] \\ &= \pi(2R_1h_1 - h_1^2) \\ &\cong 2\pi R_1h_1 \end{aligned} \tag{1}$$

where a_{12} is the radius of the inter-particle contact area and the deformation is assumed to be small:

$$h_1 << R_1, \quad h_2 << R_2 \tag{2}$$

It can easily be shown that

$$R_1h_1 = R_2h_2 \tag{3}$$

Furthermore, by definition:

$$R_2 = bR_1, \quad b \leq 1 \qquad (4)$$

The contact area is obtained by equating the energy of formation of the flat contact areas with the surface energy of the bonds formed across the surface. This technique emphasizes the clean surfaces expected to be present in lunar soils. It is assumed that free valence orbitals will be available for bond formation at the interfaces. The energy released in formation of these bonds will deform the spheres, producing the flat interfaces.

The calculation of the free energy of a surface from the heat of formation of the chemical bonds active across the interface follows the treatment by Harkins (1942) for highly covalent structures. The method is applied to the molecular silicates on the assumption that these are predominantly covalent substances and that the approximations involved are of the same magnitude as the others involved in the soil model. The possibility of alternate bonding modes (Van der Waals, electrostatic, etc.) could be included by introducing the appropriate average bond energy (for instance, the technique of Shuttleworth, 1949 and 1950, for dispersion forces).

Although the equations are derived in terms of bond energies and permit one to obtain an estimate of the bonding mode which must be active to yield the measured shear strength, for the sake of illustration some of the results have been plotted using the average covalent bond energy for a silica/silica contact. On a random basis, contact of two clean SiO_2 surfaces could form Si-Si, O-O, and Si-O bonds. By calculating the average of these bond energies weighted by their probability of occurrence, an average energy per bond of $\Delta F = 59.9$ kcal/mole is obtained.

To determine the surface energy associated with bond formation, it is assumed that one bond is formed per surface molecule. If the molecules are assumed to be isotropically distributed, the average surface area occupied per molecule (hence, per bond) is

$$k = \left(\frac{ND}{M}\right)^{-2/3} \qquad (5)$$

where N is Avogadro's number, D is the density of the particle, and M is the average molecular weight of the particle. The number of bonds formed per inter-particle contact is

$$n = \frac{A_{12}}{k} = \frac{2\pi R_1 h_1}{k} \qquad (6)$$

The total energy released in the formation of these bonds is

$$\Delta E = \frac{\pi (a_{12})^2 e}{Nk} \Delta F = \frac{2\pi R_1 h_1 e}{Nk} \Delta F \qquad (7)$$

where ΔF is the average energy of formation per bond (kcal/mole) and e is a conversion factor to convert kcal/mole to gm-cm ($e = 4.2686 \times 10^7$).

The free energy associated with the compression of the spheres is calculated by assuming that the pressure, P, is constant during the small deformation. The free energy W is then

$$W = P(\Delta V_1 + \Delta V_2) \qquad (8)$$

where ΔV_1 is the change in volume of the sphere of radius R_1 and ΔV_2 is the corresponding change for the sphere of radius R_2. Using the standard expression for the volume of a spherical sector and making use of (2),

$$\Delta V = \frac{\pi h^2}{3}(3R - h) \cong \pi h^2 R \qquad (9)$$

Substituting (9) into (8),

$$W = \pi P (R_1 h_1^2 + R_2 h_2^2) \qquad (10)$$

Using (3), one deduces

$$R_1 h_1^2 + R_2 h_2^2 = R_1 h_1^2 \left[1 + \frac{R_1}{R_2}\right] \qquad (11)$$

From (1), it is observed that $h_1 = a_{12}^2/2R_1$. Substituting in (11) and then using (4), one finds that

$$R_1 h_1^2 + R_2 h_2^2 = \frac{(a_{12})^4}{4R_1} \left[1 + \frac{1}{b}\right] \qquad (12)$$

Inserting (12) into (9), the free energy is obtained:

$$W = \frac{\pi}{4}\frac{(a_{12})^4 P}{R_1}\left[1 + \frac{1}{b}\right] \tag{13}$$

The contact area A_{12} is then calculated by equating (7) and (13). This will be derived for two types of inter-particle contact: plastic and elastic.

If one assumes that plastic flow occurs at the particle interfaces, the pressure P in (13) is taken to be the yield pressure P_Y of the bulk material. Then, on solving (7) and (13) for the contact area πa_{12}^2, one obtains

$$A_{12}(\text{plastic}) = \frac{4\pi e}{NkP_y}\left[1 + \frac{1}{b}\right]^{-1} R_1 \Delta F \tag{14}$$

where all quantities have been previously defined.

The hardness of the silicates implies that the inter-particle deformation will very likely be elastic. To find the contact area for this case, Hertz's equations for the contact of elastic spheres (Bowden and Tabor, 1950) are employed:

$$a_{12}^3 = \frac{3f}{8Y}\left[\frac{1}{R_1} + \frac{1}{R_2}\right]^{-1} \tag{15}$$

where Y is the bulk modulus of elasticity of the spheres and f is the force pressing the spheres together. But $f = P(\pi a_{12}^2)$, where P is the pressure on the contact area. Using this relation in conjunction with (4) and (15) and solving for P,

$$P = \frac{8Ya_{12}}{3\pi R_1}\left[1 + \frac{1}{b}\right] \tag{16}$$

Substituting (16) into (13),

$$W = \frac{2Y(a_{12})^5}{5R_1^2}\left[1 + \frac{1}{b}\right]^2 \tag{17}$$

Equating (17) with (7) and solving for the contact area,

$$A_{12} \text{ (elastic)} = \pi \left[\frac{3\pi e}{2YNk} \left(1 + \frac{1}{b}\right)^{-2} \right]^{2/3} (R_1^{\ 2} \Delta F)^{2/3} \tag{18}$$

The contact areas obtained above can be used in conjunction with the bulk shear and tensile strengths of the particle material to obtain the shear strength of the granular systems. Conversely, one can work backwards from known granular shear strengths to obtain the average bond energy and hence the type of bond which is active. The force required to shear the soil depends upon the assumed failure plane, the packing configuration of the particles, the particle size distribution, and the direction of the applied shearing force. For this paper, several packing configurations and particle size distributions have been assumed. The following discussion will consider in turn systems of uniform and non-uniform diameter particles.

The packing configurations assumed for systems of uniform spheres are depicted in Figure 9. Note that the system of cubic layers with close-packed stacking is essentially a face-centered cubic arrangement. The porosities calculated for these structures are as follows:

Simple cubic	47.6%
Hexagonal layers, cubic stacking	39.5%
Cubic layers, close-packed stacking	26.0%
Hexagonal close-packed	26.0%

The assumed failure planes are depicted in Figure 10. To illustrate the calculation technique, shear strengths will be calculated for the cases of simple cubic and hexagonal close-packed systems.

For simple cubic packing, illustrated in Figure 10a, each particle resists the applied force with a shear resistance F_{11}^{S}, where S refers to a shear force and the 11 subscript refers to a contact between two particles of the same radius, R_1. The contact area A_{11} is given by equations (14) and (18) for plastic and elastic interfaces, respectively. The number of spheres per square centimeter is $1/4R_1^2$. The actual contact area is therefore $A_{11}/4R_1^2$, and if one assumes a bulk shear strength of S, the total shear strength F_A of the granular system shown in Figure 10a is merely the product of the contact area per particle by the number of particles per square centimeter and the bulk shear strength:

$$F_A = \frac{A_{11} S}{4R_1^2} .$$

For a plastic particle interface, this yields

$$F_A \text{ (plastic)} = \frac{\pi e S}{2NkP_Y} \left(\frac{\Delta F}{R_1}\right) \quad (19)$$

while for elastic contacts one obtains

$$F_A \text{(elastic)} = \pi S \left(\frac{3\pi e}{64YNk}\right)^{2/3} \left(\frac{\Delta F}{R_1}\right)^{2/3} \quad (20)$$

The case of a hexagonally close-packed soil is more complicated. Since the inter-particle contact planes are not parallel to the direction of the applied shear force, one must calculate the angle φ between that force and its projection on the contact plane. The magnitude of the applied force F_A^S required to shear the contact is then

$$F_A^S = SA_{12} \sec \varphi$$

as shown in Figure 7. If a plastic interface is involved and the configuration is such that a tensile stress is applied to the contact, as shown in Figure 7, then the applied force F_A^T required to break the contact is

$$F_A^T = TA_{12} \sec \varphi$$

where T is the tensile strength of the bulk material. Note that since the compressive strength is greater than the shear strength of silicates, a contact will usually fail in shear before failing in compression. Likewise, since the tensile strength of silicates is less than the shear strength, contacts stressed partially in tension will fail in tension before failing in shear.

The assumed direction of failure for the hexagonal close-packed system is shown in the top view of Figure 10d. There are two shear contacts and one tensile contact per particle. The angles between the applied shear force and its projection on the contact planes are different for the shear and tensile contacts. These may be calculated using the general method derived in Appendix I. The applied stress per particle for initiation of shear is thus

$$F_a = A_{11} (2S \sec \varphi_S + T \sec \varphi_T)$$

Since the number of spheres per unit area is $\frac{1}{2\sqrt{3}\,R_1^{\,2}}$, the total applied shear force is

$$F_A = \frac{A_{1i}}{2\sqrt{3}R_1^{\,2}} \left(2S \sec \varphi_S + T \sec \varphi_T\right)$$

$$= \frac{A_{11}}{2\sqrt{3}R_1^{\,2}} \left[2S \left(\frac{3}{2\sqrt{2}}\right) + \sqrt{3}\; T\right] \qquad (21)$$

For plastic contact, A_{11} is obtained from (14).

$$F_A(\text{plastic}) = \frac{\pi e}{\sqrt{3NkP_Y}}\left[\frac{3S}{\sqrt{2}} + \sqrt{3}\,T\right]\left(\frac{\Delta F}{R_1}\right) \qquad (22)$$

For elastic inter-particle contacts, there is no tensile resistance as the elastic stresses are recoverable. Thus, eliminating the tensile components from (21) and obtaining A_{11} from (18),

$$F_A(\text{elastic}) = \frac{3\pi S}{2\sqrt{6}} \left(\frac{3\pi e}{8YNk}\right)^{2/3} \left(\frac{\Delta F}{R_1}\right)^{2/3} \qquad (23)$$

The other two packing configurations are treated in the same manner. The results for all four geometries are plotted in Figure 11 as a function of bond energy and particle radius for both plastic and elastic cases. A 59.9 kcal/mole average bond energy (that of a silica/silica contact) or a 10 micron particle radius is assumed where needed. The average molecular weight of the lunar surface material is taken as 66.40 AMU by determining a weighted average of the compositions of the lunar rock standards proposed by J. Green (1965). The bulk physical properties of the particles were obtained from the estimates of Weil (1961):

Tensile strength = 3.12×10^5 g/cm^2

Compressive strength = 1.53×10^6 g/cm^2

Yield pressure = 2 x compressive strength

Shear strength = 1/2 (compressive strength + tensile strength)
= 9.21×10^5 g/cm^2

Modulus of elasticity = 5.21×10^8 g/cm^2

It is noted from the curves that the low shear strengths found experimentally are obtainable only with low bond energies and high porosities. The differences between plastic and elastic contacts are not great enough for any general conclusions to be drawn from experimental data, although plastic contacts do give slightly lower shear strengths.

The shear strengths of systems of non-uniform spheres have been determined using the configurations detailed in Figure 12. Beginning with a simple cubic configuration, interstitial particles of decreasing diameter are added in the (100) planes. The radii of these grains are calculated in Appendix II, and the porosities and particle size distributions of the three systems studied are given in Figure 13. Note that the porosities of the two and three particle systems differ only by 0.8%. As for the case of uniform spheres, the direction of the applied shear force and the orientation of the failure plane must be specified. These are given in Figure 14 for the systems investigated.

The calculations for the system of uniform particles in simple cubic packing have already been described, the results being given by equation (19) for plastic deformation and equation (20) for elastic deformation.

For the system of two particle sizes, it is seen from Figure 14b that one must add a shear force $F_{12}{}^{S}$ and a tensile force $F_{12}{}^{T}$ to the forces $F_{11}{}^{S}$ active in the single-diameter system. These forces will be directed 45° from the applied shear force. Hence, for each particle, one must add a term

$$A_{12}S \sec 45^{o} \quad + \quad A_{12}T \sec 45^{o}$$

to the shear resistance calculated in the case of uniform diameters. Note that a new inter-particle contact area must be calculated for the 1-2 interface using $b = 0.414$. As in the previous discussion, it is assumed that $F_{12}{}^{T}$ is zero for elastic contact (tensile forces are recoverable).

The calculations for the system of three sizes of particles are similar to those above. For the assumed failure plane depicted in Figure 14c, the forces $F_{13}{}^{S}$, $F_{23}{}^{S}$, and $F_{13}{}^{T}$ must be added to those of the previous system. The angle between the 1-3 contact plane and the applied shear force can be calculated from the diagram shown in Figure 14d: the cosine of that angle is $R_1/(R_1 + R_3) = 1/1.108$ since $R_3 = 0.108\ R_1$. All other calculations are straightforward.

The results of the calculations for multi-diameter systems are summarized in Figure 15. The physical constants assumed for the particle material are those postulated previously for the systems of uniform diameters. Characteristic values of $\Delta F = 59.9$ kcal/mole and $R_1 = 10$ microns are employed as indicated. Note that the shear strength increases by nearly 30% in going from two-diameter to three-diameter systems, while the porosity decreases only 0.8%. This result emphasizes the importance of particle size distribution; great care must be exercised in selecting proper soil sizing for lunar simulation (cf. Johnson, 1964).

Figure 16 depicts the results of all the previous calculations as a function of the ratio of the average bond energy to the maximum particle radius $\Delta F/R_1$ in the range of shear strengths actually measured for granular systems under lunar conditions. Using these curves and a known particle radius, one can determine the bond strength required to produce a given shear strength as a function of packing configuration and particle size distribution.

These figures illustrate the following conclusions which may be inferred from the previous calculations in conjunction with the experimental shear strengths to be presented subsequently:

1. Weak bonds are usually active in granular systems under lunar conditions.
2. These soil structures are more porous than a simple cubic packing (most porous geometry studied).
3. Shear strength is very sensitive to packing configuration and particle size distribution.
4. There is apparently little difference in the shear strength produced by elastic and plastic particle interfaces.

TEST SPECIMENS

The specimens selected for this research were primarily igneous rocks provided by Dr. Jack Green who states that "the selection was made on the basis of what might be the span of research to be performed on them, convenience of collecting within a given geological area, conformity with respect to chemistry and texture, abundance for truly bulk quantity research and what might be termed a lunar rationale," (Green, 1965). These specimens included basalt, semi-welded tuff, obsidian, altered rhyolite, serpentine and granodiorite. Chemical analyses of these specimens are contained in the work by Green (1965).

Other materials used in the experimental program included powdered amorphous silica, fused silica, and borate glass. The powdered silica was prepared by titrating with dilute HCl to neutrality as determined with a Beckman pH meter. It was precipitated in a Waring Blendor, filtered and washed repeatedly on a sintered glass Buechner funnel. When the washings showed no measurable conductivity, the silica was oven dried at 150°C. The silica was further powdered in an agate mortar and sifted through standard sieves to the desired particle size and gradation.

Preparation of the rock samples was accomplished by grinding in a ball mill with 3/4-inch polished steel spheres in a dry argon atmosphere. After oven drying, the dust was sieved to the desired particle size and gradation in a dry argon atmosphere.

EQUIPMENT

Equipment and instrumentation used in the program was selected on the basis of the performance characteristics necessary to produce the desired lunar environmental conditions. The ultra-high vacuum system was designed to develop vacuums in the range of 10^{-12} torr. Synergistic effects were produced in the chamber by means of electron radiation.

Rough vacuum was produced by a molecular sieve sorption pump, GE-22 HP-111, acting in conjunction with a 100 liter per second cold cathode getter-ion pump, CVC-PDV-100, positioned below the chamber. The molecular sieve pump reduced the pressure to 10^{-4} torr, and the getter-ion pump further lowered the pressure to the 10^{-6} to 10^{-7} torr range used during bakeout. The molecular sieve pump was isolated from the system during the 275^{o} to $300^{o}C$ bakeout which lasted from one to two days.

High vacuum was produced by a 100 liter per second triode ion pump, GE-22TP250, positioned above the vacuum chamber. This unit was baked with the total system. During operation of the high vacuum pump, the CVC pump was isolated from the chamber. After the two-day bake, secondary pumping brought the system down to the 4×10^{-12} torr range.

The over-and-under location of the two ion pumps tended to produce a more nearly uniform vacuum in all areas of the chamber. Pressures were measured by a GE cold cathode trigger gage sensitive to pressures as low as 10^{-14} torr. Observations of samples and test conditions in the chamber were possible through a sapphire window, also bakeable to $400^{o}C$. Electron fluxes of 2×10^{14} - 3×10^{16} electrons per second and energies of 20 to 50 kev were produced by an "air-ended" electron gun. Samples could also be irradiated by x-rays scattered from a copper target.

Mass spectra were obtained through the use of a GE Partial Pressure Analyzer, Model 514. This model has a high sensitivity and is able to detect partial pressures of 10^{-13} to 10^{-14} torr. The analyzer tube was attached directly to the vacuum chamber. The 5,000-gauss permanent magnet accommodates a mass range of 2 to 150 A.M.U.

A schematic diagram of the equipment in its final design configuration is shown in Figure 17. Figure 18 depicts the equipment as installed in the laboratory. The electron gun, mass spectrometer, and UV window are visible, as are rotary, translational and vibration motions into the chamber. Vacuums to 10^{-12} torr have been achieved in this system.

In the earlier experiments, the powdered silica was dropped from a trough with the aid of a Syntron vibrator through a beam of electrons into the pyrex dish. Later investigations utilized a touch-and-go technique to obtain a quantitative index to adhesive bond strengths. Figure 19 shows a schematic diagram of the particle-drop technique; Figure 20 depicts the design of the touch-and-go experiments.

Bearing strength measurements were made using a Varian rotary feed-through connected to a spool of gold chain attached to a Worden Laboratory 5-gram quartz spring from which the aluminum weight was suspended. The aluminum weight was 1 cm in diameter and weighed 2.387 grams. Bearing tests were made by lowering the aluminum weight onto the simulated lunar dust and measuring the depth of penetration and the change in extension of the spring. In order to change the unit load the feed-through was rotated, varying the length of the spring and the effective weight of the aluminum probe. The modulus of the quartz spring was 50.6 mg/mm.

EXPERIMENTAL RESULTS

Experimentation has been concentrated in three areas: (1) irradiation effects on falling silica powders, (2) penetration and bearing strength measurements of silica and granodiorite powders under varying conditions of radiation, vacuum, and deposition, and (3) measurements of adhesion between solid silicates in ultra-high vacuum.

The results of the investigations of dropped granular silica are summarized in Figure 21. In general, two tests were run for each diameter of particle: one with irradiation and one without irradiation, with the exceptions of runs A, B, and E. In run A, adhesion and flocculent structure were observed on dropping the <200μ diameter silica powder under a vacuum of 5 x 10^{-8} torr after bakeout at 125° C. Adhesion could be observed for as long as an hour after opening the system to the atmosphere, after which time the silica again became a free-flowing powder with an angle of repose of about 30°. This behavior may be interpreted as largely due to static charging of the dust as it was shaken from the hopper in early runs of the experiment. The long period required for decay of adhesion effects under atmospheric pressure suggests a slow leaking of charge from the particles. Combined bakeout and high vacuum removed the double layer water, permitting closer inter-particle contacts and hence activation of stronger electrostatic forces. It cannot be assumed that the tightly-bound adsorbed water layer was removed under the above conditions of vacuum and bakeout. Hence, other inter-particle forces were probably inhibited.

In run B, finely ground (10μ) silica powder was observed to adhere strongly at atmospheric pressure both before and after baking at 400°C. Such behavior could arise from inter-particle forces such as integrated dispersion, which are important in small particles. The bakeout temperature was certainly high enough to remove most adsorbed water, but since the test was conducted in air, water could be rapidly re-adsorbed. The difficulty of distinguishing between the effects of double layer water and other inter-particle forces for small particles is evidenced by this test.

In run E, finely-ground fused quartz (3-5μ) was dropped through an electron beam (35 kev) at a pressure of 4 x 10^{-9} torr. The dust formed a pile which displaced approximately 1/2 inch toward the cathode of the electron gun. During irradiation of the falling dust, the following gases were detected in the chamber: H_2 (75%), CO (16.5%), CO_2 (7.0%), CH_4 (0.8%), and N_2 (0.8%). The silica dust adhered to a stainless steel weight lowered onto the pile (Figure 22). These phenomena indicate that the dust was positively charged by passage through the electron beam. A rough calculation of the charge per particle required to move the 5μ silica particles 1/2 inch while falling 2 inches yields an average of 25-50 electronic charges per grain. Electron irradiation cleaned the surface of the particies as evidenced by the increased pressure as the dust fell through the beam. The porous pile of statically charged dust so-formed was probably discharged on contact with the metal probe. This elimenated the static inter-particle repulsion and permitted the cleaned surfaces to interact via other forces, probably van der Waals, giving rise to the adhesion noted.

The results of the remaining runs are very similar to run E. In runs C and D, 37 μ Ludox silica was baked for 44 hours at temperatures as high as 275° C. Dust irradiated by 20 kev electrons at pressures of from 2 x 10^{-8} to 6 x 10^{-10} torr migrated all the way to the electron gun cathode where it adhered in a layer about 1/16 inch thick. With the electric field of the electron gun on, but the filament off, the falling dust formed an undeflected pile. Thus, it can be assumed that the charging was due to the irradiation. As before, the metal cathode neutralized the charge, permitting weaker attractive forces to dominate and giving rise to adhesion. The absence of any pile when the dust was irradiated (in contrast to run E) may be due to the larger grain size (possibly permitting accumulation of a larger static charge). Note that the pressure rise of about a decade, which occurred only when the dust was passed through the electron beam, indicated that even after prolonged bakeout, cleaning of the surfaces occurs within the beam.

In runs F through I, 10 and 50 micron borate glass beads were utilized. The results were similar to those for the silica samples except that the irradiation effects were more pronounced. The 10 μ beads migrated all the way to the filament when irradiated (the associated pressure rise consisting of mostly H_2O and CO_2). For irradiated 50 μ borate glass beads, a pressure rise of two decades was recorded during irradiation (mostly H_2), and the beads were scattered throughout the chamber. These borate glass particles apparently acquired a larger charge than the silica samples of corresponding size. The charge was enough for the larger particles to be completely repelled by each other (hence, the scattering throughout the chamber) and for the smaller beads to be transported to the filament. The silica samples did not migrate so far nor did they exhibit the large scattering. The importance of chemical composition in electrostatic effects is thus apparent. Note that the borate beads also adhered to metal surfaces which were lowered onto the dust. None of the above phenomena took place when the borate beads were not irradiated.

Figure 23 summarizes the penetration and soil strength measurements performed on several of the samples. Run 1 is essentially run C from Figure 21, while run 2 corresponds to run E of the previous discussion. Both samples exhibited some adhesion and large penetrations. However, run 3, which took place at very high vacuum (2 x 10^{-9} to 5 x 10^{-12} torr) and under the same irradiation conditions present for runs 1 and 2, exhibited the smallest penetrations. There was no scattering of the particles, and a well-defined pile was formed. Residual H_2 and CH_4 were detected even after bakeout at 250° C. There was slight adhesion to the aluminum probe lowered onto the surface of the dust.

These phenomena may be explained as follows. The vacuum in which this run was conducted was the best of any run. The formation of a pile with high resistance to penetration even though static charging due to irradiation was probably present indicates that, under these vacuum conditions, the cleaning of the surfaces is such that attractive interparticle forces became dominant over the repulsive static forces. The low adhesion to the aluminum surface can be interpreted as greater cohesion of the dust in the ultrahigh vacuum or as insulation by the metal oxide layer to particle discharging.

The absence of penetration in the undropped dust of run 4 emphasizes the loose structure of dust which has fallen in a moderate vacuum under irradiation. Runs 1 and 2 exhibited large penetrations, but run 3, carried out at high vacuum, showed much smaller penetration and reflected the greater rigidity of a dust structure generated under conditions quite similar to those of the lunar surface.

The data for granodiorite powder, summarized in runs 5 and 6 in Figure 23, are displayed in more detail in Figures 24-26. Consider first the penetration effects illustrated in Figures 24 and 25. The granodiorite samples were baked at 110°C, the temperature being limited by the rise in pressure (mostly H_2O). It is noted that the greatest penetration before compaction occurs at the moderate vacuum of 10^{-3} torr. The high-vacuum measurements (10^{-9} torr) show the lowest penetrations. Figure 25, which depicts the penetration as a function of vacuum for given normal loads, indicates that in all cases the least penetration resistance was exhibited at the moderate vacuum (10^{-3} torr).

The following explanation of these effects is proposed. It is assumed that the loosely-bound double layer water is removed at moderate vacuums and bakeout, leaving a soil that is somewhat more porous than at atmospheric pressure. However, the tightly-bound adsorbed water layer will still be present and will inhibit the development of strong inter-particle forces. Thus, at moderate vacuums, the soil compacts to a greater extent than at atmospheric pressure, where the pore fluids (double layer water, in particular) oppose compaction. Higher loads are required for compaction at these moderate vacua than at atmospheric pressure due to the necessity for larger displacements of the soil particles. At ultra-high vacuums, the adsorbed water layer is also removed under the combined influence of vacuum and x-ray irradiation, permitting the activation of attractive inter-particle forces. These lead to formation of a flocculent structure which reaches its maximum compaction under lower loads and with less evidence of penetration than would be possible at higher pressures. The above considerations appear to be borne out by the data of Figures 24 and 25.

The penetration test of loosly-packed granodiorite powder shown in Figure 26 represents loading of the compacted dust up to failure in shear. The sample was baked at 110°C until no more water was detected in the vacuum chamber. The pressure then dropped to 10^{-10} torr on cooling. The pressure rose excessively when the falling dust was irradiated, so the granodiorite had to be dropped without irradiation at a vacuum of 6×10^{-9} torr. The pile of dropped dust was compacted under a load of about 100 mg; this produced no increase in penetration as the load was increased as high as 125 mg, corresponding to the compaction of the undropped granodiorite discussed above. Then the powder was loaded until the pile collapsed at a load of about 2.6 grams, or 3.26 g/cm^2. The penetration during this process is depicted in Figure 26. Using the results of the theory developed earlier and assuming that the average particle diameter is 50μ, one obtains a value of $F \simeq 0.35$ kcal/mole from Figure 16c for the bond energy necessary to give the measured shear strength (simple cubic packing, elastic inter-particle contacts).

This is within the range of the dispersion energies, although it cannot be inferred that such forces are active since bulk shear and tensil strengths were employed in determining the curves of Figure 16. However, the results certainly show that chemical bonding is not present in the compacted granodiorite powder.

The results of an adhesion experiment utilizing solid basalt are presented in Figure 27. Machined basalt cylinders with cross-section area of 0.29 cm^2 were contacted under pressure of 34.5 g/cm^2. The samples had previously been held for 48 hours at pressures between 5×10^{-9} and 1×10^{-11} torr while under x-ray irradiation. Adhesion of 7.6 g/cm^2 was measured on the first contact, but no adhesion was measured on subsequent contacts. The same specimens were then irradiated under ultra-high vacuum for another 48 hours. Again the samples were contacted, this time by allowing one to fall 1/2 inch onto the other. The contact pressure was maintained 30 minutes, but no adhesion was measured (sensitivity was limited to forces greater than 4.1 g/cm^2. On opening the system, it was discovered that the basalt had firmly cold-welded to the aluminum retainer ring. Due to the geometry of the retainer, no strength measurement of weld could be made.

Although the data are limited, the following explanation is offered. The long exposure to high vacuum and radiation could have made available covalent surface bonds on the basalt. On contact of the specimens under load, covalent bonds were formed at grains oriented properly to provide the correct inter-molecular directions for bond formation. On breaking the adhesion during the measurement, the covalently bonded regions did not fracture at the old interface but along lines of weakness within the individual grains (dislocations, cracks, etc.). Thus, a new surface was formed after the initial contact, composed of the areas of weak bonds which had nucleated the fractures. On re-contacting the specimens, only weak bonds, if any, would be formed, and no subsequent adhesion would be detected (especially since the sensitivity of the system requires the adhesion to be relatively large).

The strong welding of the basalt to the aluminum probably reflects the non-directional aluminum metallic bonds which, once the oxide layer has been penetrated under the influence of heavy contact pressures, can form chemical bonds to the basalt molecules with less stringent requirements on the orientations of the molecules. Note that no welding was noted for the samples of glass beads and fused silica discussed earlier. The random nature of the surface bonds in such amorphous specimens may totally frustrate the formation of the covalent bonds necessary for welding. Hence, the finite, if microscopic, grain size of the basalt may be a necessary factor in the welding and adhesion of the material.

DISCUSSION AND CONCLUSIONS

The results of the research program conducted to date have demonstrated that a priori theoretical considerations supported by a basic experimental program yield considerable data which can provide insight into lunar surface properties. Major conclusions derived from the work performed to date are presented in the following paragraphs.

Granular silicates will become bonded in environmental conditions closely approximating those of the Moon. Theoretical considerations demonstrate that the low shear strengths measured experimentally are developed by weak van der Waals bonds. Lunar soils could theoretically be very strong providing the porosity is low and chemical bonding is active. The bonding most characteristic of lunar conditions, however, appears to be due to van der Waals forces, though covalent bonding may be active under heavy surcharge loads.

Dust dropped in a lunar environment produces a more flocculent structure than in air due to the increased importance of surface force effects over gravitational effects and the influence of ionizing radiation. Conversely, the structure produced at moderate vacuums should be denser than in air for dropped particles, due primarily to total removal of the double layer water.

The results of these experiments also demonstrate that ultra-high vacuum contributes to the formation of a relatively firm, porous structure from dropped powders. As previously discussed (Johnson, 1964), the combined effect of bakeout and ultra-high vacuum not only contributes to a clean particle surface but also assures that the surface, once cleaned, will remain clean for a longer period of time. At moderate vacuums it cannot be expected that the double layer water will be removed from the system.

A number of radiation effects were noted. The electron stream impinging on the falling dust produced static charges which acted to inhibit the formation of bonds and resulted in a loose, porous structure. Further, the low energy radiation was sufficient to assist in removal of the surface-held contaminants, resulting in stronger bonds on neutralization of the induced static charges. Moderate diameter particles (on the order of 10-50μ) were most sensitive to the effects of electron bombardment, though this conclusion may be valid for low-energy radiation only. Higher energies would doubtless contribute to increased radiation effects on larger particles. The chemical composition of the particles is important in determining their reaction to electron irradiation. Irradiation apparently enhances adhesion to conductors through the initial induced electrostatic attraction.

The shear strength of lunar soil masses produced by dropping dust particles in a simulated lunar environment is low at moderate vacuums due to both loose packing configurations and residual contaminants, chiefly adsorbed water, on the surfaces. At higher vacua and under irradiation, the dust formed a structure having increased bonding and higher strengths. After compaction in the vacuum chamber, the dust failed under unit loads which correspond to the rupture of weak van der Waals bonds.

The adhesion tests demonstrated that covalent bonding can occur at silicate/silicate and silicate/metal interfaces providing the metal oxide layer can be penetrated. For silicate/silicate adhesion the first contact seems to modify and pacify the radiation-activated surface, resulting in high adhesion strengths. A new layer of weak bonds is formed after the surfaces are separated, inhibiting further adhesion. The directional character of the covalent bonds inhibits silicate/silicate adhesion, while the non-directional metallic bonds permit strong silicate/metal welding.

A number of implications to lunar surface models are apparent from the work performed to date.

1. Simulated lunar soil tests should include an electron radiation ability since important new effects have been observed.

2. In ultra-high vacuum, the effects of radiation charging tend to be dominated by other attractive forces; hence, adhesion tends to increase.

3. Effects of adsorbed water as well as other surface contaminants can be removed only by combined ultra-high vacuum, irradiation, and high temperature bake-out.

4. The structure formed by the dust is a function of the deposition process. Dropping under high vacuum produces a porous, flocculent structure.

5. The chemical composition of the dust is important when radiation effects are investigated but is not important for the effects of vacuum alone, since the vacuum-activated dispersion forces are less chemically dependent.

REFERENCES

Adamson, A. W. (1960), Physical Chemistry of Surfaces, Interscience, New York.

Bowden, F. P. and Tabor, D. (1950), The Friction and Lubrication of Solids, Oxford, New York.

Day, M. C. and Selbin, J. (1962), Theoretical Inorganic Chemistry, Reinhold, New York.

deBoer, J.H. (1936), Trans. Faraday Soc., Vol. 32, p. 20.

Derjaguin, B. V., Abrikossova, I. I., and Lifshitz, E. M. (1956), Quarterly Reviews, London, Vol. 10, pp. 295-329.

Fleischer, R. L., Price, P. B., and Walker, R. M. (1965), "Tracks of Charged Particles in Solids," Science, Vol. 149, July 23, pp. 383-393.

Friedel, J. (1964), Dislocations, Addison-Wesley, London.

Gold, T. (1955), Monthly Notices Roy. Astron. Soc. Vol. 115, p. 585.

Grannis, P. D. (1961), J. Geophys. Res., Vol. 66, pp. 4293-4299.

Green, J. (1965), "Selection of Rock Standards for Lunar Research", Annals of the New York Academy of Sciences, Vol. 123, pp. 1123-1147.

Grim, R. E. (1953), Clay Mineralogy, McGraw-Hill, New York.

Halajian, J. D. (1964), "Gravity Effects on Soil Behavior", in The Lunar Surface Layer, Academic Press, New York.

Hamaker, H. C. (1936), Physics, Vol. 4, p. 1058.

Harkins, W. D. (1942), J. Chem. Phys., Vol. 10, p. 268.

Johnson, R. W. (1964), "Environmental Test Criteria for Lunar and Planetary Soils," paper presented to AIAA (Pasadena, California). Also in ASTRONAUTICA ACTA, Publication Pending.

....., and Griffin, R. N. (1965) "Research on Simulated Lunar Dust," Technical Information Series No. 65SD353, General Electric Missile and Space Division, Valley Forge, Pennsylvania.

Kitchener, J. A. and Prosser, A. P. (1957), Proc. Roy. Soc., London, Vol. A242, p. 403.

Kraus, E. H., Hunt, W. F. and Ramsdell, L. S. (1951), Mineralogy, 4th Edition, McGraw-Hill, New York.

Lifshitz, E. M. (1955), J. Exp. Theo. Phys. USSR, Vol. 29, p. 94.

London, F. (1942), J. Phys. Chem., Vol. 46, p. 305.

Means, R. E. and Parcher, J. V. (1963), Physical Properties of Soils, Merrill Books, Columbus, Ohio.

National Aeronautics and Space Administration (1965), "Lunar Environment Criteria for the Early Lunar Shelter Design and Comparison Study," Annex D, p. 163, Huntsville, Alabama.

Overbeek, J. Th. G. and Sparnaay, M. J. (1954), Discussions Faraday Soc. Vol. 18, p. 12.

Opik, E. J. (1958), Physics of Meteor Flight in the Atmosphere, Interscience, New York.

....., (1962), Planet Space Sci. Vol. 9, p. 211.

....., and Singer, S. F. (1960), J. Geophys. Res. Vol. 65, p. 3065

Pauling, L. (1960), The Nature of the Chemical Bond, 3rd Edition Cornell Univ. Press, Ithaca, New York.

Ryan, J. A. (1964), "Corpuscular Radiation Produced Crystalline Damage at the Lunar Surface," in The Lunar Surface Layer, Academic Press, New York.

....., (1965), "Experimental Investigations of Ultra-High Vacuum Adhesion as Related to the Lunar Surface," Douglas Aircraft Company, Report SM-47914, On Contract NAS 7-307, NASA-OART, Washington, D. C.

Salisbury, J. W. and Glaser, P. E. (1964), "Studies of the Characteristics of Probable Lunar Surface Materials," Air Force Cambridge Research Laboratories AFCRL-64-970, Special Report No. 20.

Shuttleworth, R. (1949), Proc. Roy. Soc. London, Vol. A62, p. 167.

....., (1950), Proc. Roy. Soc. London, Vol. A63, p. 447.

Singer, S. F. and Walker, E. H., (1962), "Electrostatic Dust Transport on the Lunar Surface," Icarus, Vol. 1, No. 2, pp. 112-120.

Smoluchowski, R. (1965), Science, Vol. 150, pp. 1025-1026.

Sparnaay, M. J. (1957), Nature, Vol. 180, p. 334

Terzaghi, K. (1943), Theoretical Soil Mechanics, Wiley, New York.

Wehner, G. K. (1964), "Sputtering Effects in the Lunar Surface," in The Lunar Surface Layer, Academic Press, New York.

Weil, N. A. (1961), "Probable Soil Conditions on the Moon and Terrestial Planets," Proceedings of the First Int'l. Conf. on the Mechanics of Soil-Vehicle Systems, Turin, Italy.

Winterkorn, H. F. (1963) Private communication. Prof. Hans F. Winterkorn, Princeton University, is a consultant to the General Electric Company.

Winterkorn, H. F. and Johnson, R. W. (1964), "Consideration of Properties of Simulated Lunar Soil with Possible Stabilization Techniques," in The Lunar Surface Layer, Academic Press, New York.

APPENDIX I

To calculate the angle between the applied shear force and its projection on the contact plane, assume that the contact plane is defined by the unit normal $\hat{n}$ as in Figure 28a:

$$n = a\hat{i} + b\hat{j} + c\hat{k} \qquad \text{(I-1)}$$

where $\hat{i}\ \hat{j}\ \hat{k}$ form an orthogonal set of unit vectors with $\hat{k}$ perpendicular to the over-all failure plane and $\hat{j}$ parallel to the applied shear force. The orthogonal unit vectors $\hat{e}_1$ and $\hat{e}_2$ are defined in the contact plane with $\hat{e}_2$ parallel to the $\hat{j}$ - $\hat{k}$ plane as well. Thus, $\hat{e}_2$ defines the initial direction of motion of the particle along the contact plane and in the direction of the applied shear force. One may thus write $\hat{e}_2$ as

$$\hat{e}_2 = A\hat{j} + Bk \qquad \text{(I-2)}$$

Since $\hat{n}$ is normal to $\hat{e}_2$,

$$\hat{n} \cdot \hat{e}_2 = Ab + Bc = 0 \qquad \text{(I-3)}$$

Also, since $\hat{e}_2$ is normalized,

$$A^2 + B^2 = 1 \qquad \text{(I-4)}$$

Solving (I-3) and (I-4) for A and B,

$$A = \frac{c}{(b^2 + c^2)^{1/2}}, \quad B = \frac{-b}{(b^2 + c^2)^{1/2}} \qquad \text{(I-5)}$$

The components of the normals to the contact planes can be determined by inspection of the geometry of the packing configuration. For the unit tetrahedron of the hexagonal, close-packed system oriented as shown in Figure 28b, the various normals are given by

$$\overrightarrow{1 - 4} = -\sqrt{\frac{1}{3}}\,\hat{j} + \sqrt{\frac{2}{3}}\,\hat{k}$$

$$\overrightarrow{2 - 4} = \frac{1}{2}\hat{i} + \frac{1}{2\sqrt{3}}\hat{j} + \sqrt{\frac{2}{3}}\,\hat{k}$$

$$\overrightarrow{3 - 4} = -\frac{1}{2}\hat{i} + \frac{1}{2\sqrt{3}}\hat{j} + \sqrt{\frac{2}{3}}\,\hat{k}$$

APPENDIX II

For a system of two sizes of particles, the interstitial sphere is oriented as shown in Figure 29a. Then

$$\cos 45^{o} = \frac{\overline{AB}}{\overline{AC}} = \frac{2R_1}{2R_1 + 2R_2}$$

$$R_2 = (\sqrt{2} - 1)\ R_1 = 0.414\ R_1 \qquad \text{(II-1)}$$

For three particle sizes, the configuration is given by Figure 29b. Since angle DEG is equal to 45°, $\overline{DE} = \overline{EG}$:

$$R_1 = R_2 + R_3 + b \qquad \text{(II-2)}$$

where b = $\overline{FE}$. But from triangle DEF,

$$b^2 = (R_1 + R_3)^2 - R_1^2 \qquad \text{(II-3)}$$

Substituting (II-1) into (II-2), and solving for b,

$$b = 0.586\ R_1 - R_3 \qquad \text{(II-4)}$$

Squaring (II-4) and equating with (II-3),

$$(0.586)^2\ R_1 = 3.172\ R_3$$

$$R_3 = 0.108\ R_1$$

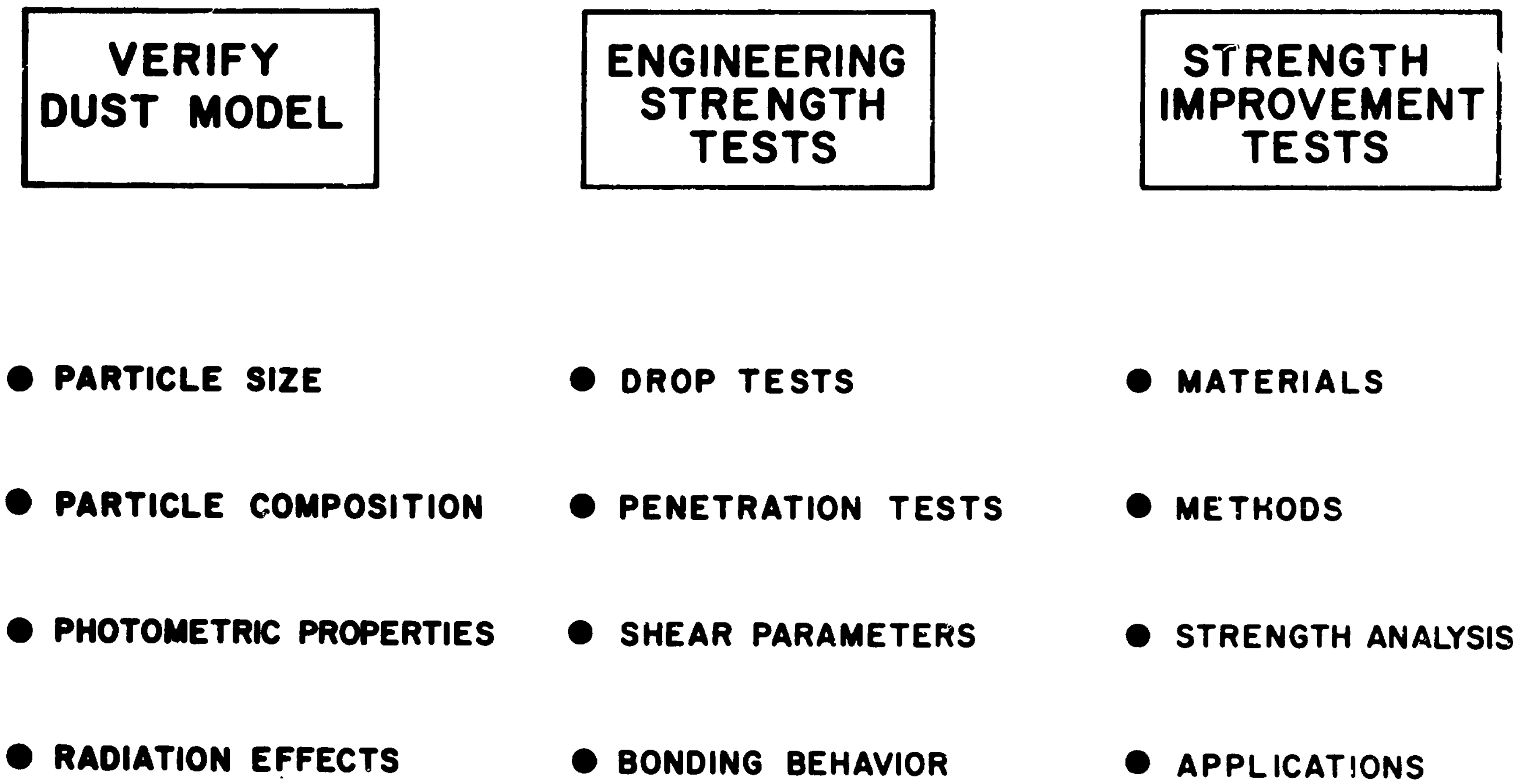
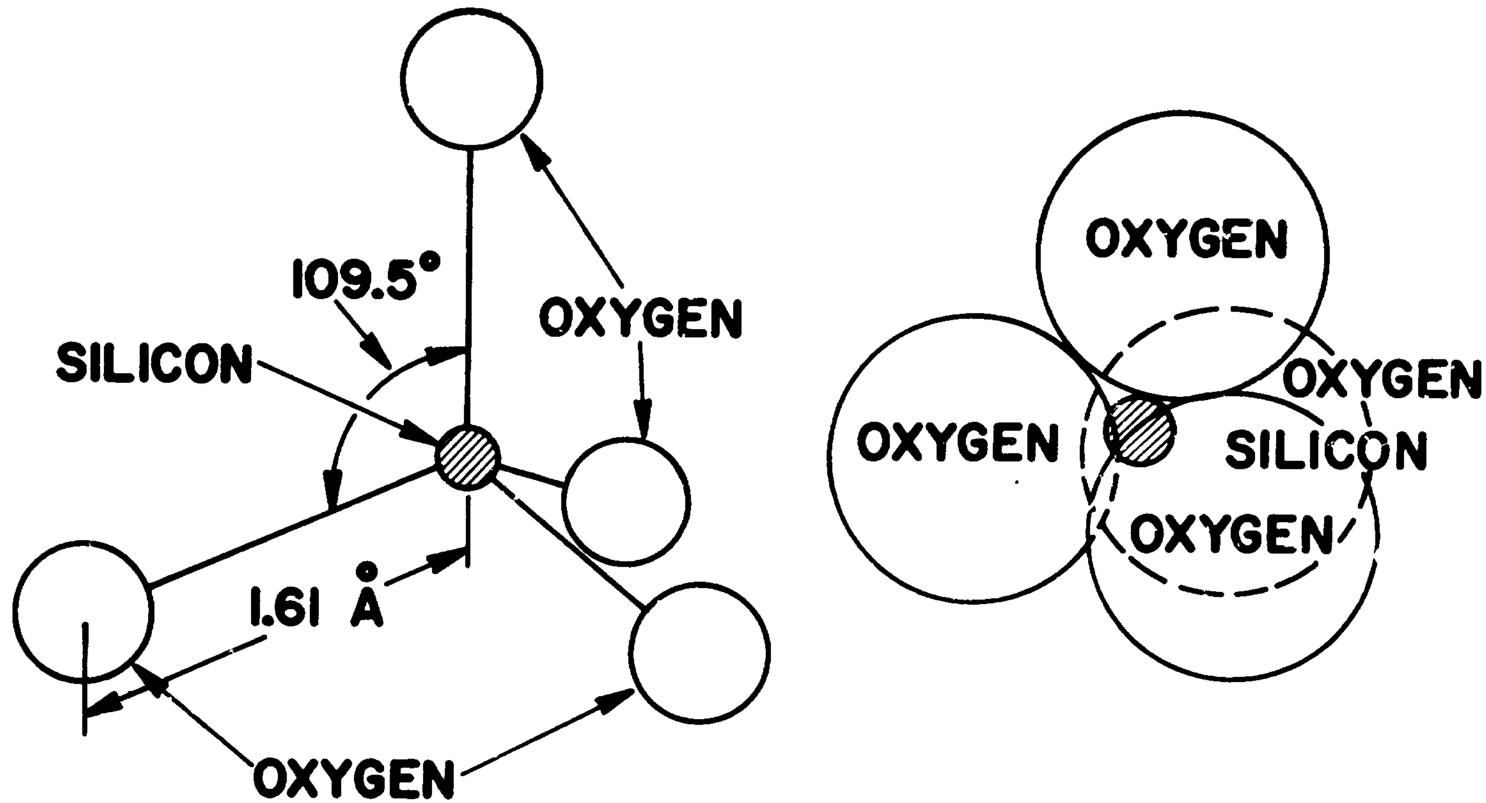


Figure 1. General Electric Research Program: Simulated Lunar Soils

TYPE	SOURCE OF ENERGY	RELATIVE STRENGTH	DIRECTIONALITY	SILICATE EXAMPLE
IONIC	ELECTROSTATIC ATTRACTION	STRONG	NON-DIRECTIONAL	ILLITE
COVALENT	EXCHANGE INTERACTION	STRONG	DIRECTIONAL	MOST SILICATES
HYDROGEN	ELECTROSTATIC FORCES	WEAK	NON-DIRECTIONAL	KAOLINITE
METALLIC	RESONANCE AND EXCHANGE INTERACTIONS	MODERATE-STRONG	NON-DIRECTIONAL	
RESO-NANCE	MIXING OF STATES	STRONG	NON-DIRECTIONAL	SI-O: 50% IONIC 50% COVALENT

Figure 2. Atomic Bonding Forces



O-SI-O ANGLE: 109.5° (TETRAHEDRAL ANGLE)

SI-O INTER-ATOMIC DISTANCE: 1.61 Å

OXYGEN TETRAHEDRAL COVALENT RADIUS: 0.66 Å

SILICON TETRAHEDRAL COVALENT RADIUS: 1.17 Å

SILICON RESIDUAL CHARGE: +0.96

SI-O BOND IONIC CHARACTER: 51%

Figure 3. The Silicate Tetrahedron

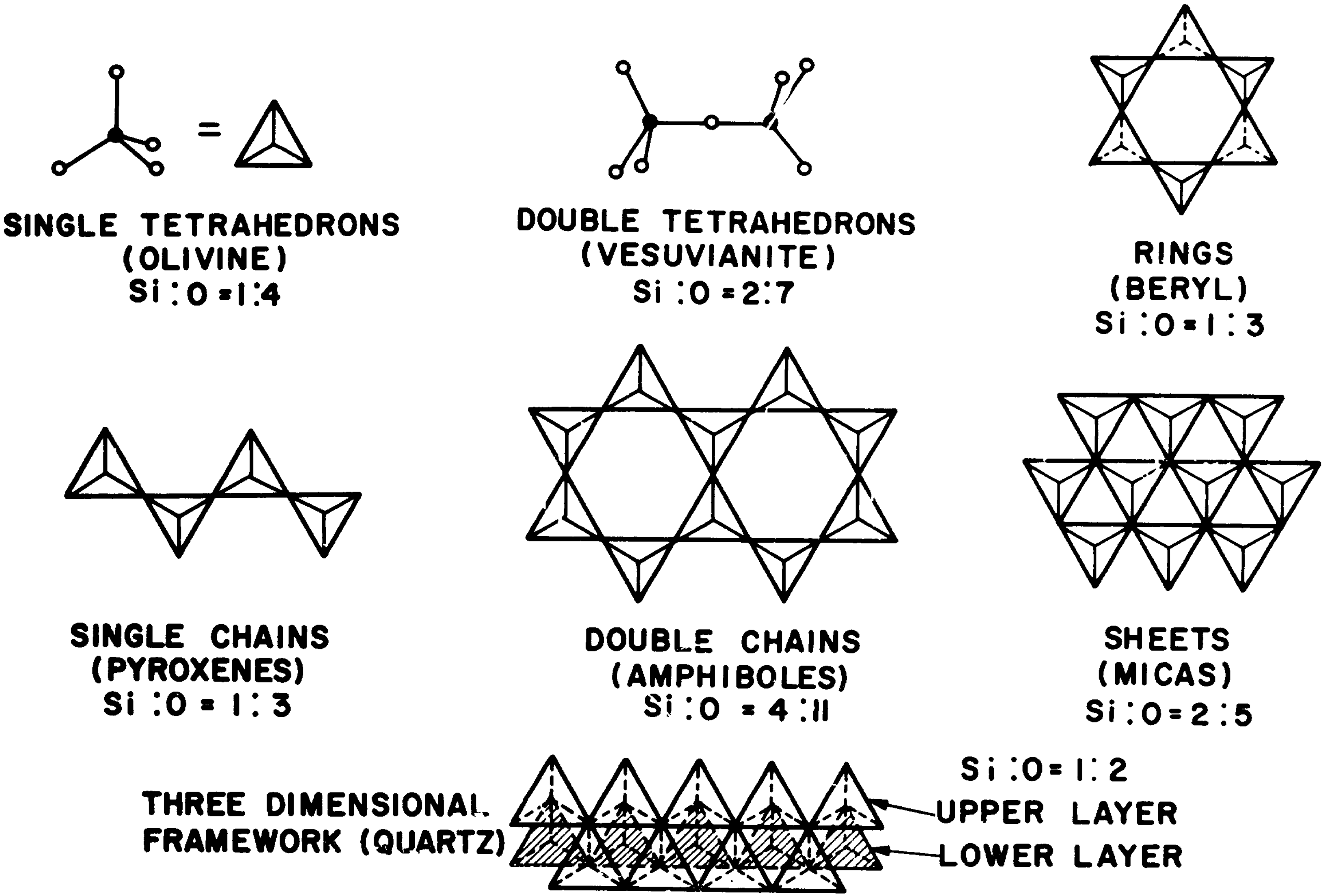


Figure 4. The Structure of the Silicates

MOLECULAR FORCES	ENERGY EXPRESSION	SOURCE	RELATIVE CONTRIBUTIONS IN H_2O	IMPORTANT IN SILICATES?
ALIGNMENT	$-\frac{2\mu^4}{3r^6kT}$	ELECTROSTATIC DIPOLE INTERACTION	77%	PROBABLY NOT
INDUCTION	$-\frac{2\alpha\mu^2}{r^6}$	POLARIZATION OF ONE MOLECULE BY ANOTHER	4%	PROBABLY NOT
DISPERSION	$-\frac{3\alpha^2 h\nu_0}{4r^6}$	SYNCHRONIZED FIELDS OF MOMENTARY DIPOLES	19%	YES

LONG-RANGE FORCES	SOURCE	IMPORTANT IN INTERACTION OF GRANULAR SILICATES?
INTEGRATED DISPERSION	ADDITIVE NATURE OF DISPERSION FORCES BETWEEN LARGE NUMBERS OF MOLECULES	YES
DOUBLE LAYER	ADSORPTION OF SURFACE CONTAMINANTS	YES, IF INSUFFICIENTLY CLEAN
SHILLER-LAYER ORDERING	REDUCTION OF CO-VOLUME OF ASYMMETRIC MOLECULES DUE TO DENSITY INCREASE	NO
LONG-WAVE INTERACTION	INTERACTION OF LARGE PARTICLES WITH LONG-WAVE ELECTRICAL OSCILLATIONS	DOUBTFUL
CHARGED DISLOCATIONS	ATTRACTION OF IMPURITIES BY DISLOCATIONS IN IONIC CRYSTALS	NO
ELASTIC FORCES	STRESS INTRODUCED BY DISLOCATIONS, SURFACES, ETC.	POSSIBLY
OTHER BONDING MECHANISMS		
SPUTTERING	INTRODUCTION OF CHEMICALLY ACTIVE ATOMS AND IONS INTO THE LATTICE	YES
ELECTROSTATIC CHARGING	SOLAR WIND, IONIZING RADIATION, ETC.	YES
SURFACE TENSION	MINIMIZATION OF SURFACE ENERGY	NO

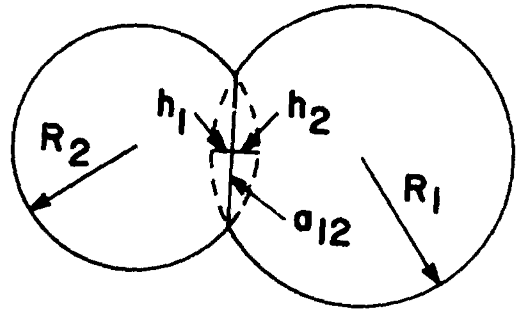
Figure 5. Summary of Molecular and Inter-Particle Forces

CONTACT AREA

$A_{12} = \pi a_{12}^2 = 2\pi R_1 h_1$

$R_1 h_1 = R_2 h_2$

$h_1 \ll R_1, h_2 \ll R_2$



$R_2 = bR_1, \ b \leq 1$

ENERGY BALANCE

CONTACT ENERGY $= \Delta E = \frac{A_{12}}{K} \times \frac{e\Delta F}{N} = \frac{\pi a_{12}^2 e \Delta F}{NK}$

$\frac{1}{K} = \frac{\text{AVAILABLE SURFACE BONDS}}{\text{cm}^2} = \left(\frac{ND}{M}\right)^{2/3}$

N = AVOGADRO'S NUMBER

D = DENSITY OF PARTICLE MATERIAL

M = AVERAGE MOLECULAR WEIGHT OF PARTICLE MATERIAL

ΔF = AVERAGE ENERGY/BOND OF PARTICLE MATERIAL

e = CONVERSION FACTOR

ENERGY TO COMPRESS SPHERES $= W = P(\Delta V_1 + \Delta V_2) = \frac{\pi}{4} \frac{(a_{12})^4 P}{R_1} \left[1 + \frac{1}{b}\right]$, P = CONTACT PRESSURE

$\Delta E = W$: SOLVE FOR CONTACT AREA A_{12}

Figure 6. Vacuum Shear Strength of a System of Spherical Particles (I)

INTERFACE CAUSED BY COMPRESSION IN PLASTIC REGIME

$$A_{12} = \frac{4\pi e}{N k P_Y} \left[1 + \frac{1}{b}\right]^{-1} R_1 \Delta F, \quad P_Y = \text{YIELD PRESSURE}$$

INTERFACE CAUSED BY COMPRESSION IN ELASTIC REGIME

$$a_{12} = \frac{3\pi P}{8Y} \left(\frac{1}{R_i} + \frac{1}{R_2}\right)^{-1} \quad \text{(DERIVABLE FROM HERTZ'S EQUATIONS)}$$

Y = MODULUS OF ELASTICITY

$$W = \frac{2Y (a_{12})^5}{3 R_1^2} \left[1 + \frac{1}{b}\right]^2 = \Delta E \qquad A_{12} = \pi \left[\frac{3\pi e}{2_Y NK} \left(1 + \frac{1}{b}\right)^{-2}\right]^{\frac{2}{3}} (R_1^2 \Delta F)^{\frac{2}{3}}$$

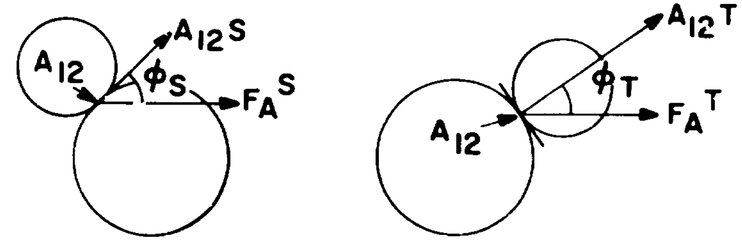
SHEAR STRENGTH

FORCE TO SHEAR PARTICLES = $A_{12}S$

FORCE TO SEPARATE PARTICLES = $A_{12}T$

S = BULK SHEAR STRENGTH

T = BULK TENSILE STRENGTH



$F_A^{S(T)}$ = SHEAR (TENSILE) CONTRIBUTION OF APPLIED FORCE

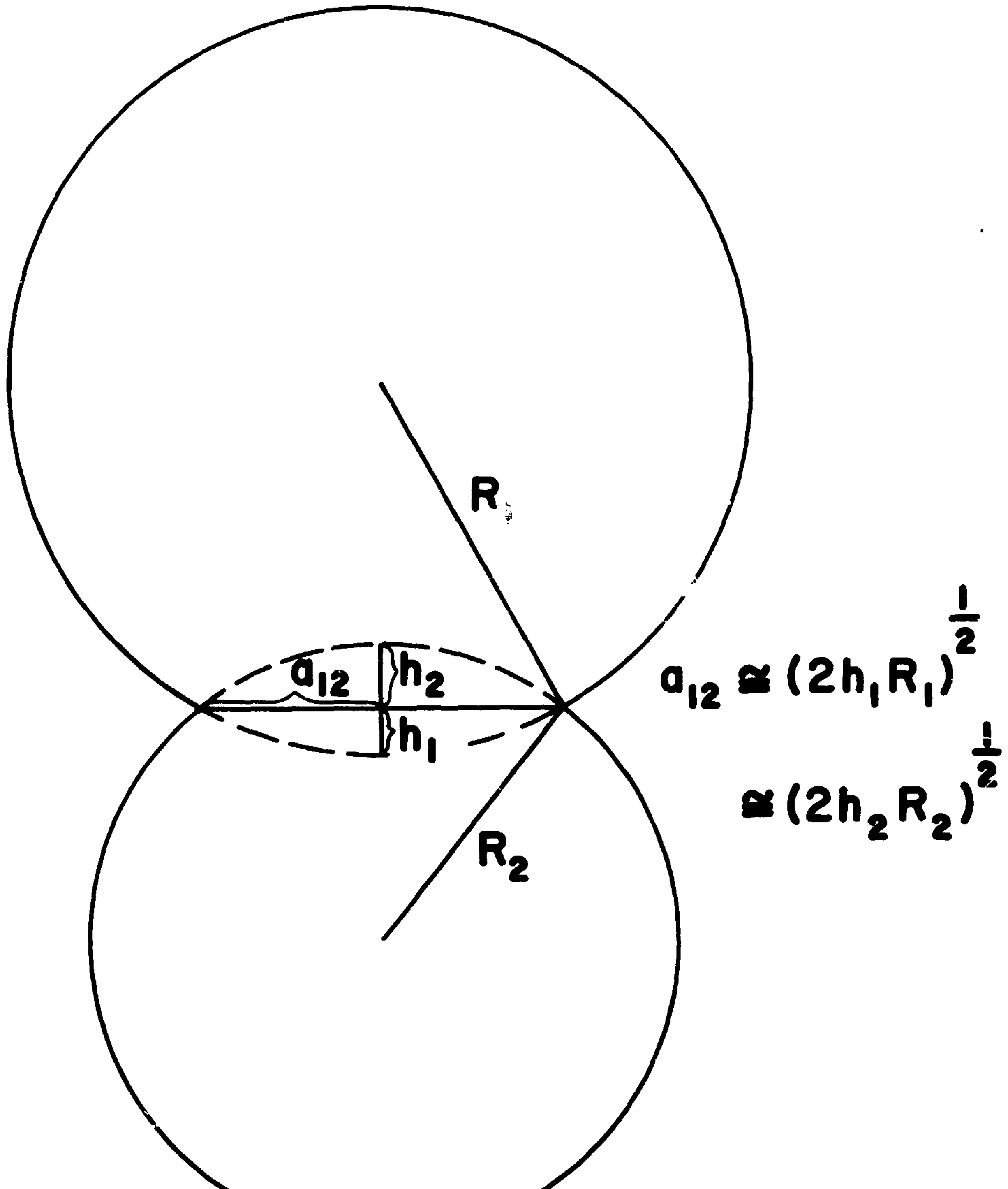
$F_A^S = SA_{12} \sec \phi_S$

$F_A^T = TA_{12} \sec \phi_T$

TOTAL APPLIED SHEAR STRESS = $F_A = \Sigma F_i$ (SUMMATION OVER PARTICLES IN UNIT AREA)

F_i = TOTAL TENSILE AND SHEAR RESISTANCE MOBILIZED BY i<u>TH</u> PARTICLE

Figure 7. Vacuum Shear Strength of a System of Spherical Particles (II)



NOTE: ASSUME $h_1 \ll R_1$, $h_2 \ll R_2$

Figure 8. Geometry of Contact Area between Two Spheres

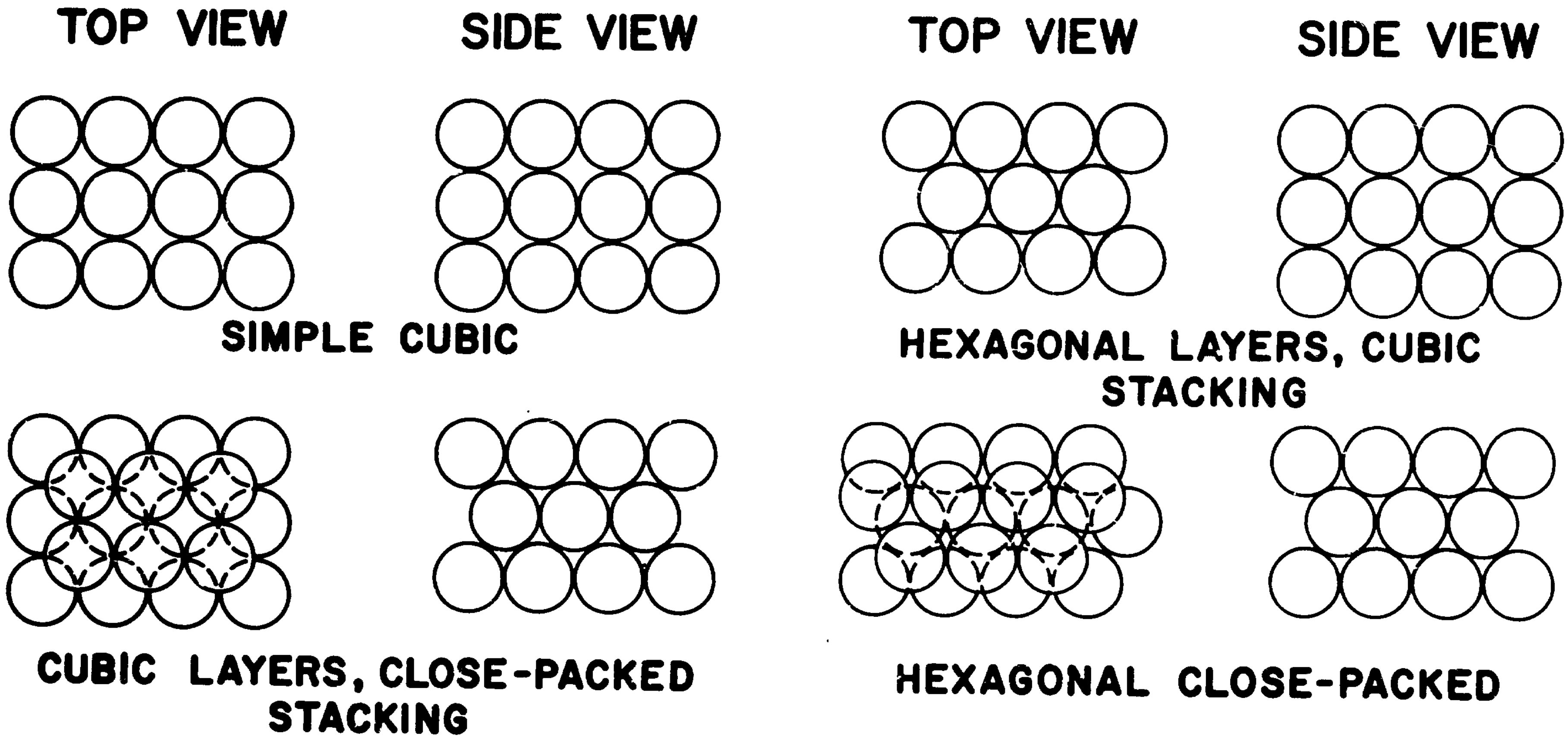


Figure 9. Packing Configuration for Model Involving a Single Particle Diameter

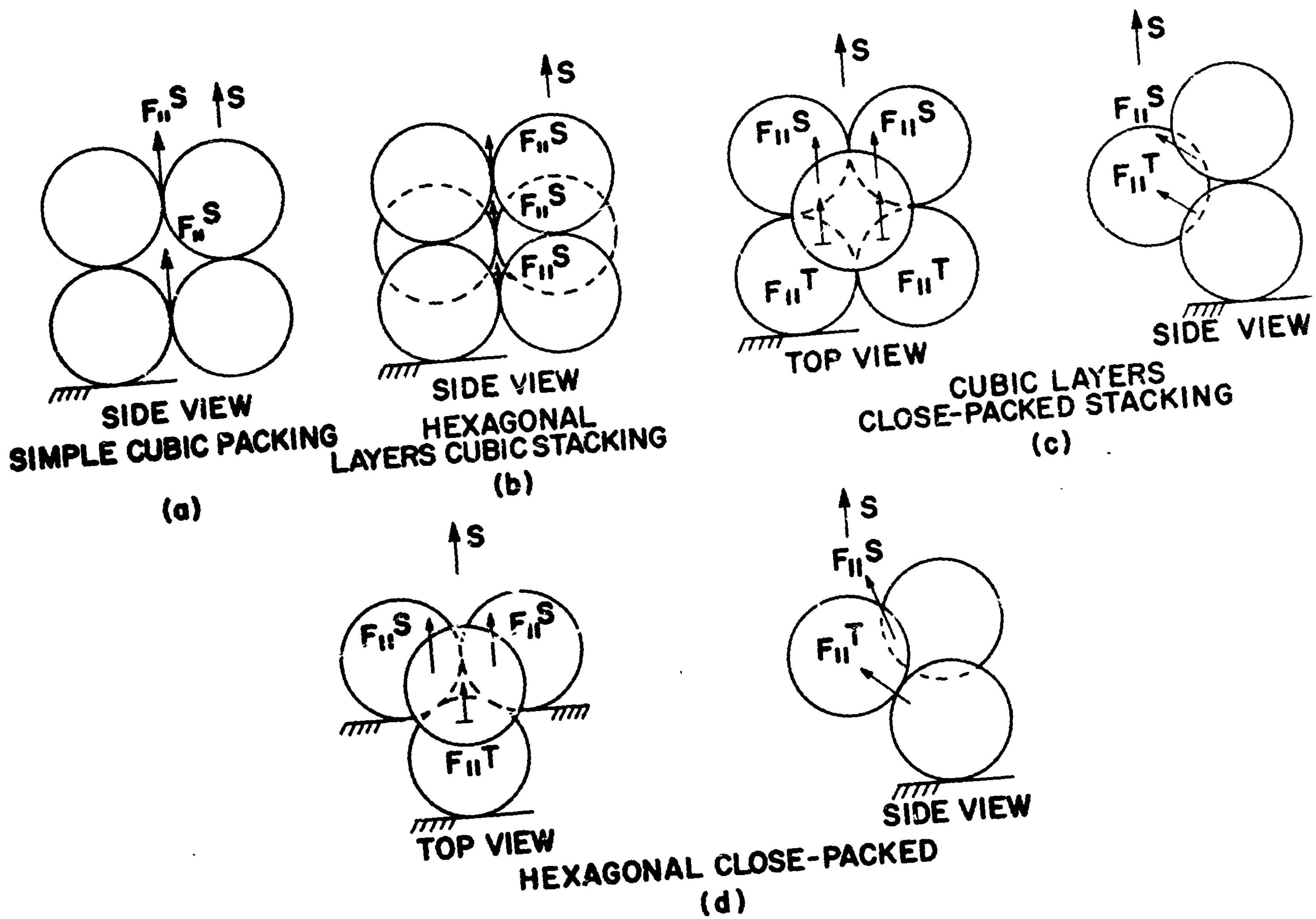
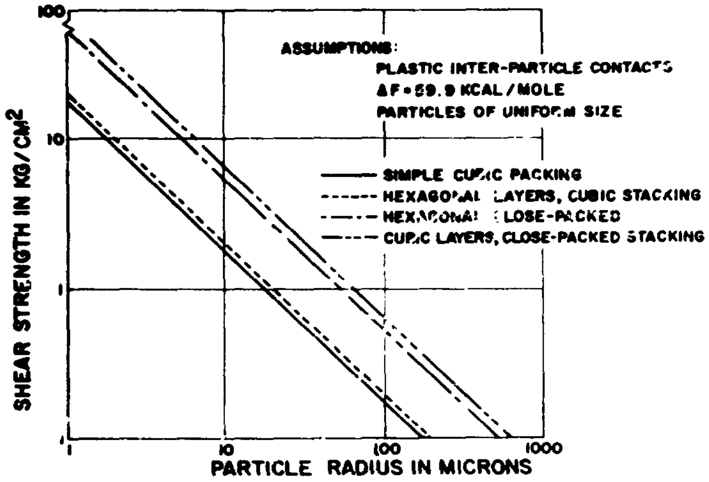
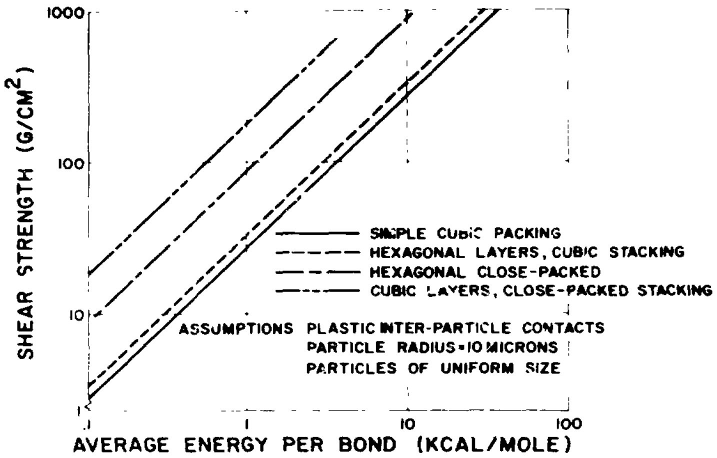


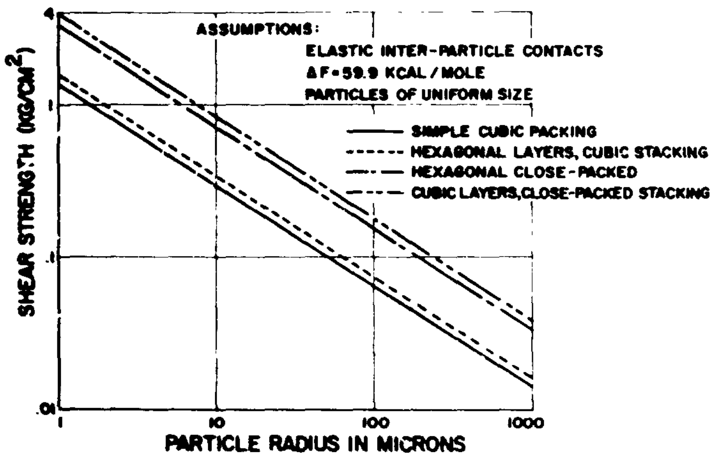
Figure 10. Assumed Shear Planes for Systems of Uniform Spheres



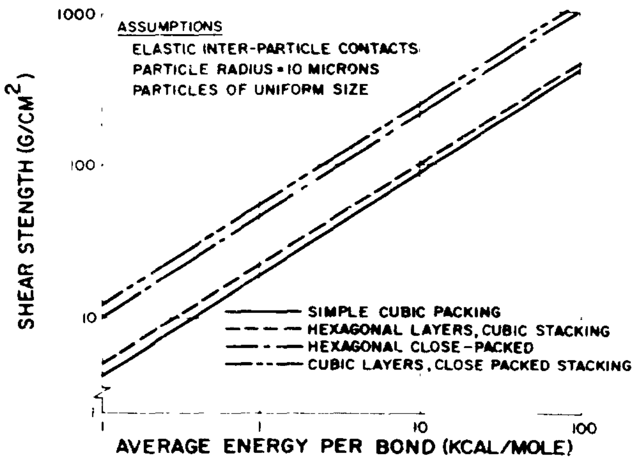
a. Shear Strength as a Function of Particle Radius - Plastic Interface



b. Shear Strength as a Function of Average Bond Energy - Plastic Interface



c. Shear Strength as a Function of Particle Radius - Elastic Interface



d. Shear Strength as a Function of Average Bond Energy - Elastic Interface

Figure 11. Theoretical Shear Strengths for Granular Systems of Uniform Particle Diameter

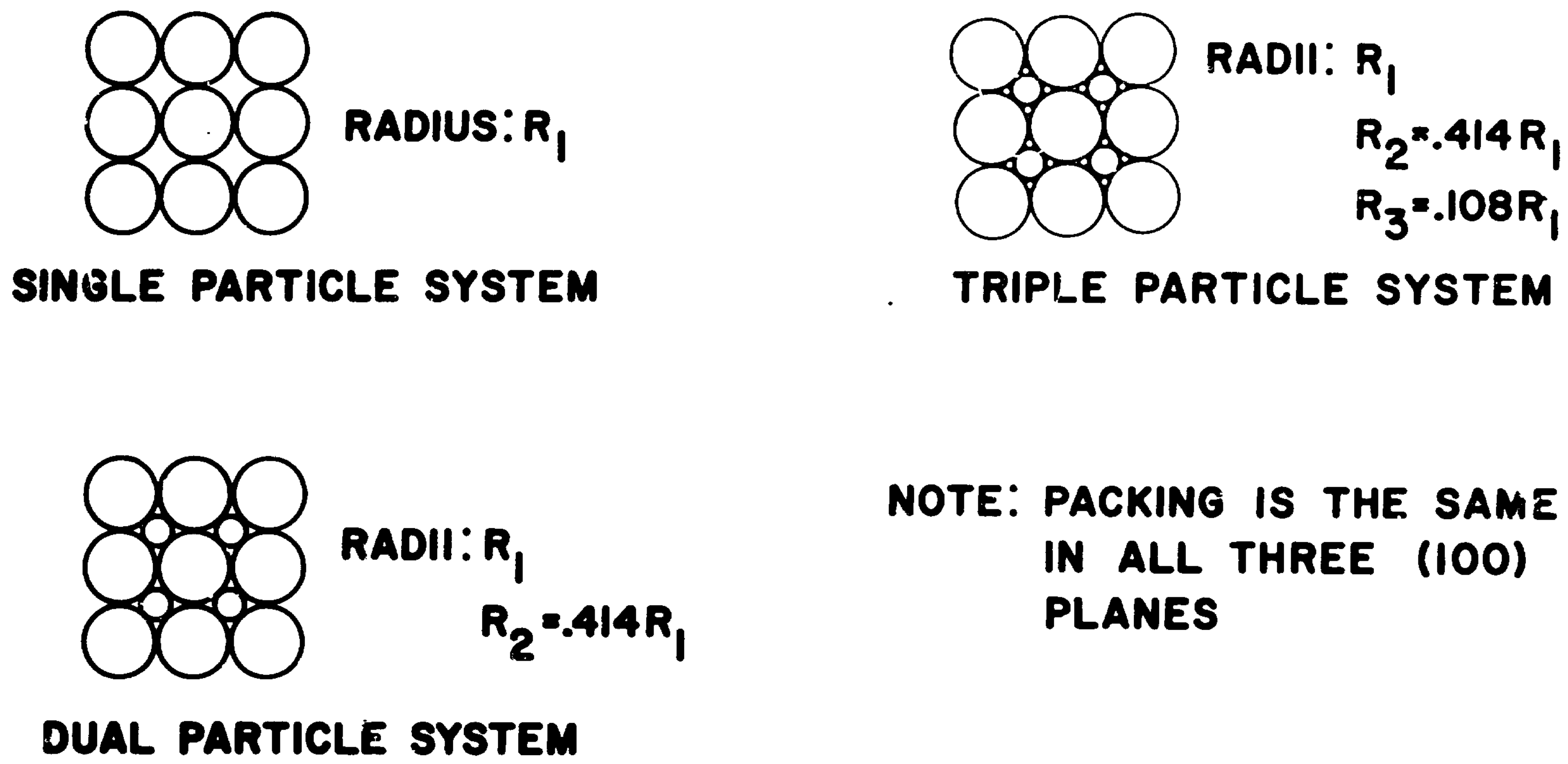


Figure 12. Packing Configuration for Multi-Diameter Particle Model

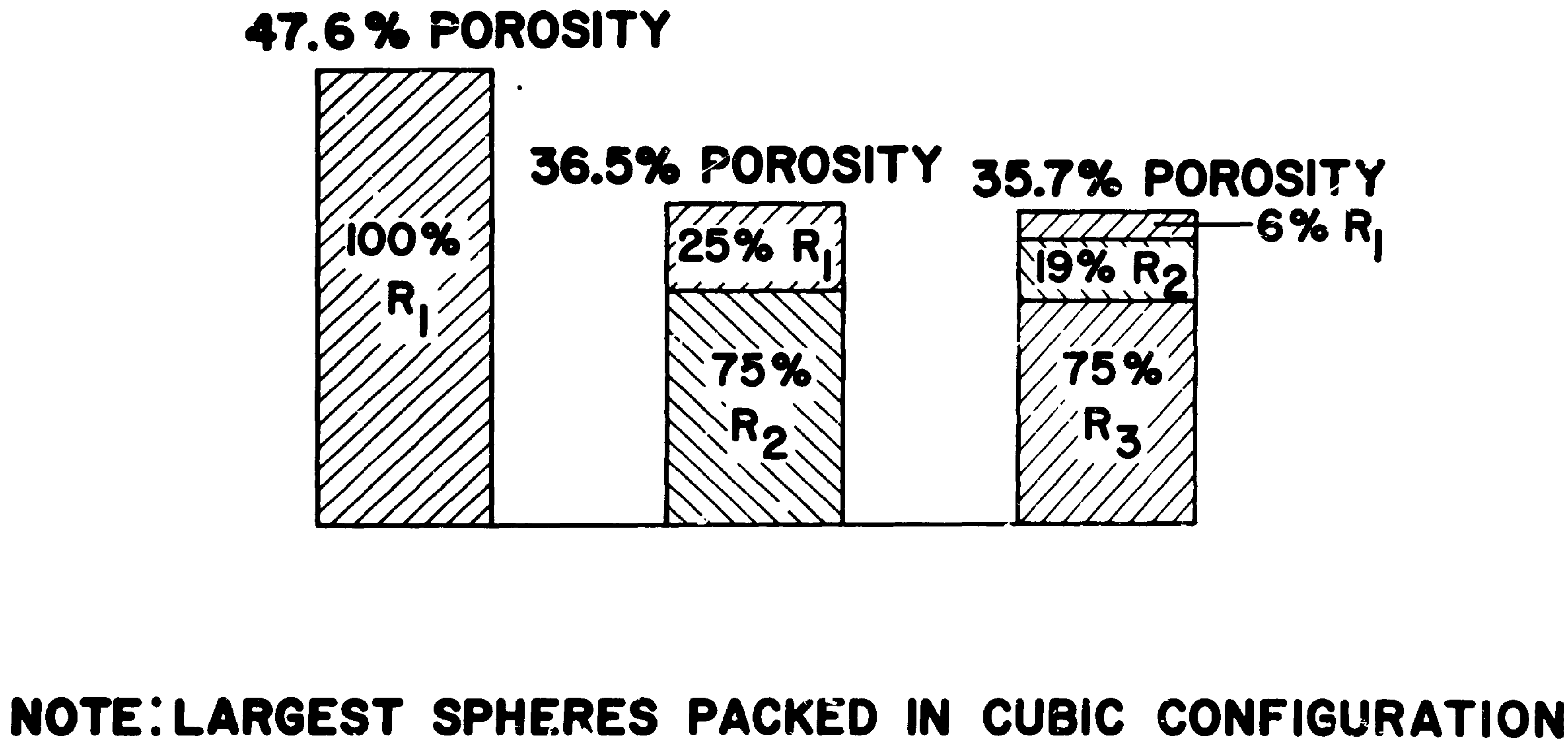


Figure 13. Porosity and Particle Size Distribution of Models Involving Spheres of Several Diameters

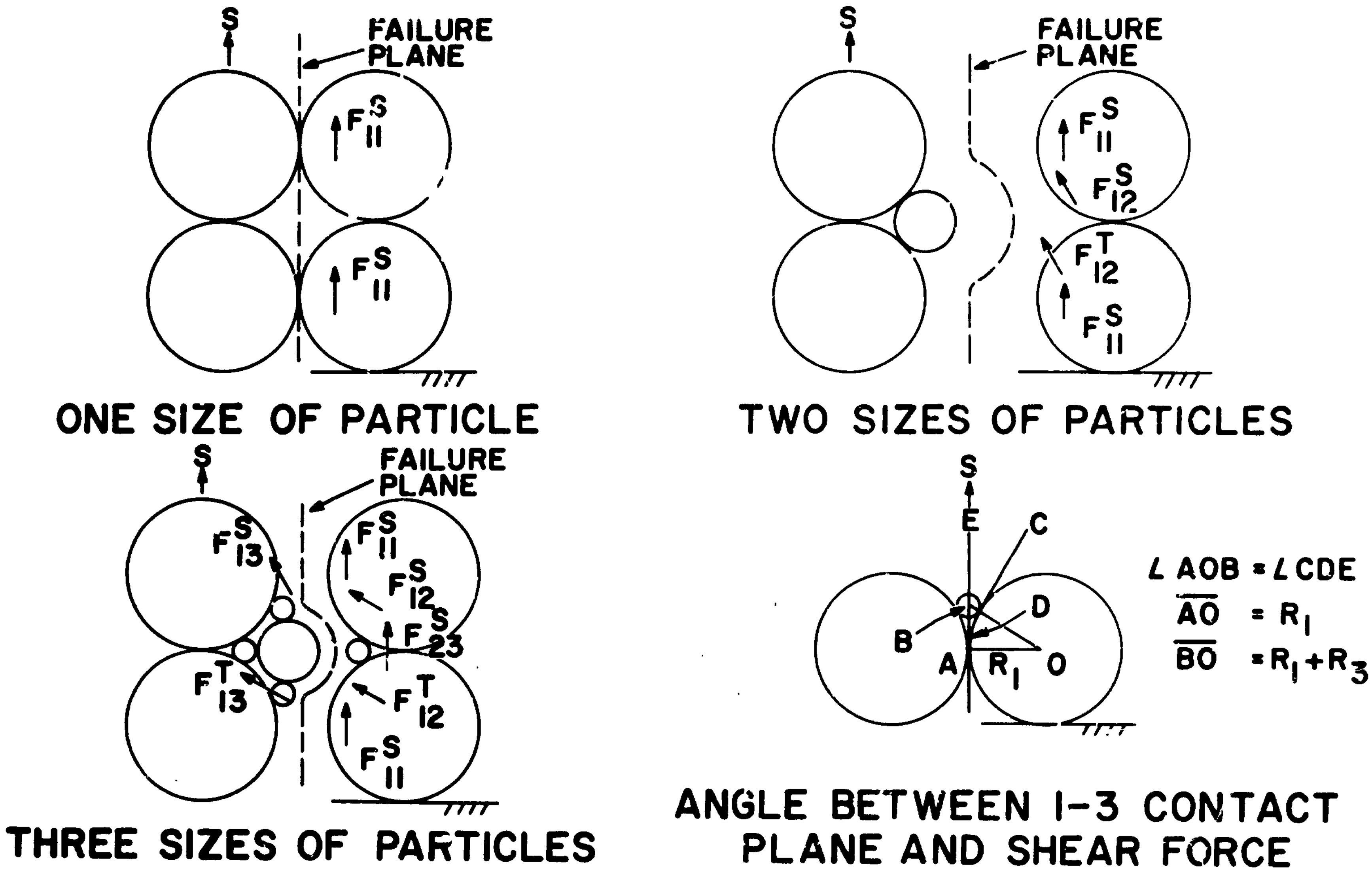
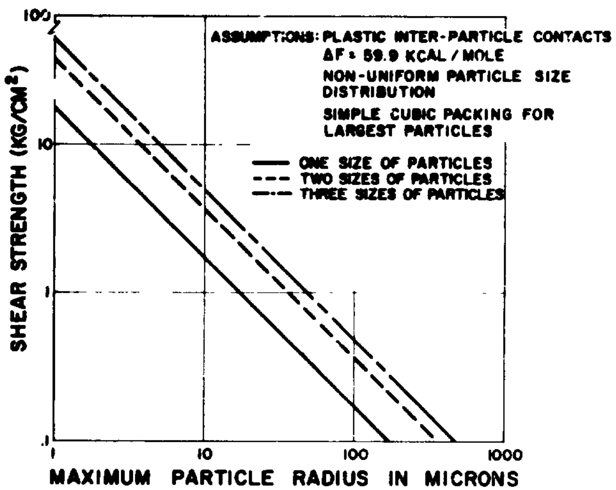
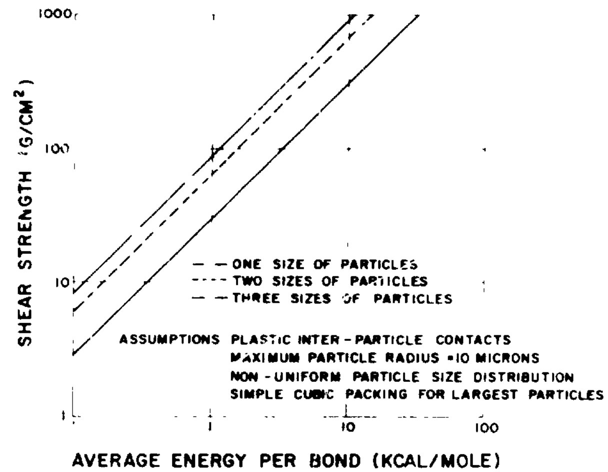


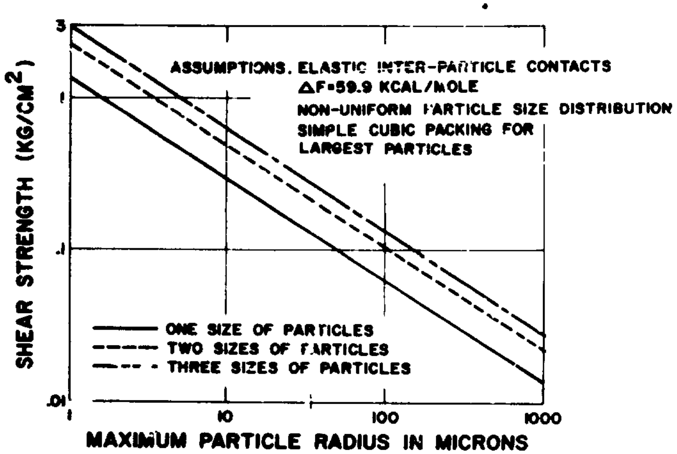
Figure 14. Assumed Shear Planes for Systems of Multi-Diameter Particles



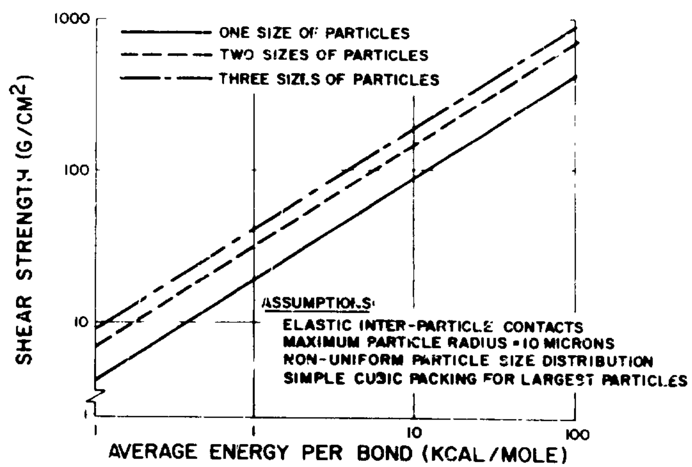
a. Shear Strength as a Function of Maximum Particle Radius - Plastic Interface



b. Shear Strength as a Function of Average Bond Energy - Plastic Interface

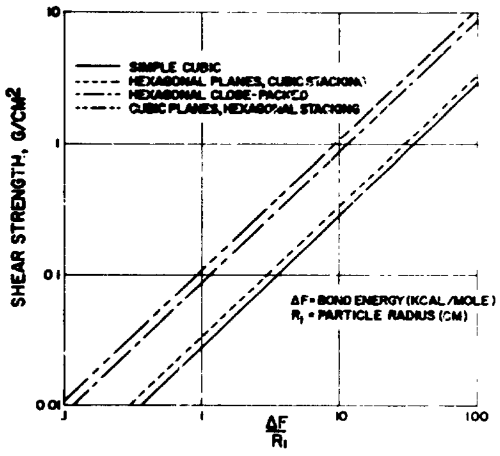


c. Shear Strength as a Function of Maximum Particle Radius - Elastic Interface

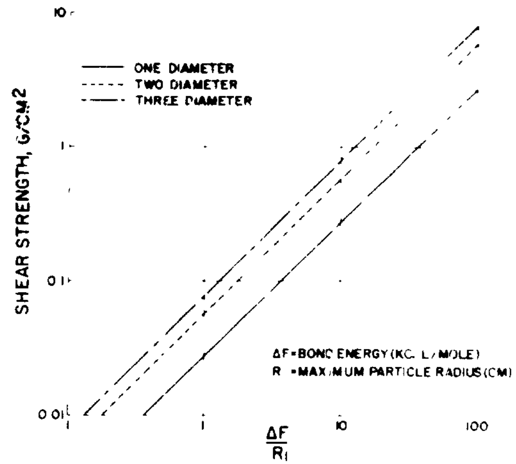


d. Shear Strength as a Function of Average Bond Energy - Elastic Interface

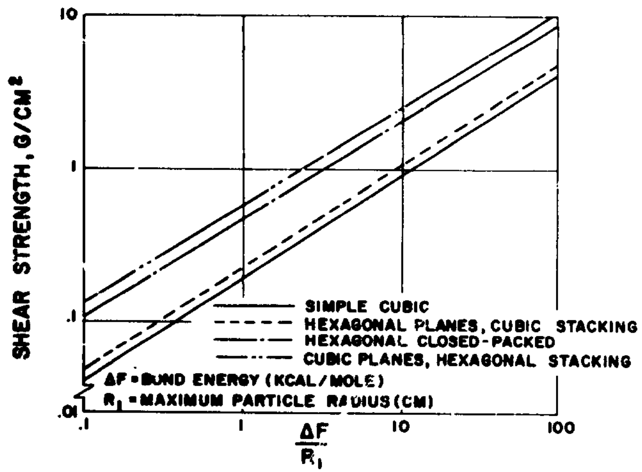
Figure 15. Theoretical Shear Strengths for Granular Systems of Non-Uniform Particle Diameters



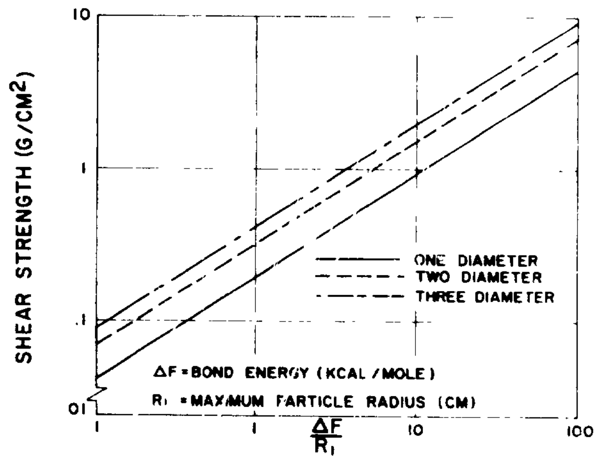
a. Theoretical Shear Strength for Systems of Uniform Diameter Spheres - Plastic Interface



b. Theoretical Shear Strength for Systems of Multi-Diameter Spheres - Plastic Interface



c. Theoretical Shear Strength for Systems of Uniform Diameter Spheres - Elastic Interface



d. Theoretical Shear Strength for Systems of Multi-Diameter Spheres - Elastic Interface

Figure 16. Theoretical Shear Strength as a Function of Ratio of Bond Energy to Maximum Particle Radius

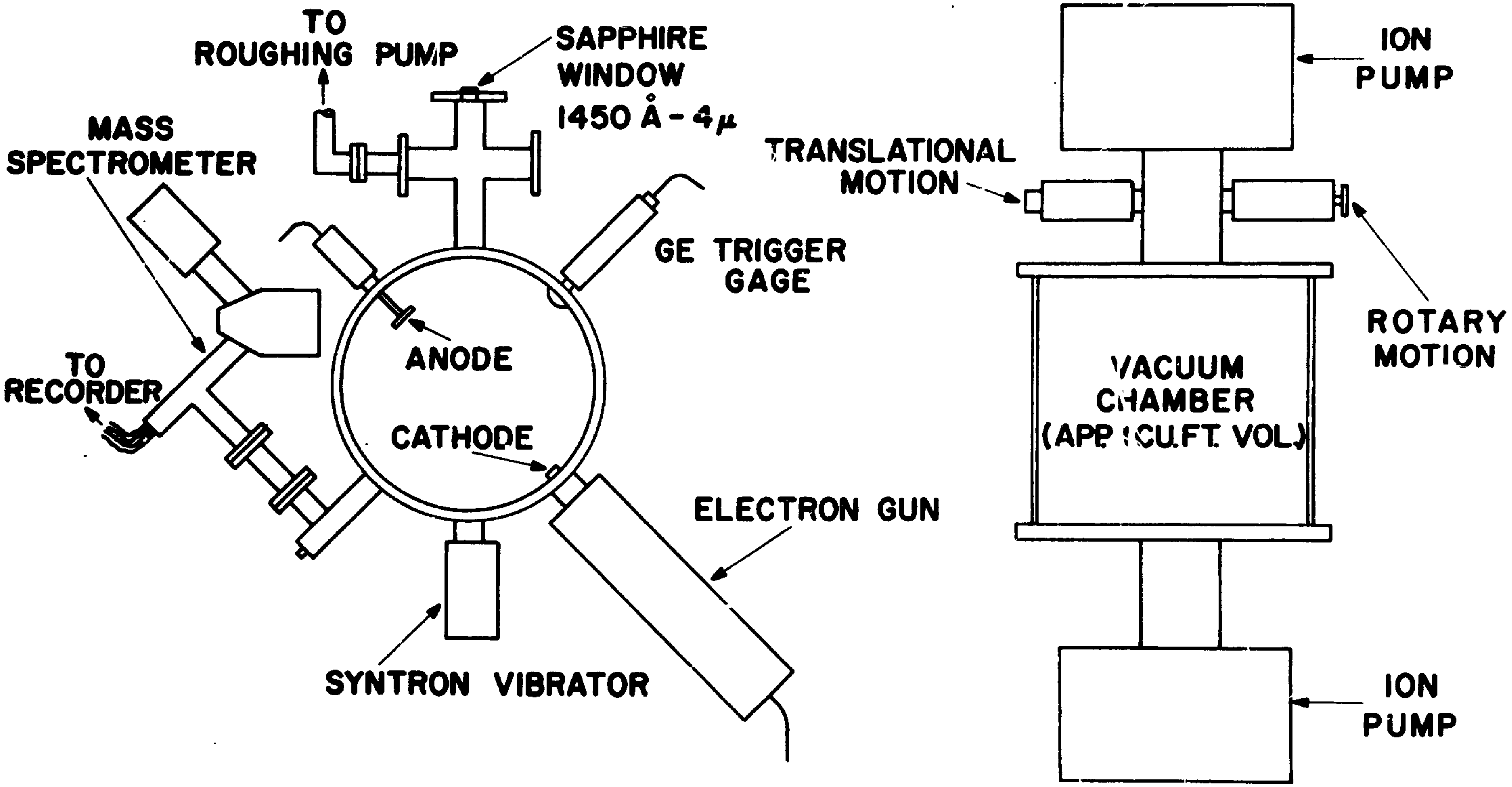


Figure 17. Vacuum Test Equipment Schematic Diagram

Figure 18. Close-Up View of Vacuum System

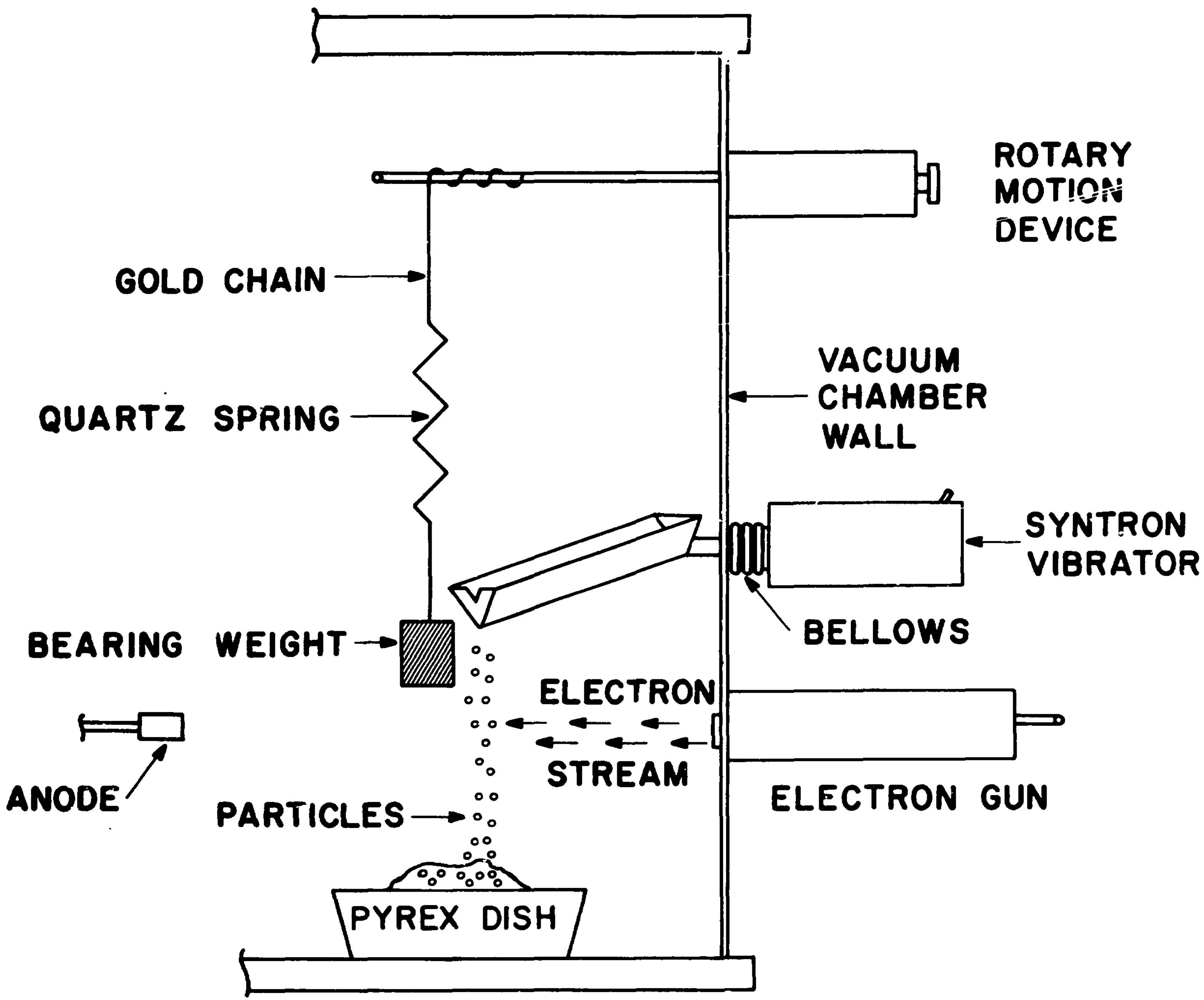


Figure 19. Irradiating Falling Silica Particles Experiment Schematic Diagram

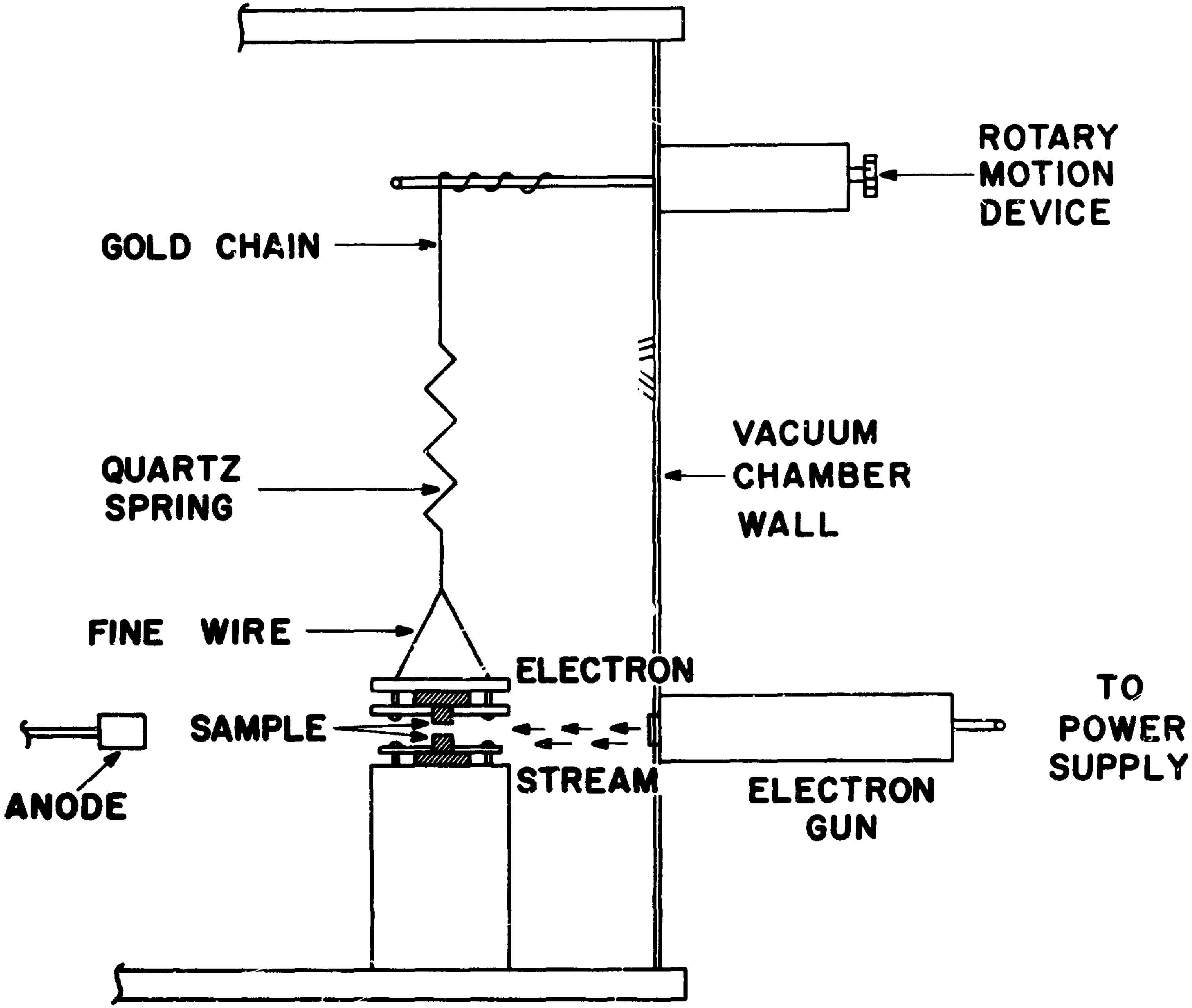


Figure 20. Bond Strength Experiment Schematic Diagram

TEST RUN	SAMPLE	PARTICLE SIZE	PRESSURE RANGE (TORR)	IRRADIATION	OBSERVATIONS
A	LUDOX SILICA	<200 μ	5×10^{-8}	NONE	ANGLE OF REPOSE: 90° IN VACUUM 30° IN AIR
B	MIN-U-SOL SILICA	10 μ	1 ATMOSPHERE	NONE	ADHERED 1/4" THICK TO UNDERSIDE OF SPATULA BEFORE AND AFTER BAKING.
C	LUDOX SILICA	<37 μ	$2 \times 10^{-8} - 6 \times 10^{-10}$	e^-	ALL SILICA DEFLECTED TOWARDS CATHODE; HENCE PARTICLES POSITIVELY CHARGED. BEARING STRENGTH <2 G/CM^2.
D	LUDOX SILICA	<37 μ	5×10^{-10}	NONE	NO DEFLECTION OF PILE WITH ELECTRIC FIELD ON, ELECTRIC GUN OFF.
E	FUSED QUARTZ	3-5 μ	4×10^{-9}	e^-	PILE WAS MOVED 1/2" TOWARD CATHODE. DUST ADHERED TO STAINLESS STEEL WEIGHT.
F	BORATE GLASS	50 μ	$10^{-7} - 4 \times 10^{-9}$	e^-	SCATTERED THROUGHOUT CHAMBER. THIN LAYER ADHERED TO STAINLESS STEEL WEIGHT. PRESSURE ROSE DURING IRRADIATION.
G	BORATE GLASS	50 μ	1.5×10^{-9}	NONE	PILE FORMED. NO PRESSURE RISE DETECTED. (G and H)
H	BORATE GLASS	10 μ	2×10^{-10}	NONE	
I	BORATE GLASS	10 μ	$10^{-8} - 10^{-9}$	e^-	CATHODE COATED WITH GLASS. PRESSURE ROSE WITH ELECTRON GUN ON (MOSTLY H_2O, CO_2).

Figure 21. Summary of Particle Drop Experiments

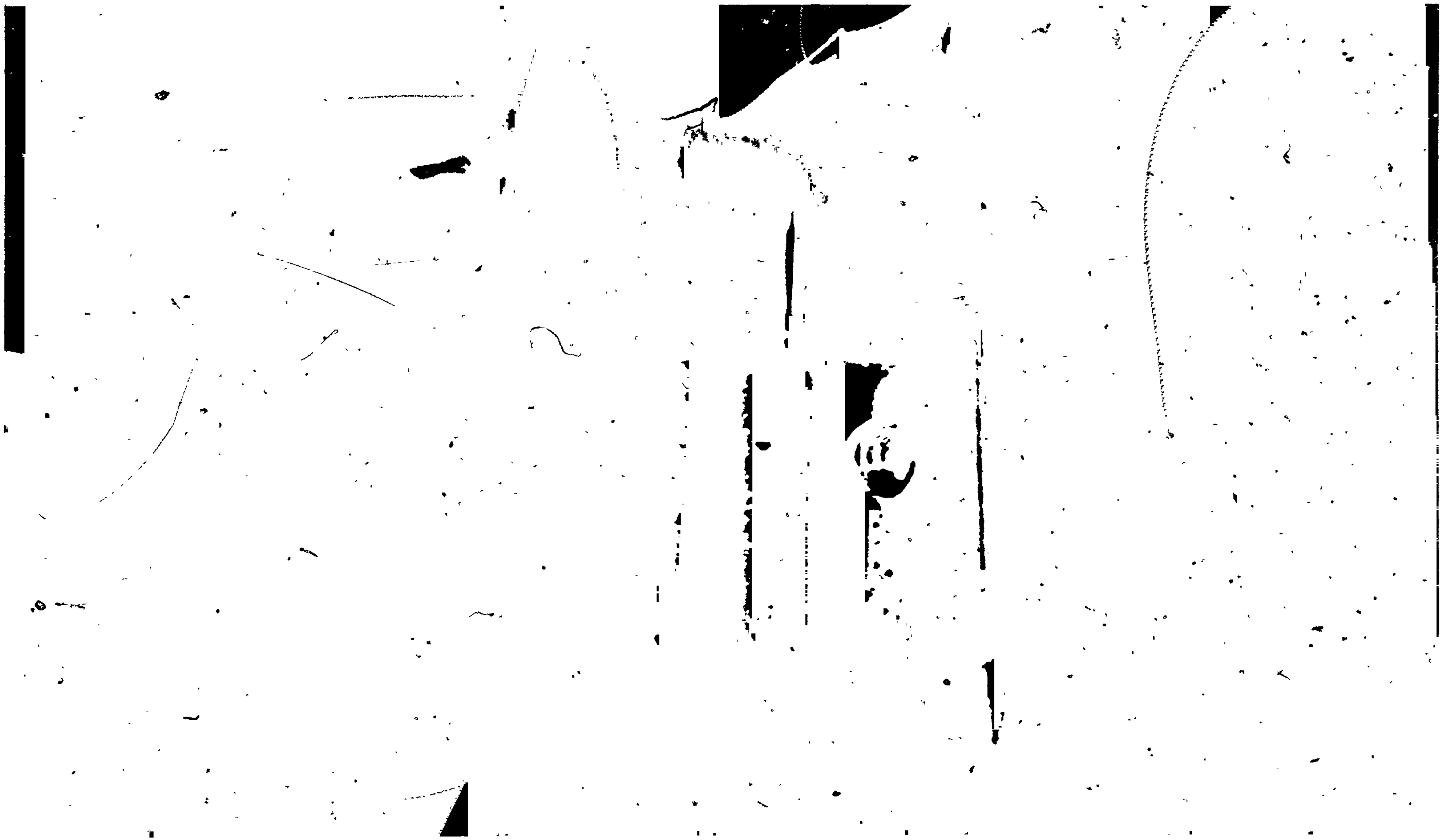


Figure 22. Silica Dust on Stainless Steel Weight

RUN	MATERIAL	PARTICLE SIZE	PRESSURE (TORR)	IRRADIATION	MAXIMUM PENETRATION (MM)	NORMAL LOAD (G/CM2)	COMMENTS
1	LUDOX SILICA (DROPPED)	< 37μ	$2 \times 10^{-8} - 6 \times 10^{-10}$	e^-	—	< 2	SLIGHT COHESION OBSERVED. DUST WAS POSITIVELY CHARGED.
2.	FUSED QUARTZ (DROPPED)	3-5 μ	4×10^{-9}	e^-	3	3.5	ADHERED TO STAINLESS STEEL WEIGHT. PENETRATION MEASURED IN AIR.
3.	SILICA POWDER (DROPPED)	3-5μ	$2 \times 10^{-9} - 5 \times 10^{-12}$	e^-	0.15	0.49	LITTLE ADHESION TO ALUMINUM WEIGHT. PRESSURE DURING MEASUREMENT = 2×10^{-10} TORR
4.	SILICA POWDER (NOT DROPPED)	3-5 μ	4×10^{-12}	X-RAYS	0	1.53	IRRADIATED SEVERAL DAYS.
			2×10^{-8}	NONE	0	1.53	TWO HOURS AT GIVEN PRESSURE
			2×10^{-6}	NONE	0	1.53	TWO HOURS AT GIVEN PRESSURE
			1 ATMOSPHERE	NONE	0	1.53	SURFACE BROKEN BY DROPPING 1.20 g ONTO DUST FROM 1". NO CRUST FOUND ON REMOVAL OF SAMPLE FROM CHAMBER.
5.	GRANODIORITE (NOT DROPPED)	< 75μ	$2 \times 10^{-8} - 1 \times 10^{-10}$	X-RAYS	—	—	RESIDUAL GAS WAS H_2O
			1 ATMOSPHERE	NONE	1.6	0.112	
			1×10^{-3}	NONE	1.2	0.191	
			6×10^{-9}	NONE	0.9	0.166	
6.	GRANODIORITE (DROPPED)	< 75μ	1×10^{-10}	NONE	1.16	3.26	PILE INITIALLY COMPACTED BY 0.125 GRAM WEIGHT. DATA IS FOR COLLAPSE OF PILE

Figure 23. Summary of Soil Strength Measurements

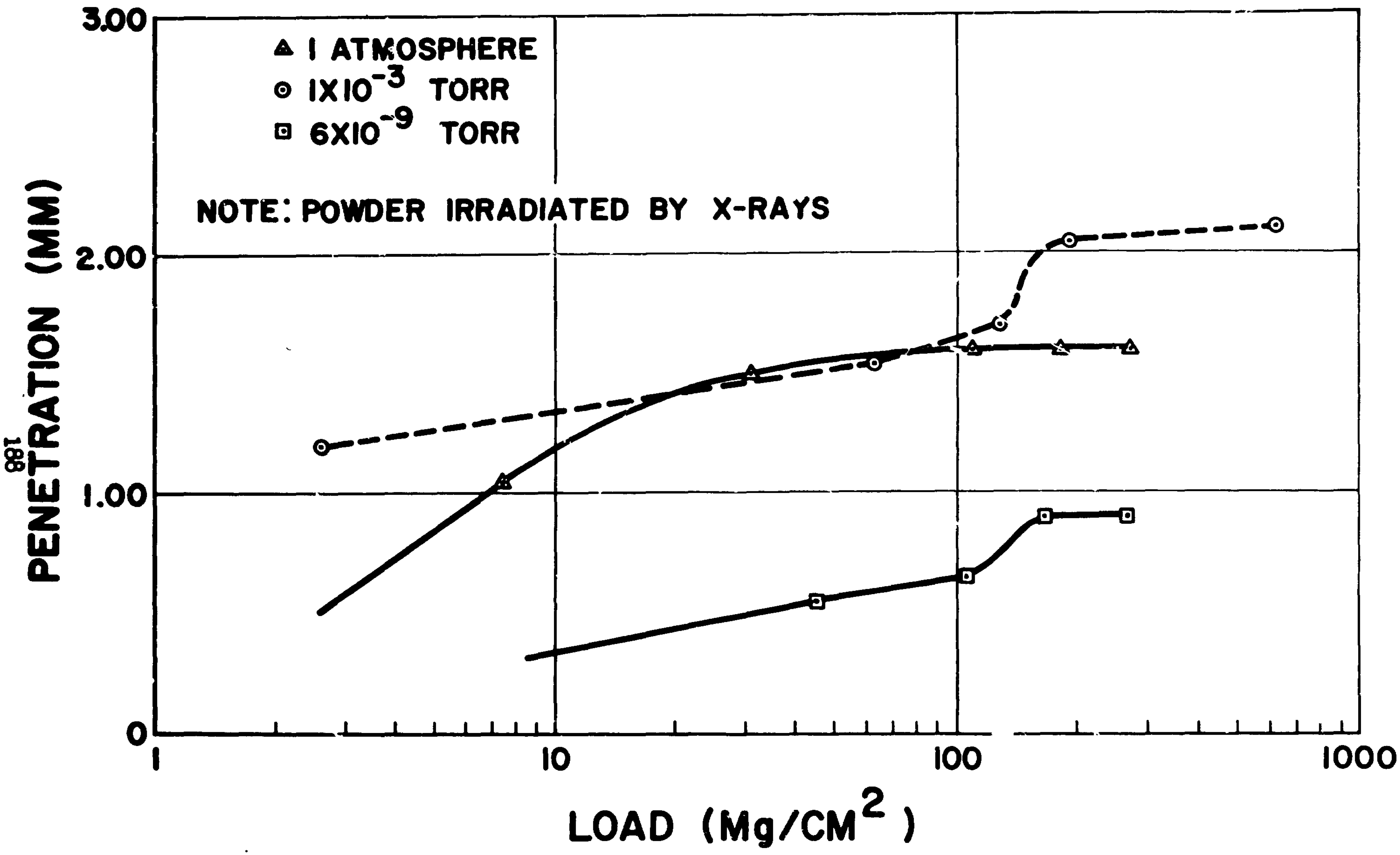


Figure 24. Load-Penetration Studies of Granodiorite Powder as a Function of Vacuum

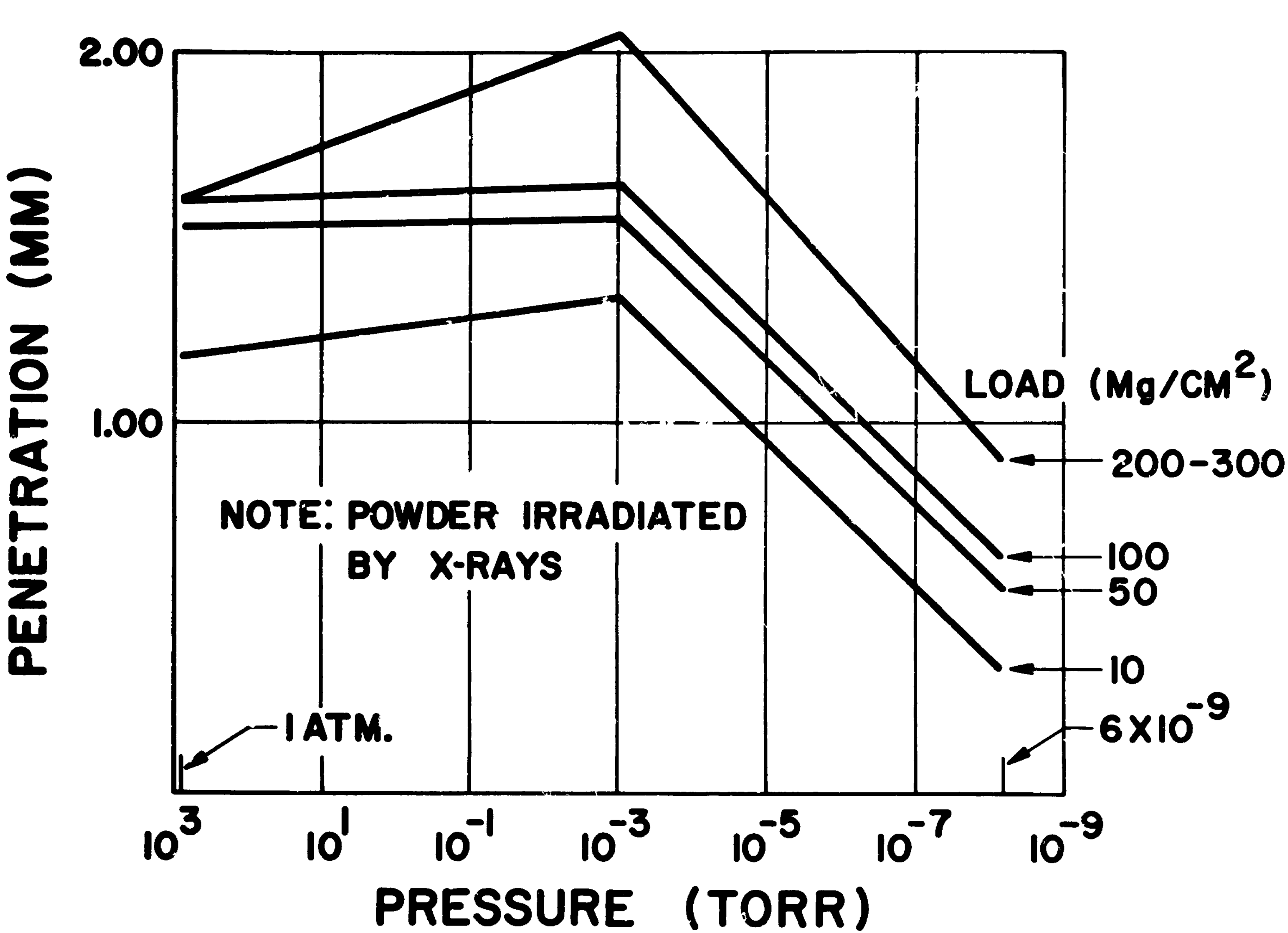


Figure 25. Penetration Vs. Pressure of Granodiorite Powder as a Function of Load

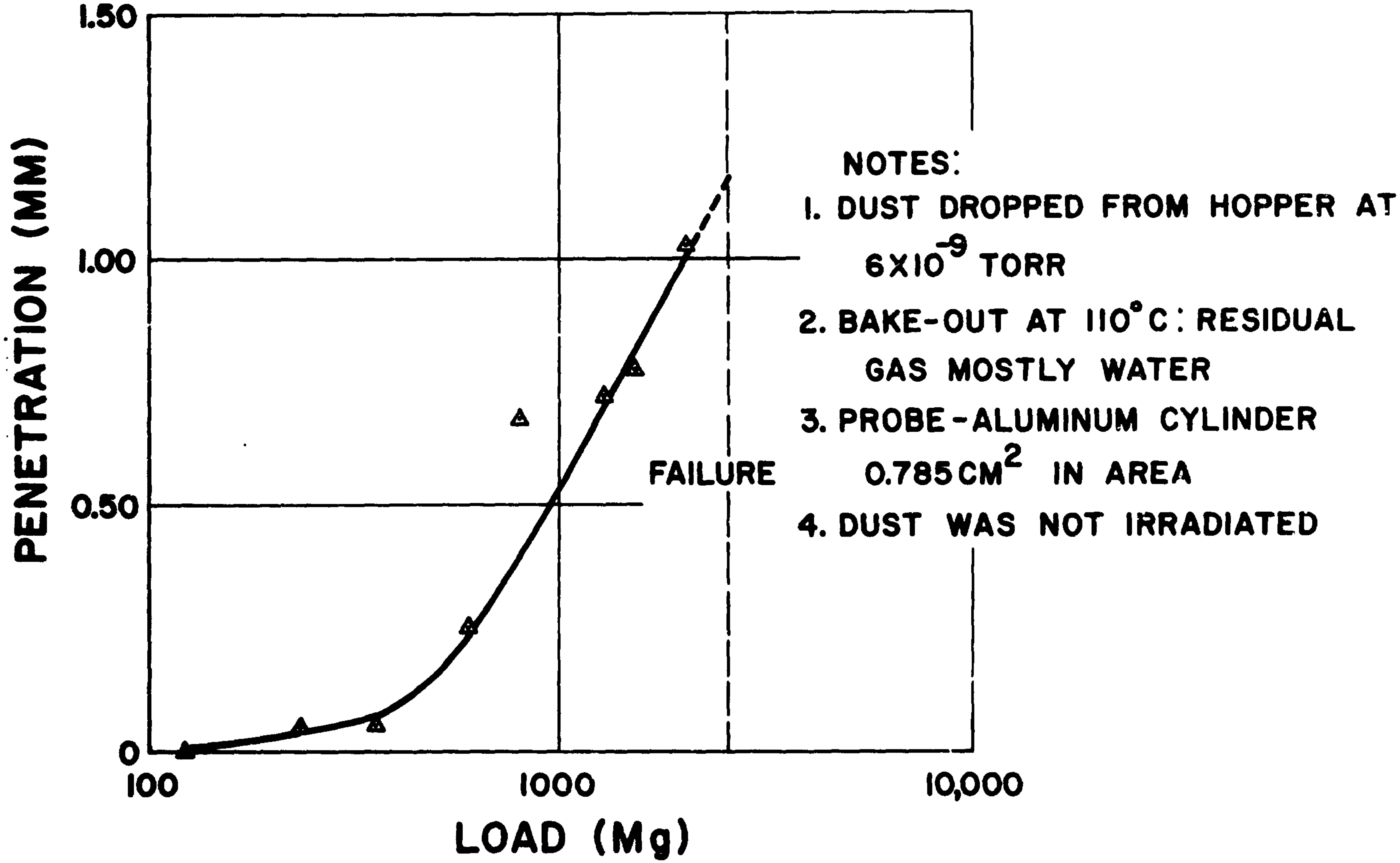


Figure 26. Load-Penetration of Loosely Packed Granodiorite Powder

SAMPLE:

BASALT (MACHINED TO CYLINDRICAL SHAPE)

WEIGHT: 10 g

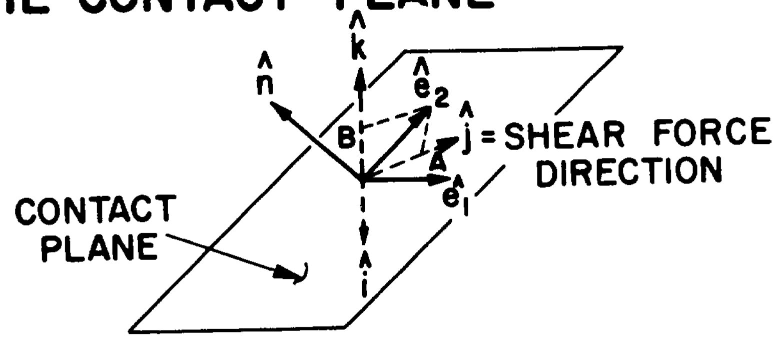
AREA: 0.29 cm^2

CONTACT PRESSURE: 34.5 g/cm^2

TEST RUN	PRESSURE (TORR)	IRRADIATION	ADHESION	COMMENTS
1.	$5 \times 10^{-9} - 1 \times 10^{-11}$	X-RAYS (48 hr)	7.6 g/cm^2	ADHESION FOUND ONLY ON FIRST ATTEMPT.
2.	$2 \times 10^{-9} - 6 \times 10^{-10}$	X-RAYS (48 hr)	$\leq$4.1 g/cm^2	SAMPLE FELL LAST 1/2". CONTACT PRESSURE MAINTAINED FOR 30 MINUTES. WHEN SYSTEM WAS OPENED, DISCOVERED BASALT HAD COLD-WELDED TIGHTLY TO RETAINER RING.

Figure 27. Adhesion of Basalt Samples

GEOMETRY OF THE CONTACT PLANE



$\hat{n}$ = UNIT NORMAL TO CONTACT PLANE $= a\hat{i} + b\hat{j} + c\hat{k}$

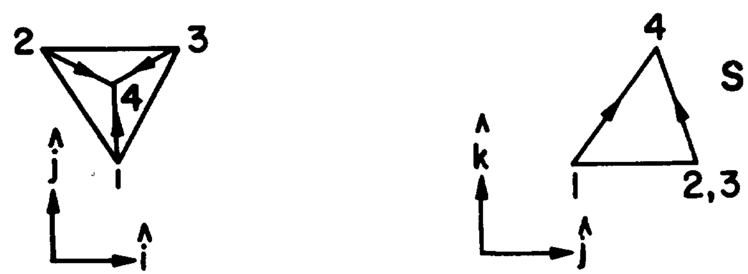
$\hat{j}$ = UNIT NORMAL IN DIRECTION OF SHEAR FORCE

$\hat{e}_1\ \hat{e}_2\ \hat{n}$ AND $\hat{i}\ \hat{j}\ \hat{k}$ ARE ORTHOGONAL SYSTEMS OF UNIT VECTORS

$\hat{e}_2 = A\hat{j} + B\hat{k}$ (LIES IN $\hat{j}-\hat{k}$ PLANE)

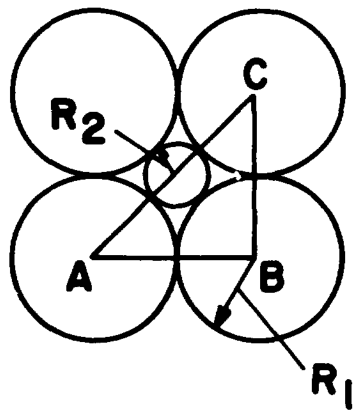
(b) NORMALS TO CONTACT PLANES IN THE HCP UNIT TETRAHEDRON

TOP VIEW

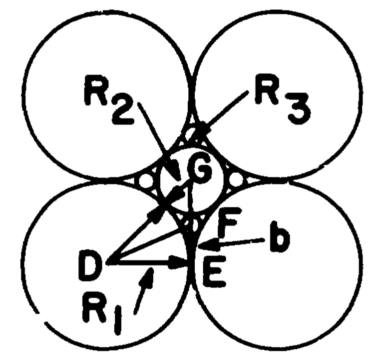


SLIDE VIEW

Figure 28. Direction of Motion under Given Shearing Force



a. TWO SIZES OF SPHERES



b. THREE SIZES OF SPHERES

Figure 29. Diameters of Interstitial Spheres

LUNAR WATER RESOURCES

by

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October 29, 1965

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LUNAR WATER RESOURCES

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Introduction

The most useful resource that man could hope to find on the moon would be a substance from which hydrogen and oxygen could be obtained economically. If hydrogen-fueled rockets such as Saturn are used to launch exploratory expeditions into deep space, the use of the moon as a refueling station would be of greatest importance to the space program. Careful consideration of possible sources of water on the moon, and the collection of experimental data concerning the extraction of water from hydrous minerals or rocks are clearly essential to the overall effort expended in extraterrestrial exploration.

While it is imperative that earth-bound scientists make every effort to utilize all available evidence to predict the physical nature and the chemical and mineralogical composition of the lunar crust before manned landings take place, it is important to emphasize and remain aware of the stringent limitations which are placed upon the accuracy of such estimates. In the absence of any detailed knowledge of selenological processes which might control the composition and distribution of lunar minerals and rocks, and because of travel limitations imposed on the first prospectors of the moon's surface, any program designed to exploit water resources should be flexible and of wide scope, at least in the early stages. The program should consider a wide variety of possible resource materials so that engineering data concerning various extraction processes designed for different materials are readily available when needed.

The value of any given mineral or rock will depend on the probability of finding the substance in the vicinity of the landing area, the abundance of the mineral or rock, the amount of water contained, and the difficulty of extracting this water. In the following sections, these factors will be evaluated. The probability of finding large quantities of crystalline or partly glassy basaltic rocks is fairly high, but the concentration of water in these rocks will be low, and extraction will pose serious engineering problems. Deposits of ice, on the other hand, would yield large quantities of water using simple extractive techniques, but the location and utilization of such deposits could require prospecting in the polar regions.

If the extraction of water from materials readily available in the vicinity of the lunar base proves difficult, then considerable effort may have to be expended in exploration and prospecting. For these reasons, dehydration studies should include a wide range of materials and should be flexible to permit the introduction (new information concerning exploration and extraction.

Possible Sources of Lunar Water

The composition of the surface layers and of the interior of the moon has been the subject of considerable speculation. While the general consensus of opinion favours rocks of basaltic composition, the existence of a variety of minerals and rock types has been argued*.

Because of the relatively low mean density of the moon (S.G. = 3.3, Kopal 1962), the presence of certain morphological features on the lunar surface, the evidence of isotasy (Cameron and O'Keefe 1961), and because there is little reason to believe thatlunar rock should be much different from rock types commonly found on earth, it is thought that the lunar maria possibly comprise basaltic substrata** covered by a layer of silicic ash flows of indetermintate thickness. Lowman (1962) has compared the maria to extensive, terrestrial lopoliths*** such as the Bushveld, Witchita and Duluth intrusives, and has postulated that the marial structures are of basaltic composition and are overlain by rhyolites, granophyres, tuffs and other silicic differentiates. From measurements of reflection coefficients for different regions of the optical spectrum, and from remote measurements of the thermal conducitivity of the materials on the lunar surface, Barabashov and Chekirda (1960) have concluded that the maria are covered with tuffaceous materials, and that the "rays" extending from them are possibly formed of volcanic glasses. Tektites, should they originate at the moon's surface, also indicate a granitic constitution for the outer portion of the lunar crust (O'Keefe and Cameron 1962), but at present, the origin of tektites is controversial****. Finally, the morphology of the moon's surface does not contradict the view that appreciable quantities of volcanic rock types are present.

Briggs (1962) has suggested that the primitive moon possessed an extensive, reducing atmosphere which was slowly lost to space and replaced by a secondary atmosphere of gases which originated in the moon's interior. After

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* Discussion of highly improbable materials such as asphalt residua, postulated to cover the maria after the vaporization of lighter hydrocarbons from petroleum on the moon by Wilson (1962), is not presented.

** Warner (1961) has applied the term "lunarite" to such material.

*** A large-scale igneous intrusvie of concavo-convex lensoidal shape, convex downwards.

**** Taylor and Epstein (1962) have presented oxygen isotopic evidence which indicates an extraterrestrial origin.

10^9 years, Briggs postulates, the atmosphere and hydrosphere escaped from the lunar surface. Had such a hydrosphere existed in the early history of the moon, the maria may be covered with sedimentary rock type ; hydrous minerals, such as the clays, may be present in hydrolysate strata covering the maria substrata (Gilvarry 1960).

The existence of ice on the moon either at the present time or at some time in the moon's history may be argued along several lines of reasoning. The most likely source of water is the interior of the moon, which, if composed of materials similar to those found on earth, may have differentiated so that water chemically bound at one time might have escaped to the surface. According to Rankama and Sahama (1950), the water which is now on the surface of the earth and which appears to have been originally chemically bound below the earth's surface amounts to about 280 kg/cm^2*. In addition, about 6 kg/cm^2 is bound in sediments and sedimentary rocks, and perhaps 50 kg/cm^2 is still within the terrestrial crust above the Mohorovicic discontinuity. Watson et al. (1961) show that if approximately 30 kg/cm^2 of water has been lost to space by dissociation in the atmosphere followed by escape of hydrogen over the span of geological time, and if the earth is well degassed below the crust-mantle boundary the primitive earth would have contained about 370 kg/cm^2, or 0.03% H_2O. The probable concentration of water in the material from which the earth evolved is approximately that observed in chondritic meteorites. If primordial lunar matter had a comparable amount of water, and if differentiation had proceeded to the same extent as that on earth, about 60 kg/cm^2 of water would have been released from the lunar interior.

Hydrous emanations escaping to the surface from lower parts of the moon's interior may hydrate a variety of [illegible]rficial material in the vicinity of fumarolic vents of fissures. Salisbury (1960) has suggested that serpentization of olivine by escaping exhalations may have formed certain lunar domes because of the increase in volume associated with the serpentinization process.

Water may have been derived also from meteoritic sources, but the amount would be exceptionally small compared to that released by a degassing process of the lunar material. Watson et al. (1961) have shown that at the present rate of meteorite bombardment (Brown 1960, 1961), meteorites could have liberated no more than 0.2 gm/cm^2, and this would have been derived largely from the carbonaceous chondrites.

A third possible source of water may be provided by the action of the solar wind on materials of the lunar surface. Oxides and other compounds

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* Expressed as mass of water per unit area of the earth's surface if the hydrosphere were distributed uniformly over the earth.

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have been shown experimentally by Wehner et al. (1963a, 1963b) to become enriched in metal ions after bombardment with simulated solar wind particles. In the process of reduction of the oxides by hydrogen ions, water molecules may be formed. Opik (1962) has suggested that such chemically created water molecules will chiefly sublimate into lunar cold spots, and that glaciers up to 100 m in thickness may have accumulated. Vestine (1958), has shown that, after catchment in permanently shaded cold traps, water in the solid phase may remain for millions of years because of the very low vapor pressure of ice at -150°C.

According to Pohn et al. (1962), about 0.5% of the total lunar surface is in permanent shade. ssuming that the temperatures of the shaded areas are at least as low as -150°C*, and that the lunar atmosphere is so rarified** that molecular transport in the vapor phase can be described purely in terms of particle trajectories, Watson et al. (1961) have constructed a detailed mathematical model to evaluate the importance of escape mechanisms such as ionization, solar wind collision, and gravitational loss. They conclude that if the moon has undergone bulk chemical differentiation as little as $1/1000^{th}$ of that which has taken place on earth, there should be detectable amounts of water in lunar cold traps. Had the moon originally contained about 0.03% H_2O, and had all of this water been released by differentiation, the quantity of water formed by degassing would be 10^4 times the amount of water which would have been lost from the lunar surface over a period of 1 billion years. However, in assessing these ideas, the possibility also has to be considered, that the lunar axis may have changed direction many times as a result of large meteorite impact (Dachille 1962), and that the "permanence" of any shaded areas is only a relative term.

From the arguments presented, it appears that possible sources of water on the moon should include both basaltic and granitic rocks, which may be widespread in large quantities, serpentine and other hydrated minerals which may be localized in the vicinity of fumarolic vents, and water in the solid phase trapped in permanently shaded cold spots in the polar regions.

Rocks

Water concentrations in rhyolitic and basaltic natural glasses are given in Tables 1 and 2. Analyses of perlites, pitchstones and other glasses which contain meteoric water or water from non-juvenile sources are not included. The average water content of crystalline igneous rocks is presented in Table 3. As illustrated by the data of Table 4, most of this water is in biotite and in minerals of the amphibole group. Few igneous

* Shown by Menzel (1923), Pettit and Nicholson (1930) and Sinton (1955) by infrared studies.

** Opik (1955) and others estimate a mean free path of 10^4 km.

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Table 1

Water Content of Terrestial Obsidians (Rhyolitic Glasses)

Location	Wt. % H_2O	Number of Analyses	Reference
New Mexico, U.S.A.	0.28	4	2
	0.27	7	3
California, U.S.A.	0.42	6	2
	0.09	3	1
	0.33	5	3
Yellowstone. Wyoming, U.S.A.	0.12	1	2
	0.12	1	1
	0.12	1	3
Alaska	0.32	1	3
Iceland	0.17	1	2
	0.21	3	3
Ascension Island, South Atlantic	0.20	1	3
New Zealand	0.10	2	2
	0.08	1	3

References:

1 Friedman, Long and Smith (1963)

2 Friedman and Smith (1958)

3 Ross and Smith (1955)

Table 2

Water Content of Basaltic Glasses

From Ross and Smith (1955)

Location	Wt. % H_2O
Basalt (pumice), Hawaii	0
Basalt, beach pellets, from 1950 Mauna Loa flow, Hawaii	1.2
Basalt (Pelee's Hair), Mauna Loa, Hawaii	1.2
Basalt (thread pumice or "reticulite"), Hawaii	3.35
Andesite (pumice), Mexico	4.75

Table 3

Water Content of Terrestial Igneous Rocks*

	SiO_2	H_2O	Number of Analyses
Silicic	68.9	0.6	794
Intermediate (including nepheline types)	54.5	0.8	810
Intermediate (excluding nepheline types)	54.6	0.7	635
Subsilicic (including nepheline types)	48.2	0.8	721
Subsilicic (excluding nepheline types)	48.4	0.7	637
Ultramafic	43.8	0.6	182

* After Nockolds (1954)

Table 4

Hydrous Minerals in Igneous Rocks*

	Biotite Wt. %	Amphibole Wt. %
Granite	5	1
Syenite	2	7
Granodiorite	3	13
Quartz diorite	4	8
Diorite	5	12
Gabbro	1	3
Olivine diabase	---	---
Diabase	1	1
Dunite	---	---

* After Larsen (1942)

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rocks contain more than 1% of chemically bound water, and these rock types* are relatively uncommon constituents of the earth's crust.

Hydrous minerals

A list of the more common hydrous minerals, with their ideal chemical formulae and water contents, is given in Table 5. The chemical composition of most minerals is considerably more complex than the ideal formulae indicate because of isomorphous substitutions such as Fe^{3+} for Al^{3+}, $3Mg^{2+}$ for $2Al^{3+}$, $2Al^{3+}$ for $Mg^{2+}Si^{4+}$, Fe^{2+} for Mg^{2+}, Na^{+} for K^{+}, and (what is particularly important in the present connection) F^{-} for $(OH)^{-}$. In consequence, the percentage of H_2O in a mineral is variable, sometimes within wide limits, as the data in Table 5 indicate.

Water from minerals is obtained mainly from hydroxyl ions, and its liberation requires a certain amount of energy, for example in the form of heat. The precise mechanism by which molecular water is formed from (OH) ions may not be the same for all minerals; possible reactions are:

(a) Direct interaction of hydroxyls:

$$(OH)^{-} + (OH)^{-} \rightarrow O^{2} + H_2O$$

(b) Proton migration to favorable reaction sites:

$$H^{+} + (OH)^{-} \rightarrow H_2O$$

(c) A combined oxidation and dehydration reaction:

$$2Fe^{2+} + 1/2\ O_{2(g)} + 2(OH)^{-} \rightarrow 2Fe^{3+} + 2O^{2-} + H_2O$$

(d) Reaction of oxygen ions in the mineral with high energy protons:

$$2H^{+} + O^{2-} \rightarrow H_2O$$

Mechanisms (a) to (c) may be activated by heating, whereas in mechanism (d), water is created by bombardment of silicate and oxide minerals with high energy protons. The latter process may take place on the moon as a result of solar wind bombardment (Wehner et al. 1963).

In addition to the minerals listed in Table 5, many other minerals contain hydroxyl ions as essential constituents. Being less common in terrestrial rocks, they can be expected to be similarly rare in lunar rocks and will not be considered further. Molecular water exists in some crystals, e.g. gypsum ($Ca_2SO_4.2H_2O$), but being less strongly bonded than hydroxyl ions, this water is released at lower temperatures and may be lost under low pressure conditions. It is unlikely that such minerals can be expected to contribute appreciably, if at all, to a lunar supply of water.

* For example: Glenmuirite (3.59%), teschenite (3.55%), bekinkinite (3.34%). See Nockolds (1954).

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Table 5

Ideal Formulae and Water Contents of Important Hydrous Minerals

Mineral	Ideal Formula	Water Content (Wt. %)
Muscovite	$KAl_2(Si_3Al)O_{10}(OH)_2$	4.2 - 4.7
Phlogophite	$KMg_3(Si_3Al)O_{10}(OH,F)_2$	1 - 4.5
Biotite	$K(Mg,Fe)_3(Si_3Al)O_{10}(OH,F)_2$	0.5 - 4.5 generally 2-3
Talc	$Mg_3Si_4O_{10}(OH)_2$	4.5 - 5.5
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	approximately 5
Chlorites	$(Mg,Al,Fe)_6(Si,Al)_4O_{10}(OH)_8$	9 -13
Serpentine	$Mg_3Si_2O_5(OH)_4$	12 -14
Kaolinite, (dickite, etc.)	$Al_2Si_2O_5(OH)_4$	13.5 -14
Hornblende	$(Ca,Na,K)_{2-3}(Mg,Fe,Al)_5$- $(Si,Al)_8O_{22}(OH,F)_2$	1.5 - 2.2
Basaltic hornblende	high ferric iron, low hydroxyl contents	less than 1

Thermodynamics of Water Evolution from Minerals

Thermodynamic data concerning the dehydration of water-bearing minerals are of considerable importance in the design of water extraction techniques. Pressure-temperature (P-T) stability relationships of the hydrous minerals have been determined by experimental hydrothermal studies, and in some cases, from thermochemical data*. Since the free energy of the reactants and products is equal at equilibrium at a given temperature and pressure, i.e.

$$(F_{M(OH)_2} = F_{MO} + F_{H_2O})_{T,P}$$

for the reaction: $M(OH)_2\ (s) \rightarrow MO(s) + H_2O$ (fluid), the equilibrium curve can be calculated provided entropy and heat content data are available for each phase over the temperature-pressure range of interest. Despite considerable attention given to some systems, such as $MgO-H_2O$ (Fig. 1), experimentally determined curves differ among themselves, and also from those derived from thermodynamic computations. Extrapolation of these curves to much lower values of P_{H_2O} involves considerable uncertainties. A procedure for this extrapolation has been recommended by Majumdar and Roy (1964) on the basis of an analysis of the various uncertainties.

Even if hydration-dehydration (P-T) curves could be reliably extrapolated to low temperatures and low water vapor pressures, they still could not be used to predict the dehydration temperature of a given hydrous mineral at a specified low P_{H_2O}; dehydration reactions at low temperatures are extremely slow, and metastable states can persist far above the temperature at which dehydroxylation would be expected on the basis of high pressure equilibrium curves extrapolated to lower pressures.

Possible stability relationships are illustrated schematically in Figure 2. Mineral A is the stable phase to the left of Curve I, and mineral B and water constitute the stable assemblage to the right of this line. If the temperature of A is raised slowly from M to N, the reaction $A \rightarrow B + H_2O$ will take place at point O. The rate of the reaction involves other considerations (see later).

If the temperature of A is raised from S to T at a lower pressure, it might be expected that dehydration of phase A would begin at point P on the extrapolated extension of curve I. For many hydrous minerals, however, the reaction rates are too slow in low P-T regions to permit detectable changes in A. Even under conditions of geological time, such reactions may not take place. The hydrous mineral may persist metastably in the P-T region where B and H_2O are the thermodynamically stable phases. At a higher temperature, sufficient energy becomes available to effect dehydration at point Q on curve II. In some cases, the products (C + water) derived from

* For example, the equilibrium curve for the brucite-periclase reaction (MacDonald 1955).

the dehydration of the metastable phase, A_m, will differ from those (B + water) derived from dehydration of the stable phase, A_s. Although P-T curves of type I are available for all of the common hydrous minerals within a certain pressure and temperature region (see Fig. 3), curves of Type II are generally unavailable, and are at present under investigation by the authors.

As an example of the foregoing general remarks, kaolinite may be considered. This mineral can be heated at atmospheric pressure to well over a hundred degrees C. above the dehydration temperature predicted by extrapolation of the stability curve obtained by Roy and Osborn (1954) before detectable amounts of water vapor appear. At low temperatures (300-500°C), the thermal energy is insufficient to permit the major structural reorganization of kaolinite to hydralsite + water.

The fact that water under high pressures exerts a remarkable catalytic effect in solid state transformations has been demonstrated in this laboratory by Roy, Roy and Osborn (1950), and by Hill, Roy and Osborn (1951). The mechanism of the action of water is still uncertain; probably, a combination of the influence of protons on ionic mobility, and the solvent properties of water is involved. In these solid-vapor reactions, water at moderate pressures facilitates the structural changes involved at very low temperatures. It is important to emphasize that the dehydration of the metastable phase always occurs at a higher temperature; this is illustrated in Fig. 4 using data for curve I from Roy and Osborn (1954) and for curve II from Ellis and Mortland (1962).

The heat of reaction, ΔH, required to dehydroxylate a hydrous mineral may be, in principle, calculated from the Clausius-Clapeyron equation,

$$\frac{dP}{dT} = \frac{\Delta S}{\Delta V} = \frac{\Delta H}{T\Delta V}$$

, or its integrated form combined with the ideal gas laws,

$$\ln \left(\frac{P_2}{P_1}\right) = \frac{\Delta H}{R} \left(\frac{T_2 - T_1}{T_1 T_2} \right)$$

, using data from the P-T curve, or it may be determined experimentally by a variety of thermochemical techniques. Since ΔH calculated from the Clausius-Clapeyron equation is proportional to the slope of the P-T curve, appreciable errors in ΔH will arise if the slope of the curve approaches that of the pressure axis. Such is the case for curve I of Figure 4 which is nearly vertical.

Heats of reaction determined by differential thermal analysis, for example, may depend on the grain size of the materials, and the gross physical nature of the product, since this influences the thermal diffusivity of the sample which in turn affects the area of the DTA peak. ΔH for the dehydration of kaolinite to metakaolinite (metastable reaction, curve II, Figure 4) whose structure may vary from that of kaolinite-less-water to that of a nearly amorphous solid depending upon the reaction rate will not necessarily be identical with ΔH for the dehydration of kaolinite to hydralsite (stable reaction, curve I, Figure 4).

Attention is called to these facts in order to emphasize the uncertainties in some of the presently available data concerning such fundamentally important parameters as the enthalpy of the reactions discussed in this chapter. The relationship between dehydration temperatures and pressures, ΔH values, grain size, and chemical compositions of the reactants are presently the subject of investigation by the authors using differential thermal analysis at water vapor pressures ranging from essentially zero to 20,000 psi, and using thermogravimetric methods at low water vapor pressures.

Kinetics and Mechanisms of Water Evolution from Minerals

The dehydration (dehydroxylation) of a mineral is a complicated function of many variables, including structures and composition of the mineral, time, temperature, pressure, which involves both the total ambient pressure and also particularly the water vapor pressure, size and shape functions for the particles composing a sample and also for the sample as a whole. Within the present context, one can make only a brief survey of each of these variables.

Structure and Composition

When dehydration is performed at low partial pressures of water and/or a total pressure of one atmosphere under conditions of steadily rising temperature, a more or less sharp weight loss is observed within a range of temperature which varies with the composition and structure of the mineral, and with the other factors mentioned in the preceding paragraph. Figure 5 shows data obtained with muscovite in the form of flakes several mm. in size, and when ground to powders of various particles sizes. Evidently one cannot discuss fully the loss of water in relation to time and temperature without considering also the other factors which have been mentioned.

The influence of structure and composition on the dehydration of macrocrystalline samples of a few of the layer silicates listed in Table 5 is shown by the data in Table 6 taken from a study by Kieffer (1949). These data and those discussed later in this section pertain to the metastable dehydration reactions (see preceding section above) since these are the only reactions for which kinetic data are presently available. The trioctahedral minerals (phlogopite, talc, and serpentine) lose water at higher temperatures than the corresponding dioctahedral minerals (muscovite, pyrophyllite, and kaolinite). The 2:1 minerals in both groups lose water at higher temperatures than the 1:1 minerals.

Crystal size also may be an important parameter (cf. Kieffer, 1951), but the extent to which this variable can be studied varies with different minerals. The micas, talc and pyrophyllite can be obtained as both fine-grained and coarse-grained materials, but kaolinite and serpentine occur normally as micron-sized crystals.

The steep rise in the thermogravimetric (TG) curve of a mineral,

Table 6

Dehydration Temperatures, °C for Some Layer Silicates (after C. Kieffer, 1949); $dT/dt = 100°/hr$.

Structure Type		T_1	T_2-T_3	T_4		T_1	T_2-T_3	T_4
2:1	Muscovite	765	785-905	940	Phlogophite	1120	1140-1210	1230
2:1	Pyrophyllite	640	690-780	850	Talc	900	925-1010	1030
1:1	Kaolinite	430	490-570	730	Serpentine	590	665- 750	800

T_1, beginning of dehydration; T_2-T_3, range of rapid reaction; T_4, end of dehydration.

resulting from loss of water, corresponds to the endothermic peak recorded in differential thermal analysis (DTA). By and large, sharp rises in TG curves correspond with sharp peaks in DTA curves, and gradual deflections with broad peaks, i.e., of low kurtosis. Data similar to those given in Table 6 can be obtained from DTA studies, but to obtain comparable temperature results, comparable experimental conditions are required. It is not possible to give fixed or constant reaction temperatures for a mineral except with reference to all the physical conditions involved.

Nevertheless, TG and DTA curves are always useful in showing the temperature ranges in which reactions are likely to occur, provided their limitations are clearly appreciated.

Time dependence

By studying dehydration as a function of time at constant temperature and (hopefully) at constant pressure, one aspires to obtain a kinetic curve which can be interpreted in terms of a theoretical model, and which will lead to the determination of a significant rate constant. There exists a considerable literature on the kinetics of solid-vapor reactions and further information can be obtained from books edited by Garner (1955) and by DeBoer (1961).

The simplest kinetic model is one in which the rate of reaction is proportional to the fraction of unreacted material. If α is the fraction reacted at time t, then

$$d\alpha/dt = k(1-\alpha)$$

and

$$\ln(1-\alpha) = kt \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This model is valid for a powder consisting of uniform sized particles sufficiently small so that, once nucleated, a particle can be considered to react in a time which is small compared with the total reaction time. The reaction kinetics then depend on the probability of nucleation of a particle or on the fraction of unreacted particles. Kaolinite dehydrated under normal atmosphere conditions appears to follow this kind of relation for about 80-90% of the full reaction, (See Murray and White, 1949, 1955; Brindley and Nakahira, 1958).

A second model is one in which reaction proceeds by movement of a reaction interface with constant velocity u. The analysis is simplified if surface nucleation is assumed to take place rapidly, so that each particle develops a reaction interface, and if all particles have the same size and shape.

For crystals in the form of thin discs of thickness 2r, the reaction equation is

$$\alpha = (u/r)t \quad \ldots\ldots\ldots\ldots\ldots\ldots (2a)$$

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Table 7

Activation Energy (Kcal/mole) for Dehydration of Kaolinite Obtained by Various Investigators

Investigators	Conditions of Measurements	Activation Energy Kcal/mole
Allison (1954)	D.T.A.	55
Murray and White (1955)	Isothermal weight loss curves, 497°C < T < 537°C	44.83
Sabatier (1955)	Isothermal weight loss curves	44
Jacobs (1958)	Dynamic T.G.A.	37.80
Brindley and Nakahira (1958)	Data on pressed discs, with extrapolation to infinitely thin disc 475°C < T < 520°C	65
Holt, Cutler and Wadsworth (1962)	$p \sim 10^{-3}$ mm Hg 360°C < T ≤ 440°C	43.5
Toussaint, Fripiat and Gastuche (1963)	$p \sim 4.3$ mm Hg of H_2O vapor 403°C < T < 431°C	25

For circular discs of radius r which react from the rim inwards, the equation becomes

$$1 - \sqrt{1-\alpha} = (u/r)t \qquad (2b)$$

For spheres of radius r and cubes of edge 2r, the corresponding equation is

$$1 - \sqrt[3]{1-\alpha} = (u/r)t \qquad (2c)$$

A generalized form of these equations is

$$1 - \sqrt[n]{1-\alpha} = (u/t)t \qquad (2)$$

with n = 1, 2, 3. More complex relations arise for solids which cannot be defined in terms of a single size parameter such as rectangular block particles, and in situations where the reaction front moves with unequal velocities in different directions. Anderson and Horlock (1962) consider that brucite, $Mg(OH)_2$, dehydrates according to a model of this kind.

A third model assumes that the reaction is controlled by a diffusion process. The simplest basis for calculation is a diffusion equation of the type

$$dn/dt = - D(dc/dl)$$

where n is the number of diffusing species per unit area of interface per unit time, dc/dl is a concentration gradient, and D is a diffusion constant. If the concentration gradient is assumed constant through the reaction layer, and if D can be treated as a constant, then the reaction equation for a spherical particle of radius r takes the form

$$\left[1 - \sqrt[3]{1-\alpha}\right]^2 = k_1 t/r^2 \qquad (3a)$$

If, however, one substitutes the more realistic assumption of a constant flux of diffusing species through the reaction product, then the equation takes the form

$$(1-2\alpha/3) - \sqrt[3]{(1-\alpha)^2} = k_2 t/r^2 \qquad (3b)$$

Equation (3a) was derived by Jander (1927) and equation (3b) by Ginstling and Brounshtein (1950) and independently by Moriya and Sakaino (1955). A further refinement made by Carter (1961a,b) takes account of a volume change between parent and product material. Holt, Cutler and Wadsworth (1962) have shown that at low water vapor pressures, kaolinite dehydration appears to be a diffusion-controlled reaction.

In practice, it is often difficult to differentiate between these and other possible interpretations. The major experimental difficulty lies with the necessity of obtaining particles of strictly uniform size and shape. The mere separation into a size fraction between two sieve sizes is probably insufifficient, as Carter (1961) has emphasized. Therefore in many experiments it may be necessary to assume a model and derive an effective rate constant as a measure of the α-t relationship, without obtaining conclusive proof that the model is correct.

Temperature dependence

The temperature dependence of the rate of a dehydration reaction is usually represented by an Arrhenius-type expression,

$$k = Ae^{-b/T}$$

where K is the rate constant at temperature T, and A, b are constants to be determined. If, as is usually done, the constant b is set equal to $\Delta E/R$, the activation energy (strictly the free energy) ΔE can be evaluated. The temperature range in which these measurements can be made is usually small, from about T_1 to a little beyond T_2 as defined in Table 6. The reaction rate should not be so great as to cause a self-cooling of the sample. The dependence of ΔE, and indeed of the reaction process itself, on the ambient water vapor pressure is considered later.

Wide variations are found in the literature for the value of the energy, ΔE, for dehydration of a particular mineral. Table 7 lists data for kaolinite which range from 25 to 65 kcal/mol. These variations doubtless reflect in part the sensitivity of the process to the particular conditions used experimentally, and in part to the manner in which the rate constant has been obtained.

Pressure dependence

The pressure dependence of mineral dehydration reactions is even less well understood than the time and temperature dependence. In the first place, as Toussaint et al. (1963) have clearly indicated, a distinction must be drawn between the role of vapor pressure within the interstices of a reacting powder mass, and the inherent effect of water vapor pressure on the reactions within crystalline particles.

The first effect was studied by Brindley and Nakahira (1958) who showed that the rate constant for dehydration of kaolinite under atmospheric pressures, as derived from the exponential formula (1) which fits most of the reaction curve, varies enormously with the size and packing of the sample. Considerable variations in the rate constant for a given reaction temperature were observed when discs ranging from about 0.5 to 2 mm. in thickness, made from compressed kaolinite powders, were used. (See Figure 6). When a larger sample of kaolinite, a disc about 5 mm. thick, was dehydrated to the extent of an overall reaction $\alpha \simeq 50\%$, the exterior powder was almost 100% dehydrated and the interior powder no more than about 20% dehydrated. These effects were attributed to a build-up of water vapor pressure within the powder interstices which greatly retarded the rate of reaction.

From the standpoint of developing lunar water resources by dehydration of coarse-grained mineral matter with particles of mm. size or larger, one has to take cognizance of the rate retarding effect of an ambient water vapor pressure provided by the process itself.

At low total pressures, there have been relatively few investigations. In the work of Toussaint et al. the effect of the self-created P_{H_2O} was reduced by using thin specimens, relatively low reaction tempera-tures, and a low pressure system. Under these conditions, they obtained the value of 25 kcal/mol at a pressure near 4.3 mm. Hg (see Table 7) for the activation energy for kaolinite dehydration. A second investigation in the low pressure range, also on kaolinite, was carried out by Holt, Cutler and Wadsworth (1962) who showed that at pressures less than about 4.5 mm. Hg the reaction was diffusion controlled, with an activation energy of 43.5 kcal/mol for dehydration at a pressure of 10^{-4} cm. Hg. The rate diminished with increase of vapor pressure and, at about 4.5 mm. Hg, the reaction changed to first-order kinetics (the exponential relation (1)). This pressure limit is near that used by Toussaint et al.

The reduced rate of dehydration under conditions where a water vapor pressure develops in the neighborhood of the dehydrating surfaces is considered to arise from adsorbed water layers on the surfaces. By covering part of the crystalline surface, the water layers may reduce the dehydration rate both by diminishing the free surface and also by creating a diffusion barrier. Further work is required in this area.

Dependence on size and shape functions of particles, and overall packing

These geometrical variables play a major role in the overall rate of loss of water from hydrous minerals. Both the size and the shape of an individual particle enters fundamentally into the equation expressing the fraction of the particle reacted as a function of time under given T, conditions. The distribution functions for size and shape variations or particles in a powder mass make it nearly impossible to study the α,T, relations unless (i) the powder has been subdivided into extremely well-defined fractions, or (ii) the work is conducted on single crystals. In any case, one is left with the 'practical' problem of achieving 'useful' data for less precisely defined powder masses.

In addition to these considerations, it now seems highly probable that any investigations of dehydration kinetics under normal atmospheric conditions may have little direct relevance to the rate of reactions under low pressure conditions, such as will be found in lunar environments, because of the retarding effect of ambient water vapor atmospheres.

Investigations currently in progress by the writers are directed towards ascertaining information on the dehydration rates of hydrous mineral powders under various atmosphere conditions, and particularly various water vapor pressures.

Conclusion

At the present time, two severe limitations are imposed on the design of a program to utilize lunar materials for provision of a water supply for bases on the moon: (1) valid information concerning the chemical composition and distribution of minerals on the lunar surface is not yet available, and (2) pressure and temperature conditions to be expected on the moon are such that most of the available data on the thermodynamics and kinetics of water evolution from minerals are not directly applicable to lunar surface environments.

The authors are concurrently engaged in a program of experimental work involving the physics and chemistry of water evolution from minerals at low pressures, so that in the near future, much of the desired information in item (2) will be made available.

REFERENCES

Allison, E. B. (1954) The determination of specific heats and heats of reaction of clay minerals by thermal analysis: Silicates Industrials, V. 19, 363-373.

Anderson, P. J. and R. F. Horlock (1962) The thermal decomposition of magnesium hydroxide: Trans. Faraday Soc., V. 58, 1993.

Barabashov, N. P. and A. T. Chekirda (1960) A study of the rocks most closely resembling the surface constituents of the moon: Soviet Astronomy, V. 3, 827-831.

Briggs, M. H. (1962) The chemistry of the lunar surface: J. of the British Interplanetary Society, V. 18, 386-389.

Brindley, G. W. and M. Nakahira (1957) Kinetics of dehydroxylation of kaolinite and halloysite. J. Am. Ceram. Soc., V. 40, 346-350.

Brindley, G. W. and M. Nakahira (1958) A kinetic study of the dehydroxylation of kaolinite: Proc. Fifth National Conf. on Clays and Clay Minerals, Nat. Acad. Sci. - Nat. Res. Council, publication 566, 266-278.

Brindley, G. W., H. Takeshi and Sally A. Wentworth (1963) Am. Petrol. Inst., Project 55; Seventh Annual Report 1962-63. Tech. Report No. 1, 18 pages.

Brown, H. (1960) The density and mass distribution of meteoritic bodies in the neighborhood of the earth's orbit: J. Geophys. Res., V. 65, 1679-1683.

Brown, H. (1961) The density and mass distribution of meteoritic bodies in the neighborhood of the earth's orbit: J. Geophys. Res., V. 66, 1316-1317.

Cameron, A. G. W. and J. A. O'Keefe (1961) Evidence of isotasy and differentiation on the moon: Astronomical Jour., V. 66, 280.

Carter, R. E. (1961a) Kinetic model for solid-state reactions: J. Chem. Phys., V. 34, 2010-2015.

Carter, R. E. (1961b) Kinetic model for solid-state reactions: J. Chem. Phys., V. 35, 1137-1138.

Dachille, F. (1962) Interactions of the earth with very large meteorites: South Carolina Acad. Sci. Bull., V. 24, 16-34.

DeBoer, J. H., et al., Editors (1961) Reactivity of solids: Elsevier, Amsterdam.

Duval, C. (1963) Inorganic thermogravimetric analysis: Elsevier, Amsterdam.

Ellis, B. G. and M. M. Mortland (1962) A comparison of two methods of determining heats of reaction by differential thermal analysis: Amer. Mineral., V. 47, 371-378.

Friedman, I. and R. L. Smith (1958) Deuterium content of water in some volcanic glasses: Geochim. et Cosmochim. Acta, V. 15, 218-228.

Friedman, I., W. Long and R. L. Smith (1963) Viscosity and water content of rhyolite glass: J. Geophys. Res., V. 68, 6523-6535.

Garner, W. E., Editor (1955) Chemistry of the solid state: Butterworth, London.

Gilvarry, J. J. (1960) Origin and nature of lunar surface features: Nature, V. 188, 886-890.

Ginstling, A. M. and B. I. Brounshtein (1950) The diffusion kinetics of reactions in spherical particles: J. Appl. Chem. (U.S.S.R.), V. 23, 1249-60, (English translation 1327-38).

Hill, V. G., R. Roy and E. F. Osborn (1951) The system alumina-gallia-water: Pennsylvania State College, School of Mineral Industries, Technical Report No. 4, Contract N6 ONR-26909, 21 pages.

Holt, J. B. I. B. Cutler and M. E. Wadsworth (1962) Rate of thermal dehydration of kaolinite in vacuum: J. Am. Ceram. Soc., V. 45, 133-136.

Jacobs, T. (1958) Kinetics of the thermal dehydration of kaolinite: Nature, V. 182, 1086-1087.

Jander, W. (1927) Reactions in the solid state at high temperature. I. Rate of reaction for an endothermic change: Z. anorg. allgem. chem., V. 163, 1.

Kieffer, C. (1949) Déshydration thermique des minéraux phylliteux: Comptes. Rendus., V. 229, 1021.

Kieffer, C. (1951) Thése (Paris), Contribution á l'etude de la stabilité et de la classification des mineraux phylliteux.

Kopal, Z. (1962) Internal structure of the moon: Paper presented at the Lunar Missions Meeting, American Rocket Society, Cleveland, Ohio, July 17-19, 1962, The Internal Constitution of the Moon. Planetary and Space Science, V. 9, 625-638.

Larsen, E. S. (1942) Handbook of physical constants.

Lowman, P. D., Jr. (1962) The relation of tektites to lunar igneous activity: J. Geophys. Res., V. 67, p. 1646.

MacDonald, G. J. F. (1955) Gibbs free energy of water at elevated temperatures and pressures with applications to the brucite-periclase equilibrium: J. Geol., V. 63, 244-252.

Majumdar, A. J. and Rustum Roy (in press) A comparison of the relative merits of thermochemical measurements and calculations as opposed to direct experimental determination of solid-vapor equilibria.

Menzel, D. H. (1923) Water-cell transmissions and planetary temperatures: Astrophys. Jour., V. 58, 65-74.

Moriya, T. and T. Sakaino (1955) On the rate of solid reaction in the Na_2CO_3-SiO_2 system: Bull. Tokyo Inst. Tech., B2, 13-46.

Murray, P. and J. White (1949) The kinetics of clay decomposition: Clay Min. Bull., V. 1, 84-87.

Murray, P. and J. White (1955) Kinetics of the thermal dehydration of clays, parts 1-4: Trans. Brit. Ceram. Soc., V. 54, 137-204.

Nockolds, S. R. (1954) Average chemical composition of some igneous rocks: Bull. Geol. Soc. Am., V. 65, 1007-1032.

O'Keef, J. A. and W. S. Cameron (1962) Evidence from the moon's surface features for the production of lunar granites: Icarus, V. 1, 271-285.

Opik, E. J. (1955) The density of the lunar atmosphere: Irish Astron. Jour., V. 3, 137-143.

Opik, E. J. (1962) The lunar atmosphere: Planetary and Space Science, V. 9, 211-244.

Pettit, E. and S. B. Nicholson (1930) Lunar radiation and temperatures: Astrophys. Jour., V. 71, 102-135.

Pohn, H., B. C. Murray and H. Brown (1962) New applications of lunar shadow studies: Publications of the Astronomical Scoeity of the Pacific, V. 74, 93-105.

Rankama, K. and Th. G. Sahama (1950) Geochemistry: University of Chicago Press.

Ross, C. and R. L. Smith (1955) Water and other volatiles in volcanic glasses: Amer. Mineral., V. 40, 1071-1089.

Roy, R., D. M. Roy and E. F. Osborn (1950) Compositional and stability relationships among the lithium alumino-silicates; eucryptite, spodumene, and petalite: Am. Ceram. Soc. Jour., V. 33, 152-159.

Roy, R. and E. F. Osborn (1954) The system Al_2O_3-SiO_2-H_2O: Amer. Mineral., V. 39, 853-885.

Sabatier, G. (1955) Kinetics of the dehydration of several silicates: J. Chem. Phys., V. 52, 60-64.

Salisbury, J. W. (1960) Origin of lunar domes: Proc. of the Lunar and Planetary Exploration Colloquium, V. 2, 22-26.

Sinton, W. (1955) Observations of solar and lunar radiation at 1.5 millimeters: J. Opt. Soc. Am., V. 45, 975-979.

Taylor, H. P., Jr. and S. Epstein (1962) Oxygen isotope studies on the origin of tektites: Jour. Geophys. Res., V. 67, 4485-4490.

Toussaint, F., J. J. Fripiat and M. C. Gastuche (1963) Dehydroxylation of kaolinite. I. Kinetics: J. Phys. Chem., V. 67, 26-30.

Vestine, E. H. (1958) Evolution and nature of the lunar atmosphere: Rand Research Memo RM-2106.

Warner, B. (1961) The nature of the surfaces of the lunar maria: Publications of the Astronomical Society of the Pacific, V. 73, 349-350.

Watson, K., B. Murray and H. Brown (1961) On the possible presence of ice on the moon: J. Geophys. Res., V. 66, 1598-1600; The behavior of volatiles on the lunar surface: J. Geophys. Res., V. 66, 3033-3045.

Wehner, G. K., C. Kenknight and D. L. Rosenberg (1963a) Sputtering rates under solar-wind bombardment: Planetary and Space Science, V. 11, 885-895.

Wehner, G. K., C. Kenknight and D. L. Rosenberg (1963b) Modification of the lunar surface by the solar-wind bombardment: Planetary and Space Science, V. 11, 1257-1261.

Wilson, A. T. (1962) Origin of petroleum and the composition of the lunar maria: Nature, V. 195, 11-13.

CAPTIONS FOR FIGURES

Figure 1

Comparison of published P-T curves for the brucite ⇌ periclase + water reaction.

Figure 2

Dehydration of hydrous minerals in the stable and metastable states.

Figure 3

P-T dehydration curves for many of the important rock-forming, hydrous minerals.

Figure 4

P-T curves for the stable and metastable dehydration of kaolinite. Metastable decomposition of kaolinite (curve II, Ellis and Mortland 1962) will take place at a higher temperature than decomposition of the stable phase (curve I, Roy and Osborn 1954) at higher water vapor pressures.

Figure 5

Thermogravimetric curves for muscovite from a New Hampshire pegmatite. Weight loss as percentage of total weight, versus temperature °C. Curves Correspond to

(a) Single flake of muscovite, about 1 cm in size.

(b) Several thinner flakes, about 0.5 cm in size.

(c) -200 mesh filed powder.

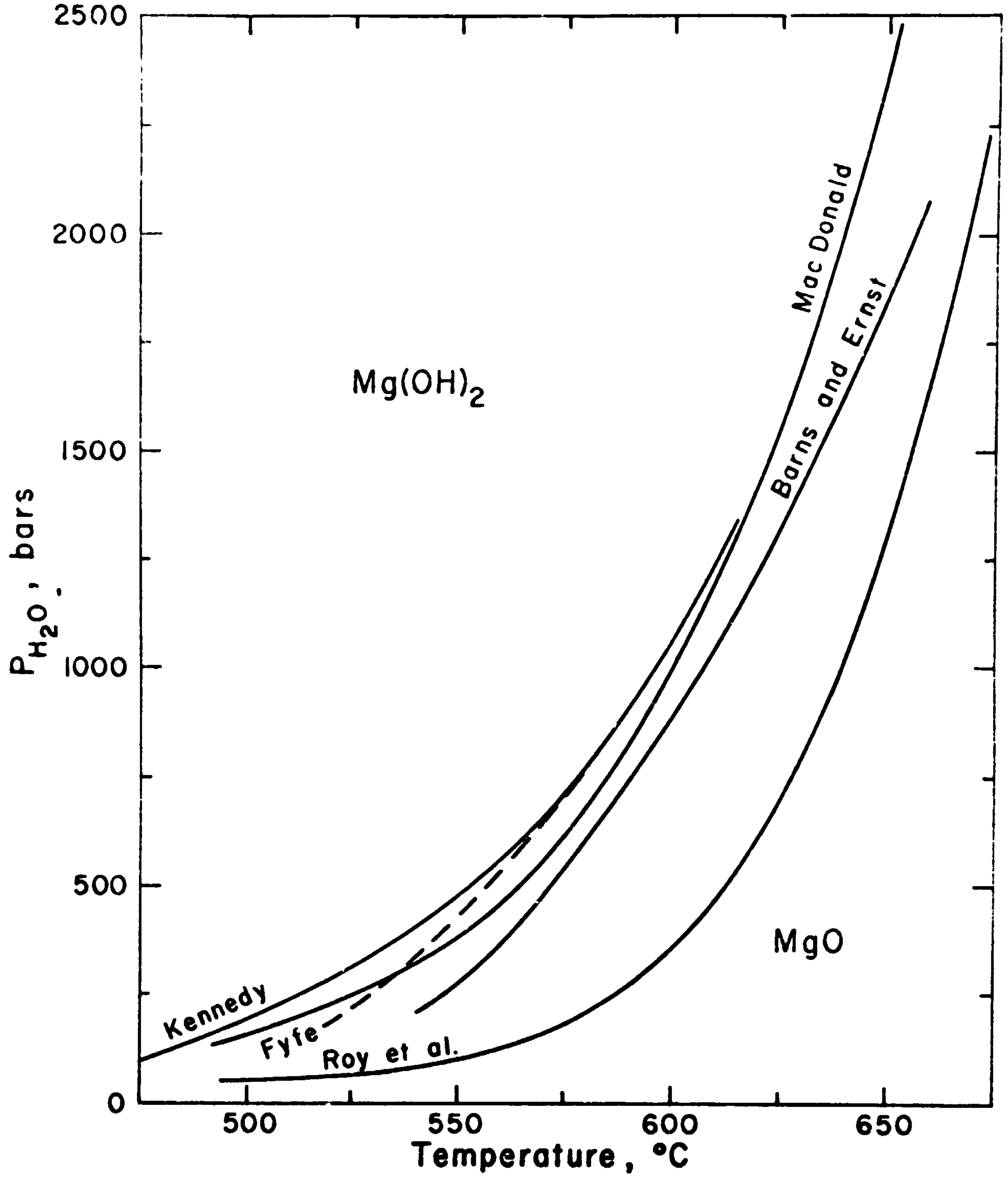
(d) 100-200 mesh powder ground under water.

(e) -325 mesh powder ground under water.

(Data by G.W. Brindley, H. Takeshi and Sally A. Wentworth 1963).

Figure 6

Dehydration of pressed discs of kaolinite at a constant temperature of 497°C. Thickness of discs as follows: (a) 0.38 mm, (b) 0.83 mm, (c) 1.55 mm, (d) 2.68 mm. (From G.W. Brindley and M. Nakahira 1957).



2500
2000
1500
1000
500
0
500
550
600
650
P_{H_2O}, bars
Temperature, °C
$Mg(OH)_2$
MgO
Mac Donald
Barns and Ernst
Kennedy
Fyfe
Roy et al.

Figure 1

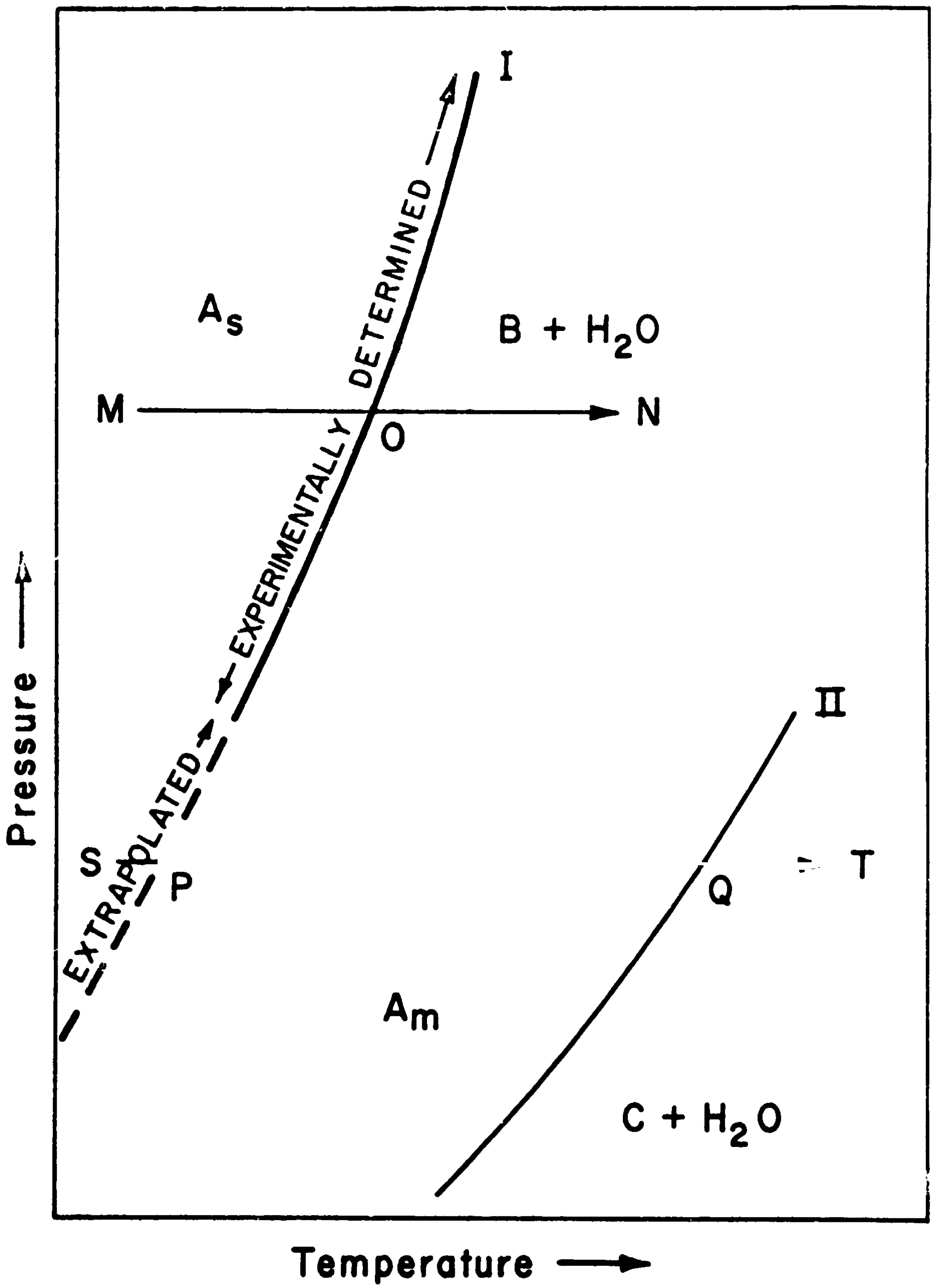
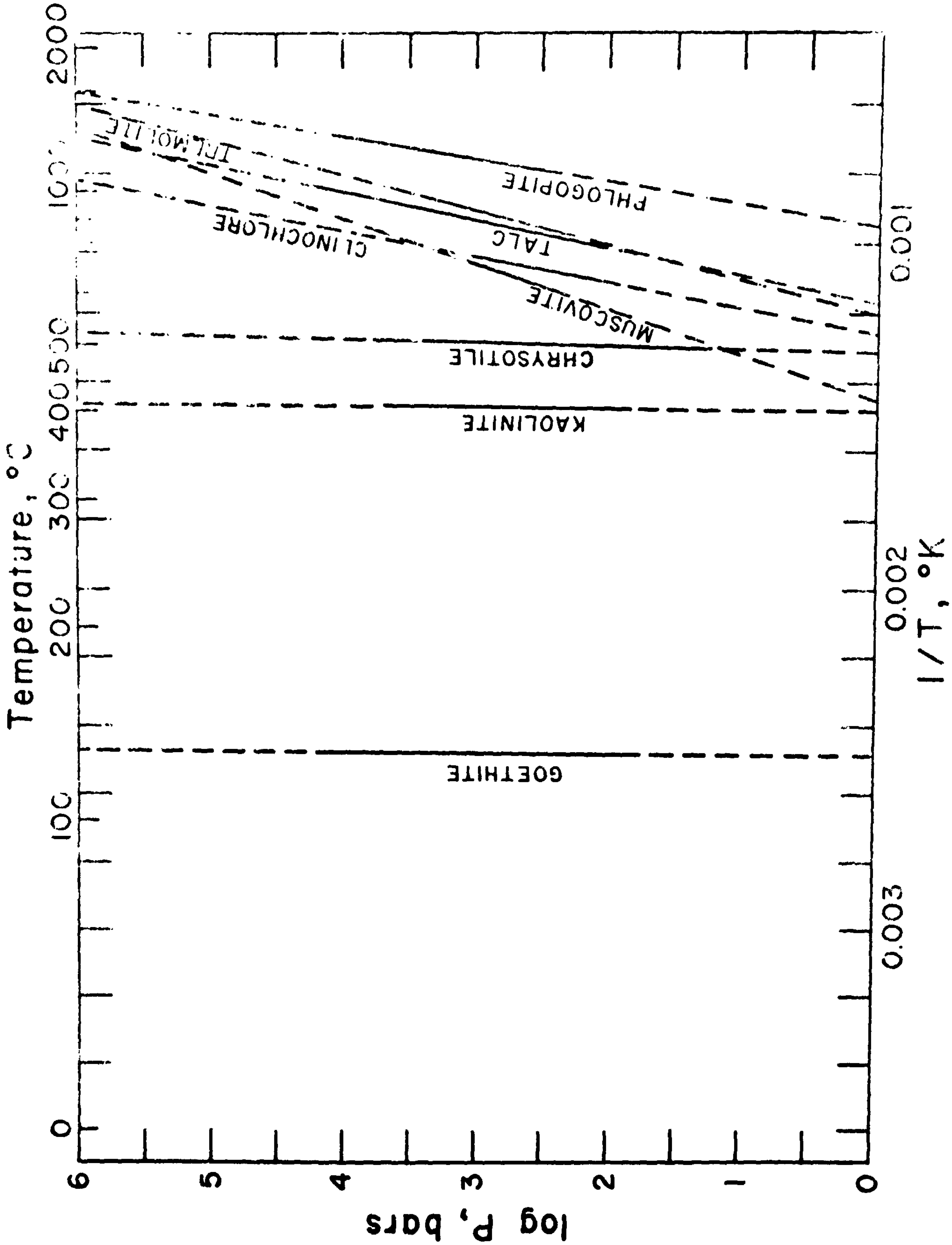

I
DETERMINED
EXPERIMENTALLY
EXTRAPOLATED
A_s
B + H₂O
M
N
O
S
P
II
Q
T
A_m
C + H₂O
Pressure
Temperature

Figure 2
223



Temperature, °C
0
100
200
300
400
500
1000
2000
1/T, °K
0.001
0.002
0.003
log P, bars
0
1
2
3
4
5
6
PHLOGOPITE
TREMOLITE
TALC
CLINOCHLORE
MUSCOVITE
CHRYSOTILE
KAOLINITE
GOETHITE

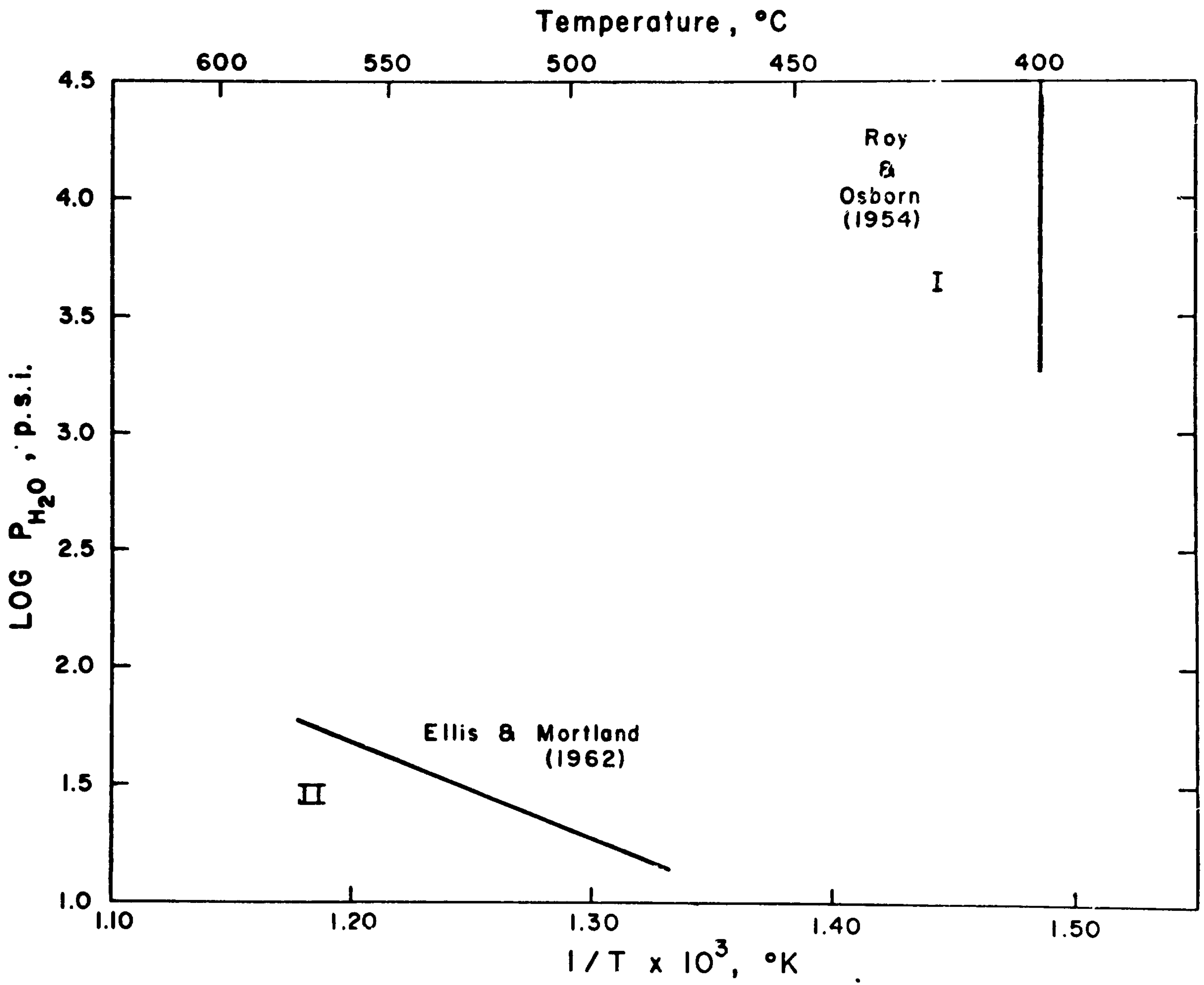
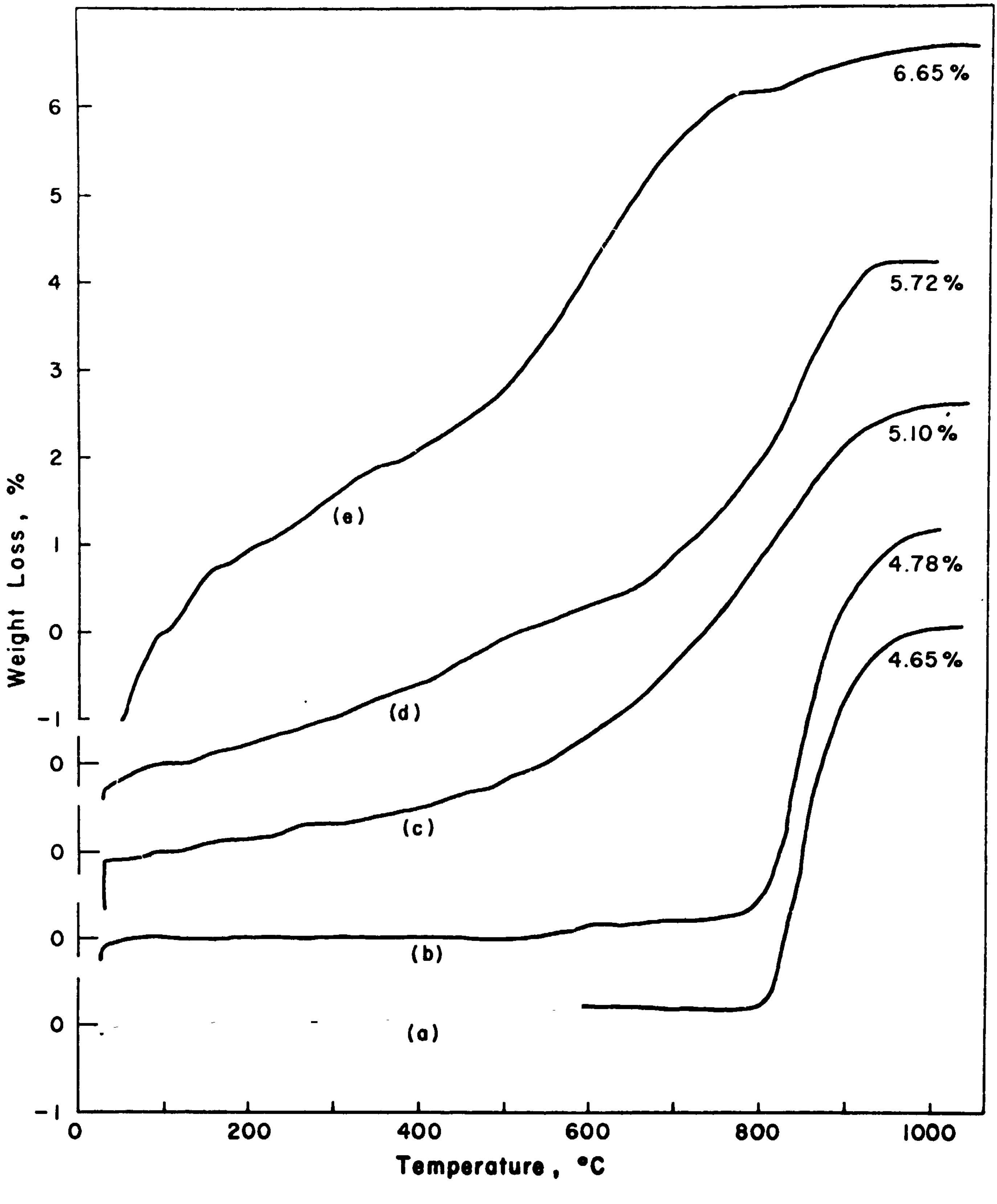

Temperature, °C
600
550
500
450
400
Roy
&
Osborn
(1954)
I
Ellis & Mortland
(1962)
II
LOG P_{H_2O}, p.s.i.
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1.10
1.20
1.30
1.40
1.50
1/T x 10^3, °K

Figure 4



6.65 %
5.72 %
5.10 %
4.78 %
4.65 %
(e)
(d)
(c)
(b)
(a)
Weight Loss, %
Temperature, °C
0
200
400
600
800
1000
-1
0
1
2
3
4
5
6

Figure 5

226

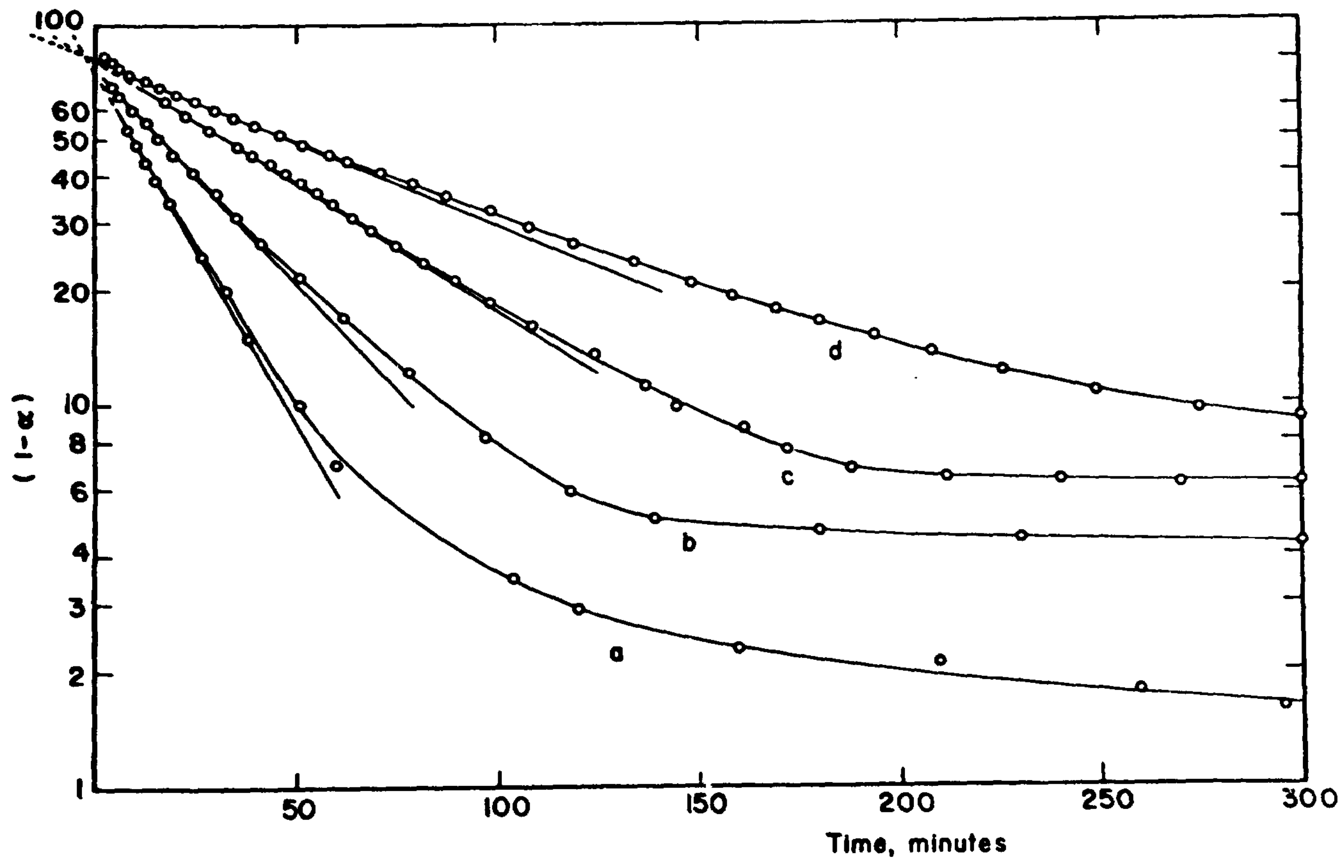
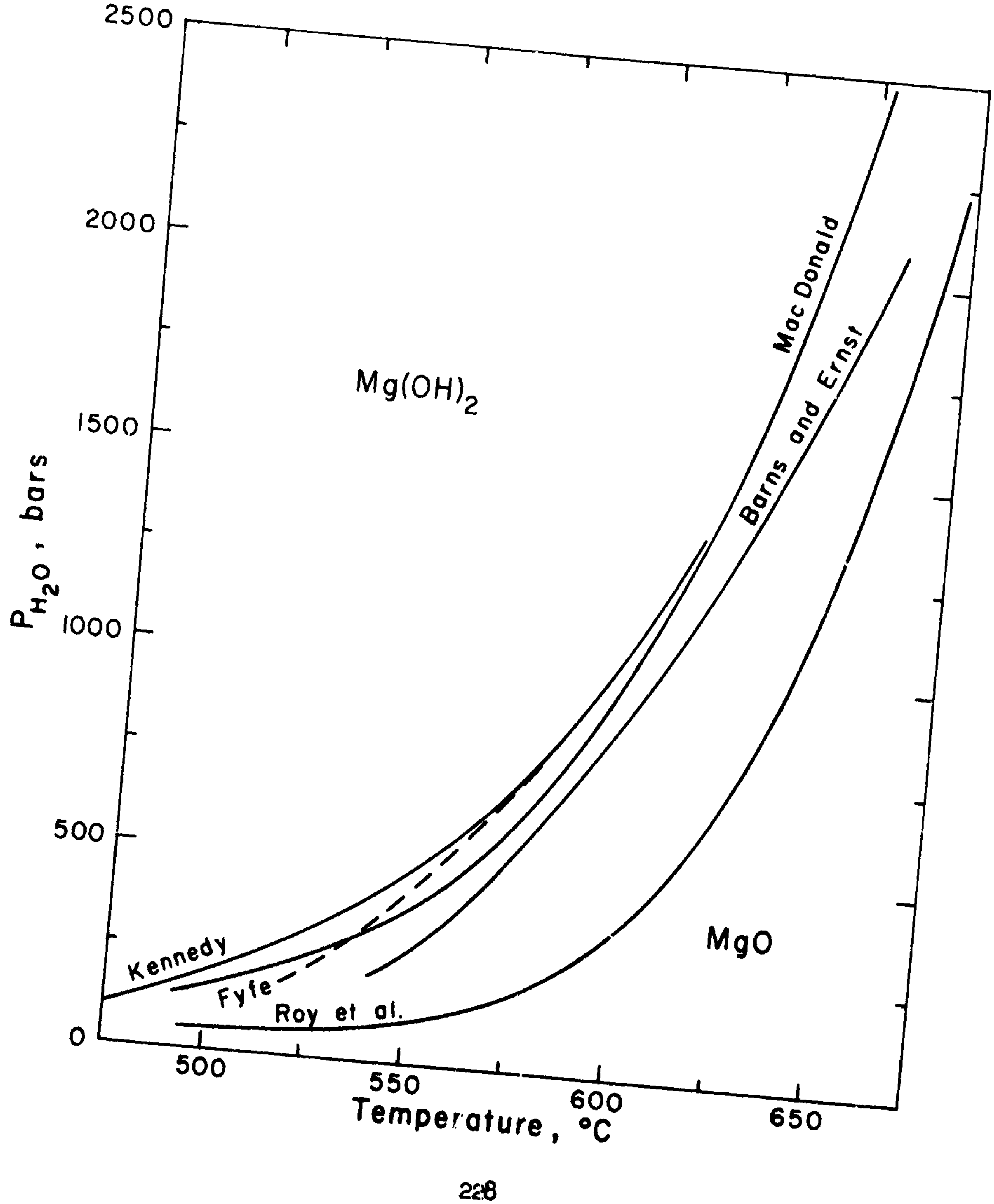
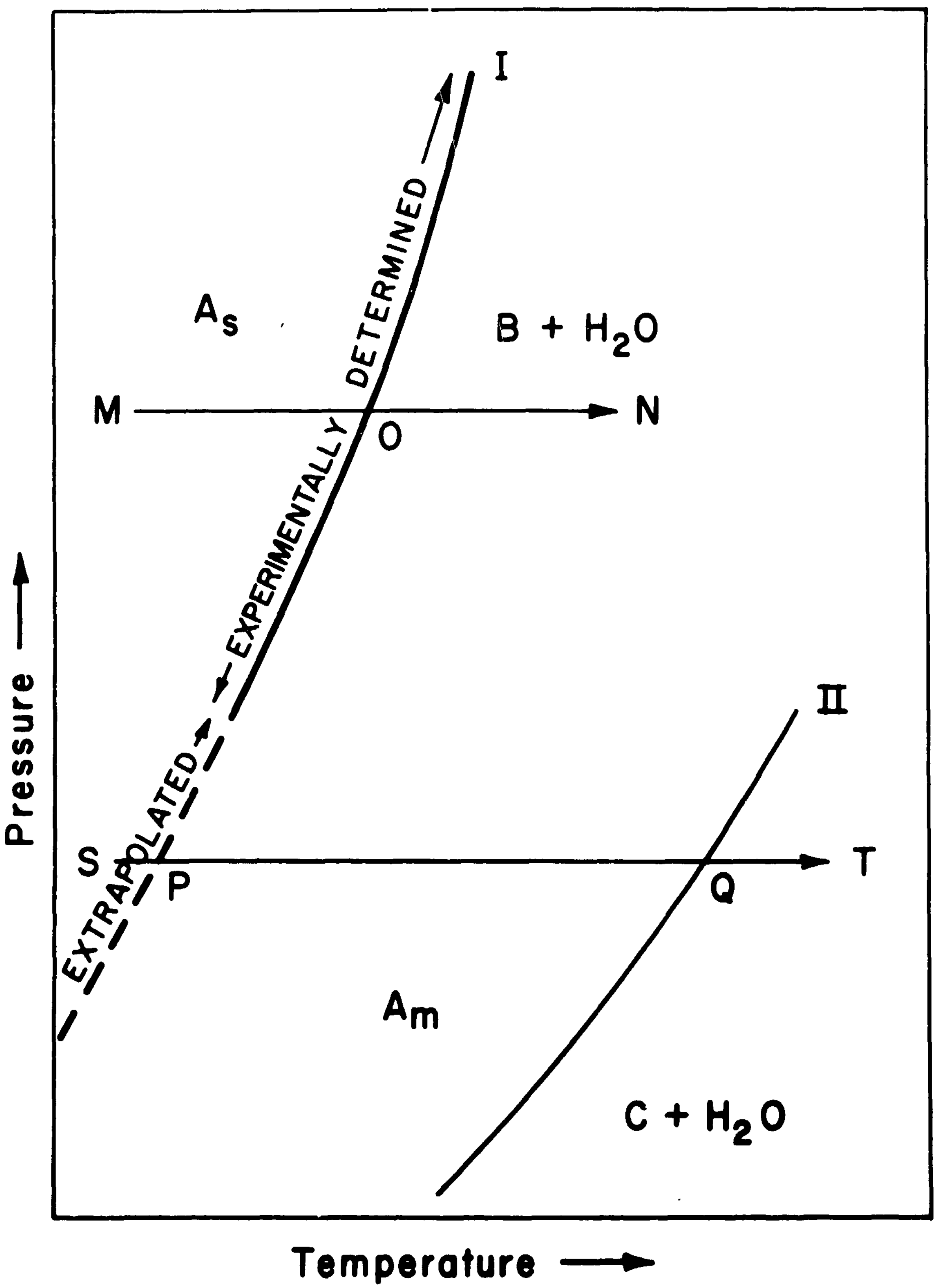
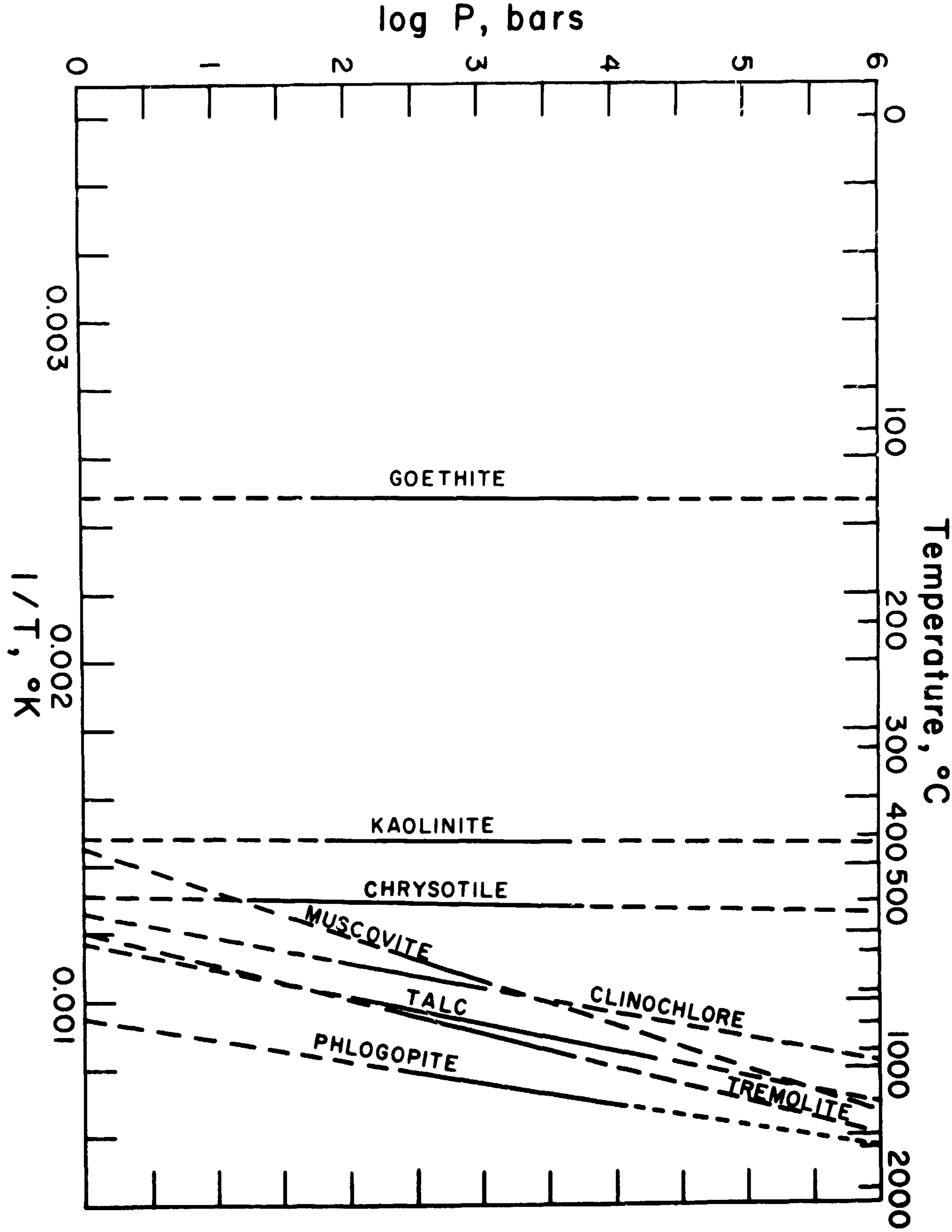

100
60
50
40
30
20
10
8
6
4
3
2
1
(1-α)
d
c
b
a
50
100
150
200
250
300
Time, minutes

Figure 6

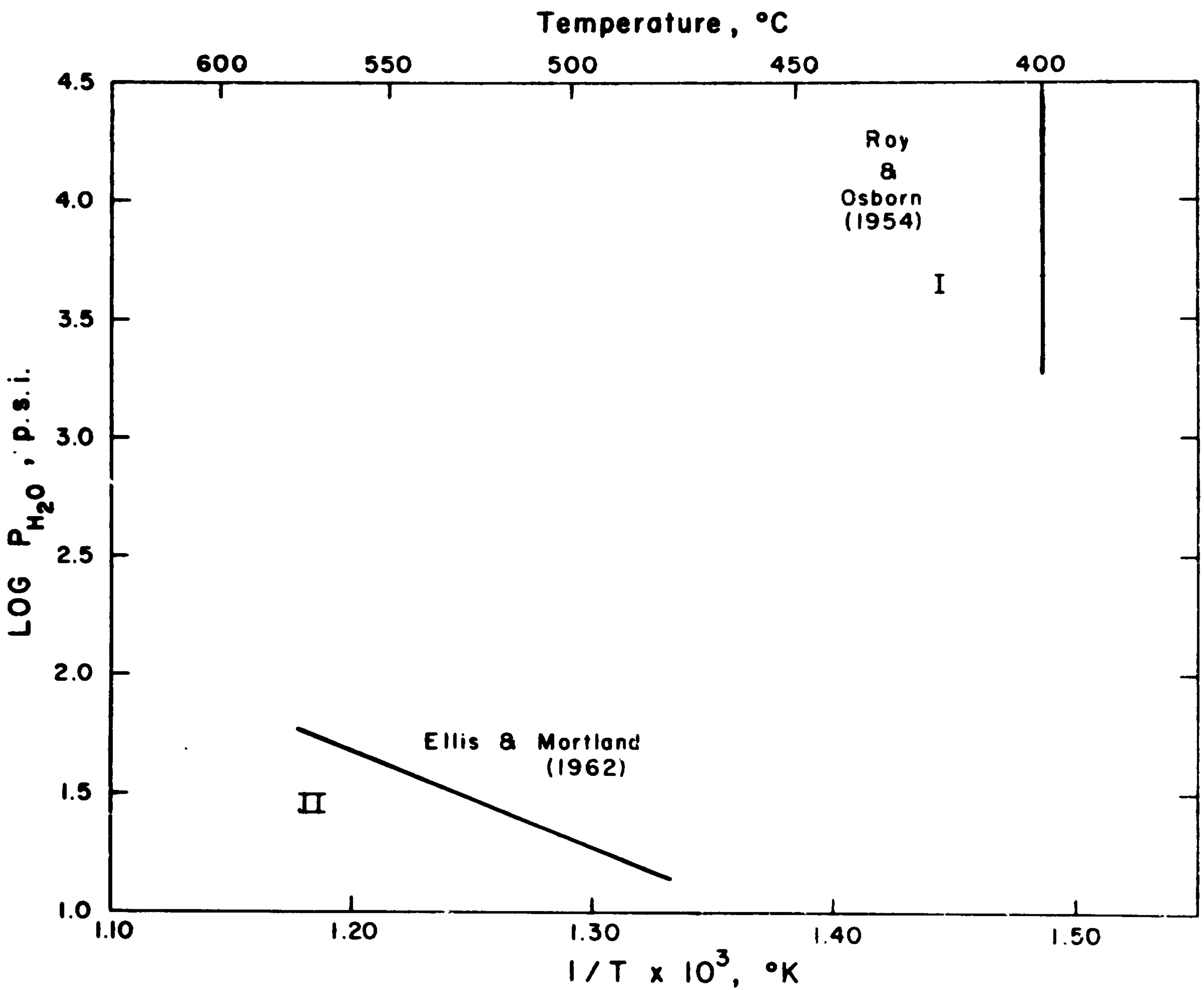


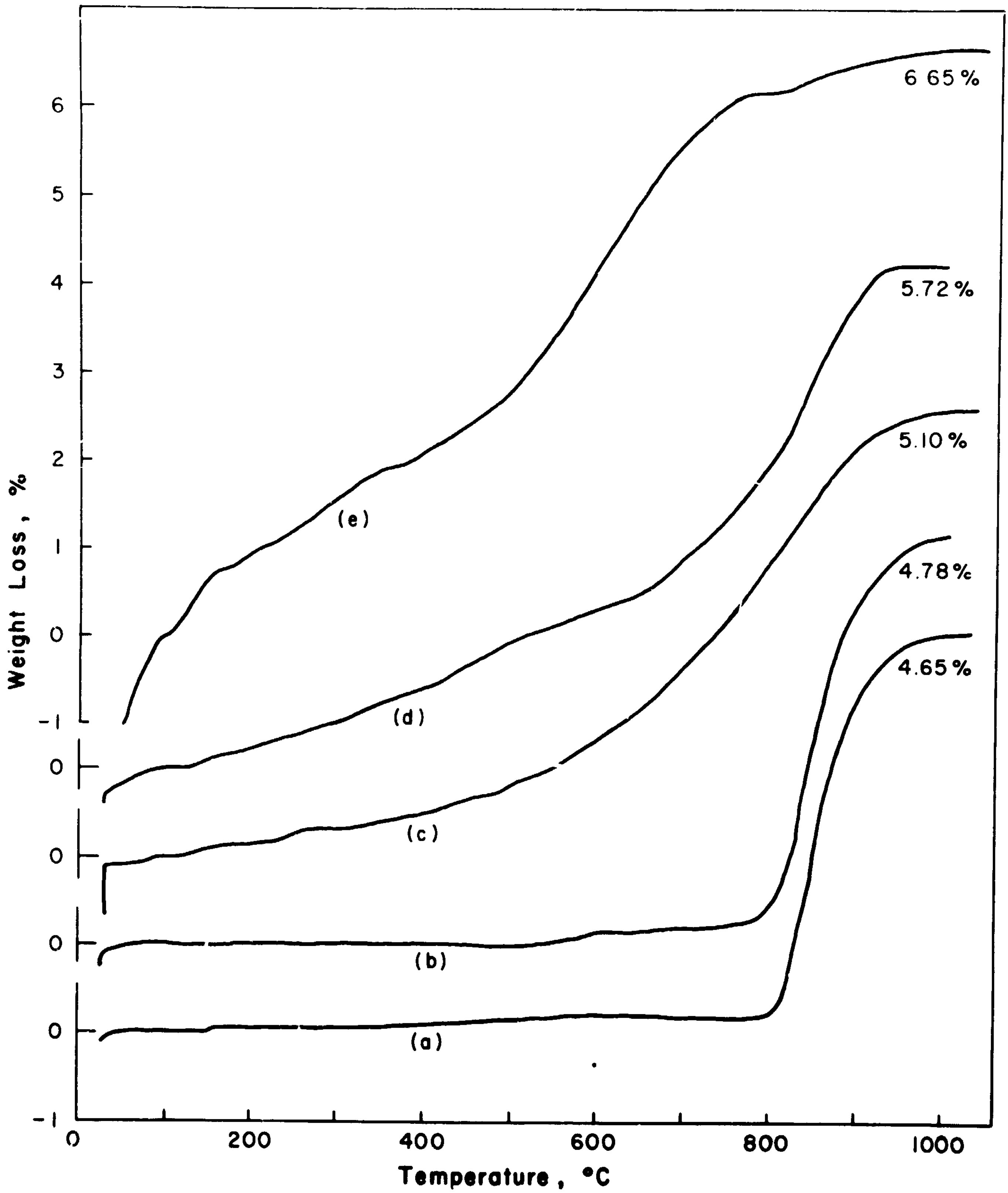
2500
2000
1500
1000
500
0
500
550
600
650
Temperature, °C
P_{H_2O}, bars
$Mg(OH)_2$
MgO
Mac Donald
Barns and Ernst
Kennedy
Fyfe
Roy et al.


I
EXPERIMENTALLY DETERMINED
EXTRAPOLATED
A_s
$B + H_2O$
M
N
O
II
S
P
Q
T
A_m
$C + H_2O$
Pressure
Temperature

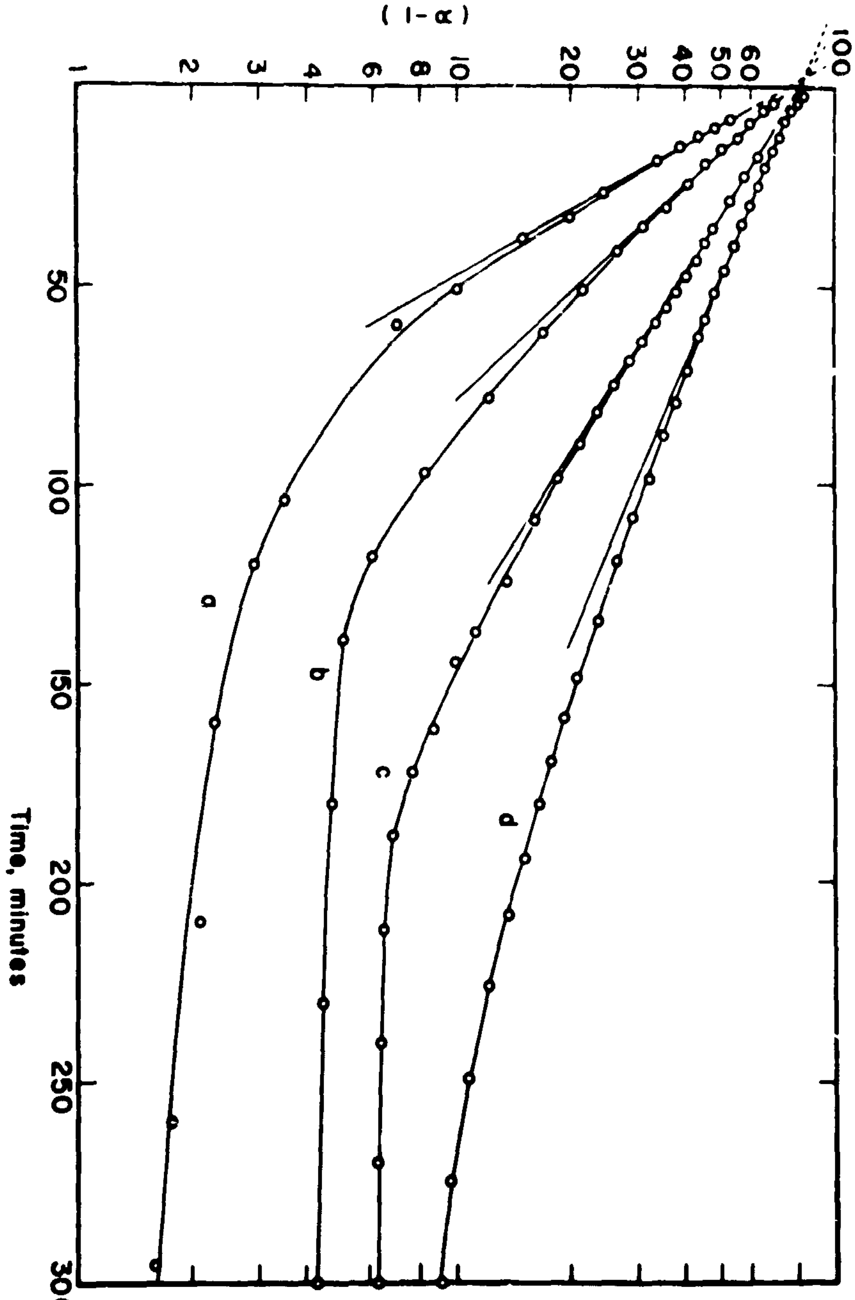


log P, bars
0
1
2
3
4
5
6
I/T, °K
0.003
0.002
0.001
Temperature, °C
0
100
200
300
400
500
1000
2000
GOETHITE
KAOLINITE
CHRYSOTILE
MUSCOVITE
CLINOCHLORE
TALC
PHLOGOPITE
TREMOLITE


Temperature, °C
600
550
500
450
400
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
LOG P_{H_2O}, p.s.i.
Roy
&
Osborn
(1954)
I
Ellis & Mortland
(1962)
II
1.10
1.20
1.30
1.40
1.50
$1/T \times 10^3$, °K



6 65 %
5.72 %
5.10 %
4.78 %
4.65 %
(e)
(d)
(c)
(b)
(a)
Weight Loss, %
Temperature, °C
0
200
400
600
800
1000
-1
0
1
2
3
4
5
6


(1-α)
100
60
50
40
30
20
10
8
6
4
3
2
1
a
b
c
d
50
100
150
200
250
300
Time, minutes

A NOTE ON PETROLOGIC PROCESSES AND LUNAR LOGISTICS

Emanuel Azmon

The geologic aspect of lunar logistics is recognized as the utilization of the lunar natural resources (whatever they may be) for support of man's activities on the moon. This utilization may take four forms: (1) direct use of raw material as it is found on the surface of the moon, (2) direct use of raw material after processing, (3) use of information derived from surface material to determine the location of buried economic minerals, and (4) use of information derived from surface material to determine the geologic environmental history and to predict future environments. The importance of understanding the petrologic properties increases in the above order from direct use to the prediction of environments. Increased sophistication in the demand for specific minerals, which will no doubt follow the initial exploration of the moon, will increase the demand for understanding the petrologic processes even more.

We have accepted the general premise that the moon is within the group of "terrestrial planets," thus implying that it is made of igneous rocks, primarily silicates (Azmon, 1962). We also maintain that the typical atmospheric-hydrospheric minerals will be scarce or lacking in the lunar environment. Hence, our efforts are concentrated on the understanding of petrologic processes in igneous rocks, with an elaboration on processes that might be favored on the moon.

Igneous rocks are essentially aggregates of mineral grains which have solidified from molten magma into a single rock. The characteristic properties of the rock are bulk properties whose net effect is determined by the combination of the individual properties of the component minerals. Although these bulk properties may not be similar to the physical properties of the components, they are nevertheless characteristic of the rock. They can be defined in descriptive terms, and they can represent a set of igneous rocks which have reached a certain genetic state.

The genetic state of many rocks is not necessarily an equilibrium or steady state. It is attained even in a large system, such as a mountain or a portion of a continent, where it is possible for one end of the system to be far enough physically from the other end to appear independent. It is also attained in an open system, where a true equilibrium may never be reached because there is a continuous incorporation of rock material into the system. More surprising, however, is the fact that such a heterogeneous reaction may still achieve a distinct genetic state and result in a rock-type end product. Even more extraordinary is the fact that, in spite of the complex combination of variables required to obtain a genetic state, such combinations are found repeated geographically around the earth and stratigraphically down the geologic column. The complex combination of parameters and events that lead to the culmination of a genetic state appears to be too systematic to be accidental. One must admit that, although the parameters and events are governed by a multitude of known thermodynamic and kinetic processes, their interactions appear to be governed by unknown universal rules.

Four groups of variables go into the establishment of the bulk properties, namely: composition, temperature, pressure, and history (Azmon, 1965). The composition may vary with respect to essential minerals, accessory minerals, and minor constituents. The temperature may vary with respect to the rate of heating, power level, duration of stay, and rate of cooling. The pressure may vary with respect to the rate of application (shock vs. gradual) and duration of stay. The history may vary with respect to the order of application of the above variables and to changes in the variables while a rock-forming process is in action.

The complexity of such rock-forming systems makes it extremely difficult to analyze the involved processes quantitatively; therefore, a descriptive treatment is required. To illustrate this, we have prepared a list of descriptive terms which define 10 sets of rocks. Each set represents all the igneous rocks that can achieve a certain, definite genetic state. Several of the sets may be null under certain conditions of composition, pressure, and temperature. The null position of these particular sets is by itself a characteristic of certain genetic states.

The 10 sets are as follows:

Original rock = K_1 = [a/all granular igneous rocks which suffer no metamorphism]

50% melt = K_2 = [b/all "a" which show 50% melting $\pm$ 10%]

Relic, original = K_3 = [c/all rocks which show relics of "a" with the bulk molten]

Vesicular = K_4 = [d/all "a" or "b" which develop vesicular structure (crystalline groundmass)]

Scoriaceous = K_5 = [e/all "d" which develop scoriaceous structure (crystalline groundmass)]

Pumiceous = K_6 = [f/all "c" which develop pumiceous structure (hyaline groundmass)]

Glassy = K_7 = [g/all "a, b, c, d, e, f" which form glass]

50% Recrystallized = K_8 = [h/all "g" which show 50% recrystallization $\pm$ 10%]

Relic, glass = K_9 = [i/all rocks which show relics of "g" with the bulk recrystallized]

Complete recrystallized = K_{10} = [j/all rocks which show complete recrystallization]

It is important to note that, as in typical Cartesian arithmetic, Set K_{11} will be identical with Set K_1. In the geologic sense, this means that, unless we can establish the relative ages of the rocks, we cannot recognize the difference between K_1 and K_{11}.

The above discussion represents a frame of reference which enables us both to treat nonnumerical data in a seminumerical way and to plot genetic diagrams showing the temperature, pressure, and/or time dependence of several sets of genetic states. Figure 1, for example, shows the time dependence of 10 genetic states for two rocks, gabbro and tholeiitic basalt. The temperature and pressure for these genetic states were maintained fixed at 1000°C and one atmospheric pressure. A close examination of these data reveals the following:

1. During the first 10 hours, both rocks went through six genetic states, which began and concluded their volcanic history (States 4, 5, and 6).

2. In the following days, the histories of the two rocks departed from each other. The gabbro reached the glassy state (7) and rose asymtotically and imperceptibly towards the crystalline states (8, 9, 10). The basalt reached the crystalline state (9), and from there it rose asymtotically to State 10.

In order to evaluate these data in terms of the forms of utilization discussed above, we can do one of two things: (1) use information of the type shown here to select the proper heat treatment needed to develop a desired genetic state, or (2) map observed petrologic features in the field and infer from the map the direction of shorter heat duration, which may also be the direction of the source of the rock. Obviously, this curve is only one example of the genetic states of two rocks at a specific temperature. To complete the picture, we then must consider similar curves for these rocks at other possible conditions.

Figure 2 shows a typical genesis diagram for gabbro, where the pressure and temperature of formation of the 10 genetic states were plotted and then contoured. We can derive the following information from this diagram:

1. Gabbro has a melting range of about 250°C (1000° to 1250°C) at one atmosphere.

2. As this range rises in temperature with increased pressure, it also narrows to about 50°C.

3. The peculiar shape of the upper curve may be related to the behavior of anorthite under pressure; that is, the melting point falls with rising pressure up to about 33 Kb (Boyd, 1962).

4. Above the melting range, the quench product is either glassy or microcrystalline. It seems as if both the glassy material and the crystalline material can be recognized on the genesis diagram as two distinct genetic states (comparable to two phases in a typical phase diagram).

5. Line 9 represents a temperature region above which the quench product is never crystalline, always glassy. It also represents a pressure region beyond which the quench product is always crystalline regardless of the temperature.

Just as in Figure 1, these data permit evaluation in terms of the forms of utilization: (1) An optimum heat and pressure combination can be selected to develop a product of a certain genetic state; (2) a field map of observed features will probably be of the same nature as Figure 2; hence, it will indicate the direction of the source of high temperature and/or high pressure.

A striking example of the good correlation between the physical parameters (the variables) that define a genetic state and the recognized petrologic characteristics of the rock can be seen in Figure 3, which displays four photomicrographs of heat-treated gabbro. Figure 3-1 shows the rock after a 2-hour heat treatment. No change from the original crystalline rock could be observed under the petrographic microscope. Figure 3-2 shows the rock after a 6-hour heat treatment. The rock developed typical volcanic scoriaceous characteristics. (We are using the term scoriaceous to mean not only higher-percentage cavities than in a typical vesicular rock, but also partial conversion of the crystalline material into glass. If all the crystalline material around the cavities converted to glass, the rock would classify as pumiceous.) At 24 hours (Figure 3-3), all the cavities had disappeared completely, thus practically concluding the typically volcanic genetic states, and some recrystallization is clearly evident. Last, at 5½ days (Figure 3-4), crystallization proceeds to replace the glassy material. Again, as in the above discussion, the utilization may take a production form, whereby this data can be used to manufacture rock of any of the above properties. Or, if used for field mapping, samples may be collected on a grid, as shown in Figure 4 (Elgin and Azmon, 1964), and examined in the laboratory for indicators of the genetic states.

We can see in the above examples how two parallel benefits can be derived from the knowledge of the processes and conditions under which various igneous rocks are formed. One is the ability to generate rock end products at will, and the other is the ability to determine the provenance of a natural rock. These benefits correspond, respectively, to (1) production of mineral concentrates of defined properties in desired shapes, and (2) means of exploration for source rock. Here, knowledge regarding two different aspects of economic geology is gained simultaneously through experiments designed to determine the processes that natural silicate mixtures must go through to generate specific rocks, and to define the four parameters controlling these processes: composition, temperature, pressure, and history. The parameters which determine the genetic state of a rock can be obtained either by inferences drawn from the observed characteristics of the rock as found in its natural environment, or from laboratory determinations of the conditions that lead to its formation.

An understanding of these rules can lead to the two benefits mentioned above: (1) an ability to generate rock end products at will, and (2) an ability to determine the provenance of a natural rock.

REFERENCES

1. Azmon, E. (1962), Lunar Soil Sampling and Testing, American Society for Testing and Materials, Special Technical Publication No. 322, Symposium on Field Testing of Soils.

2. ________ (1965), Melting Temperature of Complex Silicates, Annals of New York Academy of Science, Vol. 123, Art. 2, pages 481-494, Geological Problems in Lunar Research.

3. Boyd, F. R. (Nov. 30, 1962), Letter Communication, Carnegie Institute of Washington, 2801 Upton St., Washington 8, D.C.

4. Elgin, J., and Azmon, E. (Nov. 18, 1964), Apollo Experiment Support Mission, Lunar Surface Vehicle, Unpublished Report, Northrop Space Laboratories, LSV/S-MO-1.

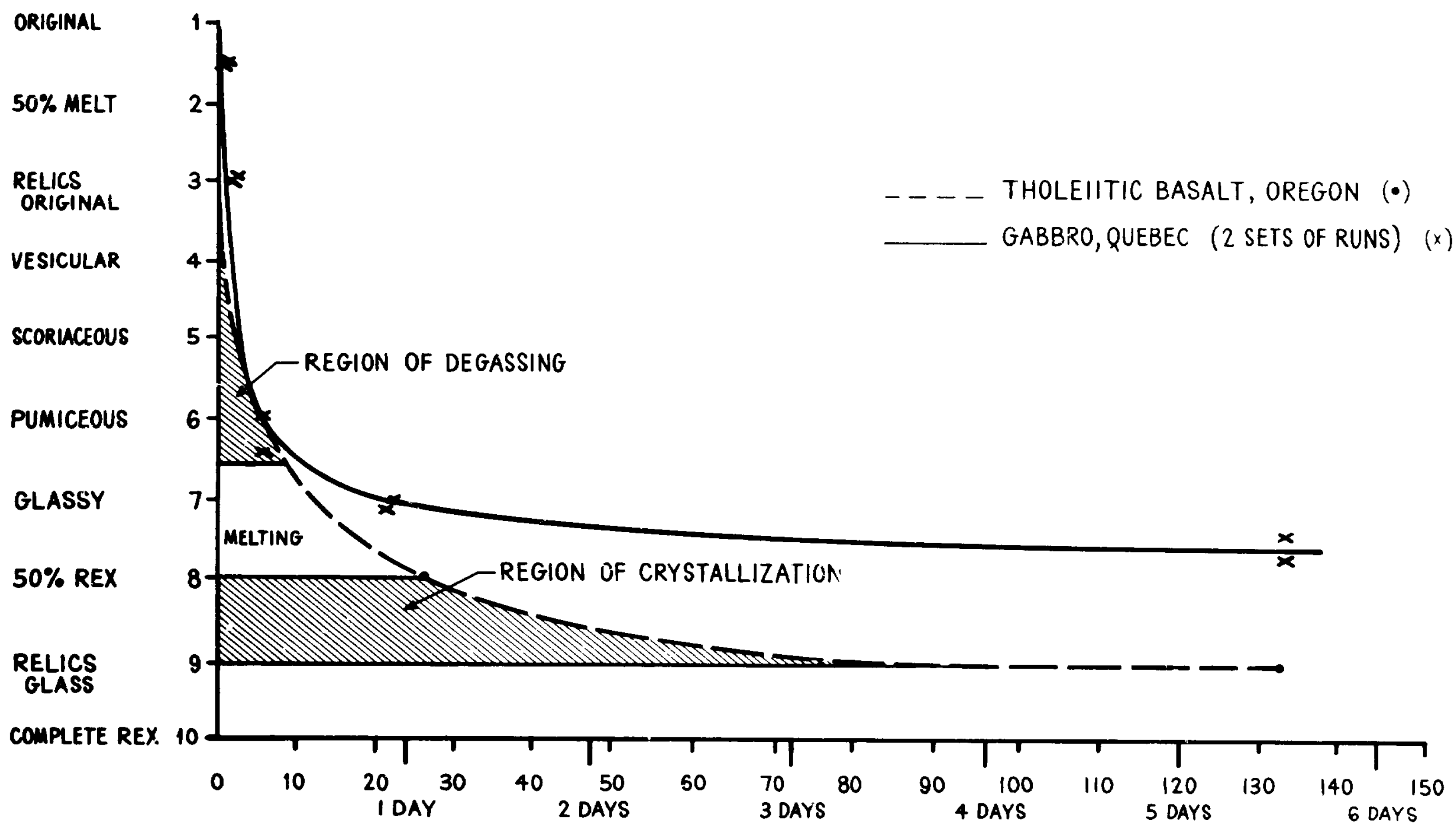


Figure 1. Time Dependence of Genetic States (1000°C at 1 atm)

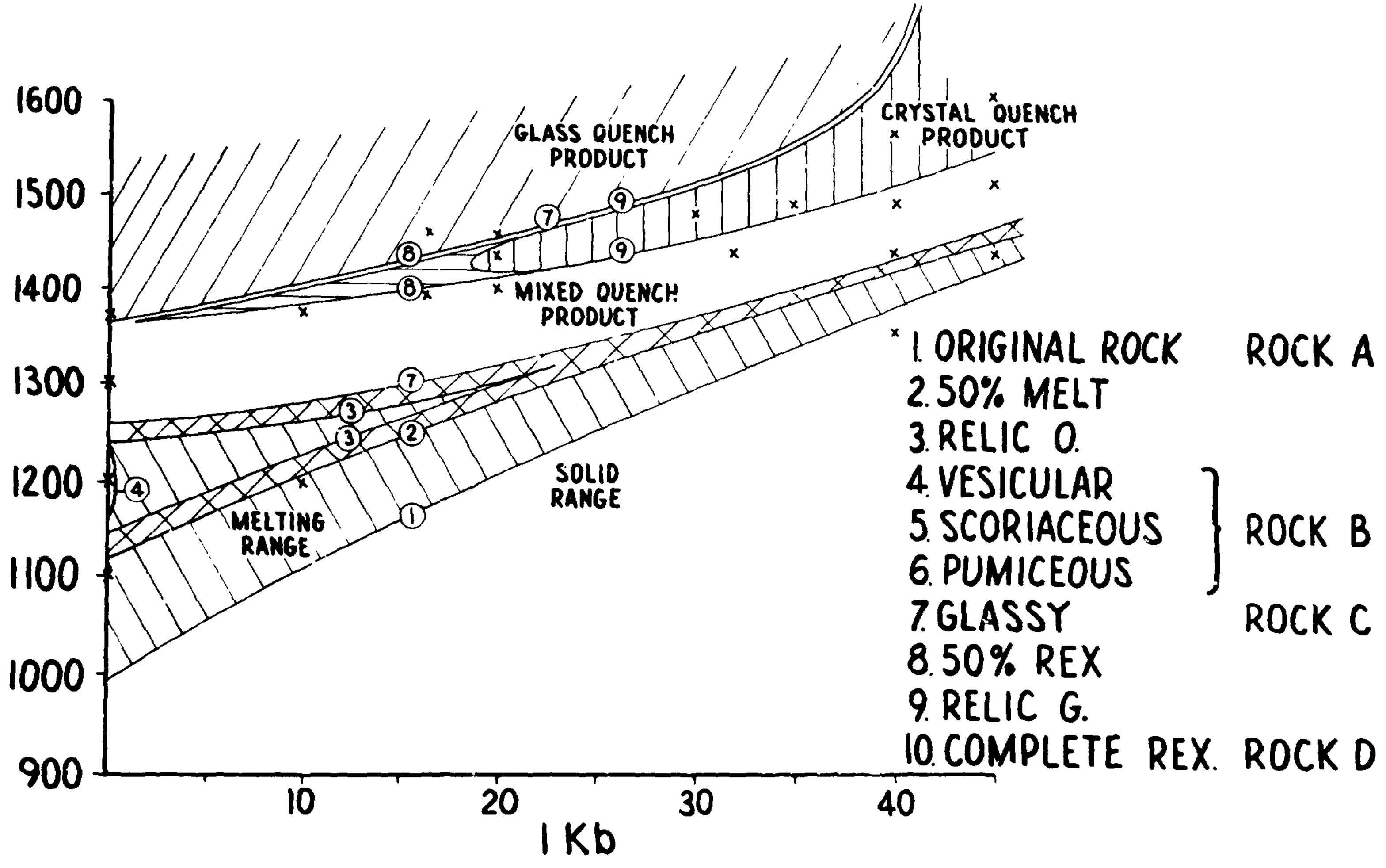


Figure 2. Genesis Diagram--Gabbro (Quebec), T° vs. P at ~ 1 min. Stay at T°, Then Quench

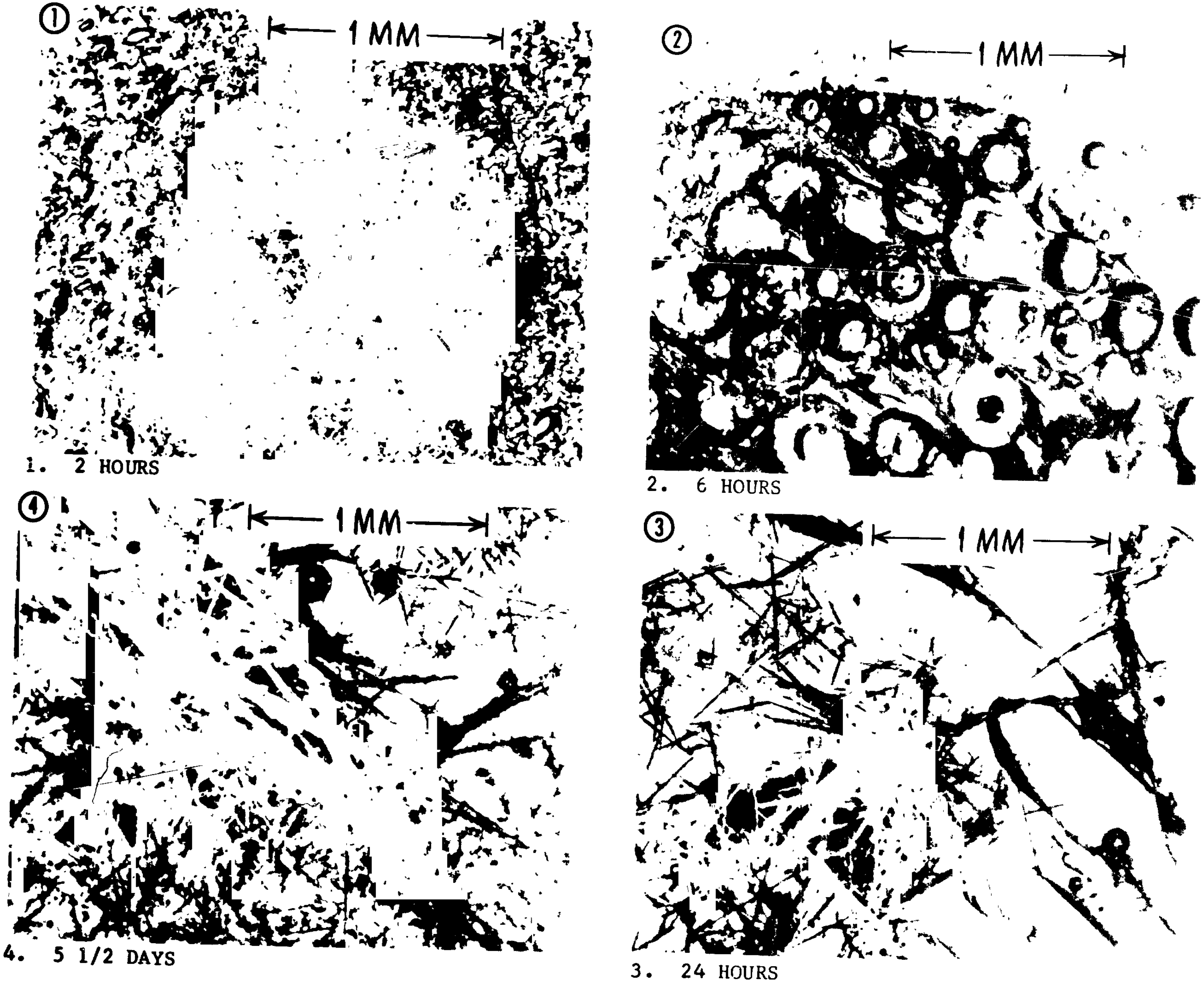


Figure 3. Development of Genetic States in Basalt
(1000°C at 1 atm)

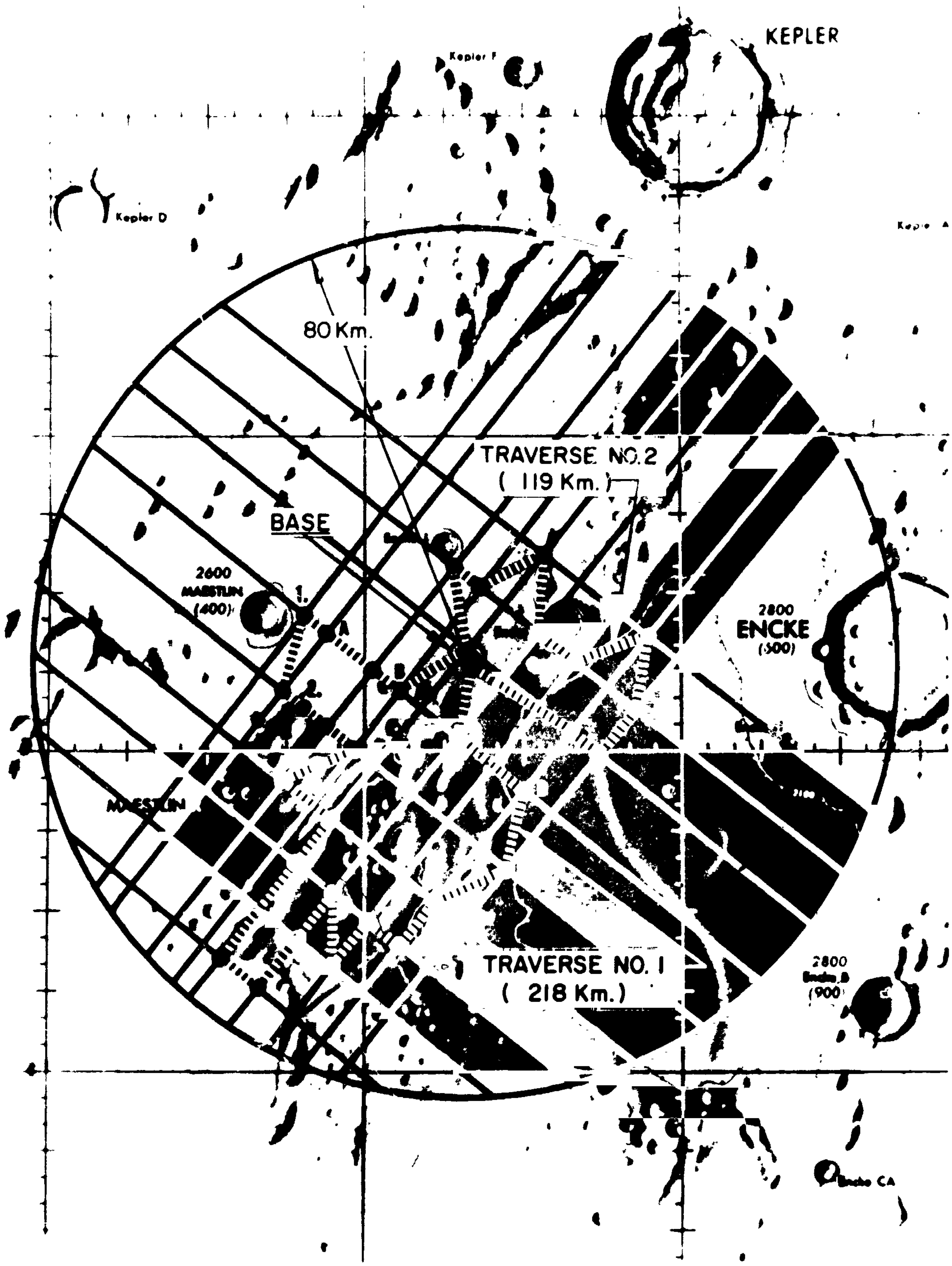


Figure 4. Typical Lunar Traverse

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CRYOGENIC STORAGE ON THE MOON

By

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Abstract

To assess the problems anticipated in storing cryogenic fluids on the surface of the moon for extended periods, methods are presented for estimating heat inputs to a storage vessel exposed to the lunar environment and to quantitatively predict the expected boil-off losses. The radiation interchange with the lunar surface was identified in terms of the observed lunar surface photometric properties and the results were compared with radiation from a surface obeying Lambert's law.

The lunar surface characteristics of importance to cryogenic storage, the selection of appropriate support concepts, the performance of highly effective thermal insulations, and the treatment of piping penetrations to reduce performance degradations are discussed. Results are presented of analyses of the heat exchange for the computation of environment heat of fluxes and the boil-off rate is estimated for a specific cryogenic vessel design.

Effects of The Lunar Environment

Implicit in the studies of processes for the utilization of lunar resources is the belief that cryogenic fluids can be stored on the moon's surface for extended periods with minimum boil-off losses. To analyze the design requirements of a cryogenic storage vessel, the thermal interactions between it and the lunar surface must be determined.

Although views differ on the nature of the lunar environment, considerable evidence has already been obtained and such significant aspects as an extremely low-pressure atmosphere, micrometeoroid impact and solar radiation effects, and the resulting thermal and photometric properties of the lunar surface materials can be postulated.

Optical and radio telescope observations have established an upper limit of the density of the lunar atmosphere and, by inference, possible atmospheric constituents. The absence of any significant lunar atmosphere shapes and controls the characteristics of the lunar surface material (Glaser, 1965), and causes any gases from the cryogenic storage vessel to be rapidly diffused.

The continuous bombardment by high-velocity micrometeoroids causes comminution of exposed materials and consequent erosion of the moon's surface.

Solar radiation consisting of non-ionizing ultraviolet light, x-rays, wind, and flares is chiefly responsible for the physical and chemical structure of the surface material. Of particular significance is the cleansing effect of this radiation which may contribute to the consolidation of particles. Consolidation may also be induced by radiation sintering of lunar surface particles (Smoluchowski, 1965).

If the lunar surface has been subjected to gas contamination from the moon's interior, adsorption of gases on particle surfaces may have taken place. Physically-adsorbed gas layers would be removed rapidly at the low surface pressures; chemisorbed-layers, although not completely removed by the vacuum alone, would be removed by solar radiation. In the absence of any contaminating gas sources, any fresh surfaces generated by mechanical action (e.g. micrometeoroid impacts) would remain clean. The topography of particle surfaces generated by such action would determine the magnitude of adhesion forces. Surface roughness combined with submicron particles at contact points will reduce adhesion between particles.

Experimental data indicate that the high vacuum can substantially increase the coefficient of friction. (Glaser, 1964) The high friction will tend to make a falling particle stick at its first contact, resist shearing forces that would produce dense packing, and thus contributes to the formation of intricate structures on the lunar surface.

Properties of The Lunar Surface Layer

The complexity of the surface layer has also been indicated by photometric measurements and recent radar radiometric measurements (Hagfors, et al., 1965). This layer is responsible for the sharp lunar surface temperature changes which have been measured by infrared and microwave methods (Shorthill and Saari, 1965). Thermal property values, obtained in laboratory simulation experiments, point to a surface composed of particles which may have been lightly sintered together to form a complicated structure. (Wechsler and Glaser, 1965)

Photometric measurements have shown that the physical arrangement of the lunar surface differs from that of terrestrial surfaces, most of which scatter light in accordance with Lambert's law. The face of the full moon appears to be of uniform brightness and its average albedo in the visual spectral range is about 0.07. The albedo in the infrared has been estimated to be greater than this average value. (Pettit and Nicholson, 1930).

The dependence of the albedo on the angle of incidence follows a photometric function which varies drastically from the commonly known functions -- particularly from Lambert's law. A photometric function which appears to conform very closely to the observed photometric properties of the lunar surface has been derived by Hapke (1963). The numerous assumptions made in the derivation of Hapke's function have been justified by the agreement of the computed photometric functions with experimental data. (Hapke and Von Horn, 1963). The data show that materials which scatter light like the moon have a complex structure, consist of a random arrangement of objects -- large compared with the wavelength of visible light and of low reflectivity -- arranged in an open network into which light can penetrate freely from any direction. These objects give the structure isotropic and homogeneous appearance which is also in accord with the postulated genesis of the lunar surface and the thermal properties of such a material. Studies of the back-scattering of hard, highly porous volcanic cinders, scoriae, and slag (Halajian, 1965) have shown that the photometric function of a surface depends primarily on the geometry of its elements, not on their actual size. Proton irradiation of fine rock particles will cause their photometric properties to closely match the observed lunar material characteristics (Hapke, 1965).

The emittance of the lunar surface is still a subject of considerable conjecture. Recent measurements (Markov and Khokhlova, 1965) indicated a variation in emittance ranging from 0.62 for the continents to 0.83 for the maria areas. Because of the lack of reliable data on lunar surface emittance and its directional properties, a conservative assumption for the radiation interchange with a cryogenic storage vessel is that the lunar surface emittance is comparable to that from a black body.

Deposition of Particles on Cryogenic Storage Vessel Surfaces

The surface of a cryogenic liquid storage vessel on the moon could be covered by a layer of particles ejected from the lunar surface by micrometeoroid impact. Estimates of the rate of accretion of particles on any object on the lunar surface are quite uncertain. (McCracken and Dubin, 1964). The depth of particles accumulated in one year can be assumed to be between one micron and 10^{-4} microns. The effect of such a thin, uniform layer of particles deposited on a surface of a diffusely reflecting material is to change the reflectivity of the surface layer. For quartz-like particles averaging one micron and one layer deep, the emittance of a vessel surface will not change significantly. However, the ratio of the solar absorptance to emittance of the vessel surface will increase by more than a factor of 3 leading to a considerable rise in the vessel surface temperature. (ADL, 1966)

Cryogenic Storage Vessel Design

Any cryogenic liquid storage system must contain and conserve the stored liquid until such time as it is used. Containment of cryogenic fluids such as liquid hydrogen, presents no serious problems. However, in a simulated lunar environment, the conservation of cryogenic fluids for an extended period with a minimum boil-off loss has yet to be demonstrated. The low temperature of the stored fluid relative to the environment temperature causes heat flow to the fluid and a subsequent loss. Thus, to conserve the fluid, the net heat flow from the outer vessel surface to the stored cryogenic fluid must be limited.

In a real system, there are many paths by which heat may be transferred to the stored fluid. The principal one is the surface of the vessel which must be isolated from the environment by a thermal insulation. Others include the structural supports and piping which interrupt the insulation at several points and conduct heat to localized areas of the vessel surface. The pipes will also radiate heat to the stored fluid unless openings are appropriately baffled. The heat leaks from each heat path can be estimated using analytical techniques and available experimental data.

In recent years, several multilayer insulations and appropriate analytical techniques to predict their performance have been developed (Timmerhaus, 1958-1965). Table 1 lists physical properties of typical multilayer insulations which may be suitable for cryogenic storage vessels. The heat flux into the cryogenic vessel is governed by the effects of variables such as the warm surface temperature, compression applied to the insulation during installation and operation, type of gas and gas pressure inside the insulation, insulation thickness, radiation shield emittance, outgassing, venting requirements, and material stability. (ADL, 1963, 1964a)

A multilayer insulation system has to be designed to operate in the different environments affecting it during launch, boost, lunar landing, and lunar storage. Considerable work has already been carried out to devise systems which can perform adequately. Among these are pre-evacuated insulations utilizing lightweight flexible jackets, pre-evacuated insulations for small vessels with outer jackets designed to resist atmospheric loads, and space-evacuated insulations which require pre-launch noncondensable gas purges to prevent liquefaction of ambient gases and post-launch rapid removal of any gas within the insulation. The effectiveness of multilayer insulation can be enhanced by the use of cooled radiation shields. (Paivanos, et al., 1965). Utilizing the refrigeration potential of the vent gases, the boil-off rate of hydrogen from a vessel can be reduced to 1/5 the value that would be obtained without vapor cooling.

<u>Structural Supports</u>

The requirements for supports of the cryogenic vessel differ for each phase of its mission. The vessel supports from launch to lunar landing will have to be sturdier than the supports during storage on the moon. To minimize heat leaks, it will be desirable to alter the supports to suit the various load conditions, various material choices, and design approaches.

Thermal conductivity, tensile strength, and modulus of elasticity are the most significant properties in the support system design. Dacron, Nomex, and glass fibers are promising support materials. However, the percent elongation at the maximum loads and the temperature coefficient

TABLE 1

THERMAL CONDUCTIVITY OF MULTILAYER INSULATIONS

Multilayer Insulation: Thickness (Inches)	Multilayer Insulation: Material	Thermal Conductivity 0.001 psi Compression (Btu-in./hr-ft^2 °F)	Density (lb/ft^3)	Thermal Conductivity 15 psi Compression (Btu-in./hr-ft^2 °F)
0.002 0.007	1145-H19 Aluminum Nylon Mesh	0.43×10^{-4}	15	160×10^{-4}
0.00025 0.007	Double Coated Aluminized Polyester Film Nylon Mesh	0.58×10^{-4}	3	180×10^{-4}
0.0005 0.001	Soft Aluminum Fiberglas Cloth (3 layers)	0.83×10^{-4}	10	330×10^{-4}
0.0005 0.014	Soft Aluminum Fiberglas Mat	1.0×10^{-4}	5	44×10^{-4}
0.002 0.020	1145-0 Aluminum 1/8 x 1/8 Vinyl Mesh	1.4×10^{-4}	16	-
0.002 0.020	1145-H19 Aluminum 1/8 x 1/8 Vinyl Mesh	1.4×10^{-4}	16	-
0.0001 0.003	Soft Aluminum Fiberglas Mat	1.4×10^{-4}	3	76×10^{-4}
0.00025	Crinkled One-side Aluminized Polyester Film	1.9×10^{-4}	1.4	410×10^{-4}

Note: Measurements taken between +70 and -423°F of expansion must also be considered. In addition, the natural frequency of a support system and cryogenic vessel must be greater than the frequency of any excitations resulting from the vibrations and accelerations induced at launch. A material will provide minimum conductive supports at the natural frequency of a tension support when the ratio of the thermal conductivity of the support to the modulus of elasticity is minimum.

Many different structural support design concepts can be identified depending upon the specific cryogenic vessel requirements. Typical concepts include (1) tension supports where the inner vessel is supported by tension members, (2) multiple thermal resistance supports consisting of assemblies of conical washers coated with magnesia powder (ADL 1964 b), (3) refrigerated supports utilizing the sensible heat of the vaporized liquid, (4) retracting supports which may be disengaged by a mechanically-actuated spring release mechanism, a pyrotechnical release mechanism or a gas pressure actuated mechanism, (5) change-of-phase supports which use subliming materials to vary the strength and cross section of a support structure, (6) magnetic supports which eliminate conduction through the supports by several re-entrant permanent magnets -- on the outer shell and support rods holding the inner container, (7) cone supports of a honeycomb material bonded to a girth ring around the inner container and a girth ring around the outer shell.

Thermal Analysis of Structural Supports

The design of a structural support can be chosen to minimize the thermal conductance and provide the desired degree of thermal isolation of the cryogenic vessel. The overall thermal conductance is determined by the dimension and thermal conductivity of the structural element. The interaction between the support and the thermal insulation is most significant among the various mechanisms by which the structural support transports heat between the cryogenic vessel and the warm outer shroud.

When a structural support penetrates multilayer insulation, a gap between adjacent ends of radiation shields results allowing radiation to bypass one or more layers. If the ends of the radiation shields are in mechanical contact with the support then heat can be transferred by conduction between them. In addition, the radiation from the space between the shields can be absorbed by the support and conducted into the vessel.

Analyses of these effects have indicated the magnitude of the degradation of insulation performance by thermal coupling and the design approaches required. (Bonneville, 1964). Because structural supports in thermal contact with insulation edges produce unacceptable heat leaks, a buffer zone must be used. Studies of the buffer zone (ADL, 1963) have shown that the penetration is thermally decoupled from the insulation system when the zone's width is equal to or greater than the thickness of the insulation.

Design of A Model Cryogenic Vessel

Figure 1 shows the design selected to be representative of a lunar-landed liquid hydrogen storage vessel. Its spherical shape is 14 feet in diameter and is supported within a cylindrical shroud of aluminum honeycomb resting on a tripod. The design was chosen to correspond to the lunar excursion module. The cryogenic vessel is attached to the main structure by a single continuous cone of mylar honeycomb and is thermally protected by a multilayer insulation system. All the piping required to fill, vent, and drain the vessel is arranged to form a single piping penetration at the top. A detail of the piping penetration, including heat stations to reduce heat leaks through this penetration, are shown in Figure 2. A five-foot wide pressure vessel within the liquid hydrogen vessel stores high-pressure gaseous helium required to pressurize the ullage in the vessel during withdrawal of liquid hydrogen.

Heat Transfer Analyses

The critical aspects of the cryogenic vessel model design have been sufficiently detailed to permit realistic heat leak computations. Computation and methods have been developed to predict the thermal condition of a cryogenic storage vessel and its contents during extended exposure to the lunar environment and to quantitatively predict the boil-off rate. (ADL, 1966)

As shown in Figure 3, the outer shroud was divided into 30 zones to compute the heat flux incident. Six zones are on the top, six on the bottom, and 18 on the side of the shroud. The cylindrical surface was divided into three bands. To consider heat leaks through insulation, conductive terms were included for those from the supports and piping. The minor leak effects from supporting legs have not been included.

To calculate the incident heat fluxes the lunar surface was assumed to reflect according to Hapke's photometric function and emit radiation according to Lambert's law. Radiation affecting the vessel was divided into three components according to the wavelength range: reflected sunlight, infrared radiation from the lunar surface, and radiation from the vessel's shadow.

The response of the lunar surface to a shadow from a nearby object was immediate. The temperature of the shadow, therefore, is not time-dependent.

The computer programs used to evaluate the study included computation of the view areas, a card-tape program, a program to obtain the temperature of the zones, and a transient thermal analysis to confirm the validity of the assumption of a non-conducting shroud with no thermal mass.

Program Results

The numerical results of the analysis of the boil-off losses from a cryogenic vessel stored on the lunar surface are discussed in this section. The computer tabulations are shown in graphical form and the significant results are summarized.

Figures 4 and 5 show the view factors from two zones of the vessel to the shaded and illuminated portions of the lunar surface. The view factor for solar radiation reflected from the lunar surface calculated from Lambert's law is greater than the view factor calculated from Hapke's photometric function The lunar surface was assumed to be Lambertian in emission; therefore, the view factor for emitted infrared radiation from the lunar surface was calculated from Lambert's law.

Figure 6 shows the reflected solar radiation incident upon Zones 1, 2, 7, and 8 for various sun elevation angles according to computations using the Hapke photometric function. Zones 1 and 2 are located at the bottom and Zones 7 and 8 on the side of the vessel.

Figure 7 shows the radiative heat flux incident upon the outer shroud at various times during a lunation. The component of solar radiation reflected by the lunar surface according to the Hapke photometric function is small compared to the incident solar flux and the lunar surface thermal-emission components. However, the solar radiation reflected by the lunar surface according to Hapke's photometric function is about half that if the lunar surface were to reflect according to Lambert's law.

The maximum incident solar flux is received by the outer shroud shortly after sunrise and shortly before sunset when both the top and the sides of the vessel are illuminated. The bottom of the vessel does not receive solar flux except during a period of about six minutes at sunrise and at sunset. A sharp decrease in the incident solar flux occurs at noon, when the sides do not receive any solar radiation. This momentary shadowing has only a small effect on the outer shroud temperature. The calculations did not take into account the fact that the solar radiation is not collimated but subtends an angle of 32 minutes. For typical conditions, the error in the temperature of the outer shroud due to the assumption that the sunlight is collimated, is about .03°K.

The lunar surface thermal emission is the most significant component contributing to the heat flux incident upon the outer shroud. Because the exact magnitude of the lunar surface infrared emittance has not been established, an assumed emittance of unity will give conservative results. The magnitude of the total radiant heat flux incident upon the outer shroud of the cryogenic storage vessel is so large, compared to the flux due to sunlight reflected from the lunar surface, that the departure of the photometric function from Lambert's law is of slight importance. The effects of the lunar surface shadow temperatures are negligible because of the small magnitude of the lunar surface thermal emission from the shadow.

Figure 8 shows the boil-off rate in percent per year for different insulation shielding factors and various ratios of solar absorptance to infrared emittance of the outer shroud. These calculations are based on the assumption that the lunar surface reflects radiation according to Hapke's photometric function. For an insulation shielding factor of about 5,000, the boil-off rate would be in the order of 30% per year for a high α_s/ϵ ratio. Reductions in the boil-off rate for an insulation shielding factor greater than 15,000 are not very significant. Increased insulation shielding factors will result in an increase in weight and thickness of the insulation and thus detract from the advantages of a decrease in the boil-off rate. Even under the most optimistic conditions of very high insulation shielding factors and very low α_S/ϵ ratios, the boil-off rate would be about 7% per year for the model cryogenic vessel considered.

Figure 9 shows the dependence of the boil-off rate on the ratios of the outer shroud solar absorptance to infrared emittance for various penetration conductances and lunar surface reflection laws for an insulation shielding factor of 10,000. Instead of using a conductance, a shielding factor was used to characterize the heat flow through the insulation. This permits calculation of the heat flow through the insulation using the difference in T^4 instead of the difference in T. To be able to relate shielding factors to multilayer insulation systems, Figure 10 shows the dependence of shielding factors on different numbers of radiation shields and emittances, and Table 2 gives typical thicknesses of multilayer insulations for different numbers of radiation shields.

The total penetration conductances, even though a small percentage of the effective insulation conductance, have an important effect on the boil-off rate. To illustrate the magnitude of the penetration and effective insulation conductance, let the insulation be exposed to a temperature of 300°K on its outer boundary and to 20.4°K on its inner boundary. For insulation shielding factors of 5,000, 10,000, and 20,000, effective conductances of the insulation are 47.2×10^{-3} watts/°K, 23.6×10^{-3} watts/°K, and 11.8×10^{-3} watts/°K respectively. The nominal conductance of the total penetration is 3.18×10^{-3} watts/°K.

Conclusion

By taking into account the interaction of the cryogenic storage vessel with the lunar surface and designing a storage vessel incorporating the principles and techniques already available, it is possible to predict the boil-off losses from such vessels. Results indicate that the magnitude of the total radiant heat flux incident upon the outer shroud is so large compared to the sunlight reflected from the lunar surface, that the departure of the photometric function from Lambert's law is not important. The effects of lunar surface shadow temperatures are

TABLE 2

TYPICAL THICKNESSES OF MULTILAYER INSULATIONS FOR DIFFERENT NUMBERS OF RADIATION SHIELDS

Number of Radiation Shields	Multilayer Insulation Thickness .007" Thick Netting Nylon	Crinkled Polyester Film	.003" Thick Glass Fiber Paper
50	0.95"	0.75	1.35"
100	1.90"	1.50	2.70"
200	3.80"	3.00	5.40"
300	5.70"	4.50	8.10"
400	7.60"	6.00	10.80"

negligible because of the slight lunar surface thermal emission from the shadow.

Considerable work still remains to be done in demonstrating that present techniques are adequate to assure efficient storage of cryogenic fluids on the lunar surface for extended periods. In particular, the design of structural supports and their interaction with multilayer insulation systems will have to be further explored. Experimental confirmation of the reliability of support designs is desirable. The analytical procedures developed for estimating the boil-off rate are adequate, provided that sufficient data becomes available to make these computations as realistic as possible.

Acknowledgments

The authors gratefully acknowledge the support given to this project under NASA Contract No. NAS8 - 11377 and the technical guidance supplied by Mr. James Harrison, NASA Marshall Space Flight Center.

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References

Bonneville, J. M., 1964: Design and Optimization of Space Thermal Protection for Cryogens-Analytical Techniques and Results. Arthur D. Little, Inc., NASA Contract No. NAS3-4181.

Glaser, P. E., ed., 1964: Studies of the Physical Characteristics of Probable Lunar Surface Materials, Part II. Final Report. Arthur D. Little, Inc. (AF 19(628)-421) (AFCRL-64-970 (II).

Glaser, 1965: Implications of High Vacuum on the Characteristics of the Lunar Surface. Presented at The Twelfth National Vacuum Symposium of the American Vacuum Society.

Hagfors, T., Brockelman, R. A., Danforth, H. D., Hanson, L. B., and Hyde, G. M., 1965: Tenuous Surface Layer on the Moon: Evidence Derived from Radar Observations. Science, vol. 150, No. 3700, pp. 1153-56.

Halajian, J. D., 1965: Photometric Measurements of Simulated Lunar Surfaces. NASA Contract No. NAS9-3182.

Hapke, B., 1963: A Theoretical Photometric Function for the Lunar Surface. J. Geophys. Res., vol. 68, pp. 4571 - 4586.

Hapke, B., and Van Horn, H., 1963: Photometric Studies of Complex Surfaces, with Applications to the Moon. J. Geophys. Res., vol. 68, pp. 4545-4570.

Hapke, B., 1965: Effects of a Simulated Solar Wind on the Photometric Properties of Rocks and Powders. Ann. N.Y. Acad. Sci., vol. 123, no. 2, pp. 711-721.

Little (Arthur D.) Inc., 1963: Liquid Propellant Losses During Space Flight. Final Report. Cont. No. NASw-615. Report No. 65008-00-04.

Little (Arthur D.) Inc., 1964a: Basic Investigations of Multilayer Insulation Systems. Final Report. Cont. No. NAS3-4181, NASA Cr-54191.

Little (Arthur D.) Inc., 1964b: Fuel Pressurization and Inerting System for the B-70. AF 33(600)-38669.

Little (Arthur D.) Inc., 1966: Study of Cryogenic Storage on the Moon. Cont. NAS8-11377. Final Report.

Markov, M. N., and Khokhlova, V. L., (1965: Coefficients of Emission in the Infrared Region of the Spectrum and Differences in the Parameter $\lambda = (k\rho c)^{-1/2}$ for the Sea and Continent Regions of the Lunar Surface. Sov. Phys.-Doklady, vol. 9, Feb., pp. 621-624.

McCracken, C. W., and Dubin, M., 1964: Dust Bombardment on the Lunar Surface. The Lunar Surface Layer. J. W. Salisbury and P. E. Glaser eds., Academic Pr., pp. 179-214.

Paivanos, J. A., Roberts, O. P., and Wang, D. I. J., 1965: Multi-Shielding-- An Advanced Super Insulation Technique. Advances in Cryogenic Engineering, vol. 10, Plenum Pr., pp. 197-207.

Pettit, E., and Nicholson, S. B., 1930: Lunar Radiation and Temperature. Astrophys. J., vol. 71, pp. 102.

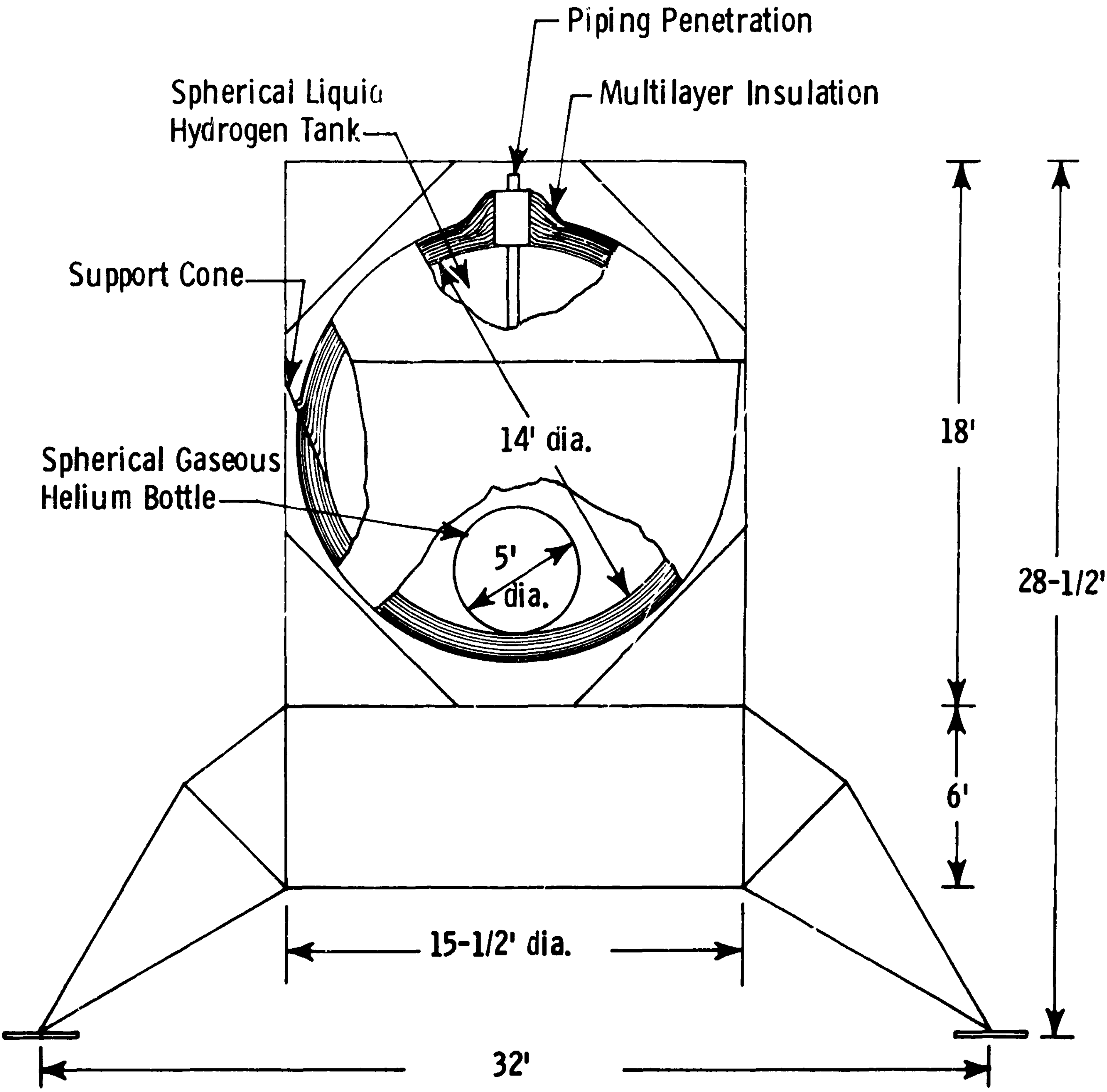
Shorthill, R. W., Saari, J. M., 1965: Radiometric and Photometric Mapping of the Moon through a Lunation. Ann. N. Y. Acad. Sci., vol. 123, no. 2, pp. 722-739.

Smoluchowski, R., 1965: Radiation Sintering of Lunar Dust. Science vol. 150, pp. 1025-1026.

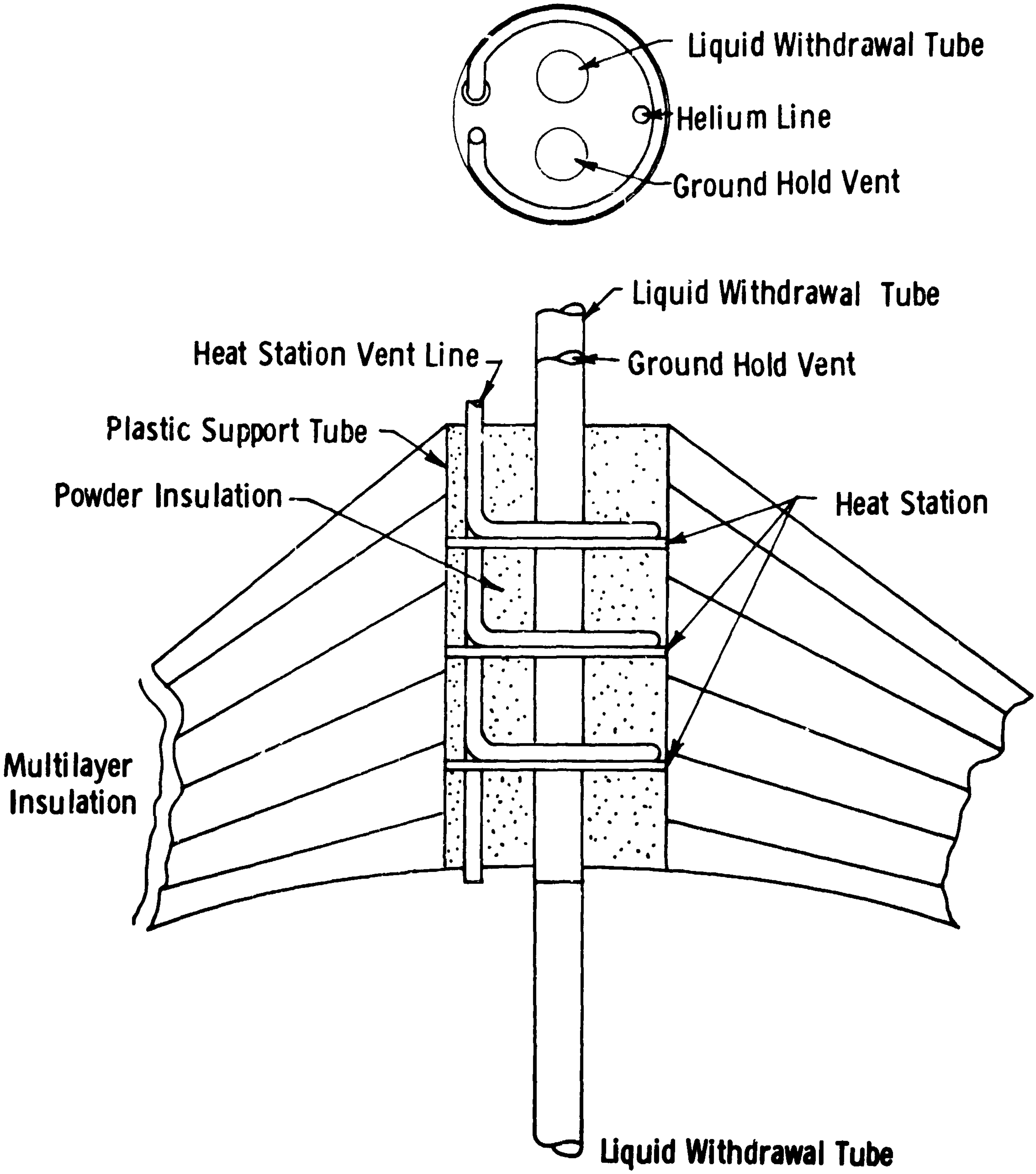
Timmerhaus, K. D., ed, 1958 1965: Advances in Cryogenic Engineering, Plenum Pr.

Wechsler, A. E., and Glaser, P. E., 1965: Pressure Effects on Postulated Lunar Materials. Icarus, vol. 4, pp. 335-352.

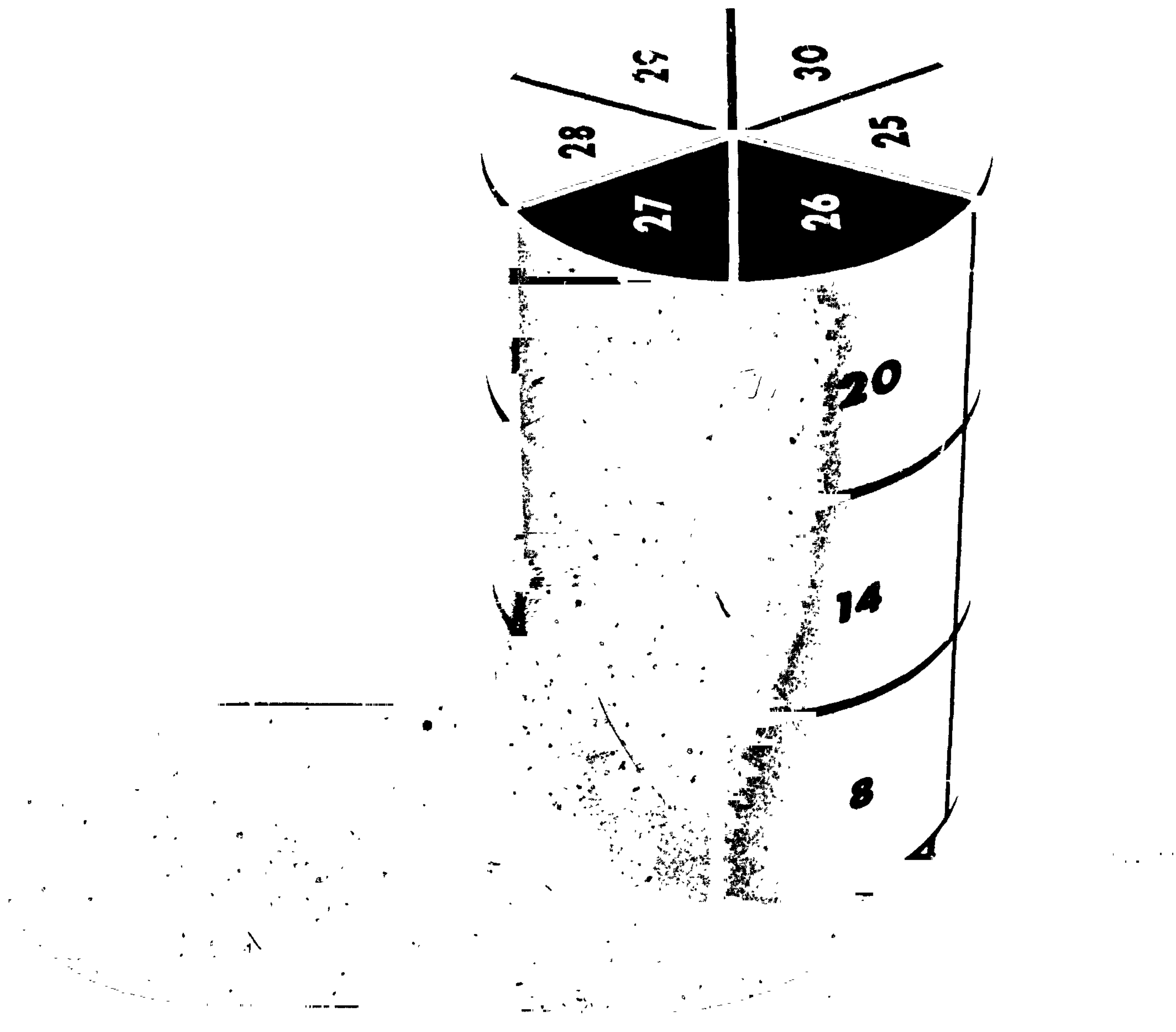
ILLUSTRATIONS



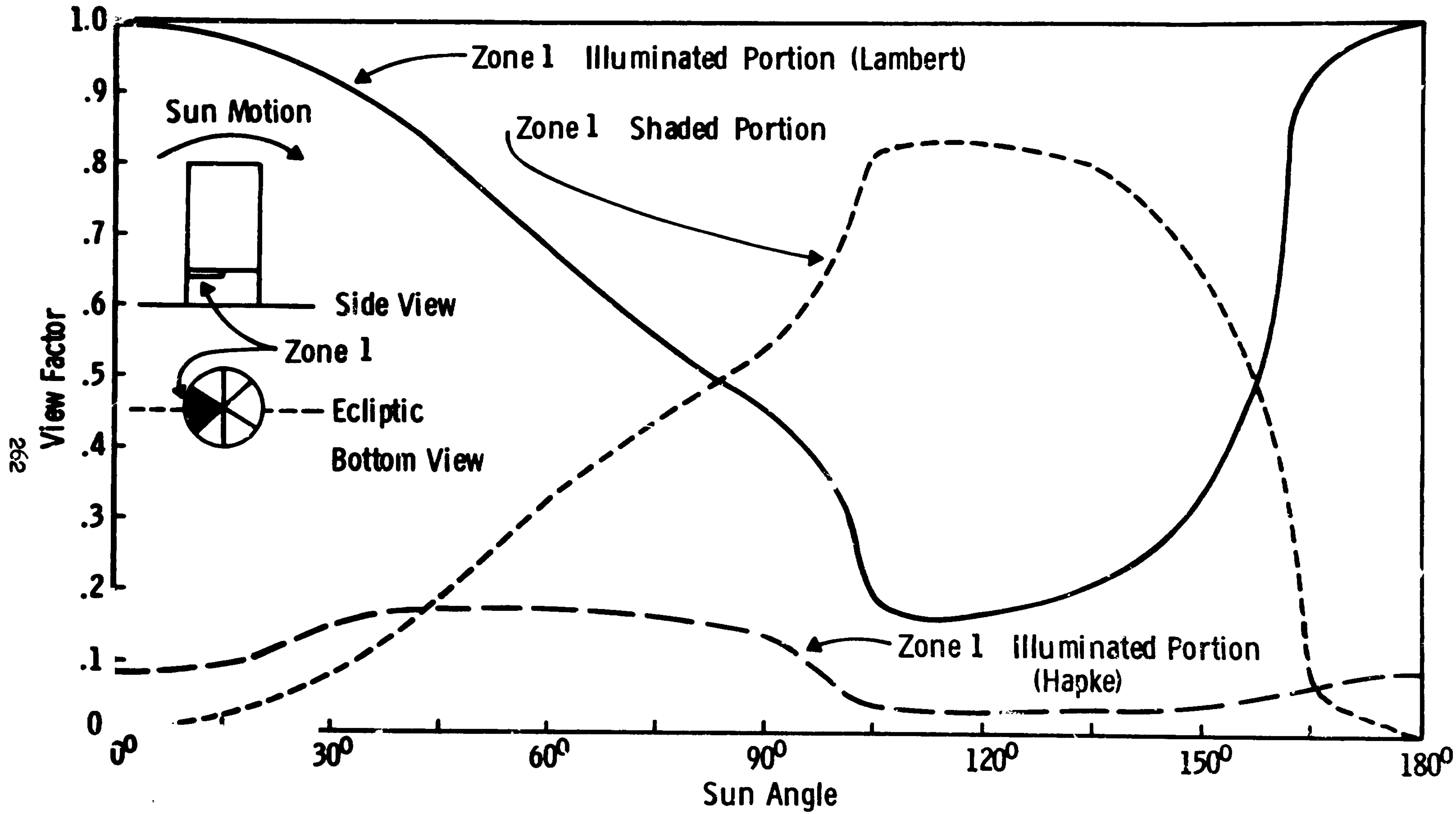
HYDROGEN STORAGE VESSEL CONCEPT



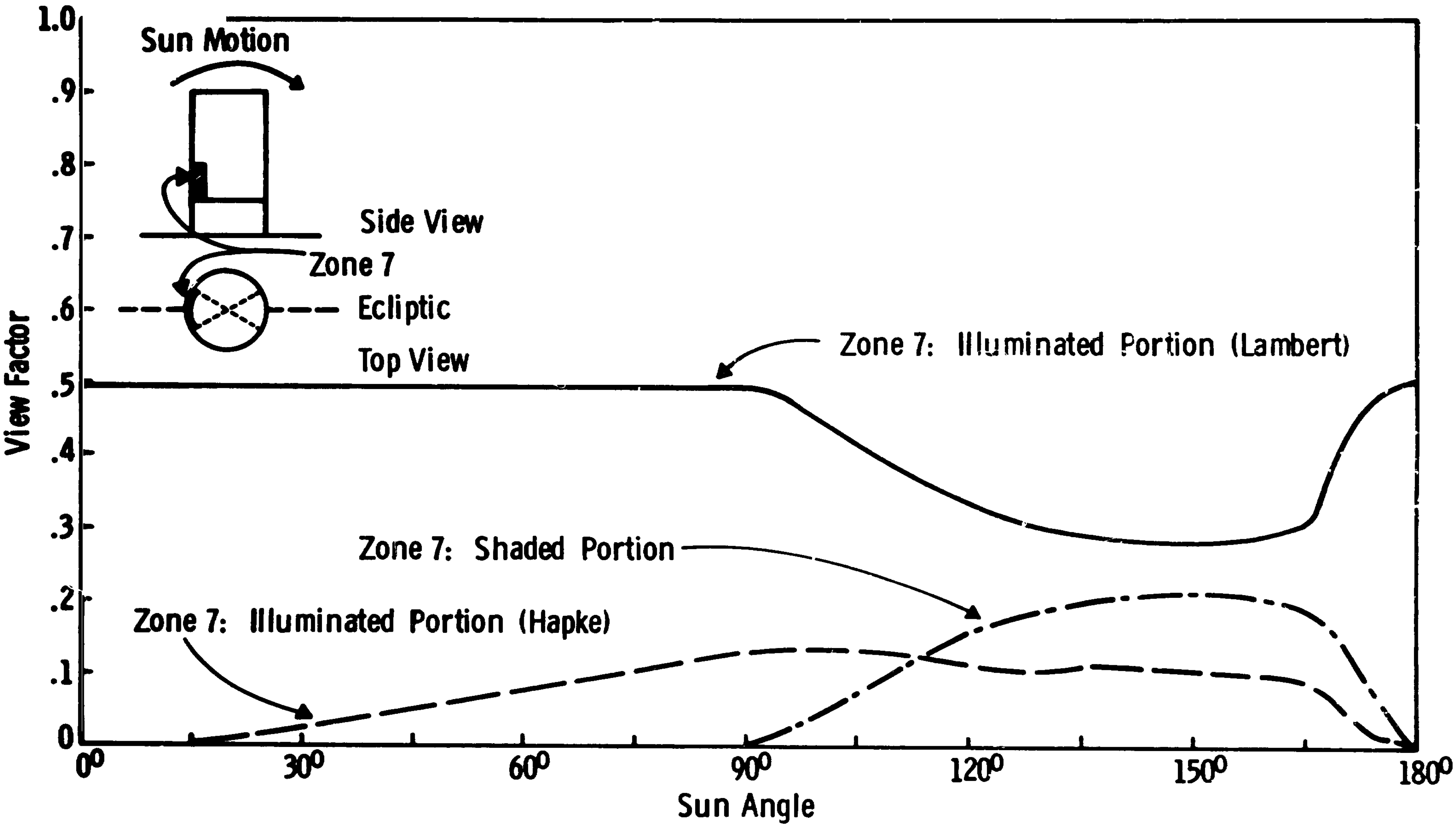
HYDROGEN STORAGE TANK CONCEPT--PIPING PENETRATION DETAIL



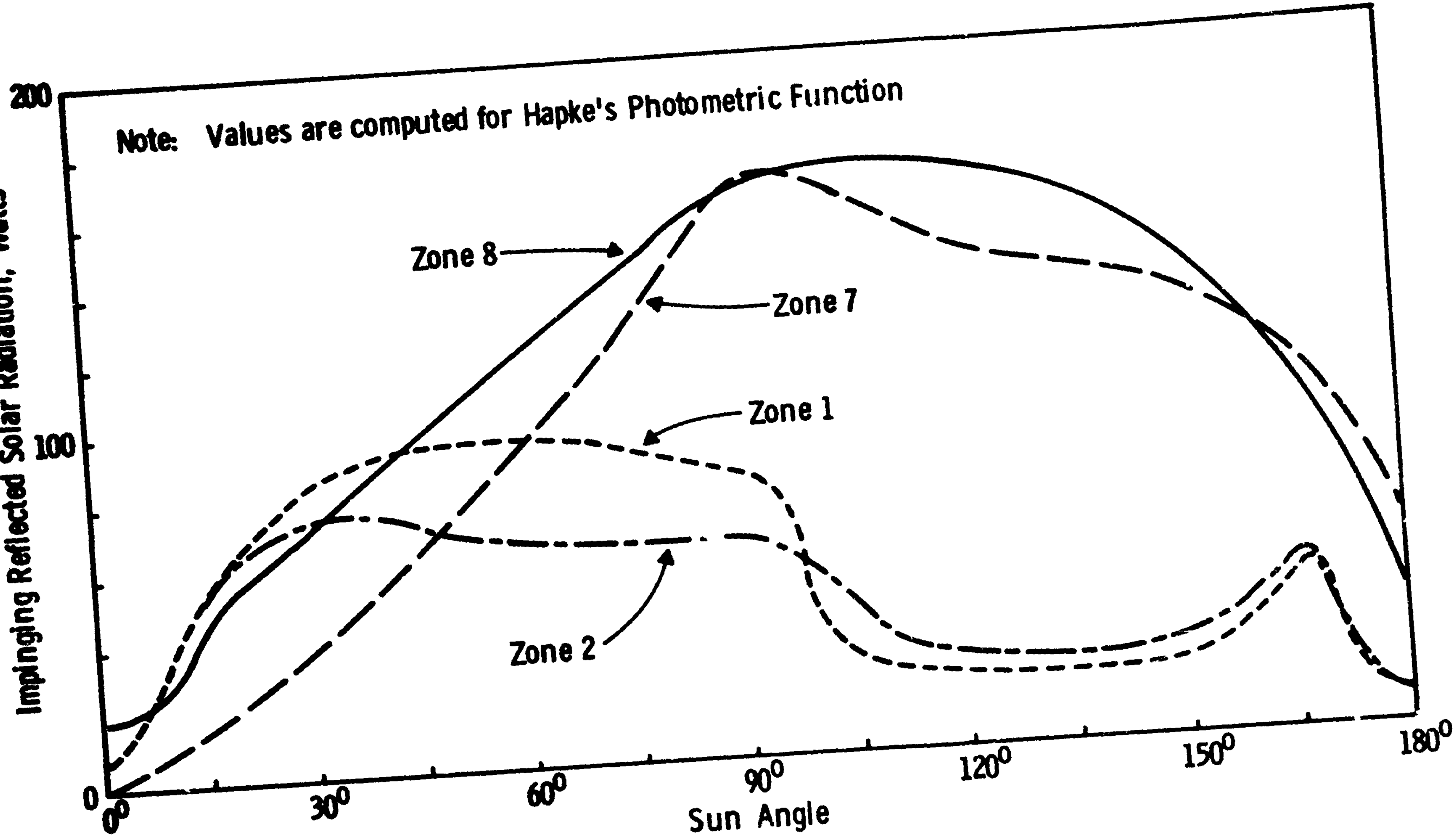
ZONAL SUBDIVISIONS OF MODEL CRYOGENIC STORAGE VESSEL



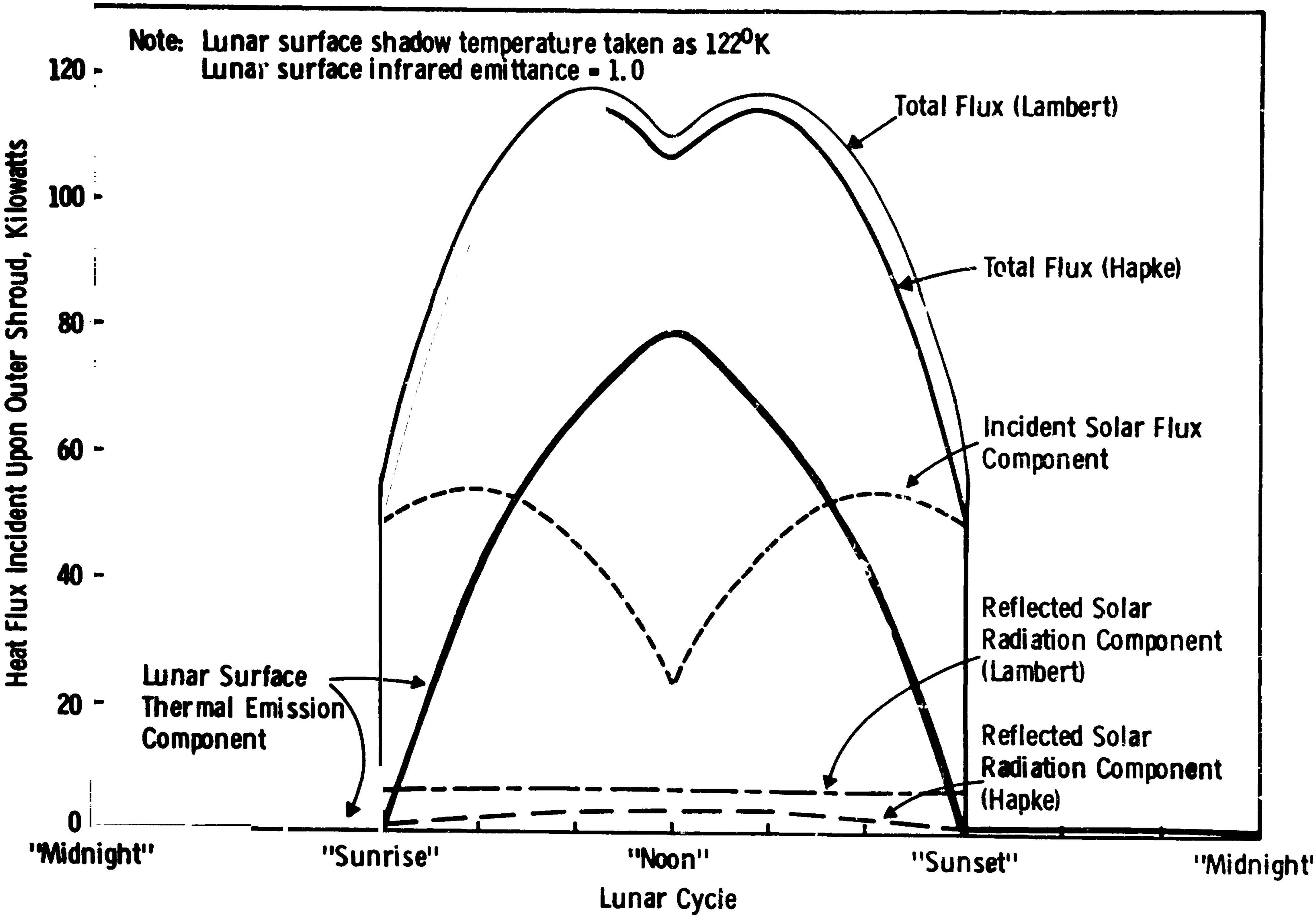
VIEW FACTOR OF ZONE 1 TO SHADED AND ILLUMINATED PORTIONS OF THE LUNAR SURFACE



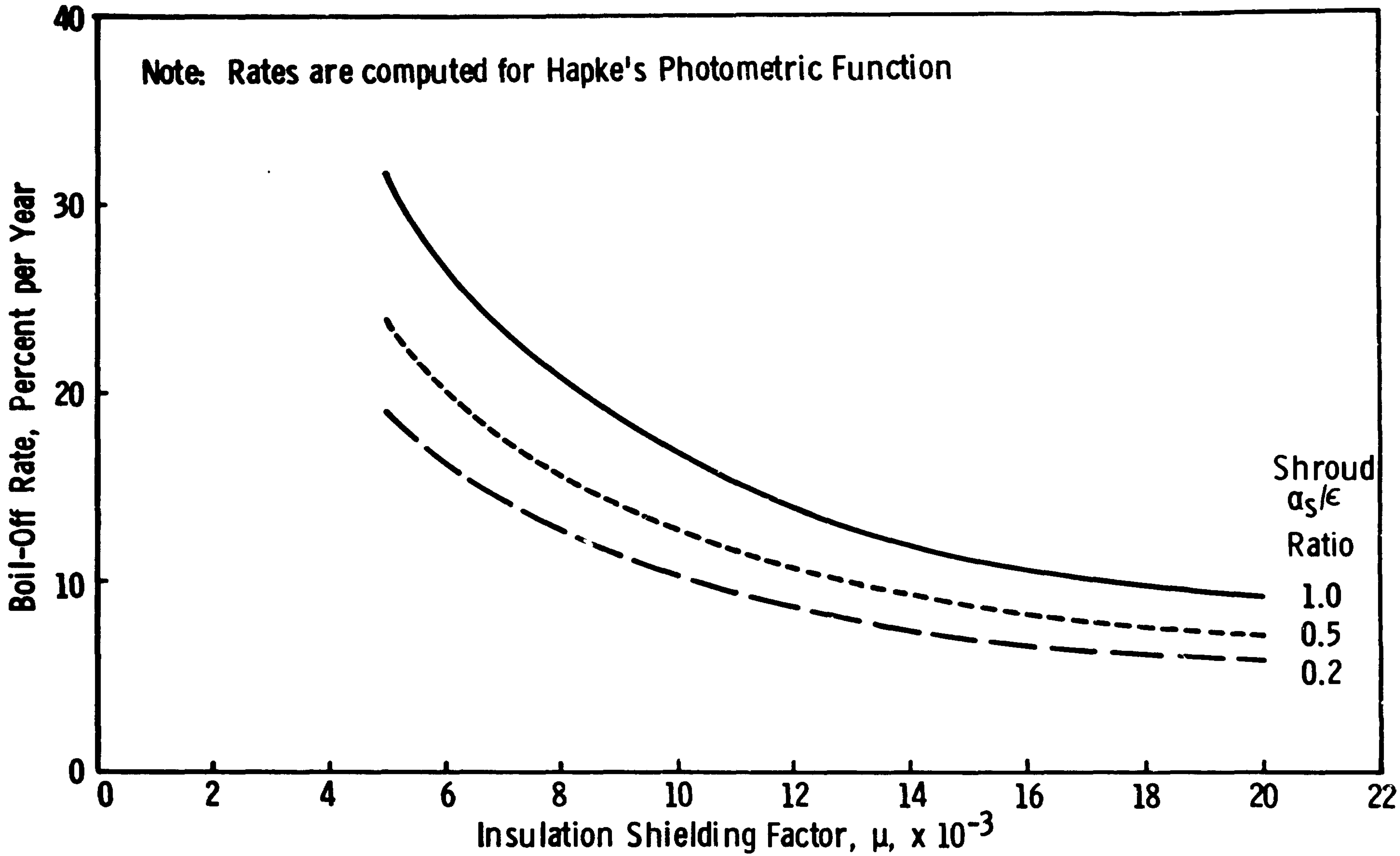
VIEW FACTORS OF ZONE 7 TO SHADED AND ILLUMINATED PORTIONS OF THE LUNAR SURFACE



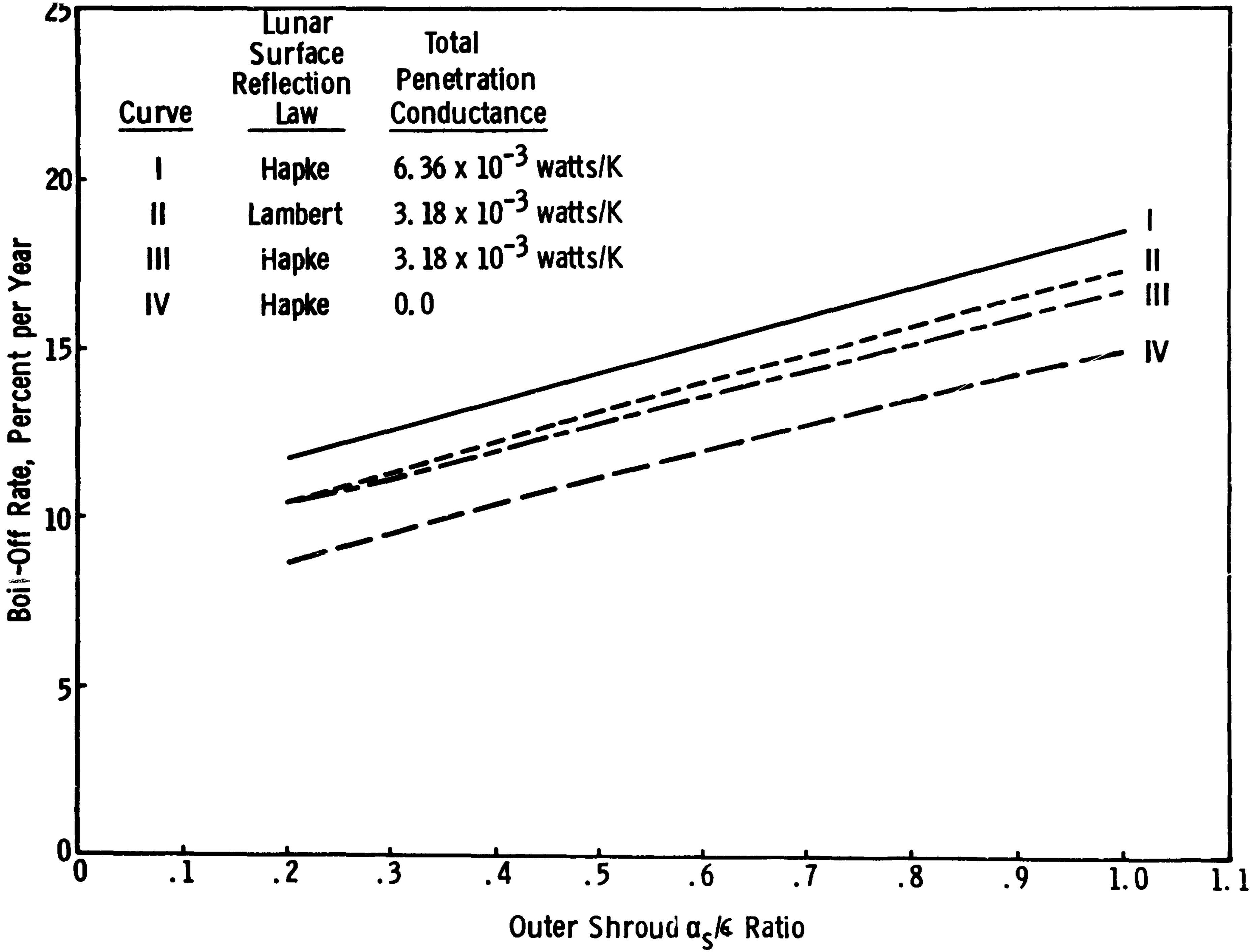
REFLECTED SOLAR RADIATION INCIDENT UPON ZONES 1, 2, 7 AND 8
VS SUN ELEVATION ANGLE



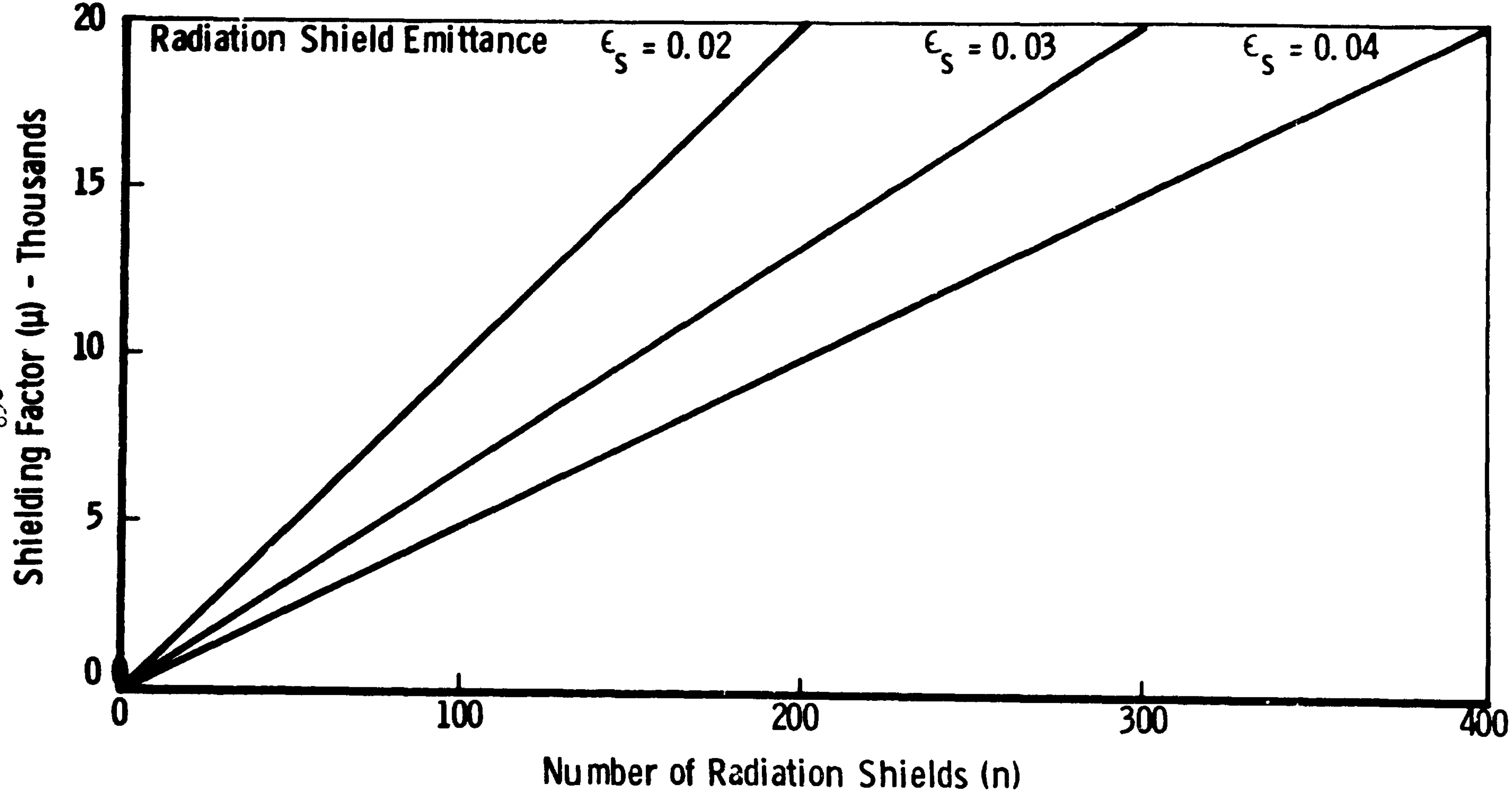
HEAT FLUX INCIDENT UPON OUTER SHROUD DURING A LUNATION



BOIL-OFF RATE VS INSULATION SHIELDING FACTOR FOR VARIOUS OUTER SHROUD SOLAR ABSORPTANCE TO INFRARED EMITTANCE RATIOS



BOIL-OFF RATE VS OUTER SHROUD SOLAR ABSORPTANCE TO INFRARED EMITTANCE RATIO FOR VARIOUS PENETRATIONS



DEPENDENCE OF SHIELDING FACTORS ON DIFFERENT NUMBERS OF RADIATION SHIELDS AND EMITTANCES

LUNAR GEOTHERMAL POWER: SOME PROBLEMS AND POTENTIALS

Carl F. Austin

J. Kenneth Pringle

Richard D. Fulmer

ABSTRACT. Power from geothermal deposits on earth is an established fact, with plant capacities ranging from a few kilowatts to several hundred megawatts. The increasing evidence for contemporary volcanic and fumarolic activity on the moon lends strong support to the validity of the concepts of utilizing geothermal fluids as a source of lunar power. Geothermal energy, whatever the size of installation desired, will probably not be an energy source during early exploratory operations, because of the inherent uncertainty in developing natural resources. On the other hand, the attractiveness of geothermal concepts with their abundant potential for byproduct fuel and life-support production, plus the potential for large continuous power outputs, suggests that the location and testing of areas of geothermal potential should be an early goal for lunar exploration efforts. This paper briefly describes the chemical and structural properties of geothermal deposits and outlines the differences expected between lunar and terrestrial deposits and their surface expressions. The problems of finding geothermal deposits, and of then deciding upon the probable subsurface exploitive testing for initial production are suggested and the problems inherent in large-scale geothermal development and utilization are indicated.

INTRODUCTION

We can start our discussion of lunar geothermal deposits with one fundamental fact: lunar bases, whatever their intent or purpose, will require energy. The moment that man lands on the moon, or for that matter on Mars or Venus, he is faced with a need for cheap, abundant, and reliable power. We can also state with reasonable conviction, that there are two fundamental sources of power on the moon, indigenous and imports. Indigenous power sources on the moon include incident radiation (which on earth has been abundantly stored as fossil fuels), geothermal power, and gravity. Imported power would include delivered items such as fuel cells, reactors, batteries and beamed energy from an orbiting power plant. Once we land on the moon, we can import power directly to the moon's surface. The question thus becomes: "Can the product of our 'Lunar Light and Power Company' compete with cheap foreign imports," a disturbingly familiar question in industrial circles.

Competition includes a good many factors, not the least of which are reliability, initial cost, long-term cost, output quantity desired and ease of expansion. When the costs are figured, they must also include the value of useful byproducts and finally the political climate and attitudes of the day. This paper will review some of the problems and potentials that face our Lunar Light and Power Company and, indeed, the problem is really no different than that of the entrepreneur who has just been offered the public utility concession in, say, Central Chad: (1) is there a market? (2) are there local power sources? (3) if there are local power sources, how do we find them? (4) is there apt to be competition from imports? and (5) are we competitive?

This paper examines geothermal power which is only one type of indigenous lunar power concept. At the outset, let us make two points very clear. Raw-material utilization in a remote area permits bootstrapping; that is, part of the output can be siphoned off to construct facilities which enable larger outputs. You drill a little steam well and run a small engine which powers a drill to make a larger steam well which powers a larger drill rig, etc. This type of growth potential is difficult to achieve, if indeed it can ever be achieved, with imported packaged power equipment, although you can obviously import more packages to add to your output. The second point is that raw-material utilization is a chancy sort of game at best. You cannot look at a good obvious prospect or steam vent and predict with certainty that you can get anything of value back out. The better the appearance of a prospect, the better the odds for success, but even the best prospects can yield unpleasant surprises. With a geothermal deposit, no matter how badly you need the product or how good the deposit looks prior to development, you can never be sure of steam or gas production in a useful quantity until production is actually achieved.

In other words, if you want power supply reliability early in a lunar development program, power must be either imported or else achieved by the use of a raw material that can be fully identified without exploration and development. Examples of the latter are power installations based on gravity or on incident radiation. Prospecting for mineral deposits, including those with a power output potential is without question a task with a high priority, and the establishment of indigenous power sources is the sine qua non for the establishment of large successful, permanent bases. However, actual reliance upon natural resources as a source of power will come only when enough deposits are established or a large enough single deposit is established to provide a statistically sound production base, one that is large enough to absorb the failure of individual wells or deposits to produce as anticipated, without a serious fluctuation in the amount of power delivered.

This paper on the problems and potentials of lunar geothermal deposits is prepared in three sections. The first section presents a summary of the present state of the evidence for lunar vulcanism, or at least active outgassing phenomena. The authors have done this because the presence of contemporary vulcanism and outgassing is controversial, yet is the fundamental assumption in establishing the validity of geothermal concepts as a power source worth detailed consideration. The second section of the paper presents the general types of deposits to be anticipated, realizing full well that specific types of deposits present on the moon cannot be established until examined in situ by a skilled geologist. The third section of this paper presents some of the methods of converting geothermal products that might be reasonably expected, into useful forms of energy and into process feed materials for byproduct production.

FUNDAMENTAL ASSUMPTION

One fundamental assumption is required in order to have geothermal concepts of interest as a potential source of lunar power. This assumption is that magmatic processes with attendant metamorphism and vulcanism have been active on the moon. If this activity is young to contemporary, the probability for geothermal deposits is very high. If the magmatic activity is old, the probability for finding useful deposits is considerably lessened but the geothermal concepts are still of some degree of interest.

At the present time, no one can say with certainty that there is or is not active vulcanism on the moon. Ronca expressed the present situation quite well when he wrote: "Due to the scarcity of data and the impossibility of direct field work, it is difficult to reach any definite conclusion on geological processes operating on the moon" (Ref. 1).

The surface features of the moon have been widely observed, using methods ranging from visual observations through infrared scanning to the close photographic coverage obtained with Rangers VII, VIII and IX. Interestingly, the same data have been consistently cited by all lunar points of view as supporting evidence for each individual set of opinions proving that a knowledge of the presence or lack of contemporary lunar vulcanism will probably wait until the first geologist arrives at the lunar surface to do some field work.

Whether or not there has been some degree of lunar volcanic activity in the past is seldom questioned and most scientists accept the probability of past magmatic activity on the moon The question of contemporary magmatism on the moon, however, leads to a quick formation of opposing forces and viewpoints. In general, we can say that the increasing body of observational facts plus the interpretation of these facts indicates a sufficient probability of contemporary magmatism and vulcanism to warrant serious anticipatory studies on the utilization of these phenomena.

One area of evidence for lunar magmatism comes from radioactive data on terrestrial rocks. Terrestrial rocks are good heat producers, because of their uranium, thorium and potassium contents, and there is considerable evidence for a heating earth, or at least an equilibrium earth (Ref. 2). Indeed, if fully insulated, terrestrial rocks are self-melting within rather modest time spans, although the natural decrease in radioactive abundances since the beginning of geologic time does yield a long-term slowing down of the heating rate and thus in the absolute sense, a "cooling" earth. If the moon is similar in origin and composition to the earth, it too should be self-heating internally. Even if the moon has a composition comparable to that of chondritic meteorites, as some investigators maintain, the moon should be self-heating. MacDonald has used chondritic composition as the basis for lunar speculations and concludes that the outer few hundred kilometers of the moon is now cooling but that the inner 1,200 kilometers is still heating (Ref. 3). MacDonald thus concluded that at a depth of 1,700 kilometers the lunar material could be at a temperature of up to 2,500°C. Radioactive heating of terrestrial rocks is an established fact. If the moon has even similar elemental distributions, it too will be a self-heating body, and regardless of the initial formational temperature, sufficient geologic time will yield a hot interior.

Of a more interesting and less speculative nature are the observational facts that suggest that magmatic gaseous emissions and vulcanism are still active. In particular, Moore (Ref. 4, 5) tabulated a number of features that suggest that the lunar surface and subsurface are both geologically active. Opponents of the concept of lunar vulcanism usually cite as one major line of evidence a lack of observed topographic changes. However, continuing observations have indicated the disappearance of Linné and also the disappearance of a crater near the border of Mare Crisium. Opponents of vulcanism tend to claim poor observations and errors are the causes of the so-called changes observed but repeated observations, by eye, have often proven better than many an attempt at photography and of course much of our observational base was achieved prior to present-day photographic techniques.

There have also been various mists or clouds reported by reliable observers. Examples are a white mist which covered the walled plain of Schickard, a mist filling the interior of Plato, a cloud in the Humboldt Mountains, a patch of vapor in the Aristarchus cleft area, a misty appearance to Canon, the obscuration of Messier A, and more recently, the "out-of-focus" appearance to the central peak in Alphonsus while everything else was in sharp focus. Explaining away most of these sightings as being caused by poor viewing conditions has been a popular notion but despite the lack of scientific popularity for lunar vulcanism in this country, these sightings are probably real. Granted, such mists or clouds do not prove vulcanism on the surface or magmatism at depth, but the actual presence of gas emissions seems rather well-established and gas emissions do suggest underlying magmatic sources. This same line of reasoning grows from the evidence of a tenuous lunar atmosphere including the twilight effect near the "cusps" of the crescent moon, the grey borders which have been observed at the edges of some crater shadows and the observations of apparent lunar meteors. Such phenomena suggest an atmosphere which, in turn, suggests active supporting gaseous emanations.

There are two other groups of observational data which strongly suggest contemporary magmatic activity. One, and by far the most exciting, is that given by Alter (Ref. 6), Poppendiek and Bond (Ref. 7), and Kozyrev (Ref. 8) who have reported volcanic-appearing activity in the crater Alphonsus. Many years ago Herschel said that he believed he had seen a volcano in eruption but modern writers have said that Herschel was mistaken, even though he was one of the greatest observers. Kozyrev now makes almost the same claim, but in this case he has a spectrogram to back it. Secondly, the work of Shorthill and Saari (Ref. 9) in the infrared range taken during two eclipses shows hundred of anomalous "hot spots" across the face of the moon. Many of these infrared anomalies correspond to features which otherwise show or indicate magmatic activity. One of these anomalous areas is at the former site of the crater of Linné. There is no proof of contemporary lunar magmatism, but the suggesting evidence is becoming rather abundant.

GEOTHERMAL DEPOSITS AND THEIR PRODUCTS

Geothermal deposits are defined for the purposes of this presentation as subsurface accumulations of water-rich gasses and associated brines derived from magmatic and metamorphic activity. During the following discussions, the term water will be frequently employed but will mean only a material that is rich in combined or partially combined hydrogen and oxygen; it will not imply a specific physical state or chemical species for to do so would be geologically unwarranted when discussing even terrestrial deposits. Although "water-rich" gasses and brines are emphasized in this presentation, we should bear in mind that "rich" is a relative concept. Thus, a geothermal deposit that is primarily CO_2 in terms of the emitted volume may be water-rich in lunar context if only a few hundred parts per million of water is present. Even with minor water contents, large continuous gas flows can yield major quantities of water, as a byproduct of power production.

POTENTIAL NATURE OF LUNAR DEPOSITS

Here on earth we see two fundamental modes of vulcanism - the widespread and abundant basalts with their deep sites of origin and our economically more interesting but sparse intermediate to siliceous volcanics with their abundant metamorphic to intrusive but less deep subsurface counterparts. Both types of vulcanism have been proposed for the lunar environment (Ref. 10). Both types of magmatic activity involve the collection of volatiles in the magma followed by the expulsion of volatiles during crystallization (Ref. 11). Unfortunately, basalts are much poorer volatile collector-emitter systems than are granitic-type magmas, but even if only basalts are present on the moon, the net result would only be to suggest that the amounts of geothermal product per unit volume of magma would be less. The processes and products should be essentially the same. In the following discussions, magmatic processes are generally emphasized but metamorphic processes which do not ever achieve full mobilization as a crystal mush should also be fully capable of yielding geothermal deposits with large power and byproduct potentials.

We do know that here on earth the processes of magmatism are capable of releasing tremendous quantities of heated water. Terrestrial vulcanism, however, is intimately associated with the abundance of connate waters, circulating groundwaters and the hydrated and hydroxyl bearing minerals so common in our crustal rocks. Although a number of isotope geochemists have stated that most emitted waters from terrestrial magmatism are not magmatic but are merely shallow surface waters that are returned to the surface, this theory overlooks the fact that the connate and other entrapped waters of rocks undergoing intensive metamorphism to yield a crystal mush should be rather ordinary in isotopic composition as well (Ref. 12). Thus the apparent lack of "juvenile" water in magmatic activity should not be equated with a lack of "magmatic" water when describing the potential volatile content for terrestrial or lunar vulcanism and associated magmatic activity.

Certainly, here on earth, the greatest amount of shallow geothermal activity is to be seen in areas of abundant groundwater, and most people do not expect groundwater to be abundant on the moon, at least not in the near surface environment. On the other hand, lunar rocks can be expected, as will be shown, to store water and volatiles in many ways and in considerable quantity. Any magmatic activity, such as an intrusion or a gas or fluid flow should thus have the opportunity to extract this water content to yield water bearing geothermal deposits and emissions.

The geologic evidence at hand indicates that magmas of both basaltic and granitic compositions, particularly the more granitic magmas, are capable of extracting water from their surroundings and that partial pressure considerations indicate that water and other volatiles will collect in the upper portions of a magma chamber. This general process of volatile collection followed by expulsion upon cooling and during surficial eruptions is well-evidenced terrestrially by the variations in volatile content seen in continuing eruptions which become progressively drier with time. At present, the same general processes of petrogenesis are expected on the moon as are active on the earth and lunar magmas and metamorphic zones, if they exist, should extract volatiles including water, from the rocks comprising and surrounding the melt or metamorphic zone. The expulsion of these volatiles in fumaroles and the collection and concentration of these volatiles in adjacent and overlying permeable zones constitutes the anticipated sources of lunar geothermal fluids and gasses (Ref. 13).

In terms of abundances, terrestrial volcanic (i.e., magmatic) emissions are mostly water in the form of steam. Carbon dioxide is apparently the next most common emitted volatile, although CO, H_2 and HCl can be very abundant (Ref. 14). Increasingly, liquid CO_2 is being recognized as entrapped in deep terrestrial rocks, leading to the suggestion that CO_2 or even CO and related carbon bearing gasses may well be the dominant gasses in relatively dry lunar geothermal systems (Ref. 15). In support of the latter suggestion is the recent identification by Urey of C_2 molecules in the spectra of gasses emitted by Alphonsus (Ref. 16).

Terrestrially, the temperature and the concentration of geothermal gasses and brines are dependent primarily on the quenching and diluting capability of the near surface environment (Ref. 17). On the moon, such quenching and dilution is considerably less likely and may, in many instances, be absent. As a result of the continued emissions of hot gasses over appreciable timespans, the conduit walls for a given lunar thermal deposit can be heated sufficiently to yield very hot gasses at the surface. Because of the general lack of shallow circulating groundwater, lunar fumarolic activity should be of a much higher temperature in near surface deposits than is normally achieved on earth, and temperature gradients should be more abrupt adjacent to active conduits. The probability of numerous localized high thermal gradients adjacent to more or less "point" hot gas sources is not inconsistent with the very interesting infrared patterns with numerous hot spots recently obtained for the lunar surface by Shorthill and Saari (Ref. 9).

On earth, the typical geothermal prospect appears as a hot spring, although strictly gaseous fumaroles (including mud volcanoes) are very common at the sites of contemporary vulcanism and at geothermal deposits undergoing subsurface boiling. On the moon, the most common surface expression of underlying geothermal deposits should be an active fumarole or steam vent emitting multicomponent gasses including water, CO_2 and the more common fumarolic gasses CO, SO_2, HCl, HF and H_2S. In view of the abundant sublimates or gas-gas reaction products observed at many volcanic sites, there is also the likelihood of considerable "dissolved solids" transport in fumarolic emissions on the moon (Ref. 18, 19).

That water and CO_2 should be the principal geothermal products on the moon can be established by analogies drawn on terrestrial observations and the probability of lunar water-rich fluids (in the absolute sense) is not as low as it might seem at first glance. If a water bearing gas traverses increasingly cooler rocks and then expands into a rather open breccia zone or scoria lapillae horizon, the result can be the frosting-out of ice, to yield a water-rich horizon. As continued gas flows deposit ice or salts in the overlying cover, and increase the flow friction of the area, the gas flows will seek new channels, leaving a now stagnant ice horizon. This can undergo heating at some later time, due to nearby intrusions or due simply to an advancing thermal gradient resulting from the original intrusion. If the degassing of this horizon has become difficult due to sealing of the ice horizon by renewed lava flows, by faulting, or by salt deposition, the result upon heating will be a water saturated horizon and a true brine, quite probably with a gas cap comprised of less easily condensed materials. The analogy with oil accumulations is identical with regard to the need for source beds, material migration and traps. For those who doubt the proper sequence of events is probable, the authors recommend a review of the genesis of terrestrial petroleum which requires an equally complex sequence of events.

Once melting is achieved, convective cooling can take place within the lunar brine deposit. Whether or not such a brine can become geologically self-perpetuating in the lunar environment, yielding large areas of subsurface circulating water is a question beyond the scope of this paper, but the problem is certainly an interesting one.

A second lunar brine possibility is found in the deposition of salts with contained water due to temperature-pressure drops or to gas stream interactions. If highly deliquescent, as for example many complex halides are, a horizon can develop with what might be termed a deliquescent salt brine. In the lunar environment a probable sequence of events yielding a power potential from a deliquescent salt accumulation would be similar to that described for ice, where metamorphism or renewed heating would liberate the stored water. The same processes of entrapment followed by liberation and storage can, of course, be cited for the heating of hydroxyl and halide bearing materials. Similar releases of volatiles are often demonstrated on earth in the metamorphism of rocks such as limestones which yield accumulations of CO_2, H_2S, or N_2; shales which yield petroliferous products, CO_2 or NH_3; and coals which yield CO, CH_4, CO_2, NH_3 and oils.

PROBABLE SURFACE EVIDENCE

Surface evidence for underlying geothermal deposits on the moon falls into several categories. These are distinctive structural environments; surface discoloration from alteration and the deposition of salts; gas emissions; and thermal anomalies.

Distinctive favorable structures for geothermal deposits are of three broad types: (1) active volcanoes (2) areas of caldera formation, particularly where there has been very recent volcanic leakage, whether they be isolated calderas or caldera type depressions marginal to major fault zones; and (3) any older petroleum-type trap, be it structural or stratigraphic, with initial attention being best concentrated on regions of doming and adjacent to faults cutting modestly dipping flows with "interbedded" pyroclastic horizons.

Surface discoloration will consist of bleaching or other alteration where wet or corrosive gasses have escaped along fracture zones and areas where colored salts and sublimates or "frosts" have accumulated over porous zones. Along fractures or along permeable outcrops, one terrestrial feature that should not be observed, however, is the common widespread bleached zone resulting from acid sulfate activity as a result of H_2S (or pyrite) - atmospheric oxygen - surface water interactions.

Gas emissions per se should be locatable on the basis of surface surveillance programs including "atmosphere sampling" surveys and observational programs based on gas-incident radiation interaction effects since local temporary atmospheres should collect around large, active vents.

Ground temperature studies are exactly analogous to those now performed on earth, and will consist of infrared reconnaissance grids as well as surface and borehole temperature studies.

METHODS OF RECOVERING GEOTHERMAL GASSES AND FLUIDS

The simplest and cheapest geothermal deposit to exploit is the fumarolic vent which spews forth gasses at some elevated pressure and perhaps quite high temperatures. A tube can be rammed into the vent throat and rocks piled around and over the tube in order to keep it in place. If two pipes in annular configuration are used, a gas cartridge can be fired to force a plastic foam through holes in the wall of the outer tube, thus helping to cement the tube to the vent throat (Ref. 13). The result is a small gas well, which should have a vent to the local atmosphere plus a feed pipe to the "power plant". The vent can be closed to the extent that the casing and adjacent rocks can withstand the "in-the-well" pressure.

If sublimation or salts deposition has been active in sealing the surrounding rocks and surface, the potential operating pressures can be quite large.

Deeper wells can be drilled using power from shallow wells, as has been done in some geothermal steam fields on earth. Depth is desired in order to provide higher operating pressures and larger flow volumes. On the moon, as on earth, a geothermal bore hole can encounter pressures between two limits. The lower limit is the weight of the gaseous or fluid column plus an increment due to flow friction if the system is not static. The upper limit on well pressures is a pressure equal to the weight of the gas or fluid column plus the weight of the overlying rock mass. By going to considerable depth, not only is an increased rock cover present but an increased flow friction derived increment of pressure is also provided. Most shallow terrestrial geothermal bore holes have low pressures and leak quite badly through the surrounding rocks. In addition, a number of terrestrial wells have cratered or blown out due to casing practices that have subjected weak near surface rocks to high pressure steam from greater depths (Ref. 20, 21). One recent well near Sulfur Bank, California has reportedly also encountered hot CO_2 at pressures approaching the upper limit for geothermal wells, causing considerable difficulty with the casing to host rock bonding in this instance. The common terrestrial problems of blowout prevention and well control will face all geothermal drilling efforts.

A serious problem with most geothermal installations is the plugging of wells and pipes with precipitates and sublimates. Although such deposits hinder power production, the deposition can be of value for chemical byproducts as in the case of the tonnage quantities of copper and silver recovered in a 90-day well flow test at Niland, California recently. All equipment and installations must be designed to facilitate cleaning with little or no down time.

The exploitation of deliquescent salt deposits and of subsurface ice deposits can be accomplished by solution mining and by gas injection. Hot gas injection can be accomplished using, for example, a dry exhaust gas from a power or process plant or a dry gas produced from some other horizon and power may be extracted either before or after the addition of the recoverable water to the gas, depending on the ease and economy of the various possible processes.

Ice horizons, deliquescent salt horizons and entrapped gas and brine-filled porous horizons may well prove to be the "fossil fuel" deposits of the moon. The anticipated products that can be expected in the production pipeline are:

Cold gasses, dry to wet, probably dust or solids bearing, in which elevated pressure is the principal power value.

Hot gasses, dry to wet, probably dust or solids bearing, in which both temperature and pressure are of power value.

Cold brines, in which differential pressure is the only power value.

Hot brines, in which both temperature and pressure provide significant power potentials.

Although water and CO_2 are the most probable large volume products from lunar geothermal deposits, the possibility of significant quantities of other volcanic gasses is quite large as is the probability of more exotic gaseous compounds in the drier fumarolic emissions.

GEOTHERMAL POWER GENERATION

Once the geothermal potential of a given lunar location is known and the quantity of fluid and gas flows established, the problem becomes one of converting the resulting geothermal energy to some useful form. At the present, geothermal power is considered to be of value in three main areas: (1) electrical power generation, (2) providing mechanical power, and (3) for heating. The terrestrial use of geothermal energy is not new. Power generation has been accomplished at several places on the earth with commercial success and considerable additional exploration is underway at the present time. In addition, the heating value of geothermal fluids has been utilized for a number of years in Iceland and has also been used for process heat at various other localities (Ref. 22). The use of geothermal energy in the lunar environment will no doubt result in some unique problems not encountered in the terrestrial use of geothermal energy and the following section of this paper is a general review of the problems and processes of lunar geothermal power exploitation.

The path pursued in the conquest of geothermal power on the moon depends on a number of factors including (1) the intended energy usage, (2) the type of geothermal emission encountered, (3) the length of time that power is needed, and (4) the phase of lunar exploitation in which the power is desired. Intended geothermal energy usage on the moon can cover a wide range of applications including conversion to electrical or mechanical power, and use as a direct heat source for processes and activities including mining, propellants production, communications and life support.

As noted in an earlier section, a wide variety of magmatic and volcanic emissions should be encountered ranging from gasses through liquids; from hot to cold, and from very clean to highly contaminated by dust and chemicals. Here on earth, only the more easily utilized geothermal deposits with relatively clean, high pressure steam have been exploited. On the moon there will not be as many choices of power sources as on earth, and if geothermal power is indeed found in exploitable quantities, it may be available in the form of geothermal gasses and liquids that are something less than ideal. The designer of lunar geothermal equipment will thus be faced with a number of problems not encountered in present-day terrestrial geothermal exploitation.

The duration of the power requirements for any given installation will be very important. In the case of relatively short-term application corrosion, erosion, and solids deposition will not be as severe a problem as at installations where the equipment must last for a number of years. Except for the special situation where clean steam or dry gasses are readily available and abundant, geothermal power will probably not be competitive with other sources of energy for short duration missions.

The existing phase of lunar exploitation will be important in determining the competitiveness of geothermal power, particularly in regard to the level of reliability required. In the later phases of lunar exploitation, geothermal power and heat are readily envisioned for use in large permanent base stations. In the case of small early bases, however, the needed output must be initially and immediately reliable as well as relatively small, thus indicating a sharp competition with packaged reactors.

POWER TRANSFORMATION SCHEMES

With a majority of the lunar deposits expected, an open cycle, or more correctly, an open process will prove initially advantageous. The geothermal fluid will run directly through conversion or heating devices and then, with respect to the power cycle, be discarded. This is not to say that the geothermal fluid cannot be used for multiple energy purposes such as first generating electrical power and then providing heat for hydroponics installations and living quarters. Nor does an open cycle imply that the geothermal fluid may not be processed either before, during, or after the power cycles for the fluid's chemical or water content. Open cycles do mean that in the end the fluid will be dumped overboard, carrying unwanted waste heat and chemicals and that the fluid will not re-enter the power cycle again.

A "closed cycle" with a recirculating secondary working fluid should be used where the geothermal fluid contains chemicals detrimental to the equipment with which it comes in contact. With closed cycles instead of circulating the geothermal fluid directly through the prime mover or other equipment the geothermal fluid would be used to heat the secondary fluid which would operate under truly cyclic processes, such as a Rankine or Brayton cycle. A secondary fluid type of system would involve more complex equipment and the thermal efficiency would not be as great as in the case of direct geothermal fluid use but the savings in equipment life might well be the difference between economic or noncompetitive operations. Heat exchangers can supply the heat to the secondary fluid with no problem. On the other hand, heat rejection from the secondary fluid is a serious problem requiring the use of a space radiator system or a secondary heat exchange system working with cooled, expanded primary fluid exhaust products or some other heat sink system. With corrosive fluids, a heat exchanger can usually be made more simply and operated more inexpensively than a corrosion-resistant prime mover or a corrosion-resistant complex heat transfer system for space or process heating. With heat exchangers, scale can be easily removed, the heat transfer surfaces replaced, and corrosion-resistant materials can be used in heat exchangers which do not have the structural characteristics necessary for turbine or other engine parts.

A number of secondary fluids can be used with heat exchangers. Water is the most obvious possibility as it may well be locally available. Power generation cycles using freon heated by geothermal steam have often been proposed for terrestrial use. With freon a larger heat input to the power cycle can be obtained than with water as the secondary fluid. The final choice of fluids for any given installation will depend on the boiler and condenser temperatures available to the cycle and the relative delivery cost of the secondary fluid at the lunar plant site.

With the present status of technology turbines appear to be the best prime movers for electrical power generation on the moon. The turbines may be gas, steam, or even liquid-driven units. Turbines will certainly find good use wherever high-speed mechanical power is needed. Turbines for lunar use will be slimmed down, optimized versions of our terrestrial units and the metals used in their construction will very likely not be the metals picked for economical service on earth. Instead, metals such as titanium which has a high strength-to-weight ratio and great corrosion resistance to brines will be of interest to the designers of lunar turbines. Turbines have the disadvantage of requiring relatively large flows of pressurized fluids, which means rather voluminous geothermal emissions will be required for their operation. This need for large volumes of emissions is of no consequence for large permanent installations but suggests that low volume, high head equipment will see more use in early installations.

Reciprocating gas or liquid-driven engines will be used where slower, "workhorse"-type mechanical power is needed, for example, for propellant liquefaction. Positive displacement engines have the advantage of being able to operate under conditions where flow rates are low but shut-in pressures are large. Early attempts to harness geothermal power using either natural vents or shallow, low-volume wells will probably be most successful in conjunction with a reciprocating device that can provide the power needed for drilling larger wells or for localized life support functions. Reciprocating devices also have the advantages of slow speeds and of being easily cleaned and repaired.

Present technology does permit a modest electrical output from large banks of thermocouples and similar nonmechanical concepts and there is certainly much room for technologic advancement. For the immediate future, the more conventional power conversion systems appear the most attractive and lunar geothermal fluid exploitation will initially at least employ various types of reciprocating devices and various types of turbines.

EFFECTS OF ENVIRONMENTAL CONDITIONS

The apparent lack of a lunar atmosphere of more than a tenuous nature will be one of the main factors to consider in the operation of equipment designed to exploit geothermal power. This lack of a dense atmosphere will provide both advantages and problems. For power generation the thermodynamicist will relish the infinite vacuum into which he can expand his working field and, in theory, a very high cycle efficiency could be obtained during fluid usage. However, as with all good things, trade-offs and limitations develop. In reality the efficiency of the cycles employed to use geothermal fluids will most likely be limited by either the physical size of the equipment involved or by the condensation of the working fluid beyond acceptable limits within the equipment. In the former case, expansion of the working fluid to low pressures results in large volumes of gas which in turn requires very large equipment. Although the equipment may not need to be heavy since the pressure differential across the walls of the equipment may be relatively low and the gravity body forces will be only about 20 percent of those encountered on earth, the shear bulk of the equipment will provide a practical limit to the amount of gas expansion that can be achieved. Furthermore, with wet or mixed gasses, when the temperature drops below the condensation point of one of the components, increased amounts of condensate will form as the working gas is expanded. Beyond a certain point, erosion in the equipment will become excessive, especially in turbines. Trade-off studies with the actual gasses or liquids in hand will be needed to determine how far any given geothermal gas mixture should be expanded.

In some respects, the abundant environmental vacuum will not be beneficial. Problems commonly cited for space applications include metal welding or adhesion and lubrication, although the presence of the working fluid in contact with most of the moving parts in turbines and engines will provide an atmosphere that should alleviate problems such as lubrication sublimation and relay welding but will bring about problems of lubricant contamination and corrosion. In many cases, the machinery will be housed within a building or gas bag possessing an artificial atmosphere made up of exhaust or product gasses. As a result of the increasing volume of knowledge on space technology coming from the existing aerospace industry, no serious problems are foreseen in the area of equipment operation as the result of a space type environment, per se.

EFFECTS OF GEOTHERMAL FLUID ON POSSIBLE POWER CYCLES

A dry or nearly dry gas will be attractive for use with turbine-type prime movers. The dry gas will allow expansion to lower pressures and temperatures without the occurrence of condensation. With dry gasses more power per unit weight of working fluid is possible. Obviously, a high initial fluid pressure is always desirable in that with either steam or gas the size of the equipment will go down as the inlet pressure goes up for the same inlet-to-exit pressure difference and weight flow of working fluid. There is a distinct possibility that on the moon there will be an abundance of relatively dry geothermal gas wells. Very likely, such gasses will contain dust as a solid contaminant. Where dust is abundant a separation process will be needed before the gas is introduced into the machinery. For a steady-state type of operation using large volumes of gasses with contained solids or condensed materials, cyclone-type separators can be used to obtain a sufficiently dust-free gas to protect the equipment. If only small amounts of solid contaminants are involved, conventional filters can be adequate. Although a dry gas is fine for power generation, it certainly will not supply one of the byproducts that makes geothermal power in general look so interesting, i.e., water. However, for most gasses, at least small amounts of water are expected to be present and separation processes in the plant exhaust can recover this water.

As the temperature and pressure of the available dry gas decrease, the amount of recoverable energy becomes smaller. Since there are lower limits on the amount of expansion that can be practically accomplished, a larger volume of gas must be processed to obtain a given amount of output and if the gas volume is available, this will simply mean larger equipment, or else multiple units in order to achieve a desired power output.

Given a choice of fluids, superheated steam would be the best general all-around fluid for geothermal operation. It would provide a good working fluid for the power cycles; it would be very good in heating applications where the phase change heat could be recovered to advantage, and steam would provide large quantities of byproduct water. Steam can be expanded through turbines or reciprocating engines but in doing so the steam will soon reach the saturation point and begin to condense. This is especially troublesome with turbines and as expansion continues, more water will condense out until a point is reached where the erosion on the turbine blades and associated parts becomes intolerable. For commercial applications on earth, this economic damage point is often set at 10 percent condensed water by weight. With moisture contents higher than this, blade erosion costs exceed the value that can be derived from the additional power obtained. In early lunar applications, exotic metals, plastics and shorter projected life times for the equipment may allow economic short-term operations with higher moisture contents in their low pressure sections. For a reciprocating unit, the allowable moisture content can be considerably higher, if speeds are slow and the exhaust valving can handle the volumes involved. Although water has been stressed, other condensable gasses are quite probable in lunar geothermal emissions.

For heating applications the degree of condensation will depend to a large extent on the amount of heat needed and the gas flow available. If large quantities of heat are needed and the flows relatively low, the heating gasses may be almost totally condensed. If large volumes of gas are available with respect to the heating needed, then very little in-the-system condensation may be necessary.

Geothermal-energy utilization will almost undoubtedly require working with a mixture of gasses. These gas mixtures may be obtained as a working fluid directly from the well, or they may result from a process whereby a hot pressurized water bearing brine or some nonaqueous solution is obtained directly from the ground and then a portion of the brine or solution is flashed into steam or gas, resulting in a mixture of water and steam or at least liquid and gas at some pressure and temperature lower than the original material. For power applications the liquid and gas will have to be separated out, using traps or some similar device such as a cyclone-type separator. After the gas-liquid separation is completed, the power generation processes will be the same as with steam or gas produced directly from the ground.

If relatively pure hot water, water-steam mixtures or other liquid-gas mixtures are obtained, they can be used directly in heating processes. If aqueous brines or other solutions are obtained, either flashed steam and gasses or else the use of heat exchangers and secondary heating liquids may prove mandatory because of the deposition of minerals caused by the resulting drop in temperature in the heating equipment.

The final case to consider is when cold liquids under pressure are encountered. If such liquids are under pressure but have no gas to expand and continuously propel them out of the reservoir, they will very quickly relieve their pressure, expand their small amount and deliver little or no power. If gas is trapped above the liquid as in the case of many terrestrial oil wells and the gas can propel the liquids out of the reservoir at a considerable velocity and pressure, then the kinetic energy of the liquid can be converted into useful power and the fluid can be used to recover the energy of the gas that is expanding within the reservoir by means of displacement engines.

DEPOSITION, EROSION AND CORROSION

Deposition, erosion and corrosion will provide serious problems for the lunar equipment designer. The deposition of solid materials in the equipment must be anticipated. This is especially true of brines or non-aqueous solutions where a drop in the temperature separately or combined with a loss in solvent content due to flashing can precipitate large volumes of undesirable solids in the equipment. Such conditions will almost of necessity be present in flashing vessels and in heat exchangers in the case where a secondary loop is involved. Provisions must be made for either continuously or at least periodically cleaning flashing vessels and heat exchangers with duplicate units necessary when a continuous output is needed. Deposition of solids will certainly have to be controlled in turbines and other hard-to-clean equipment.

Erosion will be a problem in all equipment where high velocity gas-solid or gas-liquid flows are utilized and the high-speed turbine is certainly the most vulnerable in this respect. If dust from a well is not removed, if solids precipitate in the gas stream due to sublimation or gas-gas reactions, or if liquids condense during the expansion process, the turbine will suffer rapid and serious mechanical damage. A certain amount of erosion can be tolerated, but this amount must be compatible with the expected equipment life required in order to compete with other power sources.

Corrosion will be a problem with most equipment. The handling of aqueous brines, for instance, has always involved a corrosion problem in the terrestrial chemical industry and the lunar environment is expected to be no different. There is a high probability that hydrogen chloride, hydrogen fluoride, and hydrogen sulfide plus various carbon containing gasses will be present in many geothermal emissions. These compounds, combining with possible moisture in the gas, form solutions which can be detrimental to the equipment or can corrode the equipment directly. Unlike deposition, where it is possible to clean the equipment and essentially return to the original equipment condition, corrosion and erosion are much more final; once the corroded material has left the equipment, it is gone for good.

As a result of these potential problems, careful consideration will have to be given to both the configuration and the materials used in making lunar power conversion equipment. More exotic metals and alloys will probably prove economic as will many of the new metallurgical developments such as new explosively clad metal systems. Titanium, for instance, is receiving wide consideration for use in brine processing in the chemical industry for although more costly, titanium appears to last much longer than most metals and plastics. A decrease in down time and an increase in reliability is often worth a large added equipment cost in terms of overall competitiveness. Both of these factors, less down time and greater reliability, would be welcome for lunar geothermal power installations.

BYPRODUCTS FROM GEOTHERMAL POWER GENERATION

The most important potential byproduct of the geothermal power generation process is water. In fact, water production is apt to prove as important as the power produced and will certainly add to the attractiveness of the geothermal concept. Water can be recovered as part of the processes when geothermal steam is used in either power generating equipment or in heating systems. The recovered water can be separated out from the exhaust gasses or a separate process to recover water from the fresh gasses before they enter the power plant may prove more economical.

One of the uses of such water would certainly be in life-support systems. Another valuable use is for generating rocket propellants for either return flights to the earth or for further exploration in space. The water produced can be easily separated into oxygen and hydrogen with part of the electricity from the power generation cycles. Additional power in combination with the low temperatures and pressures of the ambient lunar environment could, in turn, then be used to liquefy the two propellant components. In addition, oxygen from the electrolysis process could also be used for breathing purposes. For those gasses in which CO_2 is the most abundant constituent, oxygen can be recovered and liquefied as a propellant material or life-support gas and various carbon compounds can also be recovered as byproducts for later use in processing materials. Since lunar geothermal gasses have an excellent potential for halogen production, as do geothermal brines and nonaqueous solutions, attention should be paid to byproduct propellant gasses and liquids other than oxygen and hydrogen.

Solid chemicals derived from geothermal fluids would provide another group of byproducts from the power generation process. As noted earlier, some gasses and liquids may be quite high in mineral content. As with all indigenous products the economics of transporting the same materials or products from the earth to the moon will be the deciding factor in the feasibility of ventures based on precipitated or otherwise recovered minerals. The raw materials for on-site lunar processing must also face the problems of "foreign" imports.

REFERENCES

1. Luciano B. Ronca, "An Introduction to the Geology of the Moon," Air Force Cambridge Research Laboratories, Special Report No. 23 (ARCRL-65-357). May 1965.

2. Tom F. W. Barth, "Theoretical Petrology," John Wiley and Sons, New York, 1952, 387 pp.

3. G. J. F. MacDonald, "Interior of the Moon," Science, Vol. 133, No. 3458, 1961, pp. 1045 - 1050.

4. P. A. Moore, "What We Know About the Moon," Journal of the British Interplanetary Society, Vol. 11, 1952, pp. 19 - 29.

5. P. A. Moore, "Problems of the Moon," The Advancement of Science, Vol. 17, No. 65, 1960, pp. 33 - 41.

6. Dinsmore Alter, "A Suspected Partial Obscuration of the Floor of Alphonsus," Publications of the Astronomical Society of the Pacific, Vol. 69, April 1957, pp. 158 - 161.

7. H. F. Poppendiek and W. H. Bond, "Recent Observations of Possible Volcanic Activity Within the Lunar Crater Alphonsus," Publications of the Astronomical Society of the Pacific, Vol. 71, 1959, pp. 233 - 235.

8. N. A. Kozyrev, "Vulkanicheskaia deiatel' nost' na Lune," Priroda, Moscow, Vol. 3, 1959, pp. 84 - 87.

9. R. W. Shorthill and J. M. Saari, "Recent Results of Lunar Eclipse Measurements Showing Hot Spots," Paper presented at the Symposium on Post Apollo Space Exploration, Session V, Paper 6 at Chicago, Illinois. May 1965.

10. Edited by A. V. Markov, The Moon, A Russian View, The University of Chicago Press, 1962, 391 pp.

11. George C. Kennedy, "Some Aspects of the Role of Water in Rock Melts," The Crust of the Earth, Special Paper 62, Geological Society of America, 1955, pp. 489 - 504.

12. H. Craig, G. Boato, and D. E. White, "The Isotopic Geochemistry of Thermal Waters," National Research Council Nuclear Sci. Series, Report No. 19, Nuclear Processes in Geologic Settings, 1956, pp. 29 - 44.

13. Carl F. Austin and J. Kenneth Pringle, "An Approach to Indigenous Lunar Power - The Geothermal Concept," Paper presented at the Symposium on Post Apollo Space Exploration, Session VII, Paper 5 at Chicago, Illinois, May 1965.

14. Donald E. White and G. A. Waring, "Volcanic Emanations," Data of Geochemistry, Chapter K, U. S. Geological Survey Professional Paper 440-K, 1963, 29 pp.

15. Edwin Roedder, "Liquid CO_2 Inclusions in Olivine-bearing Nodules and Phenocrysts from Basalts," The American Mineralogist, October 1965 (in press).

16. Harold C. Urey, "On Possible Parent Substances for the C_2 Molecules Observed in the Alphonsus Crater," Astrophysical Journal, 134, 1961, pp. 268 - 269.

17. Carl F. Austin, "Selection Criteria for Geothermal Prospects," Proceedings of the 1965 AIME Pacific Southwest Mineral Industry Conference, Nevada Bureau of Mines, Reno Nevada (in press).

18. E. G. Zeis, "The Fumarolic Incrustations in the Valley of Ten Thousand Smokes," National Geographic Society, Washington, Contr. Tech. Papers, Katmai Series, Vol. 1, No. 3, 1924, pp. 157 - 179.

19. S. I. Naboko, "Volcanic Exhalations and Products of Their Reactions as Exemplified by Kamchatka-Kuriles Volcanoes," Bull. Volcanol, Vol. 20, 1959, pp. 121 - 136.

20. R. S. Bolton, "Blowout Prevention and Other Aspects of Safety in Geothermal Steam Drilling," United Nations, New York, Paper C/43, Proceedings of the UN Conference on New Sources of Energy, Vol. 3, 1964, pp. 78 - 87.

21. W. M. Middleton, "Engineering Phases of the Development and Operation of Geothermal Power Sources," Society of Mining Engineers of AIME, Preprint No. 63I308, presented at the Rocky Mountain Minerals Conf., Salt Lake City, Utah, September 1963.

22. "New Sources of Energy" Proceedings of the Conference, United Nations, Rome, August 1961, Vol. 2, 3, New York, 1964.

23. Modesto Leonardi, Member, Ad Hoc Committee on Indigenous Lunar Power Sources, personal communication.

A Committee Report

Working Group on
Extraterrestrial Resources

August 15, 1964

A PRELIMINARY LOGISTICS BURDEN MODEL FOR THE PRODUCTION OF LUNAR ORES

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SUMMARY

This report of a preliminary study attempts to establish a "Logistic Burden Model for Lunar Mining and Ore Dressing" to support the production of water, oxygen, and other logistically important life-support and propellant substances from lunar rock.

Mining methods and equipment are sensitive to many factors, and perhaps the most important of these is the required production rate. This study, therefore, is based on system production ratings of ten and one hundred times a modular unit (M) equivalent to 9 lb/hr of water or 8 lb/hr of oxygen. Other study assumptions are discussed in detail.

The mining concept upon which the study is based involves the use of chemical explosives and one or more special mining machines which, with one exception, are all vehicular in nature. Initial mining efforts are presumed to be surface operations, but it is recognized that later phases probably will involve more complicated underground operations.

Conclusions resulting from the study are reported in tables and figures and include the logistic burden rates for capital equipment, consumable supplies, electric power, and manpower—all expressed as a function of the production order of magnitude.

Significant problem areas and future study recommendations are listed, with brief comments as seem appropriate.

GOVERNING FACTORS

The production and short-haul delivery of lunar rock ore for subsequent processing may be considered a distinct operation relatively unrelated to the ultimate process or product, except as reflected in the following directly related factors:

A. The quantity and nominal size of dressed ore product required

B. Rock characteristics

C. Type of mining operation (i.e. open pit, underground, etc.)

D. Depth of the mining operation and nature of overburden (if any) in open pit operation

E. Topography, including elevational profile of mining operation

F. Miscellaneous factors, including:

1. Minimum practical sizes and weights of equipment
2. Electric power availability
3. Quantity and ratio of manpower and equipment
4. Space environment constraints
5. Assumed operational life and growth factors

Factor A will be determined as a basic initial requirement, and factors B through E are fixed but presently unknown "insitu" conditions which will be almost entirely beyond our control. Miscellaneous factors listed under F are all subject to some degree of control from the standpoint of technological developments, trade-off choices, and operational modes and objectives.

BASIC ASSUMPTIONS

In order to establish a Logistic Burden Model for the equipment, supplies, power, and personnel required to produce and deliver local rock ore for subsequent processing on the moon (whether for propellant production or other purposes), it is necessary to establish and define a set of baseline assumptions for all factors. The following assumptions are considered reasonable (based on currently available information) for initial studies of mining operations and form the basis for the quantitative aspects of the Logistic Burden Model developed by this study.

FACTOR A

Factor A, in accordance with study ground rules, is based on a modular unit M of 9 pounds of water per hour from a 10 percent rich hydrated mineral (i.e., 8 pounds oxygen and 1 pound hydrogen, earth weight). An alternate but closely related aspect of this study is the production of modular units of 8 pounds of oxygen from silicate rocks by a thermal dissociation process. Other production processes can be related to this study on the basis of dressed ore requirements expressed as pounds or tons per day.

The choice of mining methods and equipment and the efficiency achieved are dependent to a large degree upon the scale of the operation. For this reason, operational orders of magnitude of 1 M, 10 M, and 100 M have been considered in this study.

An operational capability of 1 M is considered of laboratory scale and well below the range of even a model mining system. If it should be necessary, ore in this small quantity could be mucked and dressed with simple attachments on standard lunar vehicles. No further analysis of a 1 M scale operation is made in this study.

An operational order of magnitude of 10 M is considered a likely requirement for initial ore production on the moon, although it would hardly class as a serious mining effort by earth standards. The 10 M scale mining concept suggested is based on the development of a self-contained self-powered mobile mining and ore processing vehicle operated with or without the support of a separate ore transport vehicle.

An operational order of magnitude of 100 M is considered a second-phase mining requirement and probably the minimum which would class as a conventional scale, or significant mining effort, and show reasonable efficiency on its own merits. This operational scale is analyzed for the long-range aspect and also to provide a comparison for smaller concepts.

The 100 M scale is about the smallest capacity which can be closely identified with the full and efficient use of minimum practical equipment sizes and conventional earth-mining operations and equipment; in this sense, it serves as the best preliminary study norm which can be developed from the limited data available.

FACTOR B

Factor B aspects concerning lunar rock characteristics are assumed to correspond to those commonly identified with average limestone found on earth.

FACTORS C AND D

Factors C and D have been assumed on the basis of working exposed under vacuum conditions with mobile or semi-mobile equipment from an open pit or shallow side-hill cut operation involving not more than a few feet of overburden waste. This mining mode is considered most likely for initial operations and it has the additional advantage of involving far fewer unknowns and ponderables than an underground operation. This study approach is regarded as contributing to the early development of a simple burden model having a relatively high level of confidence and reliability.

The importance of subsurface mining concepts in later phases of the lunar program is fully recognized, however. It is noted that the broad field of subsurface mining involving shafts, tunnels, cavities, hoisting, air locks, sealing, limited work space, etc., was studied at some length—but the ramifications were found to be so numerous and unlimited in scope as to make a serious parametric and/or burden investigation of these concepts well beyond the boundary limitations necessarily imposed on this study. In view of the aforementioned situation and the probable second-phase operational aspects, no attempt was made to include subsurface mining concepts in the development of this burden model study.

FACTOR E

Factor E has been assumed on the basis of generally level topography. No significant penalty has been assumed to lift ore from a hole (i.e., a shallow open-pit method has been assumed), and no gravity advantage has been assumed for a possible "down-hill" profile for ore transportation and primary processing.

FACTOR F

F(1)

Factor F(1) for the 100 M scale of operation has been assumed on the basis that the blasting technique employed would produce broken rock, the greater portion of which would have one or more dimensions of 12 inches or less for a 14-inch crusher jaw opening. Larger nominal size limits would seem to involve impractical increases in crusher and handling equipment, while smaller sizes require excessive drilling and blasting effort.

For the 10 M scale of operations it is assumed the grizzly would be sized to reject and waste all rocks not passing a 9 x 14-inch grate for a 10 x 16-inch jaw opening. It is presumed that trade-off studies would justify this high rejection rate (i.e., wasted blasting and material handling effort) for a small crusher as preferable to providing a heavier excessively high-rate crusher with a somewhat larger size capacity and lower rejection rate.

F(2)

Factor F(2) has been assumed on the basis that primary power units, at least in the range of general sizes and types presently under development, will be perfected and available by the date of initial mining operations.

F(3)

Factor F(3) is assumed on the basis that some equipment and operations can be controlled semi-automatically in the 100 M concept, but that at least a limited amount of personnel will be locally available to control all operations (to a greater or lesser degree in each operation as determined by future developments and man/machine trade-off studies). No phase of the subject operations can be fully automatic.

F(4)

Factor F(4) involves such familiar current problem areas as bearings, seals, materials, life support systems, etc.; in this sense, it has been assumed that reasonable solutions will have been developed in all these supporting technological areas by the date of initial mining operations.

F(5)

Factor F(5) has been assumed on the basis that a maintainable life of at least 2 to 3 years would be necessary to justify a 10 M scale mining operation, and that a program life of 5 to 10 years would be necessary to justify a 100 M scale operation. It has been assumed that (1) there would be a minimum practical operational magnitude or scale and that future growth aspects would be recognized if significant logistic or operational penalties were not incurred, but that (2) significant penalties would not be allowed in the initial system and equipment to provide for projected large scale future needs which, aside from other considerations, might well involve alternate mining sites or methods.

MISCELLANEOUS CONSIDERATIONS

ENVIRONMENT

It has been assumed that initially the entire operation, from blasting through coarse crushing and delivery to the processing plant, will, of necessity, be accomplished in an exposed environment on the lunar surface. Ore reduction below approximately 1-1/2-inch nominal size must be accomplished by equipment of different types and probably in a protected fluid environment to avoid short-term cold-welding of the particles; such a protected environment would logically be associated with the processing plant to avoid handling, storage, and transportation problems.

DRILLING AND BLASTING

The initial excavation, or breaking out, of the ore is presumed accomplished by a lunar blasting system utilizing chemical explosives. Although, admittedly, such a method requires some development effort, its use at this time appears more feasible and practical for the purpose under consideration than other foreseeable methods which have been proposed.

The drilling rig is considered as an accessory on the multi-purpose mining vehicle (described later) for a 10 M operational scale. However, for large-scale operations, the drill rig should probably be mounted on a special-purpose remote-controlled vehicle (or as an accessory on a general-purpose lunar vehicle) to avoid tying up the operator and a major piece of equipment during prolonged drilling periods.

EXCAVATION

Loading of the broken rock would be accomplished by use of a combination dozer blade and forked mucker tool for all operational concepts, although the size and drive power would vary somewhat with the scale of operation. Initial loading would be into small on-board receiving hoppers or scoops which would discharge to the coarse crusher.

VEHICULAR EQUIPMENT

All operational concepts require a special mining vehicle equipped with on-board power supply, an operator's module, a dozer/mucker device with a lifting capability, a receiving hopper, and at least low-speed mobility.

In the case of a machine for a 100 M mining concept, this vehicle would be specialized, powerful, of high capacity in these areas, and equipped with electronic equipment for the remote control of separate mining equipment (i.e., drilling rig, crushers, etc.).

In the case of a 10 M operational concept the dozing and mucking capability would be scaled down and other equipment of minimum scale would be added to make it a complete multi-purpose mining machine. This added equipment would include a grizzly and screen system, coarse jaw crusher with semi-automatic feeder, discharge hoppers, a blast-hole drill rig, etc. In familiar earth terminology, this machine would be similar in function to a portable rock-crushing plant discharging into an on-board dump-truck body and powered by a combination bulldozer/skip loader; in addition, of course, the vehicle would have a special power plant, operator's module and life support system, communication equipment, and a relatively wide speed range.

Preliminary design studies have demonstrated the feasibility and advantages of such a multi-purpose machine concept. This self-contained mobile mining and ore-processing vehicle would utilize basic equipment of a minimum practical size and would achieve its major scale reduction by combining functions, reducing ore handling requirements, integrating power requirements, and reducing the automation and maintenance problems associated with remote fixed equipment. The limiting design factors would be material-handling capacity and travel capability, since mucking and crushing capacity (although minimal) would necessarily be oversized for practical considerations.

Other special vehicles related to a 100 M system would include a remote-controlled drill-rig vehicle and a manned transporter fitted to haul large cans of crushed rock over considerable distances to the processing plant.

The preceding vehicle and machine descriptions are applicable mainly to exposed-surface type mining operations, and the concepts and basic functions would be greatly altered if underground operations are considered.

ALTERNATE ORE TRANSPORTATION METHODS

Although not considered in the development of this study model, the possibilities of other materials-handling and transportation modes are recognized for large (i.e., 100 M) scale operations above ground. These alternate methods probably would have their greatest application where the vertical distance is great with respect to the horizontal distance (i.e., lifts in mine shafts or horizontal hauls over surface areas of steep slope). Such transport or handling conditions could very well indicate the use of modified cableways or railways as opposed to self-propelled wheeled vehicles. Such slopes might be used to advantage if the gradient is a downhill incline.

CRUSHER EQUIPMENT

An overhead eccentric-type jaw crusher has been selected as most suitable for the coarse crushing operation. Advantages include basic simplicity (favoring operational dependability and ease of maintenance), maximum adjustment and application flexibility, favorable capacity to weight and power ratios, high reduction ratio, and a minimum of wearing surface. Also, it is noted that successful operation is not critically related to operating speed (as are certain other types), and choking can be cleared relatively easily if it should occasionally occur due to the cold-welding tendency of fines and the high pressures developed on the crushing surfaces.

A short-head cone crusher seems to be indicated for secondary fine crushing (approximately 1-1/2-inch or 1-1/4-inch down to not less than 1/8-inch size), if this degree of size-reduction is required. The reasons supporting the choice of this particular type of fine crusher are very similar to the reasons noted for the primary jaw crusher.

For the 10 M operational concept, the coarse crusher (jaw type) is located on-board the multi-purpose mining vehicle. For the 100 M concept, the coarse crusher is skid-mounted and located close by the excavation area to minimize haul by the mucker vehicle and to obviate the necessity for either rehandling through an additional transport system or compromising mucker/dozer design to improve transport capability.

Regardless of operational scale or subsequent processing requirements, if fine crushing in a fluid environment is required, then the crushed ore must be loaded into the fine crusher on a batch basis. This requirement for pressure-vessel construction with pump-down equipment and a supply of processing gas (not completely recoverable) is foreseen as a serious complication and penalty for a small-scale operation utilizing exposed equipment; however, these problems would be much less severe, or almost non-existent, in later phase subsurface operations where an artificial gaseous atmosphere can be maintained in a sealed mine cavity or tunnel system.

It should be noted that rock-crushing is severe service for the best of equipment and that a relatively high rate of wear and maintenance should be expected, all efforts toward improved design notwithstanding. In view of the ruggedness and massive proportions of conventional crushing equipment, a program is definitely indicated to optimize performance, improve maintainability, reduce overseeing requirements, and improve the performance/weight ratio while recognizing the constraints of space design and the requirement for the toughest possible crushing surfaces. Space rating must be accomplished by extensive tests of full-sized models in low-vacuum chambers.

It is possible that some difficulty will be encountered in dissipating the heat energy developed as a result of the rock-crushing operation. It is noted that much of this heat will be carried away by the discharged rock and will be absorbed and radiated slowly by the crusher structure itself. If additional heat dissipation capacity is required, it can be obtained by incorporating special radiation surfaces into the crusher structure and/or providing a closed-circuit cooling system for the crusher jaws (i.e., jackets with a liquid coolant circulating to a high-efficiency radiator).

Some interesting facts concerning jaw crushers are noted for general information. Jaw crushers of the type proposed are sized by the "l x w" dimensions of the jaw inlet opening and powered at the rate of approximately one-tenth horsepower per square inch of this inlet area. Crusher output, normally expressed as tons/hour, is controlled by the actual rate and size gradation of the feed, is greatly affected by the rock characteristics, and is always quoted for the maximum feed of random-sized rock at a specified jaw discharge or "gap" setting (i.e., nominal ore product size). In practice, the output capacity of a given machine is found to vary almost directly as the jaw discharge setting (i.e., cutting the jaw gap in half—as from 3 inches to 1-1/2 inches—will cut the discharge rate in half). Operating speeds on the order of 300 cycles per minute are common; these speeds are established by the manufacturer on the basis of overall optimum performance and minimum wear on the machine, with little direct regard for minor variations in rock characteristics. The jaw faces are replaceable as wearing parts.

The possibility of reducing ore below about 1/8-inch nominal size by the use of grinding mills has been considered, but disregarded as unfeasible, in the development of the Logistic Burden Model. The reasons for this decision are illustrated in Figure 2 and discussed in some detail near the end of the following section.

STUDY CONCLUSIONS

The "Logistic Burden Model for Lunar Mining and Ore Dressing" as developed in this study is summarized and set forth in tables on the final pages of this report. The burden charges noted are considered realistic on the basis of judgement, available information, and preliminary study; although some unforeseen degree of optimization might admittedly be accomplished in specific areas, it has been assumed these plus items would be offset by unforeseen complications in other areas.

Operational modes and equipment types suggested are based in large measure on an estimated order of magnitude for a practical scale of production. Excepting the special objectives and criteria which might be assigned to a pilot operation (both mining and subsequent processing), it is doubtful that the mining and crushing operation could be called reasonably efficient on its own merits if the scale of operations is less than 10 M units.

Table 1 is an analysis of the quantitative aspects of supplying dressed ore for the several arbitrarily-selected scales of operation. It is noted that blasting effort must be calculated on the basis of at least 1.4 times the net tonnage of dressed ore required; approximately seven-eighths of this excess will be unrecoverable or rejected as oversize at the mine site, and the balance will be lost or scalped in handling and crushing.

Figure 1 provides a convenient means of determining the water or oxygen output corresponding to any selected M scale of operation and also establishes the working capacity (i.e., size) of a mining system which would be necessary to provide a specified 24-hour average M rate of output during any specified average daily work period (at least 4 hours per day should be allowed for equipment maintenance).

Table 2 summarizes a number of alternatives and indicates the specific choices of equipment and methods which have been made for a complete surface-mining and ore-dressing system appropriate for each of the orders of magnitude under consideration.

Tables 3 and 4 present a first-order breakdown of the basis for establishing the Logistic Burden Model for the 10 and 100 M scales of operation. The numbers presented are frankly little more than educated guesses based on preliminary studies and the best data available at this early date.

Table 5 summarizes and compares the data developed in Tables 3 and 4 to provide a Logistic Burden Model for the entire mining and ore dressing process. The data is tabulated separately for a system which accomplishes coarse crushing only (to approximately 1-1/2-inch minimum nominal ore size) and a system which accomplishes both coarse and fine crushing (to not less than 1/8-inch minimum nominal ore size). As might be expected, the larger capacity 100 M system shows twice the weight and five times the manpower efficiency (or one-half and one-fifth of the burden charge, respectively) of the smaller 10 M system for Case 1 assumptions.

Figure 2 presents a graph of the empirical energy requirement for crushing and grinding a standard limestone rock from 12-inch nominal size down to any required gravel or particle size. It is noted that ore reduction below 1/8-inch nominal size is almost prohibitive (from a machine weight and ball replacement standpoint) if a high-efficiency ball mill of minimum operational proportions is considered; if some of the older types of grinding mills are considered because of their suitability for scaling down size, the maintenance and horsepower factors become prohibitive. The conclusion drawn, therefore, is that ore reduction below 1/8-inch nominal size appears to be prohibitive and should not be considered feasible for lunar operations without the support of a serious study in this area.

Undoubtedly, a workable lunar mining system can be developed, and at some stage of development and scale of operation it will be fully justifiable as an extraterrestrial support system. There are, however, numerous areas which require considerable study and R&D effort, and these are summarized in the following section of the report.

FUTURE STUDY RECOMMENDATIONS

Specific problems and areas suggested for long-lead research and development effort (exclusive of technological details and basic power and life support systems) are identified as follows:

1. Identification and classification of candidate ore types at the earliest possible date.

2. Development of a lunar blasting system, including the necessary equipment for drilling.

3. Exploratory studies to establish a reasonable degree of optimization and adaptation of conventional rock-crusher designs and theory to the lunar environment and anticipated crushing requirements, as well as a study of heat dissipation aspects.

4. Performance of vacuum chamber tests using full-scale, pilot-model crushers working on representative ores to assess the cold-welding effects of ores undergoing crushing, screening, and short-term storage; these tests would recognize nominal ore size as the primary variable. It is suggested that ore reduction below 2-inch or 2-1/2-inch maximum size in a vacuum environment will create progressively more serious problems because of the cold welding of fines and choking of the crusher discharge opening (and screens if their use should appear desirable).

5. Parametric and definitive design studies of a multi-purpose self-contained mining machine capable of mucking, dozing, loading, coarse-crushing, and transporting lunar ores from a mine site to a processing plant site.

6. The refinement of preliminary power and weight estimates based on crusher tests in vacuum and definitive studies of the vehicles and equipment.

7. An upgrading of the Logistic Burden Model based on the results of the foregoing recommendations and the more specific requirements which have now been outlined in concurrent studies of subsequent ore processing.

8. An investigation of the usefulness of the proposed multi-purpose mining machine for construction-type tasks in and about a manned lunar base. The rooting, dozing, loading, heavy transport, and rock crushing capability would have important application in many phases of base construction. An integrated study should be able to develop a basic construction machine design which could be readily converted to a mining machine at a later post-construction date.

Table 1. Quantitative Analysis of Ore Requirements

BASIC QUANTITY UNIT FOR STUDY - Symbol M

Requirement is for production units of 9 lb/hr of water from 10 percent rich hydrated mineral.

Assuming extraction process is 72 percent efficient, $\frac{90}{72}$ = 125 lb/hr dressed ore required for 1 M rate.

ANALYSIS IS RELATED TO 10 AND 100 TIMES THE BASIC M FOR PRACTICAL CONSIDERATIONS

BASIC ORE QUANTITIES	EXCAVATION BY BLASTING	MUCKING AND TRANSPORTATION	COARSE CRUSHING	TRANSPORTATION ORE TO PLANT	FINE CRUSHING
For 1 M lb/hr	176 - 44 = 132	132 - 2 = 130	130 - 3.5 = 126.5	126.5 - 1.5 = 125	125 lb/hr
For 1 M lb/Day	4210 - 1050 = 3160 (Assume 75% Exc.)	3160 - 50 = 3110 (Assume 1-1/2% loss)	3110 - 80 = 3030 (Assume 2-1/2% loss)	3030 - 30 = 3000 (Assume 1% loss)	3,000 lb/Day 90,000 lb/Mo.
For 10 M lb/Day	42,100 lb Blasted 31,600 lb Exc. 10,500 lb Left	31,600 lb Loaded 31,100 lb Delivered 500 lb Lost	31,100 lb Rec'd. 30,300 lb Crushed 800 lb Scalped	30,300 lb Loaded 30,000 lb Delivered 300 lb Lost	30,000 lb Rec'd. 30,000 lb Crushed No Loss
For 100 M lb/Day Tons/Day	421,000 lb/Blasted 210.5 Ton Blasted	316,000 lb Loaded 158.0 Ton Loaded	311,000 lb Rec'd 155.5 Ton Rec'd	303,000 lb Loaded 151.5 Ton Loaded	300,000 lb Rec'd 150.0 Ton Rec'd
	316,000 lb Exc. 158.0 Ton Exc.	311,000 lb Delivered 155.5 Ton Delivered	303,000 lb Crushed 151.5 Ton Crushed	300,000 lb Delivered 150.0 Ton Delivered	300,000 lb Crushed 150.0 Ton Crushed
	52.5 Ton left in place	2.5 Ton Lost enroute	4.0 Ton Scalped an oversize 6.3 Tons/Hr Rate ←	1.5 Ton Lost (Crushing Rate)	No Loss → 6-1/4 Tons/Hr Rate

EARTH WEIGHT LISTED ABOVE: LUNAR WEIGHT LISTED BELOW:

For 100 M Tons/Day	34.7 Ton Blasted 26.1 Ton Exc.	26.1 Ton Loaded 25.7 Ton Delivered	25.7 Ton Rec'd 25.0 Ton Crushed	25.0 Ton Loaded 24.8 Ton Delivered	24.8 Ton Rec'd 24.8 Ton Crushed

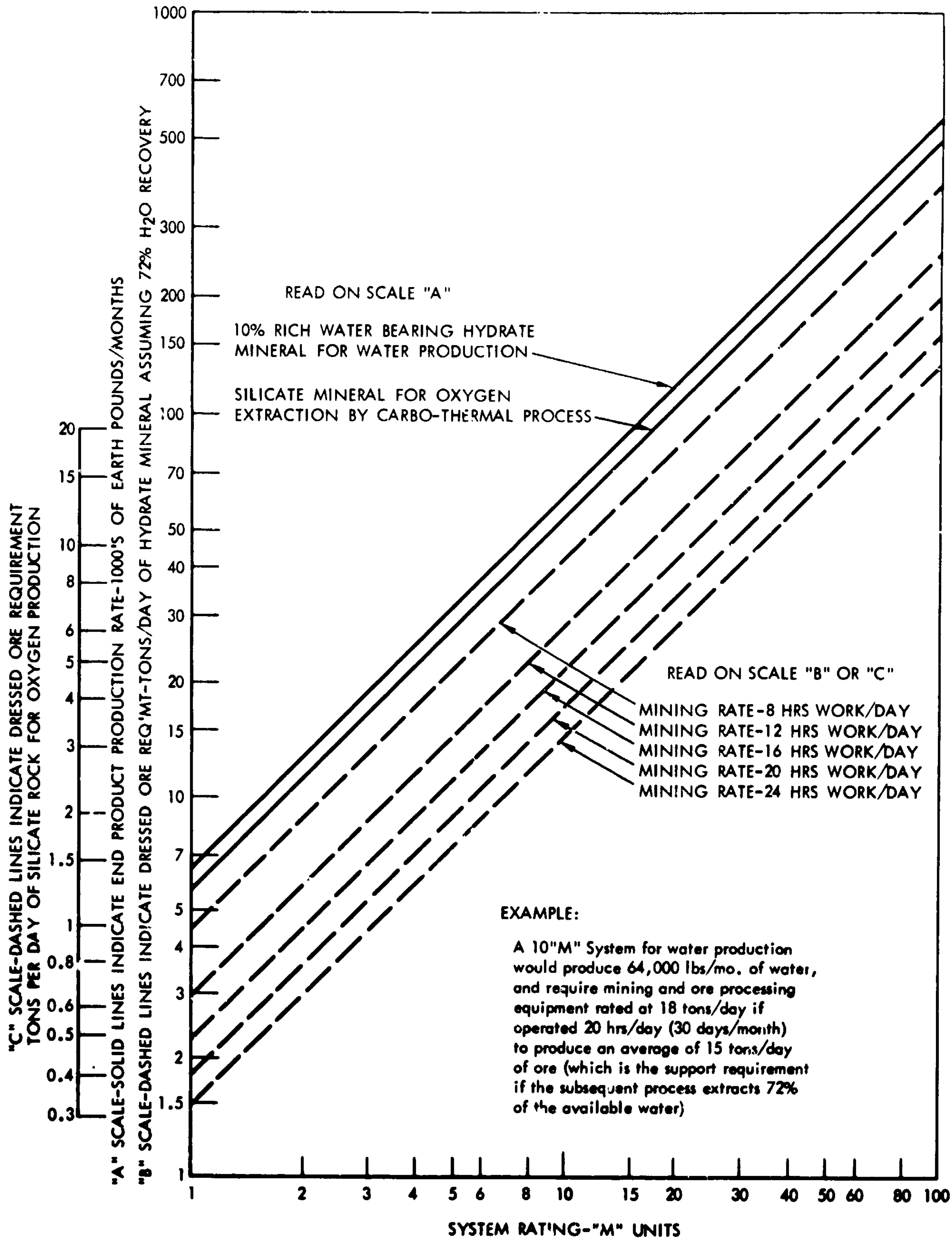

Figure 1. Relationship of Overall System Rating to Resultant Production and the Corresponding Mining Rate Necessary at Various Duty Cycles

Table 2. System Analysis for 10 M and 100 M Operational Capability

	EXCAVATION BY BLASTING	MUCKING AND TRANSPORTATION	COARSE CRUSHING	TRANSPORTATION ORE TO PLANT	FINE CRUSHING
OPERATIONAL METHOD **Breakdown is applicable to 100 M scale as shown.** **For 10 M scale first 4 functions are combined on one vehicle.**	DRILLING BY: a. Mech drill b. Shaped charges c. Laser beam d. Plasma jet EXCAVATION BY: a. Chem. explos. b. Nuclear devices.	SPECIAL VEHICLE to: a. Doze b. Muck c. Transport d. Lift 100 M - High-rate mucking with limited mobility. 10 M - Compromise performance with multiple speeds for transport use	SKID-MTD UNIT - 100M VEH-MTD UNIT - 10M a. Loading hopper b. Grizzly c. Crusher d. Screen system e. Disch. hopper Closed Circuit Operation.	VEHICULAR a. Truck/cans b. Dump truck c. Tractor/wagon CABLEWAY a. Continuous bucket-veyor b. Counter-balance two-bucket type. RAILWAY Cable cars on prefab track.	PART OF FIXED PLANT a. Special adaptation of conventional crushing equip. b. Explosive shattering using electrolyte and waste, solar or nuclear heat for boiler. c. Combination of above.
ENVIRONMENT	Exposed-Vacuum	Exposed-Vacuum	Exposed-Vacuum	Exposed-Vacuum	Artificial atmos. in a chamber, structure or underground cavern.
LOCATION AND ROUTING FACTORS	Mining Site as established. →	Raw Ore Transport → distance: 500 to 1000 feet →	Conveniently near mining site to minimize transport. Barricade 1 side →	Crushed Ore Transport → distance assumed: approx. 1 mile	As determined by operational analysis. a. Exposed above-ground (1) Pres. vessel construction. (2) Pres. structure b. Underground in sealed cavern.
	The preceding notes are for 100 M scale operation. For a 10 M scale operation, all functions noted and equipment listed are on-board multi-purpose vehicle.				

Table 3. Logistic Burden Analysis for a 10 M Operational Level

	EXCAVATION BY BLASTING	BLAST-HOLE DRILL RIG	MUCKING AND TRANSPORTATION	COARSE CRUSHING	TRANSPORTATION ORE TO PLANT	FINE CRUSHING
CAPITAL EQUIPMENT weight in earth lbs. incl. power units.	Blasting Equipment Total 100 lbs	Multi-purpose vehicle frame and 3500 lb Oper. Mod. = 9 000 lb 40 HP basic power/drive system 5, 000 Drill rig 900 lbs and dozer/mucker 2, 100 lbs 3, 000 Coarse crusher 3, 600 Grizzly, screens, hoppers and misc. accessories 2, 900 Total, pounds 23, 500				Short head cone crusher* 8, 000 Accessories 3, 000 Power sys. 3, 500 Total 14, 500
CONSUMABLE SUPPLIES weight in earth lbs. **(hourly rate based on average for 24-hr duty cycle)**	Explos. 12. 0 Blast sup. 3. 0 ln/day - 15. 0 lb/hr - .625	Spare parts - Vehicle 2%/90 days x 9, 000 lbs = 2. 0 lb/day Drive 2%/90 days x 5, 000 lbs = 1. 2 lb/day Crusher 5%/90 days x 3, 600 lbs = 2. 0 lb/day Misc. 2%/90 days x 3, 600 lbs = 0. 8 lb/day Drill points = 1. 2 lb/day Total supplies and parts fo mining machine = 10. 2 lb/day				Spare parts only assume 5% of crusher replaced every 90 days. $\frac{400}{90}$ = 4. 45 lb/day $\frac{4.45}{24}$ = . 185 lb/hr.
POWER (weight incl. in capital equipment estimate)	Negligible (for blasting use only)	40 HP SNAP-type unit with general-purpose drive motor and transmission/power takeoff system				Assumed 20 HP on part-time oper. basis
PERSONNEL **number/function and man-hr rate**	Part-time to place explosives 0. 1 man-hr/day	Min. one operator up to 10 M rate - 23. 9 man-hr day (probably two operators necessary if machine is operated at much more than 10 M rate and operators' module should provide for this possibility)				Not incl. this est. All overseeing assumed by process plant oper.

NOTE: Fine crushing may/will require recycled fluid to control cold-welding and heating—this fluid incl. a gas is not included above.

NOTE: Crusher data based on conventional equipment operating under normal earth conditions, on the assumption that optimization will result **in a 1/3 weight reduction** in addition to satisfying space environment penalties.

***Based on** optimization of smallest known short-head cone crusher in current production.

Table 4. Logistic Burden Analysis for a 100 M Operational Capability

	EXCAVATION BY BLASTING	MUCKING & SHORT-HAUL TRANSPORT	COARSE CRUSHING	TRANSPORTATION ORE TO PLANT	FINE CRUSHING
CAPITAL EQUIPMENT weight in earth lbs. (Oper. modules est. at 3000 lb ea. incl. life support systems)	Remote-controlled vehicle 3,000 Power sys. 2,000 Ballast (2,000) Drill 900 Blast equip 100 Total 6,000	Mucking/Transport Vehicle Incl. Operators Module Vehicle 12,000 Power Sys. 4,500 Total 16,500	Overhead Eccentric Jaw Crusher with Accessories Crusher 7,000 Accessories 2,500 Power Sys. 2,500 Total 12,000	Transport Vehicle incl. cans and Operators Module Truck 6,000 4 Cans 1,000 Power Sys. 3,000 Total 10,000	Short head cone Crusher* 8,000 Accessories 3,000 Power Sys. 4,000 Total 15,000
CONSUMABLE SUPPLIES weight in earth lbs. (hourly rate based on average for 24 hr duty cycle)	Drill points 42.1 Explosives 101.0 Blast supply 20.0 Spare parts 1.9 Total lb/day 165.0 $\frac{165}{24}$ = 6.85 lb/hr	Spare Parts only assume 10% of machine replaced every 90 days. $\frac{1200}{90}$ = 13.3 lb/day $\frac{13.3}{24}$ = 0.56 lb/hr	Spare Parts only assume 20% of machine replaced every 60 days. $\frac{1400}{60}$ = 23.4 lb/day $\frac{23.4}{24}$ = 0.97 lb/hr	Spare Parts only assume 5% of truck replaced every 90 days. $\frac{300}{90}$ = 3.33 lb/day $\frac{3.33}{24}$ = 0.139 lb/hr	Spare Parts only assume 20% of machine replaced every 60 days. $\frac{1600}{60}$ = 26.7 lb/day $\frac{26.7}{24}$ = 1.11 lb/hr
POWER REQ'M'TS (weight incl. in capital equipment estimate.)	For Drilling and Vehicle Movement 10 HP	For all Vehicle Requirements 30 to 40 HP	For Crusher, Screen and Hopper operation 15 HP	For Vehicle Oper. 20 HP	For Crusher and Hopper operation 30 HP
PERSONNEL number/function and man-hr rate	Oversee auto-drill and part-time to place explosives ←	One operator full-time in module 24 man-hrs/day (also controls drill and crusher)	Oversee semi-auto crusher and control loading. ←	One operator full-time in module 24 man-hrs/day (also controls crushers) →	Oversee semi-auto crusher and control loading.

NOTE: Fine crushing may/will require recycled fluid to control cold welding and heating - this fluid incl. a gas is not included above.
NOTE: Crusher data based on conventional equipment operating under normal earth conditions, on the assumption that optimization will result in a 1/3 weight reduction in addition to satisfying space environment penalties.
*Based on optimization of smallest known short-head cone crusher in current production.

Table 5. Summary and Comparison of Logistic Burden to Support Lunar-Dressed Ore Production Rates Equivalent to 10 and 100 M Units

Analysis on Basis of Requirement for Coarse Crushing Only (Ore Size Equal or Larger Than 1-1/4- to 1-1/2-Inch)

Operational Scale	Capital Equipment	Maintainable Life Assumed	Capital Burden	Supply Burden	Total Wt Burden	Labor Burden	Total Burden Charge Per M Unit †
(Earth Units)	Pounds	Years	Lb/Day*	Lb/Day	Lb/Day	MH/Day	Lb/M & MH/M
10 M Units avg daily rate	23, 600	2-1/2 (Case 1) 5 (Case 2) #	19.5 9.8	25.2 26.5	44.7 36.3	24 24	.186 lb + .100 MH .151 lb + .100 MH
100 M Units avg daily rate	59, 500	8	15.3	205.0	220.3	48	.092 lb + .020 MH

Analysis on Basis of Requirement Through Fine Crushing Only (Dressed Ore Not Less Than 1/8 Inch Nominal Size

Operational Scale	Capital Equipment	Maintainable Life Assumed	Capital Burden	Supply Burden	Total Wt Burden	Labor Burden	Total Burden Charge Per M Unit †
(Earth Units)	Pounds	Years	Lb/Day*	Lb/Day	Lb/Day	MH/Day	Lb/M & MH/M
10 M Units avg daily rate	38, 100	3 (Case 1) 5 (Case 2)#	26.1 13.1	29.7 31.2	55.8 44.3	24+ 24+	.233 lb + .100 MH .185 lb + .100 MH
100 M Units avg daily rate	74, 500	8	19.2	231.7	250.9	48	.105 lb + .020 MH

*Capital burden rate assumes average 25% salvage value of entire system including power supply.
†Comparative burden charges and M unit production rates based on average hourly rate over 24-hour period.
Case 2 is calculated from Case 1 and assumes an average 5% increase in supply burden for spare parts.

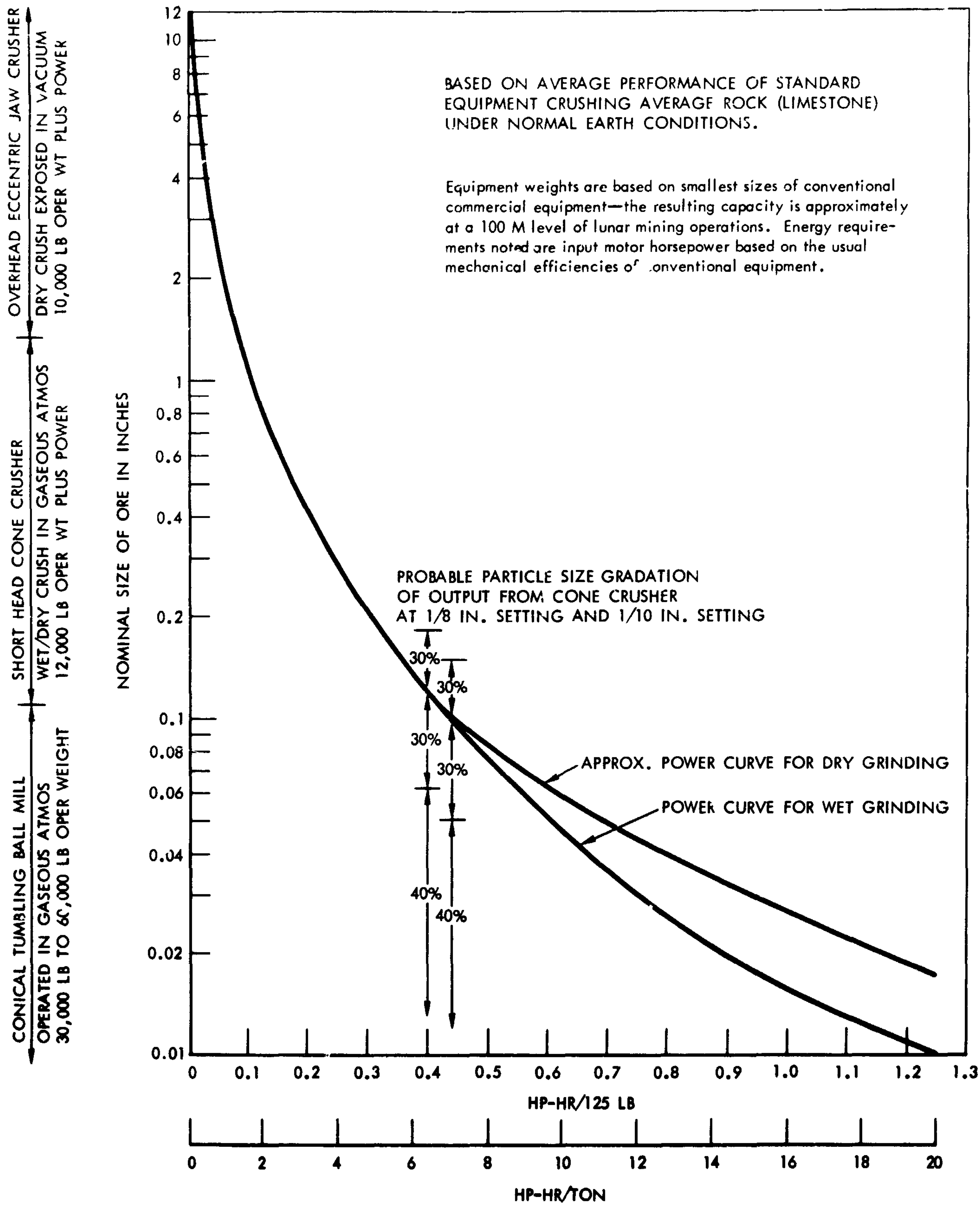

Figure 2 Energy Requirement for Rock Reduction Based on 12 in. Feed Reduced to Sizes Indicated

BIBLIOGRAPHY OF PRINCIPAL REFERENCES

1. Taggart, A. F. Handbook of Mineral Dressing. New York: John Wiley & Sons, Inc. (Feb. 1964).

2. Stubbs, F. W., Jr. Handbook of Heavy Construction. New York: McGraw-Hill Book Co., Inc. (1959).

3. Peele, Robert. Mining Engineers Handbook, Vol. II, Third Edition. New York: John Wiley & Sons, Inc. (Sept. 1963).

4. Fairhurst, C. Rock Mechanics. Oxford, England: Pergamon Press, Ltd. (1963). Published in U.S. by The Macmillan Co., New York.

5. Cook, M. A. Science of High Explosives. New York: Reinhold Publishing Corp. (1959).

6. Baumeister, Theodore (Editor). Marks Mechanical Engineers Handbook, Sixth Edition. New York: McGraw-Hill Book Co., Inc. (1958).

7. Recommendations for Utilization of Lunar Resources. JPL report presented in Seminar Proceedings, Working Group on Extraterrestrial Resources (8 March 1963).

8. Cole, D. M., and R. Segal. A Design Criterion for Lunar Propellant Manufacture. General Electric Report (8 April 1964).

9. Hayward, C. B. A Preliminary Study and Report on a Lunar Blasting System. NAA S&ID Report (25 March 1964).

10. Gross. Crushing and Grinding. Philadelphia: Reprint by Lefax, Inc. (Lefax Order No. 38-62, Dewey 622.73) (1947), abstracted from U.S. Bureau of Mines Bulletins.

N66 35515

IMPULSE PROPULSION GAINS RESULTING FROM "FREE" RETANKING OF PROPELLANTS ON VARIOUS ORBITS AND STATIONS AT THE EARTH, THE MOON, MARS, AND VENUS

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ABSTRACT

The utilization of extraterrestrial resources to supply propellants for tanking rockets at various stations along the routes of round trip expeditions to the planets has been evaluated, on the assumption that the propellants are "free", in the sense that they are available at the station without cost or complication. The method used in the evaluation is to plot and compare curves showing the remaining mass fractions as functions of the hyperbolic excess speed for single-stage rockets leaving each station. Families of curves are shown for various propellants for departures from all interesting orbits and stations at the Earth, the moon, Mars, and Venus. From these, it is possible to evaluate hundreds of individual retanking operations. Representative cases are shown. For example, in certain interesting cases, a ten-fold reduction in launch mass is possible through retanking at a cis-lunar station. Assuming water on the moon and on Mars, it would be possible to transport heavy cargos back and forth between the cis-lunar station and the surface of Mars, or the surface of Venus, with an indefinitely reusable rocket.

INTRODUCTION

Most of the cargo carried by the launch rocket for a solar system expedition is propellant for maneuvers subsequent to the launching. Expedition planning centers largely in reducing the amount of propellant which must be carried, through selection of propellants having a high specific impulse; employment of aerodynamic braking upon entering the atmosphere of a destination planet; selection of trajectories characterized by small terminal velocities; exchange of orbit energy with Venus; refinement of operational techniques; and retanking of the rocket with propellant locally manufactured at the target planet, or at a way station. The present paper is concerned with the last of the just-mentioned means.

Curves are presented which can be replotted in appropriate combinations to evaluate the performance gains or losses achievable by retanking at various stations in the vicinities of the Earth, the moon, Mars, and Venus. A set has been plotted for each of thirteen stations. Each set consists of three curves, one corresponding to the performance of oxygen with hydrocarbon, another to the performance of oxygen with hydrogen, and a third to the performance of hydrogen heated in a nuclear reactor. From the thirty nine curves, hundreds of comparisons are possible, including close approximations to all interesting cases.

DESCRIPTION OF CURVES

The thirteen sets of working curves are shown in Figures 1 through 7. Some of the later figures are replots of some of the same curves in combinations to show what may be gained by retanking with locally produced propellants at various interesting locations.

In all cases, the remaining mass, in percent of initial mass, is plotted against hyperbolic excess speed, in EMOS, or Earth-mean-orbital-speed. One EMOS = 29.8 km/sec. Initial mass is the mass of the loaded rocket before the propulsion maneuver which causes it to depart from its station. The remaining mass is that which remains after the propulsion maneuver, and includes both the spent rocket and its cargo. Hyperbolic excess speed is that which remains after the propulsion maneuver, and after the rocket has coasted to infinity. It is also the speed at infinity necessary to impart to the rocket the speed with which it actually arrives at the destination planet. In all cases it is measured in EMOS, even though the rocket may be in the vicinity of some other planet, such as Mars.

The use of hyperbolic excess speed in preference to actual speed is fully justified by its generality. The actual speed depends on altitude, eccentricity, and position on orbit, as well as on the orbit parameters themselves. The hyperbolic excess speed for any given interplanetary transfer trajectory is a fixed quantity. The use of EMOS rather than kilometers per second is justified by the experience of workers in the field of orbit mechanics and trajectory selection. Besides making the work easier for the experts, it also assists the beginner to learn and use the trajectory data.

In order to plot the remaining mass as a function of the hyperbolic excess speed, the hyperbolic excess speed can first be converted to kilometers per second on the specified parking orbit. This is done by converting both speed and gravitational energy into compatible units, measured by the square of actual or equivalent, appropriate, speeds. The relationship is as follows:-

$$\Delta V = (V_p^{\,2} + V_\infty^{\,2})^{\frac{1}{2}} - V_c$$

where ΔV = the speed increment required for the maneuver;

V_p = the parabolic speed, equal to bare-escape speed, and $V_p^{\,2}$ = the energy required to escape from the altitude of the station:

V_∞ = the hyperbolic excess speed, and $V_\infty^{\,2}$ is proportional to the energy required to place the vehicle on the desired hyperbolic orbit; and V_c = circular speed in the specified parking orbit.

It will be recalled that $V_c \times 2^{\frac{1}{2}} = V_p$.

If departure is from the surface of the planet, rather than from a parking orbit around the planet, V_c vanishes from the equation. In calculating departure from the moon, a two-stage calculation is required in which escape from the moon into the Earth's gravitational field, and escape from the Earth into the sun's gravitational field are simultaneously calculated, taking into account also the orbital speed of the moon around the Earth. In all cases, it has been assumed that departures are tangential to the parking orbits. The numerical values corresponding to departures are equal to those corresponding to arrivals, of course.

All the curves have been plotted from numerical data calculated at closely spaced intervals. The tabulated data are omitted from the present paper in the interest of brevity, and because the plotted curves themselves can in all cases be read with sufficient accuracy for planning and design purposes.

Visual inspection of the sets of curves will reveal that, although only three values of specific impulse have been shown, it is easy to interpolate closely enough for mission mode selection. For the purposes of the present paper, more values would only add confusion, and for any detailed engineering study in the future, it will only be necessary to calculate curves for the propellants under consideration.

Finally, it should be mentioned that the curves are idealized, in that they do not include such inefficiencies as non-tangential departures, or gravitational losses due to changes in elevation during the propulsion maneuver. They also leave to the reader the problem of guessing at the distribution of mass between useful cargo and spent rocket. Again, they do not measure the feasibility of a given maneuver, such as manufacture of propellants on the moon. But they do show, rather accurately, the limiting potential gain of any assumed maneuver in comparison with any other assumed maneuver. In other words, they can be used to eliminate hopeless cases, and to indicate promising regions. The promising regions can then be further studied.

RESULTS OF SOME COMPARISONS

Figure 8 is a replot of curves for departure from the earth-moon system. To reduce the confusion on an over-crowded chart, only the curves for a propellant specific impulse of 444 seconds are shown, corresponding approximately to the performance of oxygen with hydrogen.

The plotted curves show that for low hyperbolic excess speeds the remaining mass is greater from high-altitude orbits, whereas for high hyperbolic excess speeds, the remaining mass is greater from low-altitude orbits. The reason is that the energy supplied by the propellants is partly derived from chemical energy, and partly from kinetic energy associated with a low position in the gravitational field. The greater the altitude of the parking orbit, the less work there is to do, and the less energy there is to do the work. For low hyperbolic excess speeds, the effect of the reduced work requirement predominates, while for high speeds, the effect of the reduced propellant energy predominates.

A comparison of the remaining mass after departure from the eccentric parking orbit with the remaining mass after departure from the low, circular, parking orbit is highly instructive. At all speeds, the remaining mass is doubled. However, transfer from the circular orbit to the eccentric orbit is approximately the same as escape from the circular orbit to parabolic speed, or to a hyperbolic excess speed of 0.0 EMOS. From the chart, it is seen that the starting mass on the eccentric orbit is only half the starting mass on the circular orbit. Thus, the remaining mass is both doubled and halved, with no net change. If retanking is done from the Earth, the cargo mass in percent of the total initial mass on the surface of the Earth is the same, whether retanking is done on low-altitude circular orbit, eccentric parking orbit, heliocentric orbit, or at the destination planet. Only operational advantages need be considered in choosing where to retank.

The situation is different if retanking is done from the moon. In order to make the initial comparisons it is well to ignore considerations based on inefficient rocket design. For the comparison, assume an efficient rocket of large size, burning hydrogen with oxygen, and having a plug nozzle, throttleable motors, balloon tanks, and front-end steering motors. Although such a rocket does not now exist, it can be built now, using existing engineering knowledge, and keeping all engineering exchange coefficients small. Without staging, it can place a large cargo, mainly of propellant for subsequent maneuvering, on any of the stations in Figure 8. The entire rocket can be completely retanked by other rockets of the same size and design.

The circular parking orbit around the Earth at 60 Earth radii, at the same altitude as the moon, requires almost the same speed increments as a parking station in any one of the five lunar libration points. With trivial error, we can use it to evaluate retanking at the cis-lunar libration point.

An itemized comparison follows:-

- o Circular, low-altitude, Earth parking orbit.

  Requires no lunar base, but requires expenditure of 9 tankers from the surface of the Earth.

- o Lunar surface.

  Require lunar base, but no tankers.

- o Circular parking orbit around the moon;
- o Cis-lunar station;
- o Eccentric orbit around the Earth; and,
- o Heliocentric orbit.

  Each requires two recoverable tankers from the surface of the moon.

Presumably, the eccentric orbit could be timed for rendezvous with tankers from the moon, but it also must be oriented for alignment with the departure direction required for an interplanetary transfer. It requires tricky planning and execution, and may be regarded as unsuited for all-purpose use.

The heliocentric station delivers less cargo than the cis-lunar station. At the same time, it permits only infrequent, tightly scheduled, and tricky rendezvous with lunar-based tankers. The cis-lunar station permits unscheduled rendezvous at all times.

The circular orbit around the moon yields a slightly greater cargo than does the cis-lunar station, but requires careful planning to insure alignment with departure directions for interplanetary transfers.

Departures from the surface of the moon require no rendezvous, and alignment problems are as small as in the case of the cis-lunar station. In spite of somewhat reduced cargo, lunar surface retanking might be preferred, except for one difficulty. Initial transfer from the surface of the Earth to the surface of the moon consumes most of the mass, leavi... ttle room for interplanetary cargo. Therefore, in order to transport a massive cargo to Mars or Venus, a large launch vehicle is required, and the theoretical gains to be achieved by retanking on the moon cannot be realized. This conclusion might be modified by the assumption that part of the non-propellant cargo would be such provisions as water and oxygen, stocked on the moon. In an open-cycle ecology, these provisions are a major part of the total non-propellant cargo. Further reflection, however, suggests that the stocking of provisions at the cis-lunar location is also possible, without adding more tankers. Therefore, rather than land a big rocket on the moon, it is better to send a smaller rocket to the cis-lunar position, and stock it there with provisions and propellants.

From the above discussion we can now eliminate, on a feasibility or a competitive basis, all except two cases, namely:-

- o Retanking on low Earth parking orbit, requiring nine expended tankers from the Earth, but no lunar base.
- o Retanking on cis-lunar station, requiring a lunar base and two recoverable tankers, but no expenditure of tankers.

A third alternative is to send a single vehicle to Earth parking orbit; transfer excess propellant from the over-sized, main propellant tanks to empty tanks in the nose cone; jettison the now empty main rocket; and to let the nose cone continue alone into heliocentric orbit. Figure 9 shows the comparison graphically. The limiting hyperbolic excess speed is 0.33 EMOS for the single rocket without retanking. It is 0.55 EMOS for the same rocket with retanking, in either case.

Refering again to Figure 1, on low-altitude, circular parking orbit around the Earth, 0.33 EMOS for a specific impulse of 444 seconds corresponds to 0.60 EMOS for a specific impulse of 830 seconds, possibly achievable by nuclear propulsion. Actually, heavier engines, shielding, and tanks in nuclear rockets may reduce the difference considerably, but the point to be made here is that retanking from a lunar base gives about the same performance by a chemical rocket that is possible by a nuclear rocket without retanking.

Figures 10 and 11 are included for further comparisons. As a matter of academic interest, the speed at which the curves cross is independent of propellant specific impulse, and is a function of orbit mechanics alone. The reader is invited to replot the curves in any of many possible combinations, in order to develop a "feel" for the relative merits of different schemes.

Figure 12 is a replot of curves corresponding to a propellant specific impulse of 444 seconds, showing departures from various stations in the vicinity of Mars. As might be expected, escape from the surface of Mars is extravagant of propellant, confining departures to speeds generally less than 0.2 EMOS. Differences among parking orbits are relatively small, owing to the small mass of Mars, which is 0.11 times that of the Earth. I would make no appreciable difference whether retanking is done on a low circular orbit, at Phobos, or at Deimos.

Figure 13 compares trips in both directions between the Earth and Mars, for different assumptions. The reader is invited to make other comparisons by replotting various curves in appropriate combinations. A single example of this kind of exercise is shown in Figure 14, which is based on the presently unjustified assumption that water is readily available on the moon and on Mars. The single-stage rocket already described is now sent to the cislunar libration point. It reaches a low altitude, circular, parking orbit around the Earth with a remaining mass of 0.12. Transfer to the cis-lunar libration point leaves a remaining mass of 0.477 x 0.12 = 0.057, including 0.023 as empty rocket, and 0.034 as removable cargo. The rocket is retanked from the moon, and sent to Mars, where it decelerates and lands entirely by means of retro-thrust, without the aid of aerodynamic braking. On the surface of Mars it is again retanked, directly from a local propellant factory. The rocket can be sent repeatedly back and forth between the cis-lunar station and the surface of Mars. The lower curve in Figure 14 is a plot of all the combinations of terminal speed increments for the maximum removable cargo which can be sent from the surface of the Earth to the cis-lunar station. 0.10 EMOS is the speed at each end of a Hohmann transfer trajectory between the Earth and Mars.

The upper curve in Figure 14 is the limiting case for the same rocket with zero removable cargo. All cases below and left of the upper curve are possible. However, no additional cargo is made possible by operating below and left of the lower curve.

It is now possible to perform the exercise of evaluating a round trip to the surface of Venus. It is necessary to assume a favorable environment on some part of Venus. For the exercise, assume a double-Hohmann trip to Venus, separated by a 500-day stopover on the surface of the planet. Each of the two transfers will require about 120 days, and have terminal speeds at each end of about 0.1 EMOS.

Again leave the cis-lunar libration point with a fully tanked rocket. From Figure 8 we read a remaining mass of 0.59. From Figure 7 we read a remaining mass of 0.54 after entry by retro-thrust into a low-altitude, circular parking orbit. 0.54 x 0.59 = 0.32 x the mass before the maneuver to escape the cis-lunar point. On Earth, the rocket can land from parking orbit on a prepared launch pad by retrothrust, with a remaining mass of 0.23 times the mass on orbit. This somewhat favorable ratio is due to the beneficial base drag of the atmosphere during retrothrust entry. Assume the same for entry from parking orbit, and landing on Venus. 0.23 x 0.31 = 0.07 times the mass of the rocket which left the cis-lunar point, which was also the mass of the same rocket on the launching pad on the surface of the Earth. Subtracting the mass of the rocket, which is 0.023, we obtain 0.048 for removable cargo. Since the maximum removable cargo which can be transported from the Earth to the cis-lunar point is 0.038, we see that we have a propellant reserve of 0.01 x the initial mass of the fully loaded rocket. The trip back to the cis-lunar point requires slightly more than the trip to Venus, but falls within the reserve. 0.038 x 7000 metric tons is 266 metric tons of removable cargo.

No plot for Venus such as Figure 14 for Mars is included for the reason that reserve propellant opens no additional options in trajectory selection. The short stopover trip to Venus is not possible within our assumptions, and the long stopover trip, unlike the long stopover trip to Mars, does not have a long window for arrival dates. There is little reason to deviate significantly from the double-Hohmann trip. It may be added, however, that there appears to be no way, other than by retanking with propellants manufactured on Venus, to make round-trip landings on Venus.

Yet, with retanking, as we have just seen, it is possible to make repetitive round-trip landing expeditions from the cis-lunar station, using the same rocket repeatedly, just as in the case of Mars.

CONCLUSIONS

Families of curves have been presented showing the remaining mass of a single stage rocket as a function of departure speed from all interesting stations in the vicinities of the Earth, the moon, Mars, and Venus. Curves for three representative propellants have been included.

It has been shown how the curves can be replotted in appropriate combinations to compare and evaluate various retanking maneuvers. Among the hundreds of combinations which could be plotted, a few examples have been examined.

Retanking a rocket at the cis-lunar libration point has been shown to multiply ten-fold the cargo which can be sent on an interplanetary trip, assuming a propellant factory on the moon.

It may be doubted whether the investment in a lunar propellant factory and retanking capability will be worthwhile, merely to expand the capability of expendable rockets. However, assuming water on both the moon and Mars, it has been shown to be energetically possible to transport large cargos in both directions between the cis-lunar point and the surface of Mars, reusing the same rocket repeatedly for an indefinite number of round trips.

Assuming a favorable environment on Venus, it has been shown to be energetically possible to use the same rocket in the same manner to make repeated round trip expeditions to the surface of Venus.

DEPARTURE FROM EARTH

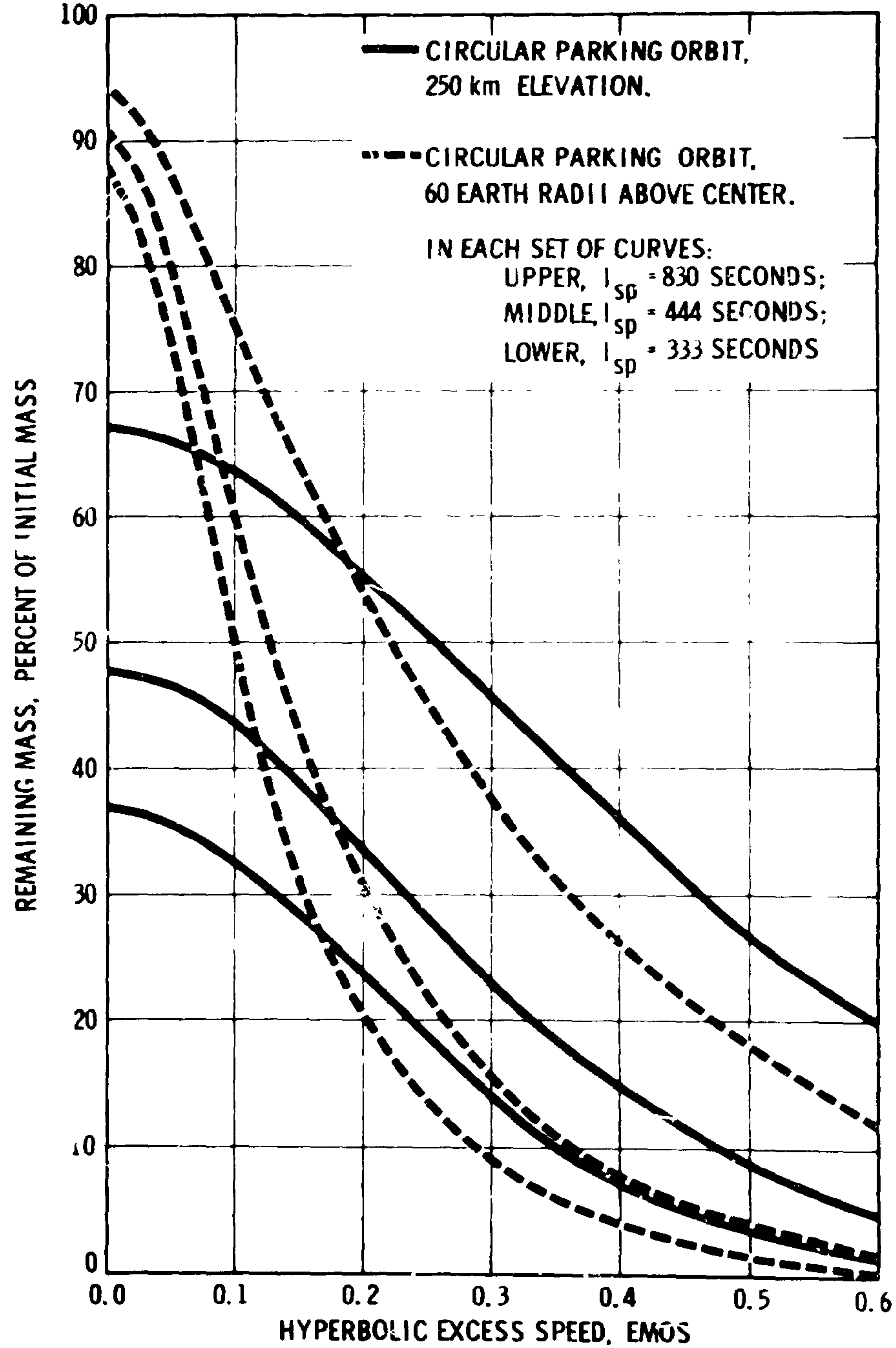


FIG. 1

MT65-11,380
11-1-65

DEPARTURE FROM EARTH

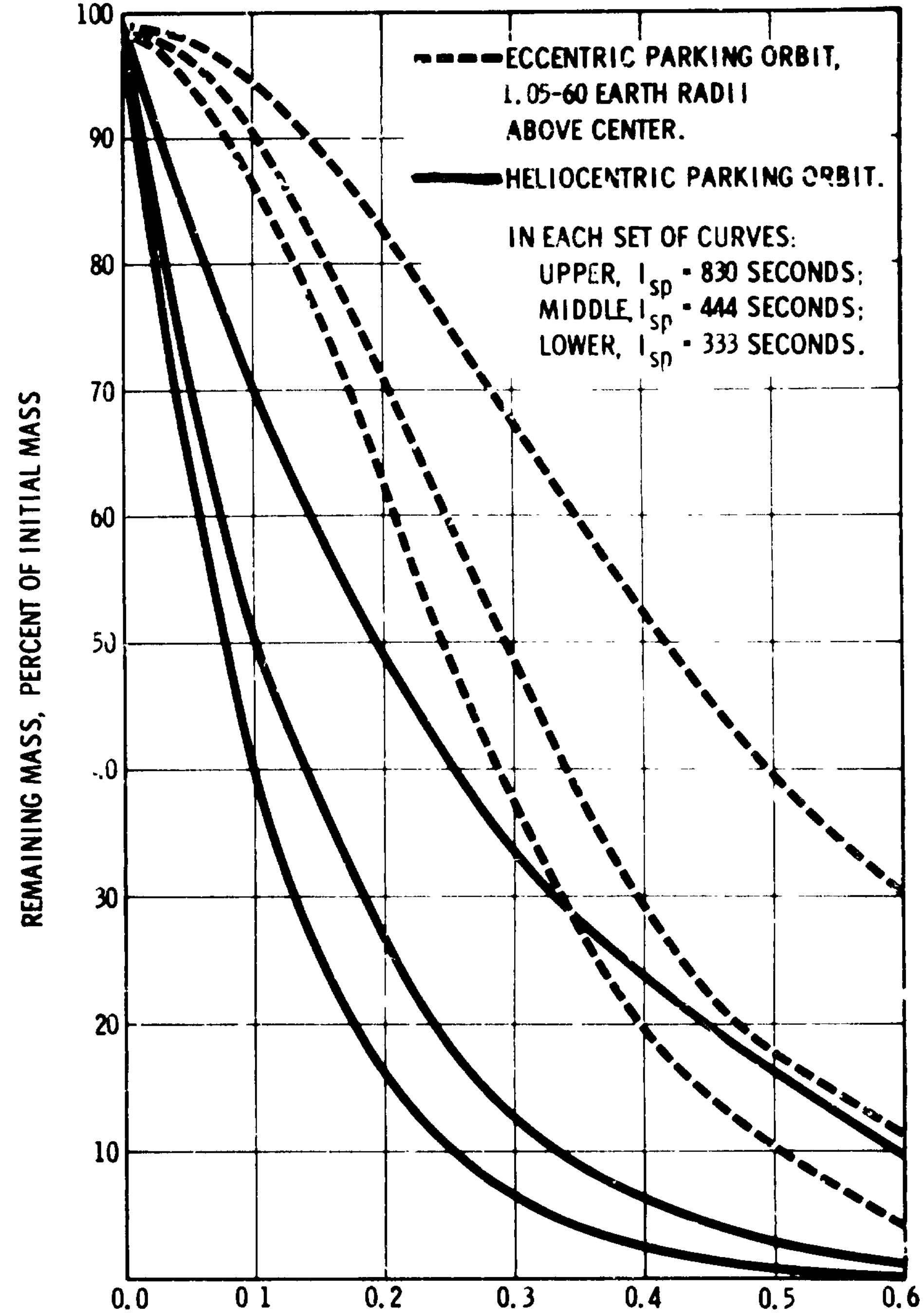
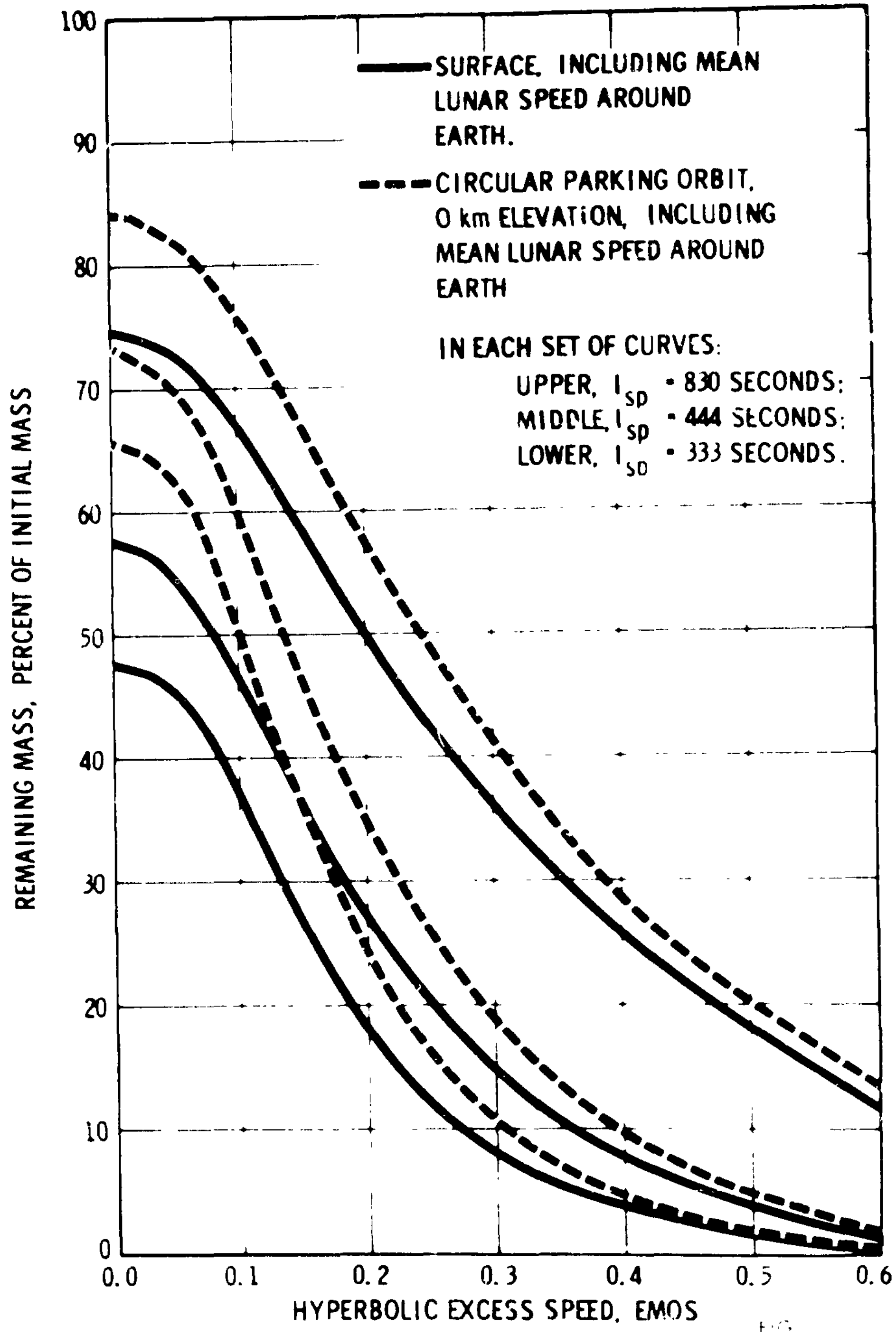


FIG. 2

MT65-11,379
11-1-65

DEPARTURE FROM MOON



MT65-...,378
11-1-65

DEPARTURE FROM MARS

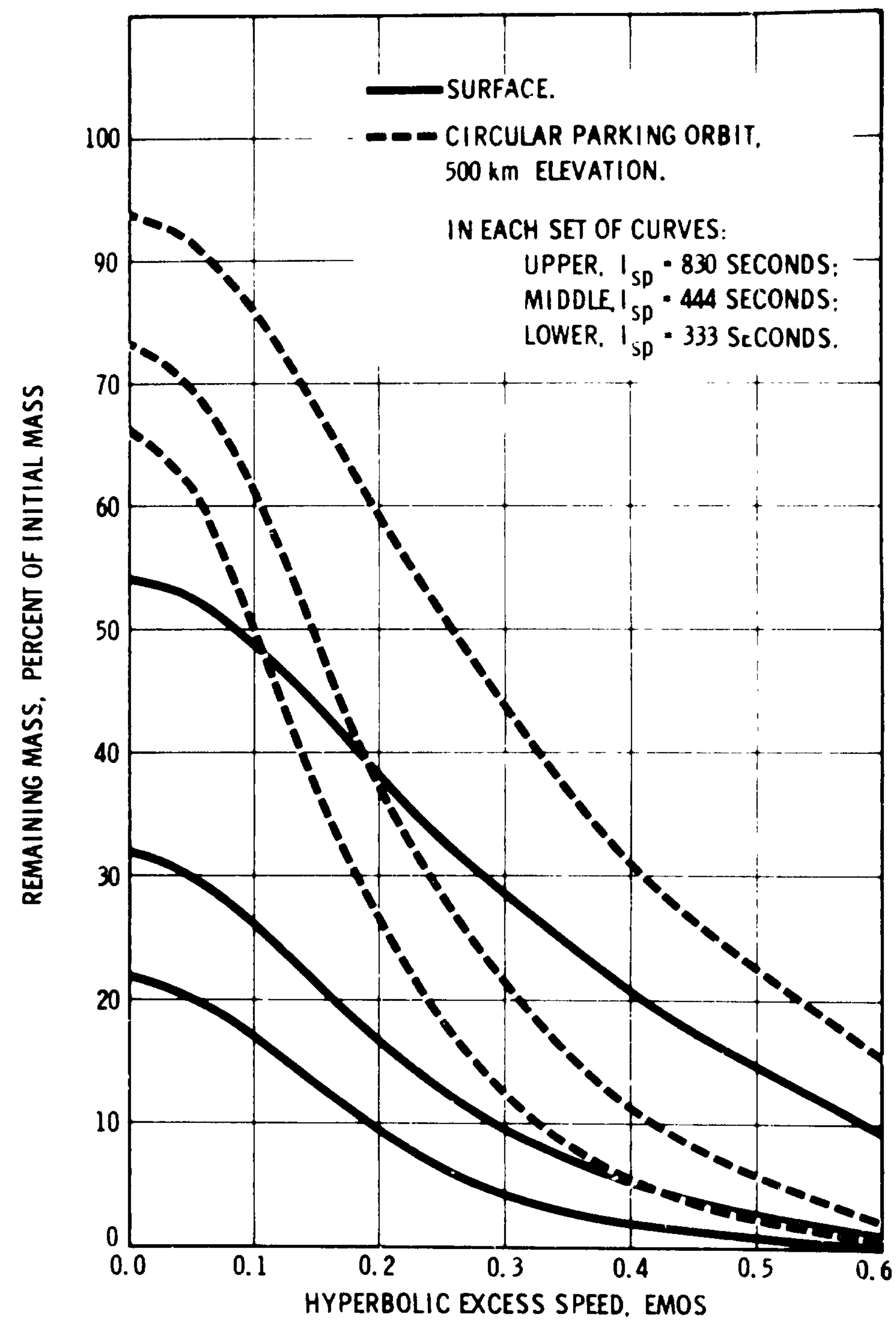


FIG. 4

MT65-11,377
11-1-65

DEPARTURE FROM MARS

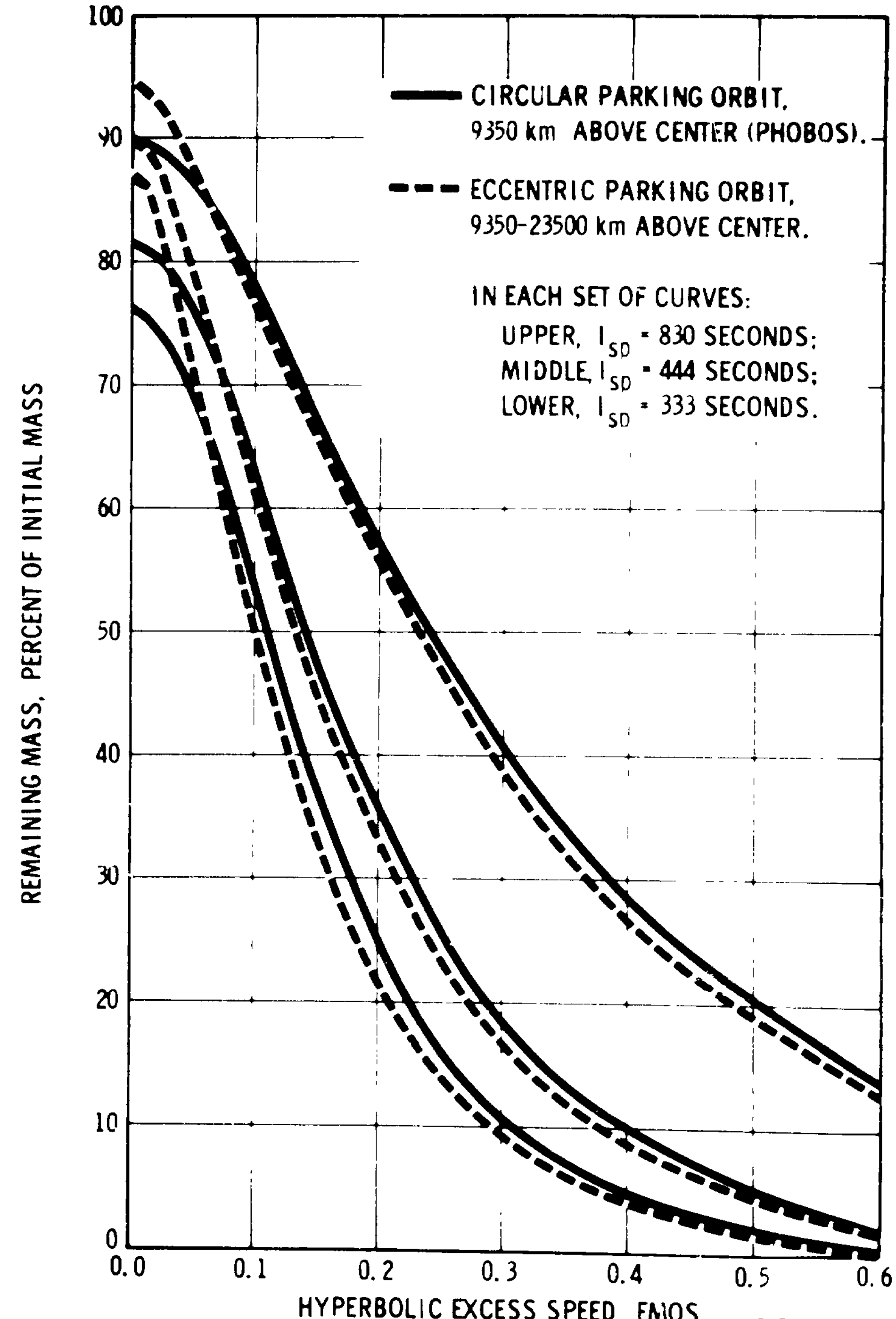


FIG.

MT65-11,376
11-1-65

DEPARTURE FROM MARS

332

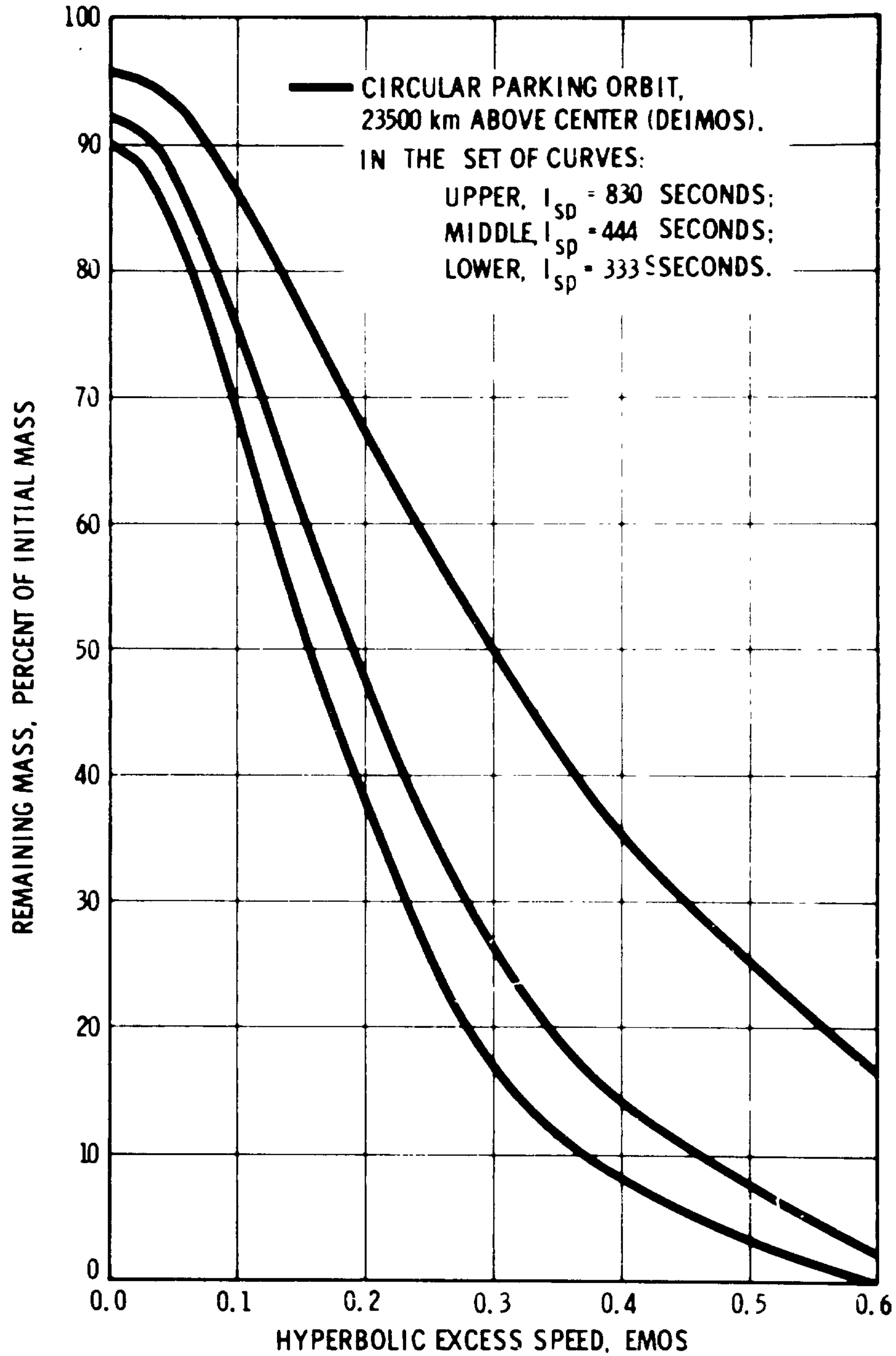


FIG. 6

MT65-11,375
11-1-65

DEPARTURE FROM VENUS

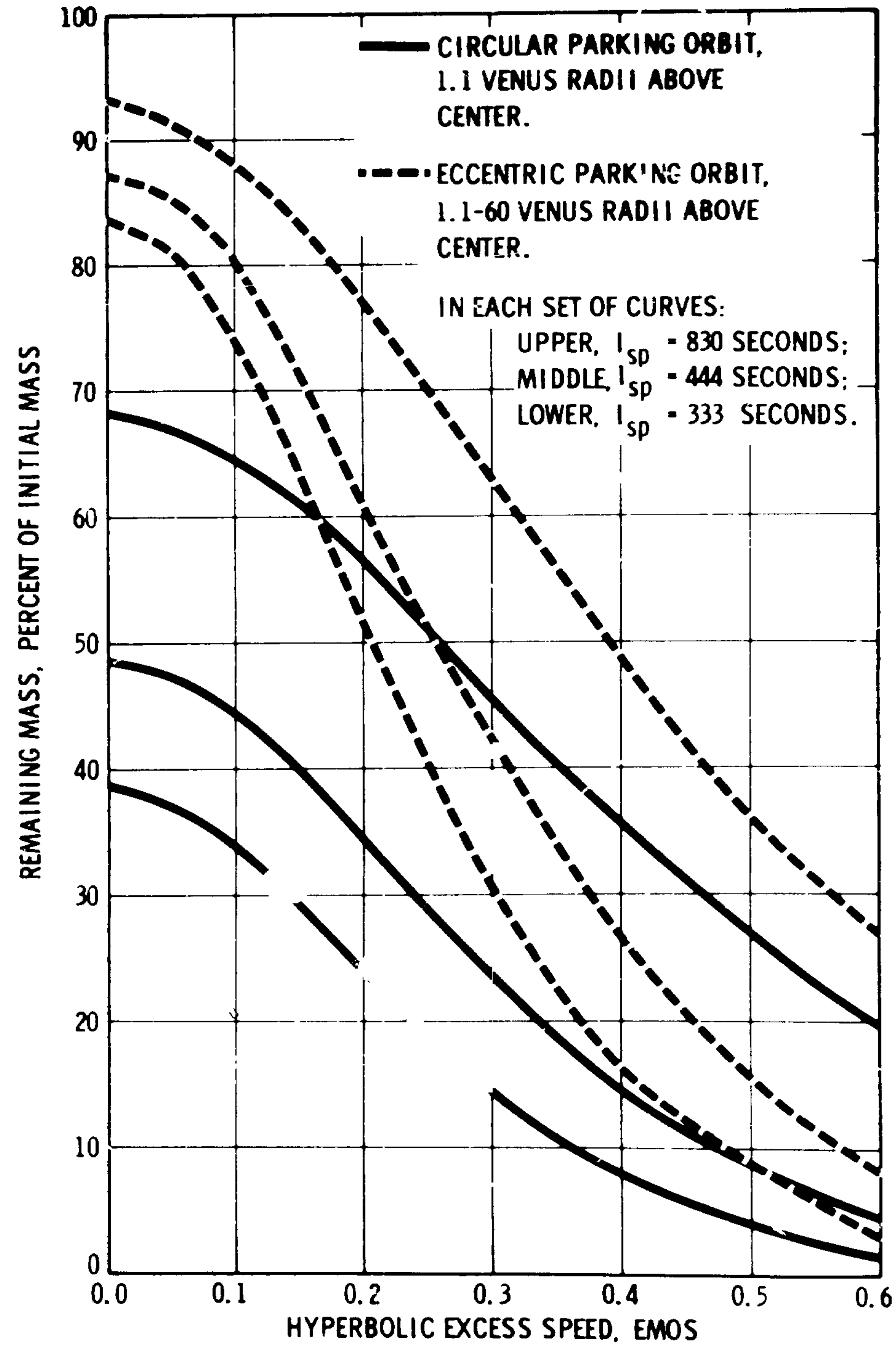


FIG. 7

MT65-11,374
11-1-65

DEPARTURE FROM EARTH-MOON SYSTEM

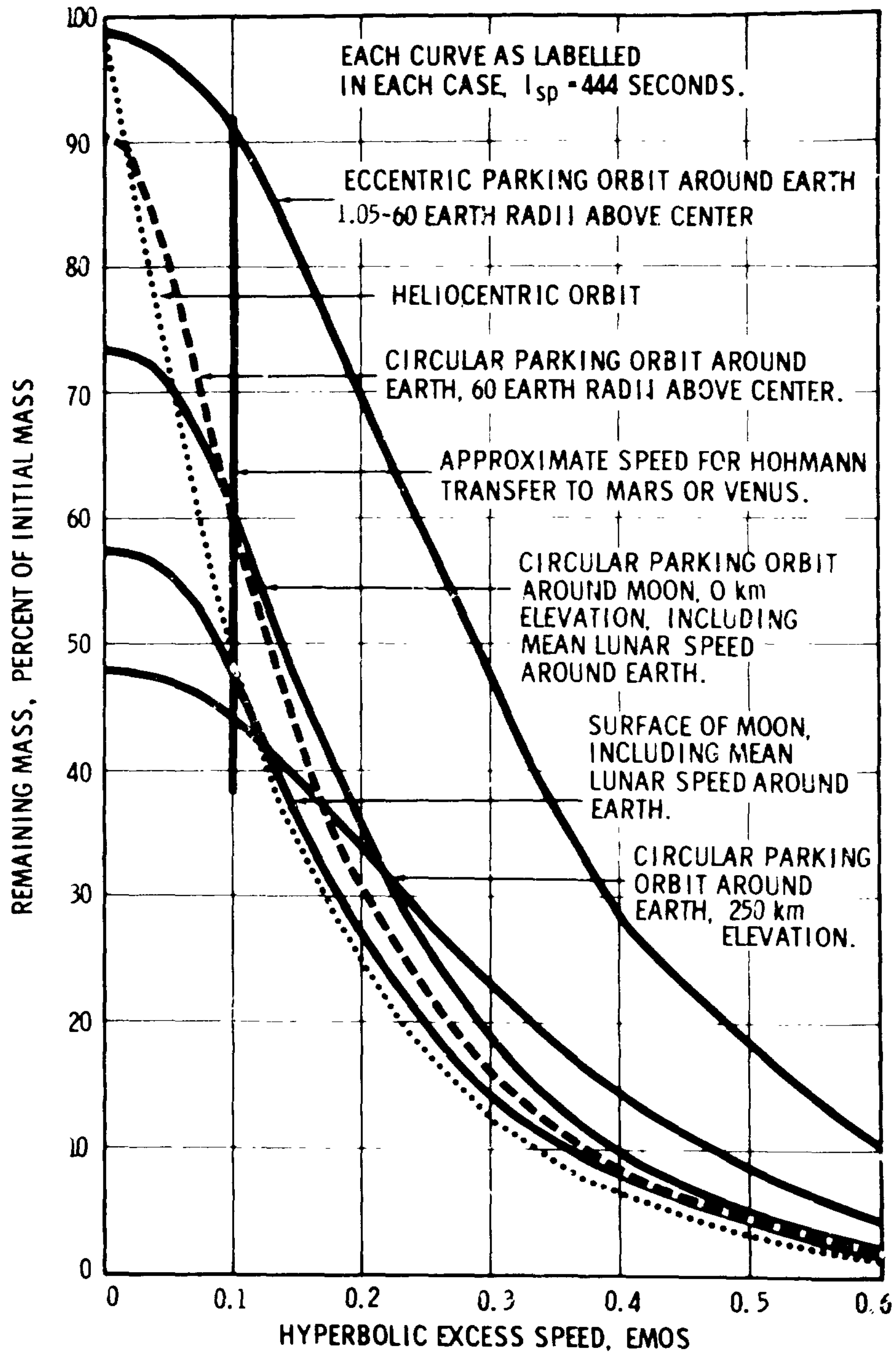


FIG. 8

NASA MT65-11,373
11-1-65

COMPARISON OF RETANKING PLANS

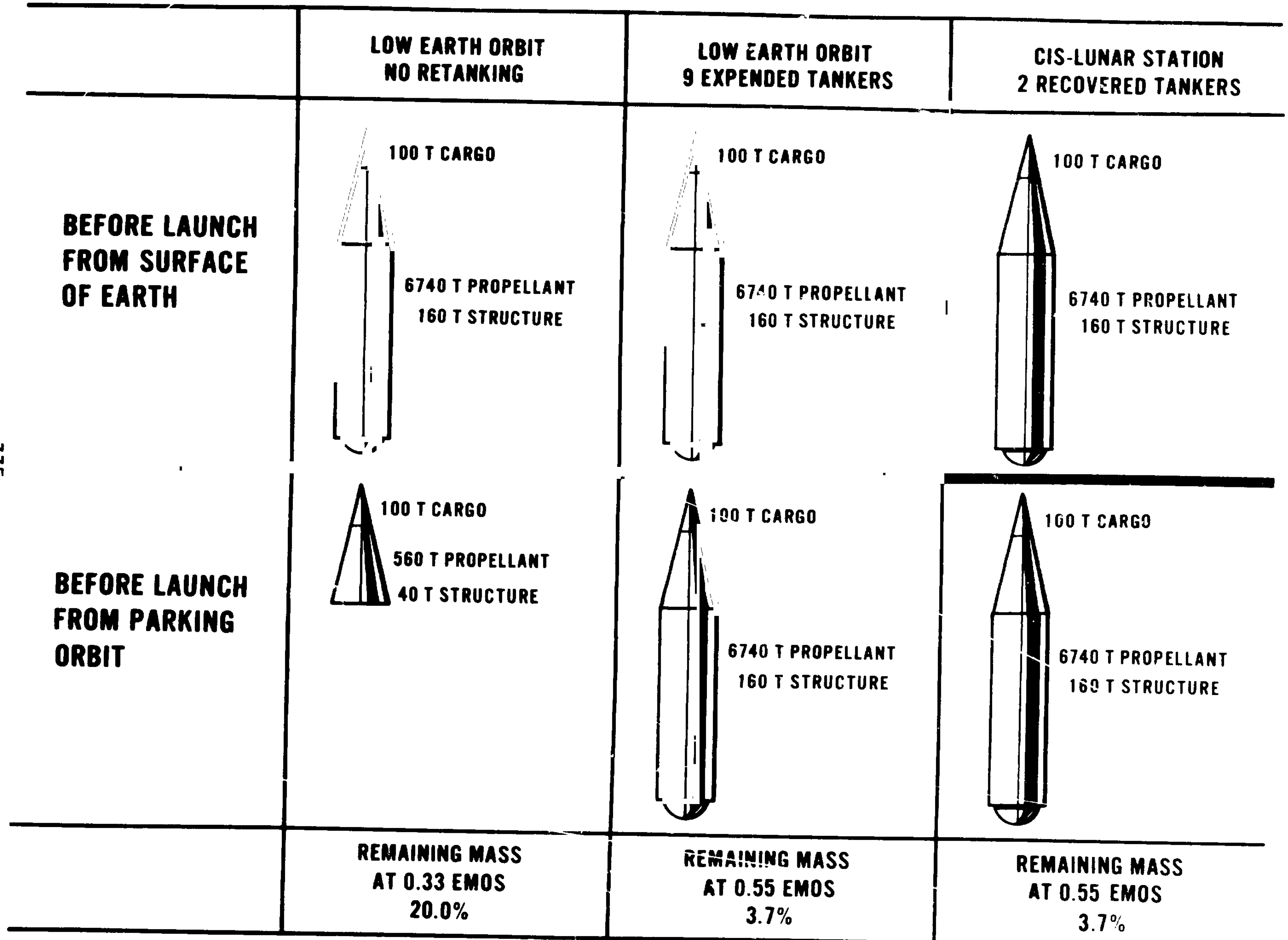


Fig. 9

NASA MT65-11,489
11-1-65

DEPARTURE FROM EARTH-MOON SYSTEM

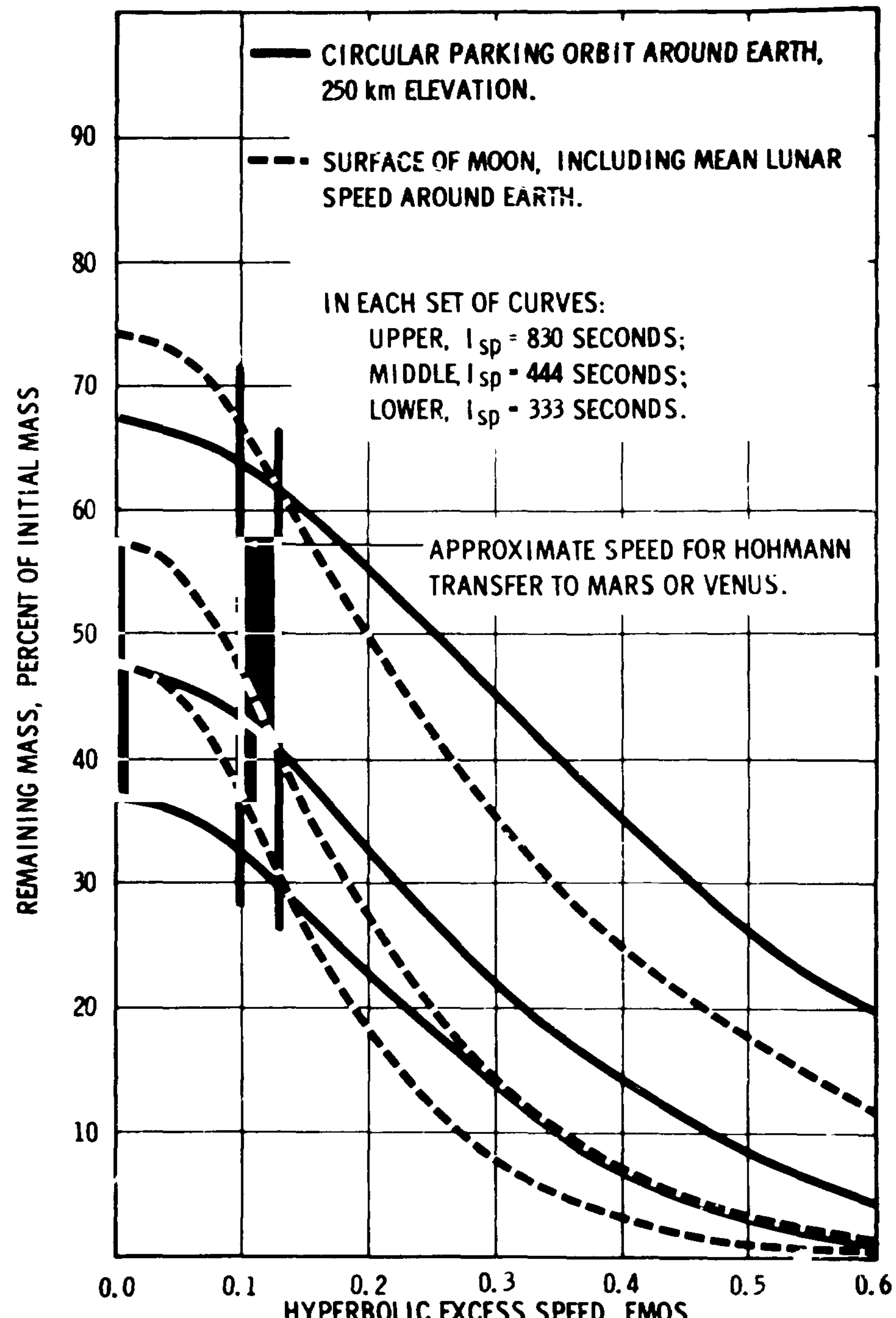


FIG. 10

NASA MT65-11,372
11-1-65

DEPARTURE FROM EARTH-MOON SYSTEM

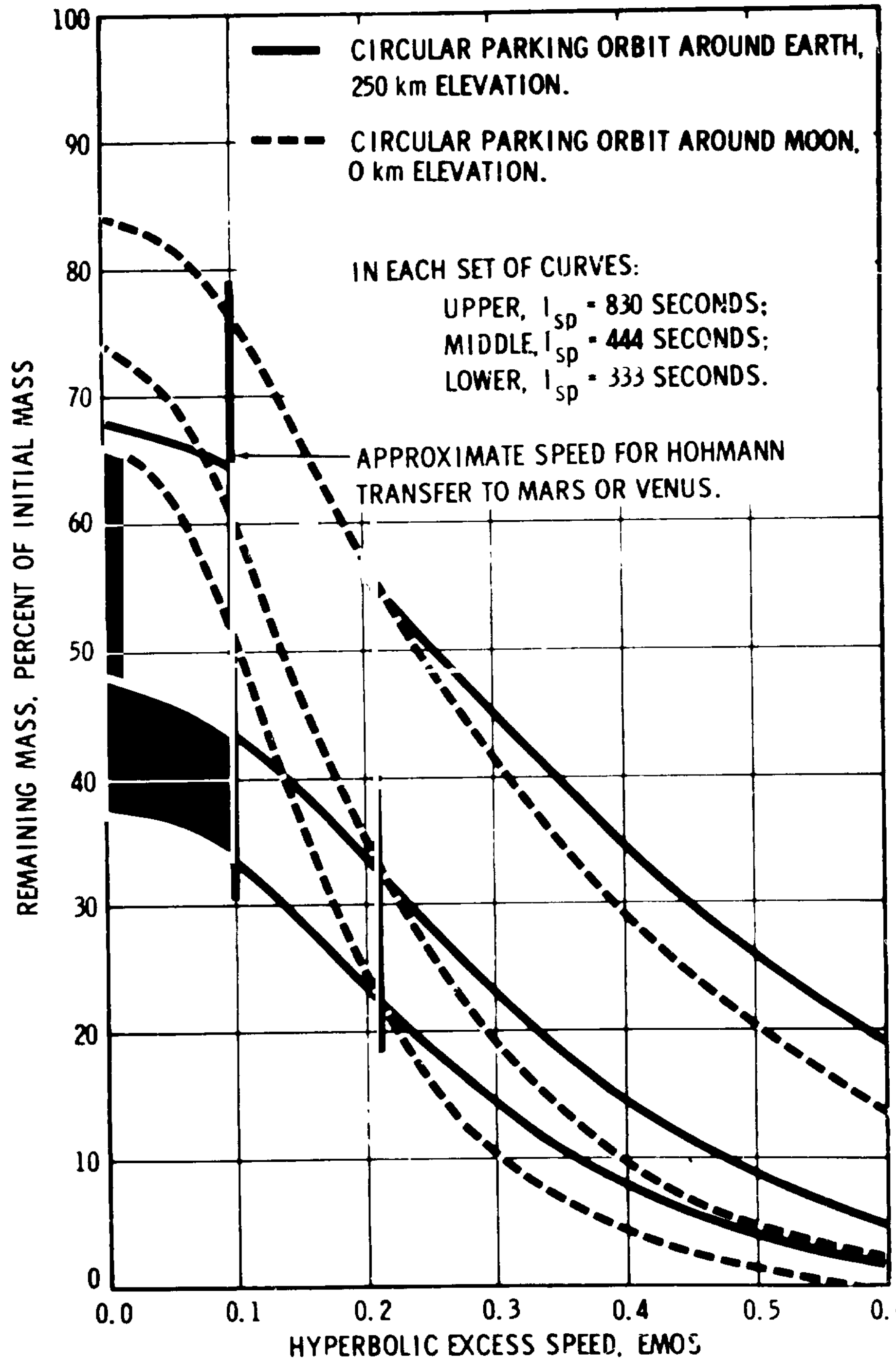


FIG. 11

NASA MT65-11,369
11-1-65

DEPARTURE FROM MARS

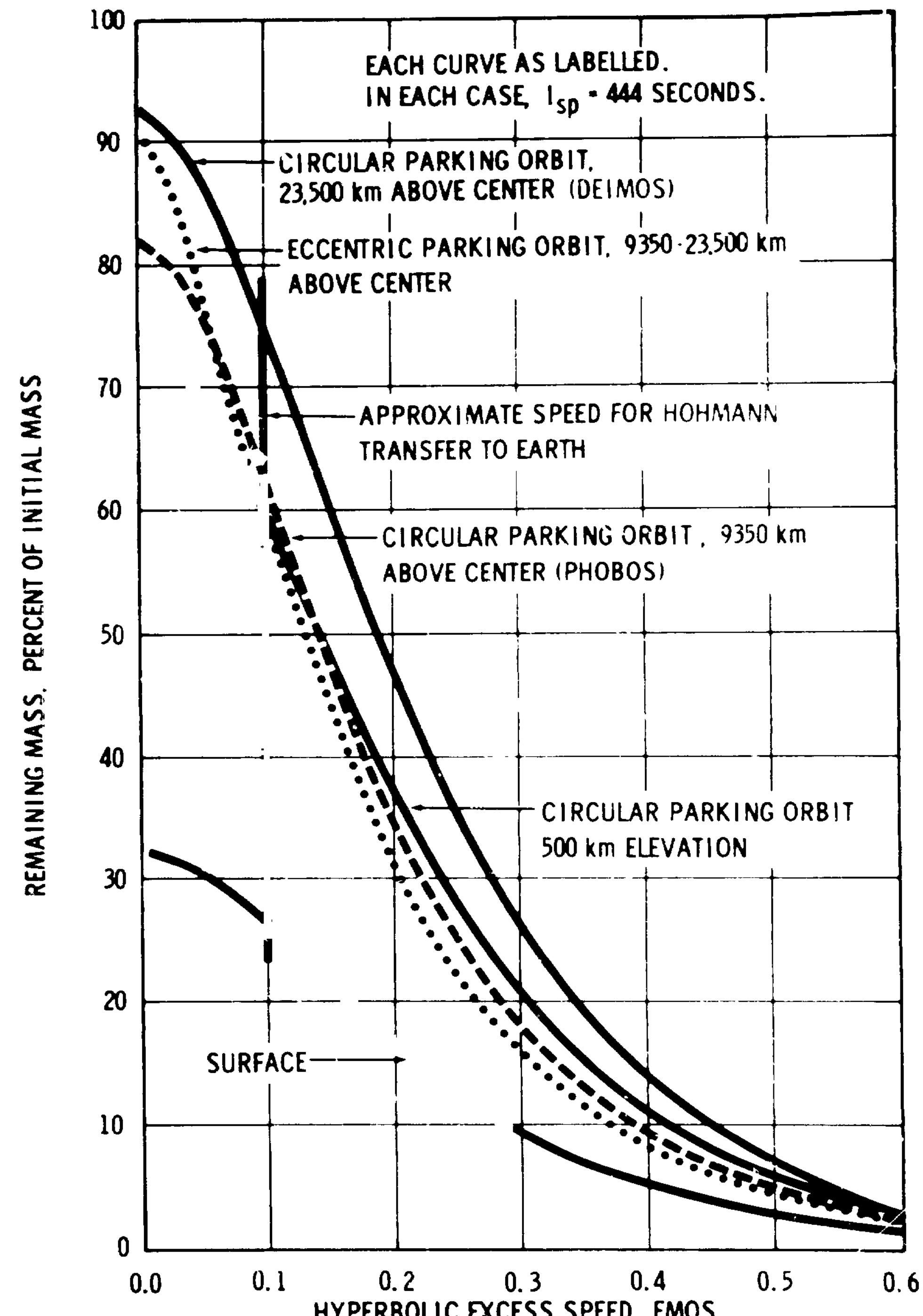


FIG. 12

NASA MT65-11,371
11-1-65

EARTH-TO-MARS AND MARS-TO-EARTH

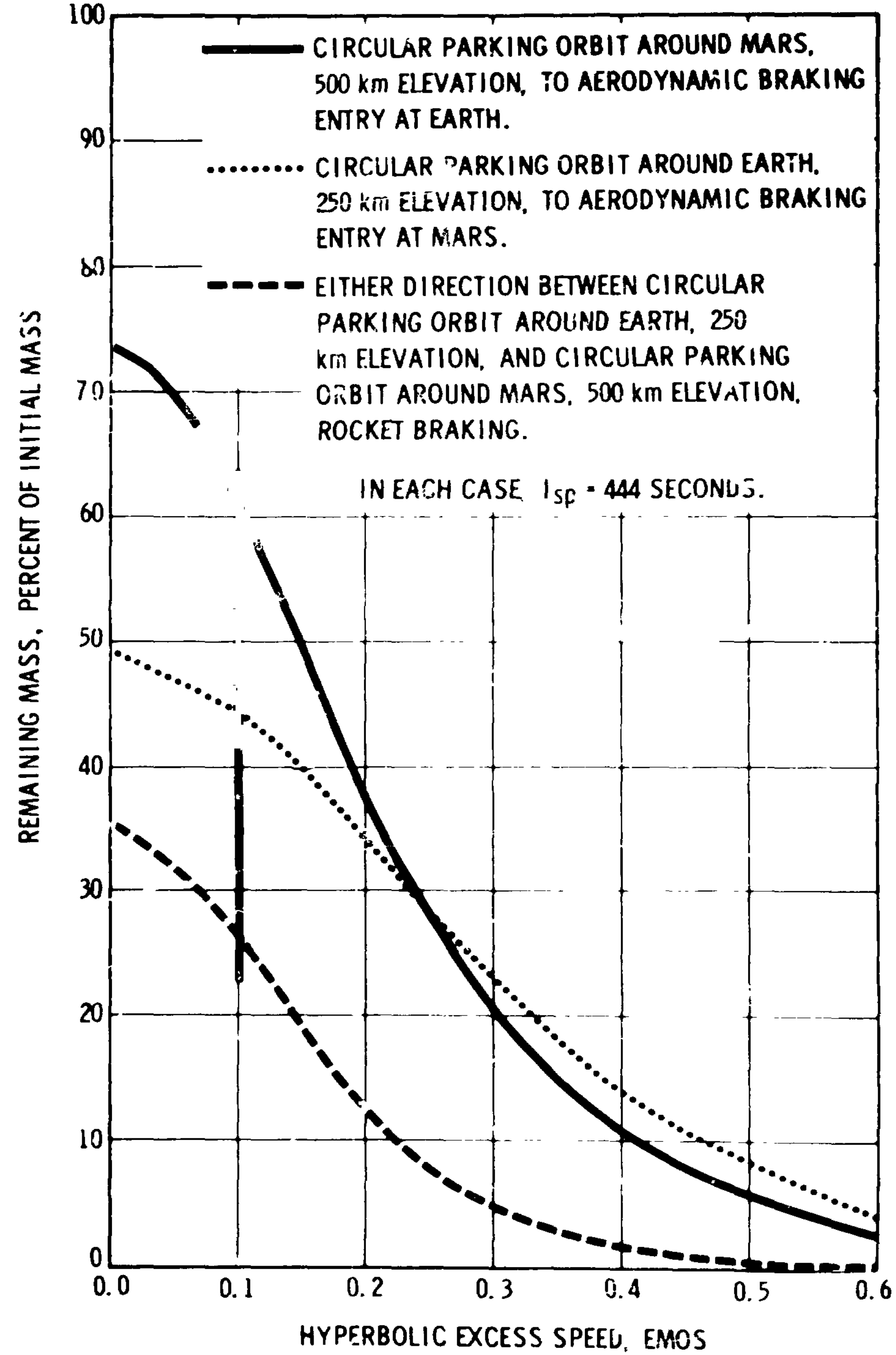


FIG 13

NASA MT65-11,368
11-1-65

GATE FOR ROUND TRIPS BETWEEN CIS-LUNAR STATION AND SURFACE OF MARS

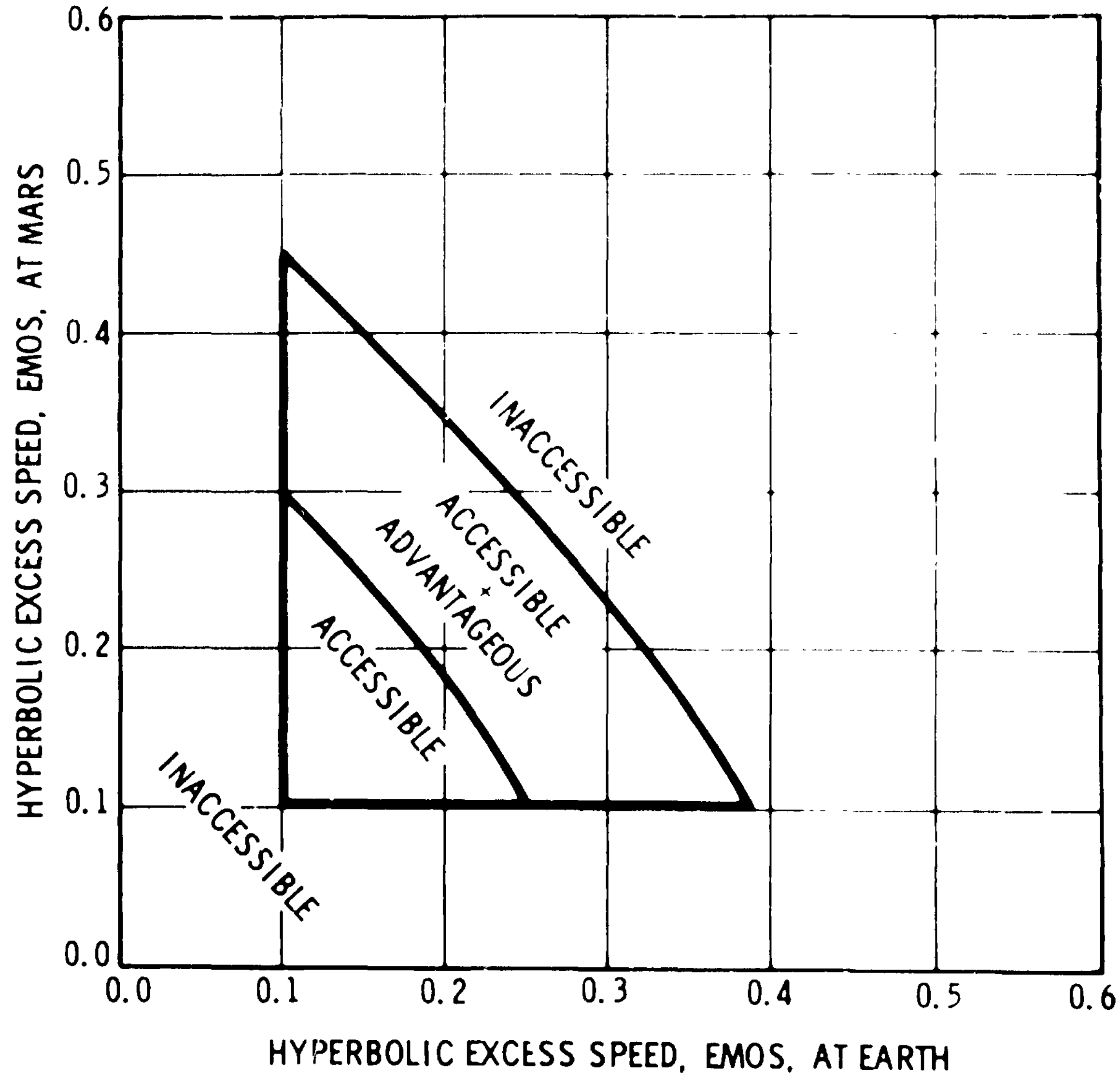


FIG. 14

NASA MT65-11,370
11-1-65

ECONOMIC ANALYSIS OF EXTRATERRESTRIAL PROPELLANT MANUFACTURE IN SUPPORT OF LUNAR EXPLORATION

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NOVEMBER 15, 1965

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ECONOMIC ANALYSIS OF EXTRATERRESTRIAL PROPELLANT MANUFACTURE IN SUPPORT OF LUNAR EXPLORATION

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ABSTRACT

Economic considerations, affecting a "transport or manufacture" decision concerning the resupply of propellants for use in lunar exploration operations, are developed and analyzed. Factors are suggested which will be prerequisites to an economic justification for the manufacture of propellant from lunar resources. This paper presents a postulated extrapolation of a lunar surface activities framework, establishes therefrom a demand estimate, considers a number of lunar resource processing concepts, and establishes the economic "break-even" conditions between transport and manufacture modes of resupply. Parametric results are presented which will permit basic decisions to be formulated concerning the desirability, from an economic viewpoint, of planning for lunar propellant manufacture as an adjunct to advanced lunar operations. In particular, the analysis concentrates on the use of propellant manufacture to support crew rotation flights from the lunar station to Earth (preliminary analyses have designated this as a most promising area for concentration). This paper will support a first order answer to the question of economic feasibility related to lunar propellant manufacture within the lunar exploration era of lunar activities.

ECONOMIC ANALYSIS OF EXTRATERRESTRIAL
PROPELLANT MANUFACTURE IN SUPPORT OF LUNAR EXPLORATION

David Paul, 3rd

INTRODUCTION

The exploitation of extraterrestrial resources for the enhancement of a national space flight capability has been ardently proposed and vigorously pursued for a number of years. Until recently much of the fervor exhibited for this approach was based on intuitive judgments and oversimplified analyses necessitated by the lack of sound engineering estimates and credible projections of a reasonable space flight program. However, efforts by the Working Group on Extraterrestrial Resources, various government agencies, and funded and unfunded aerospace industrial organizations are currently establishing a data base which will permit first-order analyses of the feasibility of these concepts. If proven feasible, extraterrestrial resource utilization promises many benefits to the space program planner; it is therefore prudent to assess the economic desirability of schemes whose conceptual feasibility has been postulated, so that future time and dollar expenditures can be beneficially directed toward the development of the most rewarding approaches.

This paper: builds upon a methodology, presented in an earlier work by the author (reference 7), for an economic analysis of transport and manufacture strategies in support of advanced lunar exploration missions; postulates a demand for propellant oxygen in the 1975 and beyond time frame; assesses the economic factors governing the desirability of lunar propellant production for a number of proposed concepts; and establishes a number of first order prerequisites to the achievement of an economically attractive lunar based oxygen production facility

METHODOLOGY

As discussed in reference 7, and as depicted on figure 1, an economic assessment of the exploitation of lunar resources within the national space program depends on the establishment of a transport cost analysis, a manufacture cost analysis, and most importantly on the postulation of a resource demand estimate. The earlier work emphasized the development of a detailed approach to the transport option analysis (figure 2). This approach, dependent on the projected scope of the space flight program and considering the contributions of probabalistic launch failures and expected learning factors, attempted to predict logistic transport cost burden relationships as a function of propellant production rate and with respect to time. The present analysis, to achieve clarity, has minimized the number of variable parameters and considerably simplified this aspect of the problem by assuming a fixed transport cost burden for payload delivered to the lunar surface. This assumption, while admittedly naive, is sufficient to allow the establishment of first order desirability assessments.

The development of the manufacture option cost burden is dependent on the many varied factors shown in figure 3. Limited available data on resource production and acquisition concepts has until recently precluded analysis of the costs associated with extraterrestrial resource development. For purposes of this analysis, the author gratefully has utilized the work of Rosenberg et al. (references 8 and 9), Glaser et al. (reference 5), and others whose concepts are contrasted herein. It can be seen from figure 3 that the selected approach has been to estimate the mass of required equipments, as delivered to the Moon, the manpower requirements to affect their operation, and then to apply appropriate shipping cost burdens to convert these mass demands into cost estimates.

A "market analysis" is an important prerequisite to a demonstration of economic desirability. Figure 4 portrays the factors contributing to the demand for extraterrestrial oxygen. It is most obvious that the scope of the national space effort plays an important role in this determination; it is mandatory therefore to postulate a projected level of lunar exploration effort in order to assess the economic desirability of lunar manufacturing facilities.

POSTULATED LUNAR SURFACE EXPLORATION PROGRAM

The total lunar exploration program can be sub-divided into a number of phases or eras characterized by the scope and depth of scientific investigations allowed by the mission equipments. These phases: (1) the initial landing program, (2) a reconnaissance and early exploration era, (3) the exploration phase, and (4) an exploitation phase are depicted in figure 5 with the author's postulation of a reasonable schedule for these programs. With the exception of possible small scale feasibility demonstrations or prototype tests during the early eras of lunar exploration, the application of extraterrestrial resources to support lunar operations is most reasonably accomplished from a fixed scientific station characteristic of the exploitation phase of lunar exploration.

It should be noted that to this reference an "exploitation" phase of lunar operations can have several connotations. It was first used above to denote scientific activities which exploit the Moon as a vantage point, in space, for the study of the Earth, planets, stars, and the space environment. It is now also possible to refer to this era of lunar exploration to suggest the utilization of lunar resources either: (1) in support of lunar operations; or (2) more ambitiously, in support of deep space or planetary flight operations.

Projections more than 15 or 20 years into the future are considered by the author to be unsuited for other than broad policy orientations. It can be observed that the projection of figure 5 extends only through 1985; it is readily admitted that the visualization of lunar operations becomes quite cloudy and subject to considerable misjudgment in the post-1980 time frame. It is quite probable that conclusions based on the scope of operations postulated herein will not be applicable for all time.

In order to establish a resource demand estimate for purposes of this paper, it is postulated that a quasi-permanent lunar scientific station will be established in 1975 and maintained, by crew rotation and logistic support, through 1985. The base is assumed to be initiated at the six-man level which is increased, with time, to a 12-man complement as shown in figure 6.

LUNAR RESOURCE UTILIZATION CONCEPT

This paper addresses the question of economic feasibility of lunar manufactured propellants for the support of lunar operations and is not concerned with possible application to planetary or deep-space flights or to combined demands which might provide concept enhancement. To maximize the possibilities of an economic justification for lunar manufacture under the above guidelines, it is essential that a substantial demand for these propellants be created. Within the context of a reasonable projection of our space flight effort, it is difficult to postulate large demands for liquid oxygen on the basis of life support or mobility system requirements; it is necessary therefore to conceive a crew transportation system which can utilize lunar produced propellants for the return trip to Earth. Such a concept might be formulated around a spacecraft capable of transporting three men from Earth to Moon and back to Earth via a direct flight mode. This spacecraft might consist of a modified Apollo Command Module, a service module/lunar landing stage or stages (capable of being refueled on the lunar surface), and a lunar braking stage. Various staging options are doubtlessly available but have not been considered in this analysis. An uprated Saturn V launch vehicle could be used to complete the transportation concept.

Since this crew transport vehicle would be refueled on the lunar surface with return trip propellants (or return LOX only), it conceivably can carry cargo to the Moon, in addition to the men, equivalent to the mass of propellant required for return propulsive thrust. Obviously, this reduces the number of logistic flights required to support the expedition. It would also be possible to apply this "extra" payload toward the accommodation of additional crew members to increase the efficiency of crew transportation. For purposes of this analysis, a first-order assessment, these schemes are identical.

Applying the crew transport mode suggested above to the support of the postulated lunar mission described on figure 6 will establish the resource demand estimates for this study. The analysis is based on a precept of non-interference with the primary scientific mission of the station, thus a processing plant crew complement is superimposed onto the scientific staff (this will be discussed in more detail later; there are obviously iterations required at this point in a detailed analysis). It is noted that a six-month staytime for lunar base crew members is assumed which, in turn, dictates the number of required crew flights.

From the results of advanced lunar transportation system studies, such as reference 16, it is estimated that the liquid oxygen required to propell an Apollo-type, three-man, command module from the lunar surface to Earth is approximately 15,500 pounds. For purposes of this analysis the complementary 3,100 pounds of liquid hydrogen are assumed to be transported from Earth by the spacecraft on its trip to the Moon. The analysis described in this paper considers only the production of liquid oxygen. Of course, the availability of a hydrogen source will favorably enhance the economic situation; however, this increment is not sufficient to invalidate the conclusions presented in this paper.

The combination of the crew flight rate, the propellant requirement for the flight, a spillage factor of 15 percent, and an additional nominal amount for base operations (life support demands plus an allowance for mobility devices) establishes the resource demand estimates. As shown on figure 6, the LOX demand could be expected to be of the order of 10,000 pounds per month in 1976 and grow with base size to 20,000 pounds per month. These estimates establish a zone of interest for lunar manufacture of liquid oxygen applicable to the support of a reasonable lunar exploration and exploitation program.

CANDIDATE CONCEPT DESCRIPTIONS

Two resource processing schemes which are conceptually feasible have been sufficiently detailed to permit economic analysis. One concept, utilizing the chemical reduction of lunar rock silicates as a source of oxygen, does not depend on the existance of lunar water, in any form, for its feasibility. It has been estimated by many authorities that the lunar surface composition, not unlike the Earth's crustal rocks, is predominantly oxygen (40 to 50 percent by mass). The silicate reduction concept has been proposed by Dr. S. D. Rosenberg et al. and has been detailed in references 8 and 9. It requires that lunar rock be delivered to a process reactor where a two step chemical reduction of the metal silicates produces a slag and water. The water can be electrolyzed to produce gaseous oxygen which in turn can be liquefied. The resulting hydrogen must be recycled to the process - no hydrogen is produced unless the rock input contains water in some form. Ideally, the reaction requires only lunar rock and electrical power, other reactants can be recycled.

A second concept has been proposed by Dr. P. E. Glaser et al. (reference 5). This approach recommends an in-situ process but requires that water exist on the Moon either as hydrated minerals, adsorbed water, or in the form of permafrost. This concept visualizes drilling a well into a sizable deposit of water bearing rock, emplacing a nuclear reactor powered heater down the hole, capping the well, and piping the resulting steam into an electrolysis and liquefaction plant. Electrical heaters, isotope heaters, liquid metal heat exchangers, or an entire reactor could be utilized as a heat source; for ease of calculation electrical heaters were assumed in this paper. The obvious inefficiencies associated with this approach are not significant to the particular case investigated (the favorable permafrost case) but with less water available more efficient heat sources would pay dividends. This concept, of course, can produce liquid hydrogen as well as liquid oxygen. One of the most advantageous features of the in-situ process is its potential operational simplicity; lunar mining and rock transport operations are eliminated. On the other hand, drilling of large-bore, deep wells on the lunar surface represents a significant undertaking.

LUNAR POWER PLANT MASS BURDEN

Rosenberg and Glaser, in the references cited, have estimated the power requirements for their respective processing concepts. Figure 7 depicts these power requirements as a function of the monthly demand or production rate of LOX. The data shown for the Aerojet Carbothermal Process (silicate reduction process) represents a general average of two slightly different concepts outlined in reference 8. The power estimates for the in-situ water boiloff concept must be augmented by the power requirements of the electrolysis, liquefaction and storage portions of the scheme. Various estimates for these kilowatt demands are shown on the curve. Use of the right hand portion of the chart allows the easy conversion of kilowatt demand to required payload mass on the lunar surface.

Inspection of figure 7 shows that kilowatt requirements are extremely high within the zone of interest defined by the resource demand. Electrolysis and liquefaction requirements alone vary from 50 to 100 kilowatts and are common to all concepts. The silicate reduction concept requires a total power requirement between 180 and 340 kilowatts over the range of interest of LOX demand. Total power necessary for the in-situ process is a function of the strength of the water-rock bond and is shown for three cases. It can be seen that the power requirements for the hydrated rock case (even with 10% water) are excessive (300 to 600 kilowatt - these could be reduced by efficient heat transfer concepts as discussed above). The absorbed water situation, with 1% water, is essentially represented by the silicate reaction and will not be considered further in this analysis. The case of the 50% water-50% dust, permafrost deposit is interesting because of its inherently low power requirements. Since it represents an optimistic, upper-limit for resource acquisition, it will be considered as a potential candidate in this paper despite the generally pessimistic expectation of locating such rich deposits.

The conversion of these power demands to logistic demands and eventually to cost burdens depends on an assessment of the state-of-technology. These lunar resources, to be useful to the lunar exploration program, must be timely. It is recalled that production was scheduled to be initiated in 1976; thus automatically establishing the technology spectrum. It has been assumed, for purposes of this analysis, that SNAP-8 technology will have progressed to the point that a 50 to 60 kilowatt nuclear power plant will be capable of being delivered to the Moon by a Saturn V logistic vehicle. Such a capability is represented by the 500 pounds per kilowatt burden factor curve. This burden factor can range over the spectrum between 1,000 (current SNAP-8 for lunar applications) and 200 (represented by a new fast-spectrum reactor design). Of course, the new technology approaches must accept the time and dollar burdens of an extensive research and development program.

PROCESS EQUIPMENT MASS BURDENS

A number of lunar cryogenic production facilities have been conceptually defined by others. Their mass estimates have been plotted with respect to liquid oxygen output rate in pounds per month (see figure 8). The data, apparently independently achieved, displays a fair degree of consistency which lends some support to its usefulness. In the zone of interest, it can be observed that the process equipment is approximately one order of magnitude lighter than the power plant mass. Figure 8 also shows two estimates of the mass of a lunar mining machine (front loader or back-hoe) which assumes an attachment for a lunar roving vehicle chassis to permit the digging and transport of rock to the processing station. It will be shown later that one such vehicle can supply the rock requirements, for the processes considered, over a wide spectrum of LOX production rates. It is assumed for convenience that this same mass allotment will suffice for the drill required for in-situ processes.

MANPOWER REQUIREMENTS

A lunar production facility will require a manpower input to function effectively. Man might be expected to perform the following functions: process monitor and control, equipment maintenance, fault isolation and repair, raw material acquisition, product dispensation, etc. The analysis of this paper will consider two broad functions characterized by: (1) the raw material acquisition effort performed with the use of the roving vehicle, and (2) a process control effort performed at the process facility. Figure 9 denotes the number of pounds of rock which must be acquired, as a function of the production of liquid oxygen, for a number of various hydrous rock deposits (assuming an extracted rock process using a kiln-like reactor). For the silicate reduction process the rock requirements are somewhat reasonable; however, if rock must be used, without the benefit of the Carbothermal Process, it can be seen that cooperative deposits (with high water contents) must be located to avoid the handling of vast quantities of lunar rock.

A limited amount of data is shown on Figure 10 which can assist in the estimation of the manpower requirements for rock acquisition. Curves are shown for various specific gravity assumptions which convert a given rock acquisition rate into an appropriate manpower requirement. A few terrestrial analogues are indicated which might aid estimation. Published lunar "soil" handling estimates, known to the author, are also referenced. With respect to the needs of this analysis, the rock handling rates shown on the abscissa must include the rock transport time from quarry to processing plant and vehicle "dead time," if any, in addition to the actual excauation time. It must be confessed that the actual design point chosen for this paper was based heavily on numerical convenience.

Figure 11 depicts the soil handling manpower considerations super-imposed upon two estimates of monitor and control task manpower requirements. The lower set of curves assumes that the facility operates essentially automatically - one one-man shift is provided per day for maintenance and miscellaneous tasks. The upper set of curves presumes that a constant, round-the-clock control task is desired. Over the range of the zone of interest, for the processes under consideration, it can be seen, for either shift estimate assumed, that the man-time for rock acquisition is slight compared to the control task. Many studies of lunar operations (references 1, 2 and 6 included) have indicated that a nominal lunar manday consists of 8 hours of mission time, 4 hours of housekeeping, and 12 hours of personal time (which includes sleep time). Therefore for this preliminary baseline analysis it is convenient to assume that rock acquisition requirements can be met by a 3-man control crew which devotes 10 or 11 hours per man to mission tasks per day. The housekeeping tasks are then presumed to be shared by the scientific crew complement.

MANPOWER MASS BURDEN

It is assumed that a 15,000 pound shelter can adequately house three men during their six-month tour at the lunar facility. It is estimated that approximately 7,000 pounds of cargo, in addition to the shelter, will be required per man per year for support of the plant operations (expendables, space suits, personal items, food, etc.). It is assumed also that the crew rotation flights (three men per flight - two flights per year) are equivalent cost-wise, to 30,000 pounds of cargo delivered to the lunar surface.

MANUFACTURING CONCEPTS LOGISTIC AND COST BURDENS

For a realistic analysis the parametric data of figures 7 and 8 must be modified to reflect an appropriate equipment module size. For this analysis a 60 kilowatt nuclear power package was chosen, 6,000 pounds per month LOX output per module was chosen for the silicate reduction plant, and a 5,000 pounds per month output electrolysis and liquefaction module was envisioned for the in-situ process. These modular logistics packages and the various other mass burdens already discussed are shown as individual logistic requirements on figure 12 and accumulated as a total manufacturing cost variation on figure 13. To generate figure 13, a transport cost burden factor of $5,000 per pound delivered to the lunar surface was applied to the data of figure 12. The addition of a yearly transport cost burden, as a function of LOX use rate, transforms figure 13 into an economic analysis allowing an assessment of the "transport vs manufacture" break-even point. Inspection of these curves indicates that the break-even point for the silicate reduction concept occurs beyond the zone of interest. For the in-situ process, the break-even point occurs at about 18,000 pounds of LOX per month - just inside the zone of interest.

The analysis to this point is considerably simplified and could not substantiate elimination of either candidate. A number of questions which naturally evolve from this analysis should be answered.

These curves implicitly assume a yearly replacement of the power plant, process reactor, soil handling equipment and crew shelter. It should be determined whether the reduced costs associated with longer equipment life times will significantly enhance the break-even assessment.

A three man operations crew was assumed in figure 13, on the basis of a desired round-the-clock monitoring capability. What is the effect of an automatic plant (maintenance and mining crew only) on the economic analysis?

An assumed nuclear power plant technology was established by the restriction to a 500 pounds per kilowatt power factor. The sensitivity of the analysis to a variation of this term should be assessed.

In addition it is realized that a development cost factor should be included to properly penalize schemes which extend the state-of-technology.

To refine the methodology and assess the sensitivity of the economic analysis to the variants defined above, the matrix of options shown in table 1 was considered. It is necessary when considering long lifetime equipments to plan for a continuing logistic burden for maintenance, repair, and replacement of sub-systems and components. The assumptions associated with equipment lifetime, and used in this analysis, are shown in table 2.

YEARLY OPERATIONAL COST BURDEN

Application of the guidelines of table 2 to the matrix of table 1 through the mass burdens shown in figure 12 will permit at least a first-order assessment of the requirements for successful economic justification of lunar propellant processing. Figure 14 graphically portrays the influence of applying various combinations of: Option 1 (increasing process plant lifetime), Option 2 (increasing nuclear power plant life from one to two years), and Option 3 (reduction of operating crew from three men to one man). It has been assumed in these calculations that a three man advance party would precede the operational phase by six months to set-up the equipment. It is also assumed that costs for equipment are accounted for in the year prior to their operational use. Percentages are shown in figure 14 for the various cost items considered; the values represent percent of total 10 year program costs. The major categories of manufacturing cost increments are shown in summary form on figure 15 for the various steps toward cost reduction and economic enhancement which were considered. In the baseline concept, the power burden is about twice the crew burden. The election of Options 1 and 2, increasing equipment life, creates a situation wherein the power and crew

TABLE I

SENSITIVITY OPTION DEFINITION

Process Type	Option Number	OPTION 1 Process Equipment Lifetime		OPTION 2 Nuclear Power Plant Lifetime		OPTION 3 Plant Operations Crew Size	
		1 year	10 yrs	1 year	2 yrs	3 men	1 man
Silicate Reduction	Baseline	X		X		X	
	B + 1		X	X		X	
	B + 1 + 2		X		X	X	
	B + 1 + 3		X	X			X
	B + 1 + 2 + 3		X		X		X
In-situ Water Boil-off	Baseline	X		X		X	
	B + 2	X			X	X	
	B + 3	X		X			X
	B + 2 + 3	X			X		X

TABLE 2

EQUIPMENT LIFETIME ASSUMPTIONS

ITEM	LIFETIME	MAINTENANCE BURDEN
Crew Shelters	over 10 years	5 % per year
Soil Handling Equipment	5 years	10 % per year
Process Equipment:		
baseline	1 year	none
option 1	over 10 years	10 % per year
Nuclear Power Plants:		
baseline	1 year	none
option 2	2 years	none

burdens are nearly equal and together they dominate the cost picture. The resulting incentive toward reduced crew associated costs results in the third situation in which the power costs again dominate (almost three quarters of total cost).

DEVELOPMENT COST CONSIDERATIONS

It has been indicated that development program costs must be included if the analysis is to be meaningful. Naturally, little or no information is available which provides good estimates of research and development programs leading to qualification of the necessary equipments for lunar application. The author has therefore made gross estimates of the magnitude of the various sub-programs which can be integrated for the various concepts and options discussed in this paper. These estimates are found in table 3. It has been the author's intention to under estimate these costs rather than bias the results; it is hoped that the insensitivity of the results to these assumptions and the applicability of the conclusions can be demonstrated. Table 4 lists the total development cost assumptions for each concept and option considered.

REFINED ANALYSES

The application of the refinements suggested above to the sophistication of the analysis yields the break-even curves shown on Figure 16. It is noted that the curves represent cumulative costs, over the time period shown, for a program obeying the assumptions and restraints discussed previously. The curve for transport costs represents the cumulative cost of transporting the assumed LOX demand from Earth at a unit cost of $5, 000 per pound.

DISCUSSION OF RESULTS

The silicate reduction process, which appears totally unfavorable from an economic viewpoint on figure 13, does exhibit break-even situations when the refinements to the analysis are considered. As would be expected, the results tend to indicate that economic justifications will be easier to show if the resource demand is increased,but the actual data supporting this view has not been developed in this analysis.

The in-situ process, due primarily to its reduced power demand and the resulting reduction in the logistics burden, exhibits a more favorable economic analysis. Break-even situations are shown for a variety of options which might be available.

For either concept, the application of all enhancement options decreased total program costs by approximately 50%. Of the options considered, the extension of processing equipment lifetime, Option 1, had the most modest effect. This was due to the minor percentage of total cost which this item represents in the baseline concepts. The doubling of the nuclear power plant lifetime, from one to two years, Option 2, has a substantial effect for either concept; it is most influential in the silicate reduction

TABLE 3

DEVELOPMENT COST INCREMENTS

ITEM	MILLIONS
Silicate Reactor	200
Electrolysis, Liquefaction, & Storage System	400
Soil Handling Equipment and/or Drill	150 *
Baseline Power Plant	200
Advanced Power Plant	500
Processing Automation	150
Process Plant Lifetime Extension	100

* assumes prior development of lunar mobility

TABLE 4

DEVELOPMENT COST ASSUMPTIONS

SILICATE REDUCTION PROCESS		IN-SITU PROCESS (PERMAFROST)	
CASE	MILLIONS	CASE	MILLIONS
Baseline	950	Baseline	750
B + 1	1050	B + 2	1250
B + 1 + 2	1550	B + 3	900
B + 1 + 3	1200	B + 2 + 3	1400
B + 1 + 2 + 3	1700		

concept due to its high power requirements. Application of these options to the baseline concept causes the crew related costs to assume a magnified significance thus providing the incentive toward further reductions through application of Option 3, automation.

If the optimistic, economic enhancements, represented by Options 1, 2 and 3, are assumed and if the concept for lunar base support, through lunar refueling of crew rotation flights, is assumed feasible, then a significant reduction in the cost of lunar operations over an extended program appears possible. In reality, the author must remind the reader of the simplifications of this analysis. It must be remembered that the quantitative data developed are based on a simplified logistics transport burden factor. Most seriously this factor does not reflect probablistic equipment losses, cost reductions through experience, realistic packaging restraints, and operational restrictions. These perturbations which would affect a real life situation require a much more detailed simulation to be completely understood; such an analysis would require a substantial improvement in the confidence and the amount of the available input data.

CONCLUSIONS

The presented analysis, despite its limitations, can be useful in identifying certain prerequisites to the economic justification of lunar propellant manufacturing plants for the support of lunar exploration operations.

In-situ processes, exemplified by the permafrost case studied, are shown to be attractive if the power requirements can be restricted below that required for the silicate reaction. This is certainly the case for the 50% permafrost deposit. Less optimistic finds would require careful analysis of the power requirements. It appears that if the water boil-off thermal requirements could be supplied by direct thermal means (rather than inefficiently through the conversion to electrical power) then many cases which have not been considered in this paper will become interesting. It should be remembered that the in-situ processing scheme must also concern itself with significant geological and operational problems which cannot be readily analyzed quantitatively.

Since the silicate reduction process is considered to be an engineering problem alone (it is not dependent on the proof of any particular theory concerning the lunar composition, environment, or history for a source of reactants) its significance is promoted and its application should be studied in detail.

A prerequisite to the economic desirability of the silicate reduction process is the development of an effective nuclear power plant. For the crude analysis conducted herein, a doubling of the operational lifetime (1 year to 2 years) is equivalent to a halving of the power burden factor (500 lb/kw to 250 lb/kw). A burden factor of 250 lb/kw has been suggested as feasibly applicable to Saturn V logistics vehicle packaging limitations for lunar surface utilization. If an advanced reactor could achieve the

the favorable burden factor and also demonstrate an extended lifetime, the enhancement to this analysis would be significant.

A second prerequisite to effective utilization of a silicate reduction, oxygen production plant is the achievement of essentially an automatic operation. Large numbers of operators pose a signficant roadblock to the achievement of an economically attractive concept. It is almost certain that man will have to play some part in the acquisition of the resource (either actual mining or prospecting); however, that involvement must be minimized.

In the case of extracted rock, kiln-type, water boil-off processes which involve the crushing or grinding of rock prior to injection into the kiln, the appropriate power and equipment burdens must be added to the in-situ process discussed. It must be concluded that schemes of this nature, which may be burdened by the necessity to adapt to low grade ore (1 to 2% water content); will be jeopardized by the magnitude of the mining and rock handling operations and will find it difficult competing with the silicate reduction process.

REFERENCES

1. AiResearch Manufacturing Company. "Study of Human Factors and Environmental Control - Life Support Systems for Lunar Exploration Systems for Apollo." NASA Contract Number NAS8-11447. July 1965.

2. General Dynamics/Fort Worth Division. "Operations and Logistics Study of Lunar Exploration Systems for Apollo." NASA Contract Number NAS8-11361. 26 February 1965.

3. General Dynamics/Fort Worth Division. "Utilization of Lunar-Produced Propellants." Report Number MR-O-113. 2 April 1965.

4. General Electric Company/Missile and Space Division and Air Products and Chemicals, Incorporated. "Early Post-Apollo Cryogenic Fuel Production Systems." Presentation at George C. Marshall Space Flight Center. 8 September 1965.

5. Glaser, P. E., Wechsler, A. E. and George, J. H. B. "Feasibility of Liquid Hydrogen Production on the Lunar Surface." Proceedings of 3rd Annual Meeting, Working Group on Extraterrestrial Resources. Arthur D. Little, Incorporated. Cambridge, Mass. 19 November 1964.

6. Lockheed Missiles and Space Company. "Study of Deployment Procedures for Lunar Exploration Systems for Apollo (LESA)." Office Chief of Engineers/ NASA Contract Number DA-49-129-ENG-534. 15 February 1965.

7. Paul, David 3rd. "A Methodology for an Economic Analysis of Transport and Manufacture Strategies for the Resupply of Lunar Base Resources." Proceedings of 3rd Annual Meeting, Working Group on Extraterrestrial Resources. 19 November 1964.

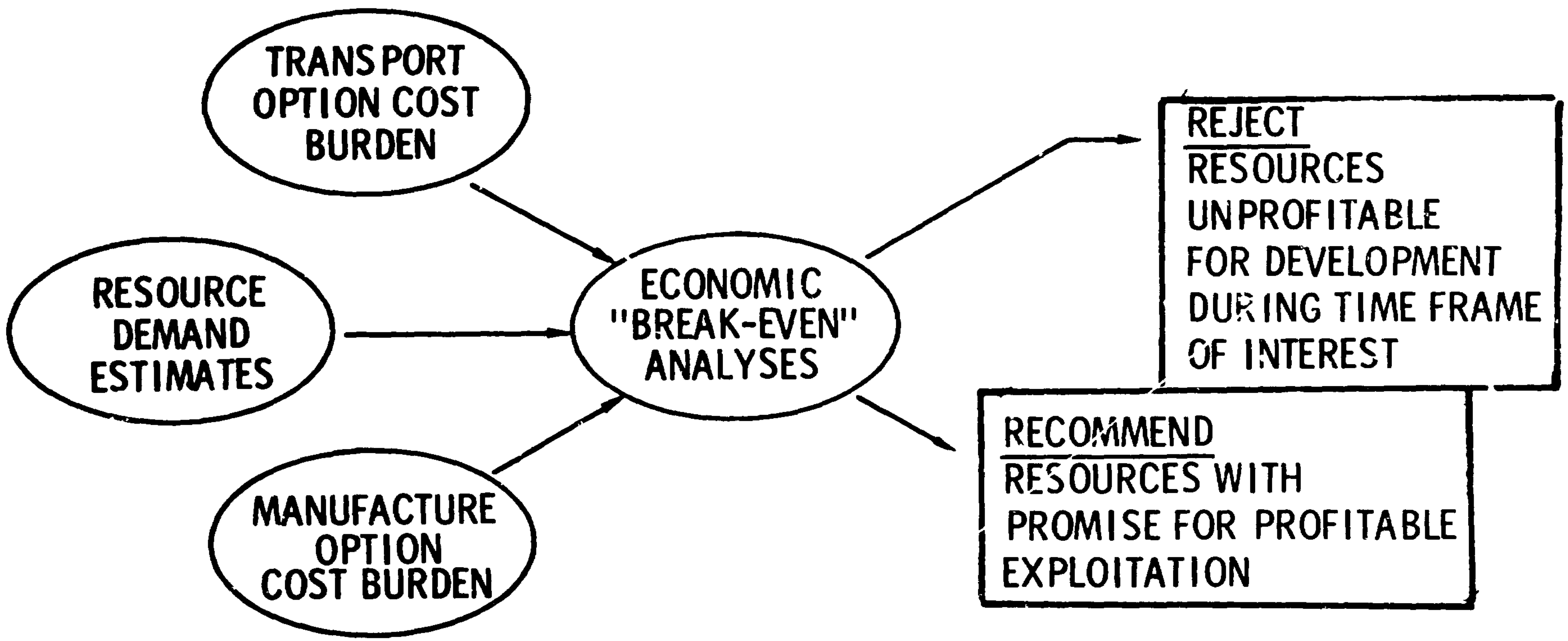
8. Rosenberg, S. D., Beegle, R. L., Jr., Guter, G. A., Miller, F. E. and Rothenberg, M. "The Manufacture of Propellants for the Support of Advanced Lunar Bases." Von Karman Center, Aerojet-General Corporation. SAE Paper Number 650835. 7 October 1965.

9. Rosenberg, S. D., Guter, G. A. and Rothenberg, M. "Requirements for On-Site Manufacture of Propellant Oxygen from Lunar Raw Materials." Proceedings of 3rd Annual Meeting, Working Group on Extraterrestrial Resources. 19 November 1964.

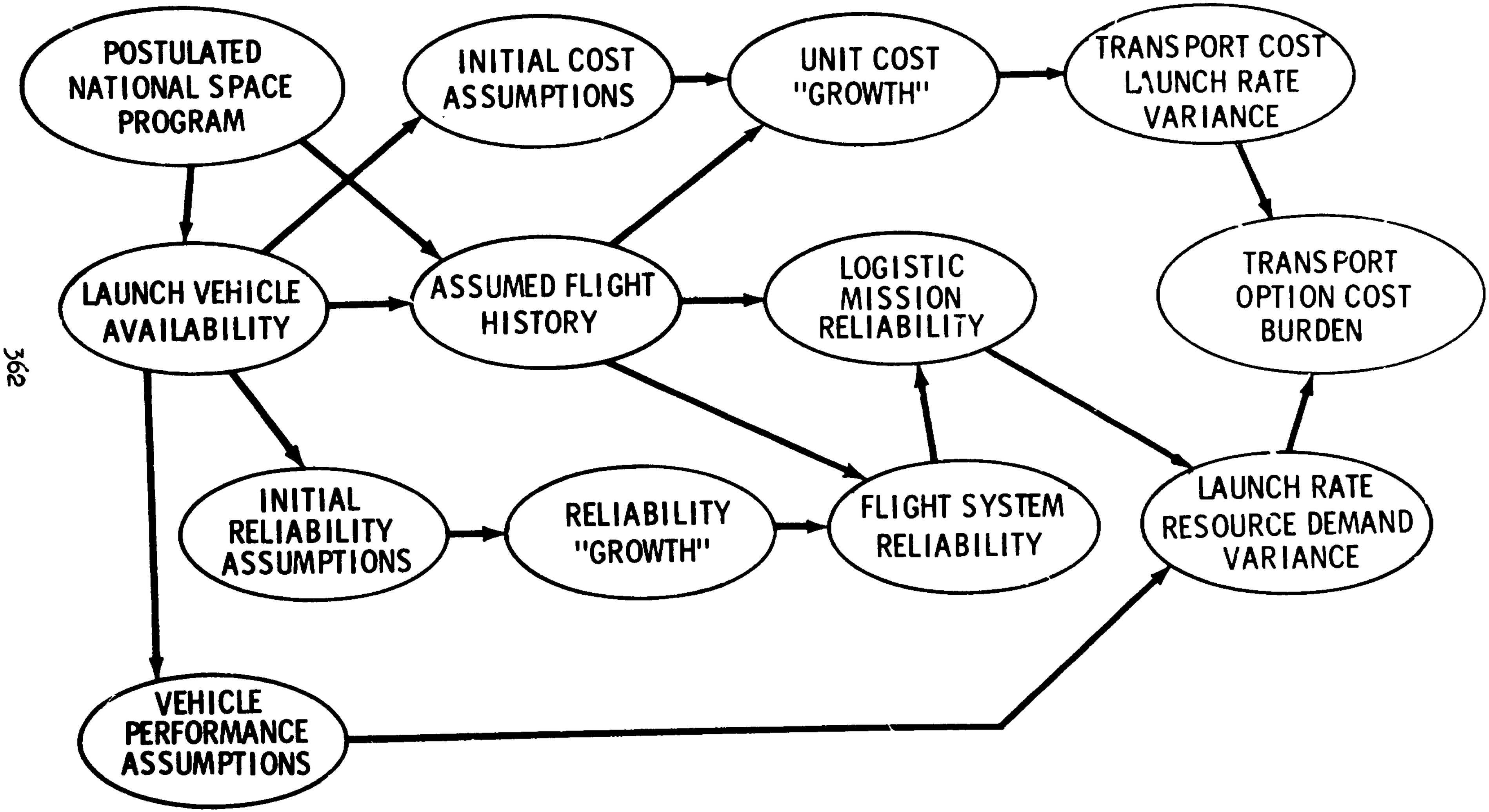
REFERENCES
(Cont'd)

10. TRW-Space Technology Laboratories. "A Comparative Design Study of Modular Stage Concepts for Lunar Supply Operations." NASA Contract Number NAS8-11022. 12 December 1963.

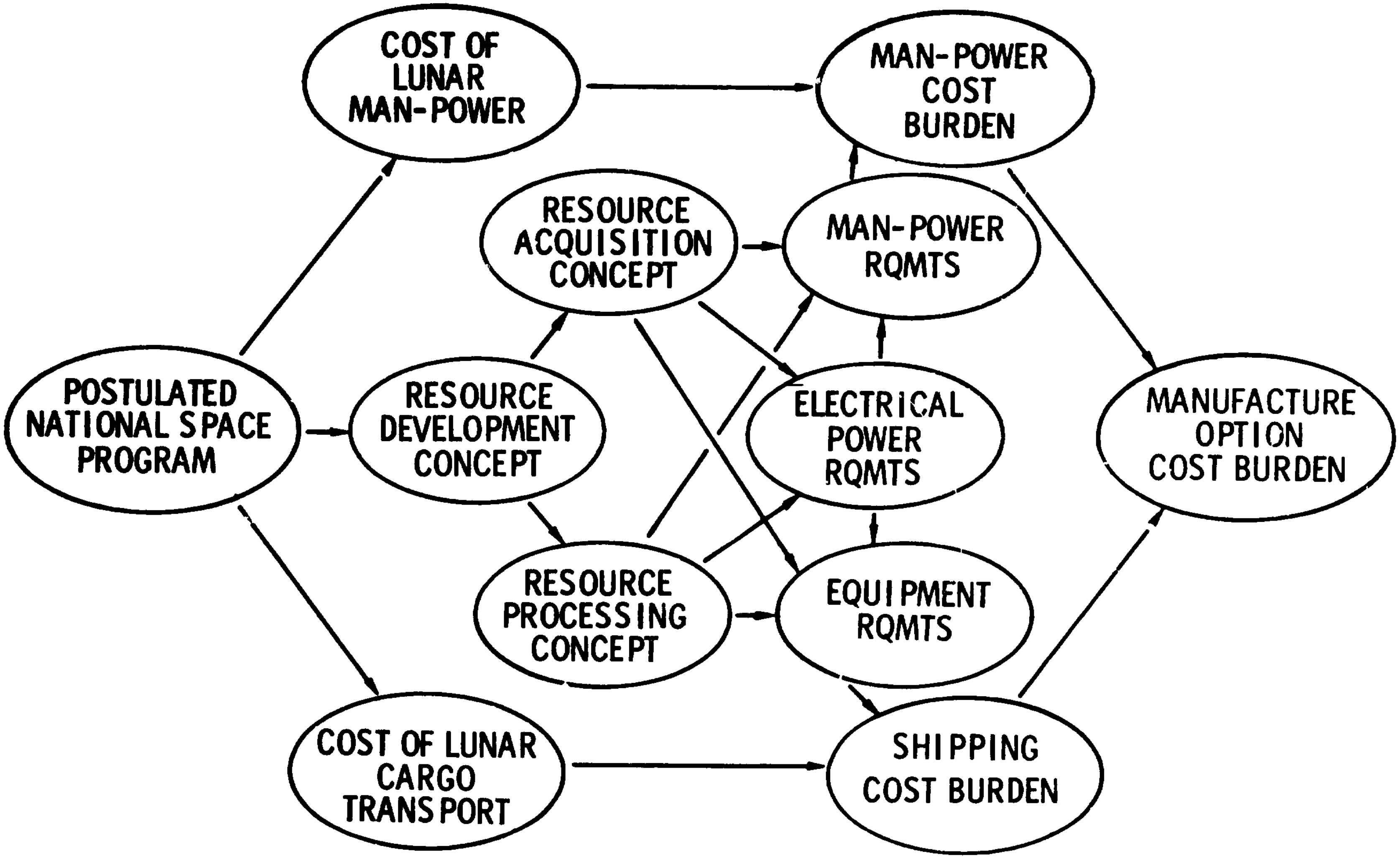
ECONOMIC ANALYSIS METHODOLOGY



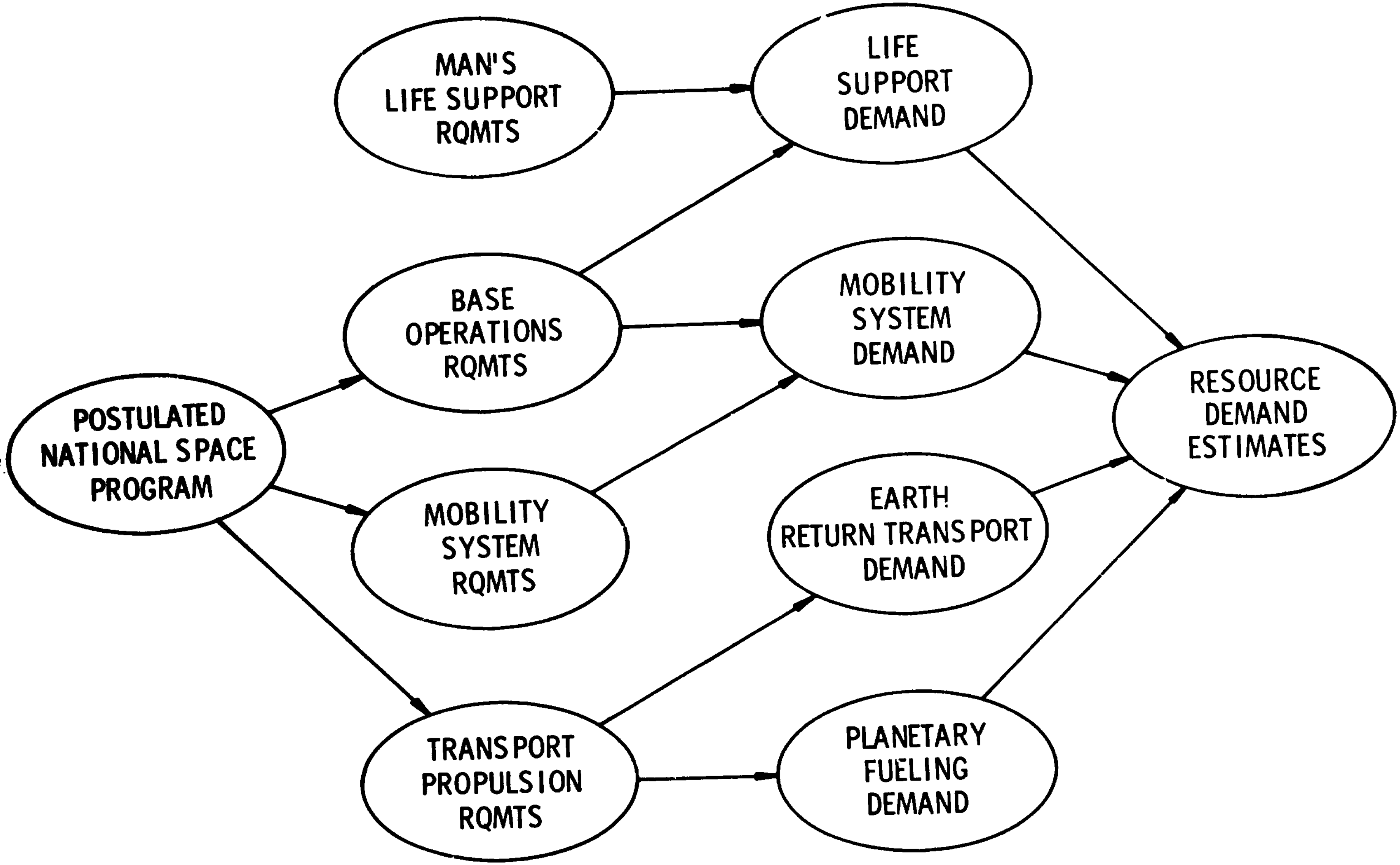
TRANSPORT OPTION COST ANALYSIS METHODOLOGY



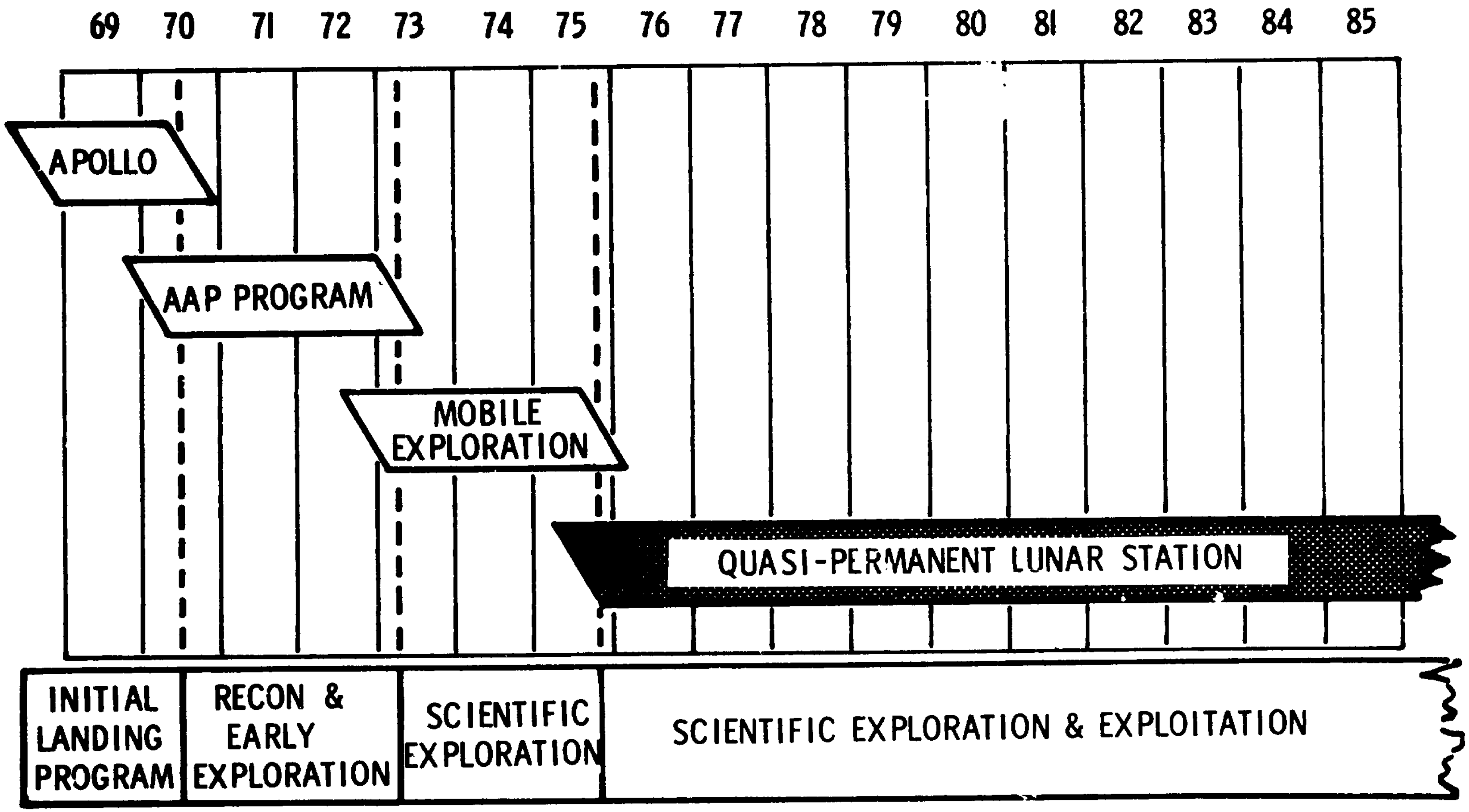
MANUFACTURE COST ANALYSIS METHODOLOGY



RESOURCE DEMAND ESTIMATE METHODOLOGY



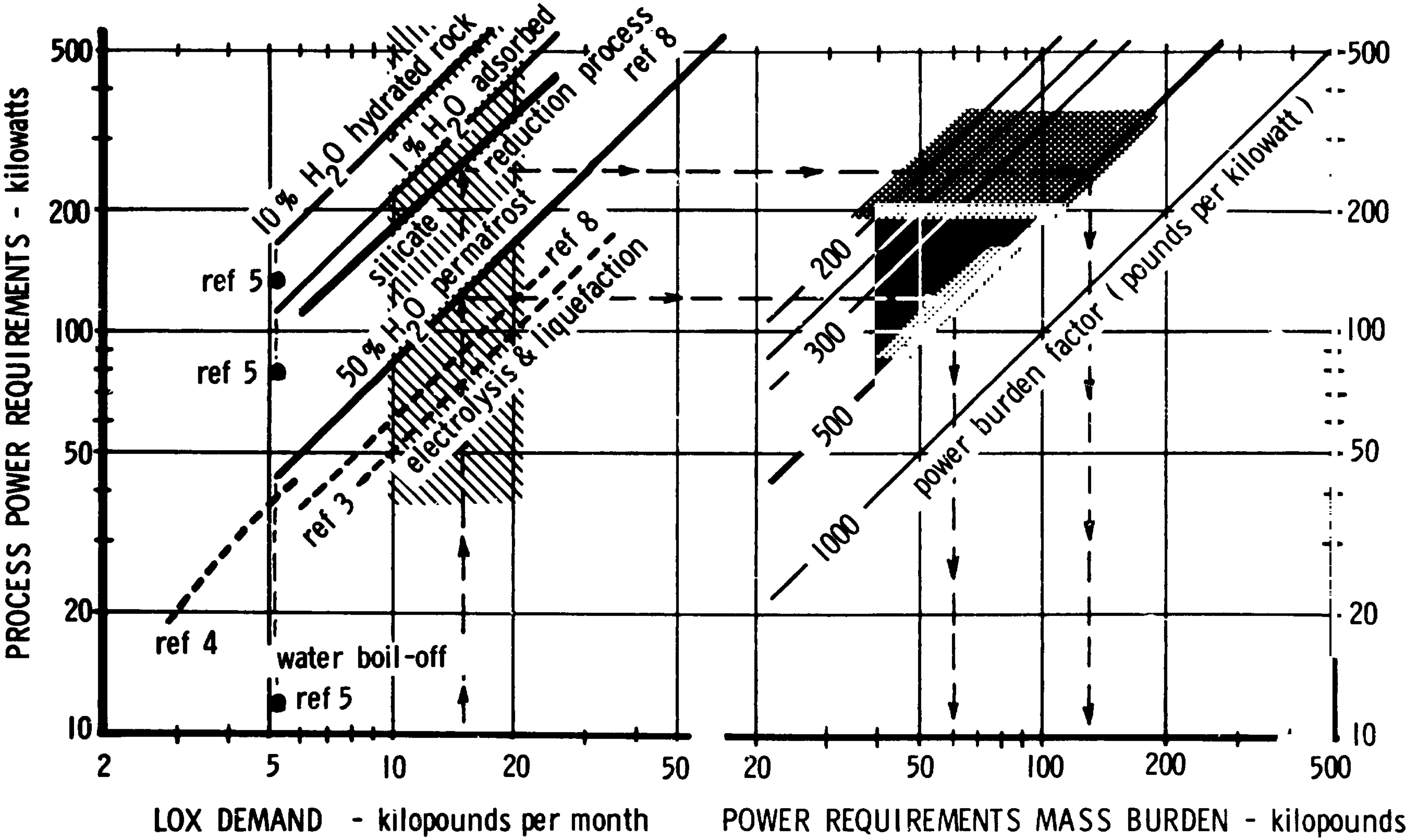
POSTULATED SCHEDULE OF LUNAR EXPLORATION



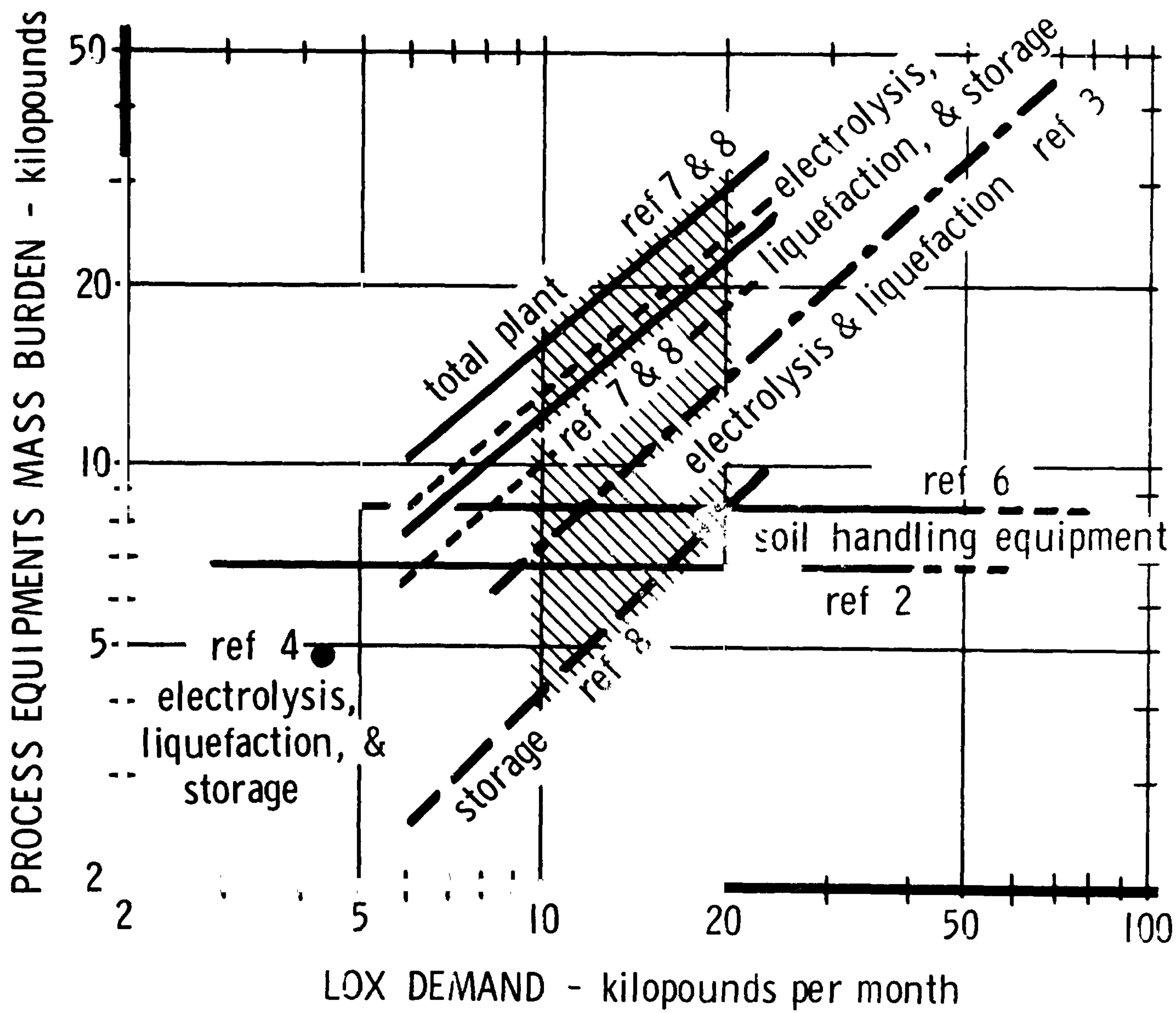
POSTULATED LUNAR OPERATIONS SCHEDULE

	76	77	78	79	80	81	82	83	84	85
Scientific Personnel (base size)	6	6	9	9	9	9	12	12	12	12
Plant Operations Crew	3	3	3	3	3	3	3	3	3	3
Total Men on Station	9	9	12	12	12	12	15	15	15	15
Number of 3 Man Crew Flights	6	6	8	8	8	8	10	10	10	10
Liquid Oxygen Requirements :	(thousands of pounds per month)									
flight requirements	7.8	→	10.4	→			13	→		
spillage allowance (15 %)	1.2	→	1.6	→			2	→		
misc. requirements	1	→	3	→			5	→		
TOTAL LOX DEMAND	10	→	15	→			20	→		

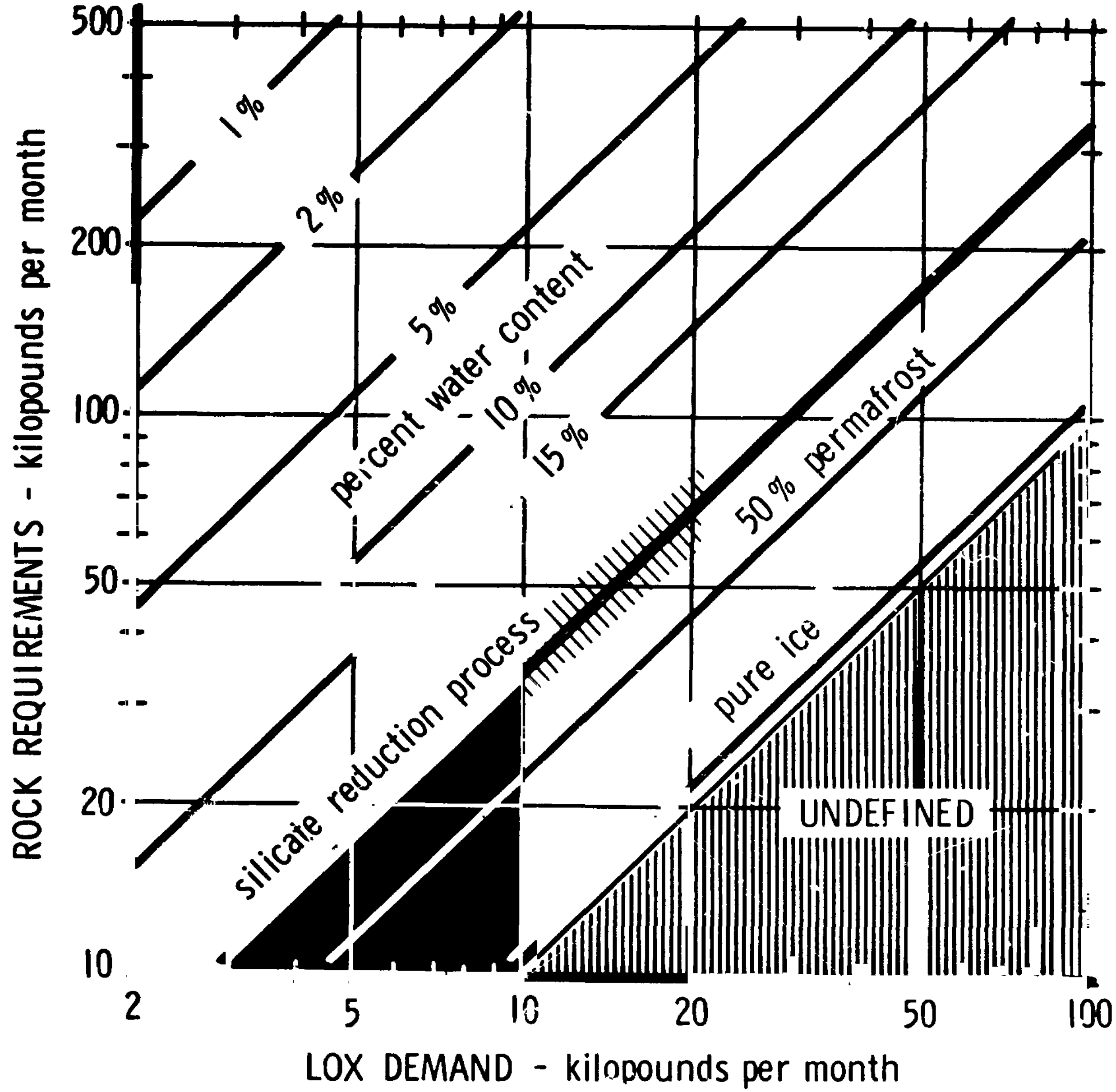
MASS BURDEN - NUCLEAR POWER PLANT



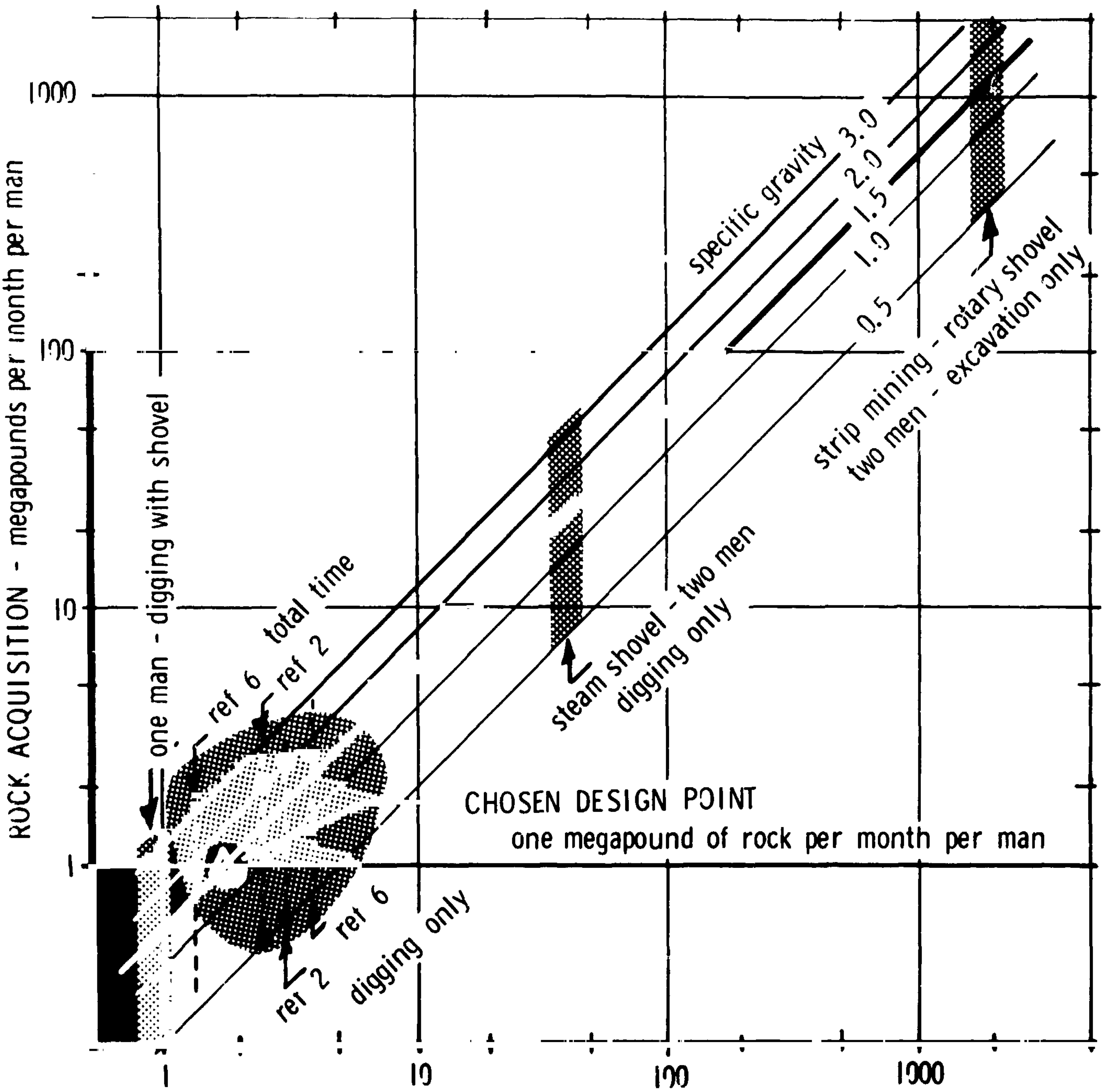
MASS BURDEN - PROCESSING EQUIPMENT



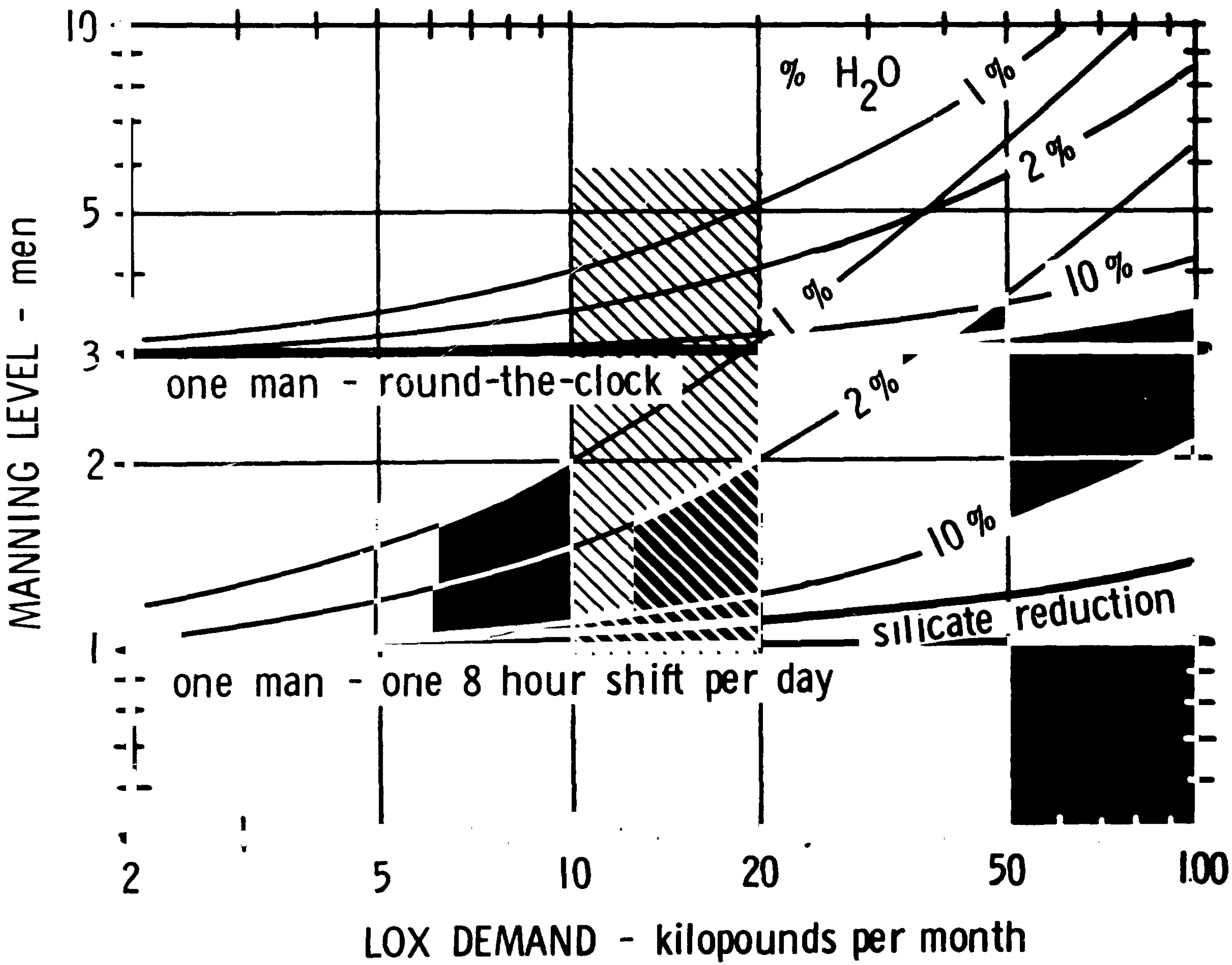
LUNAR ROCK REQUIREMENTS



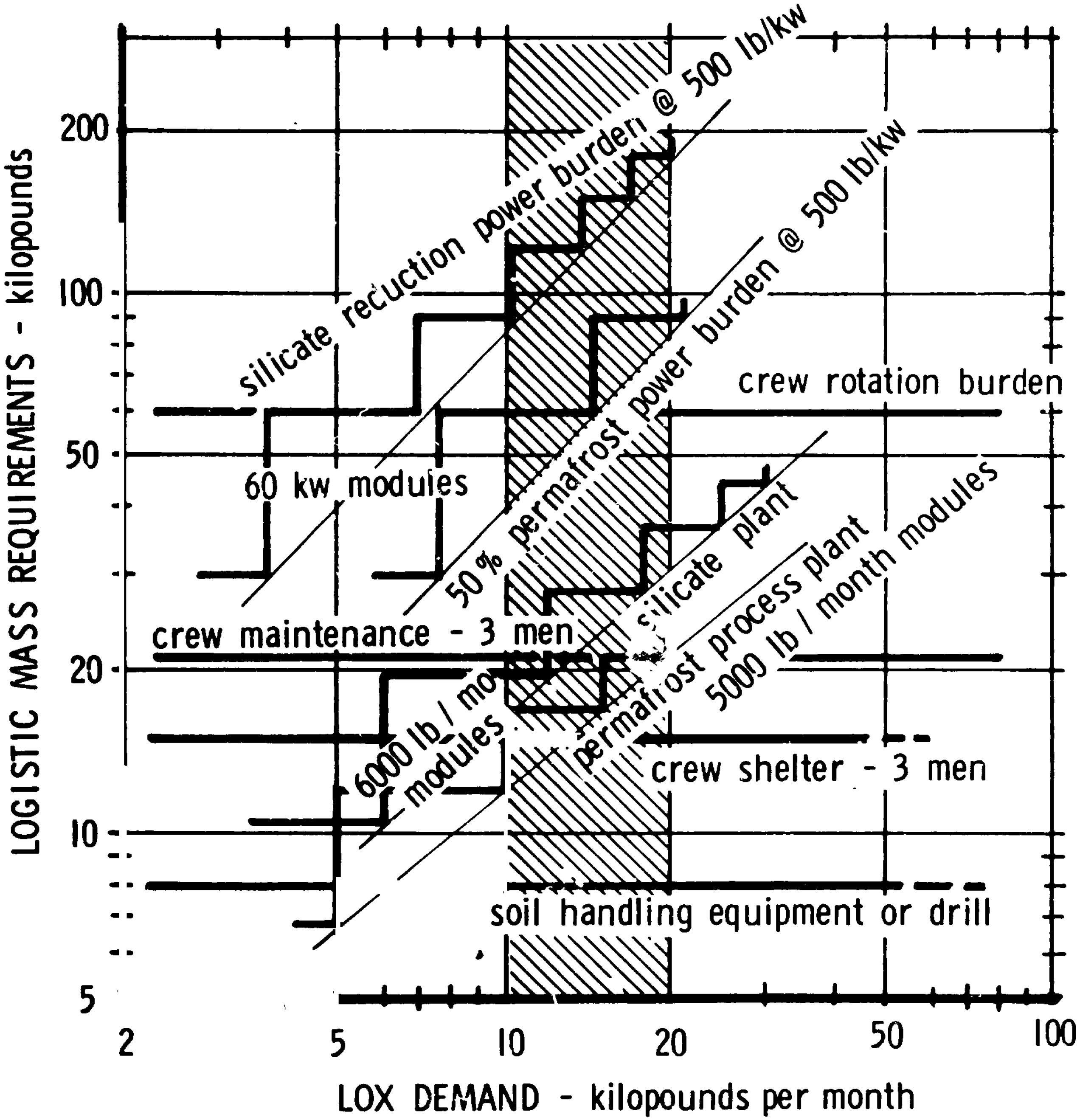
ROCK ACQUISITION TRENDS



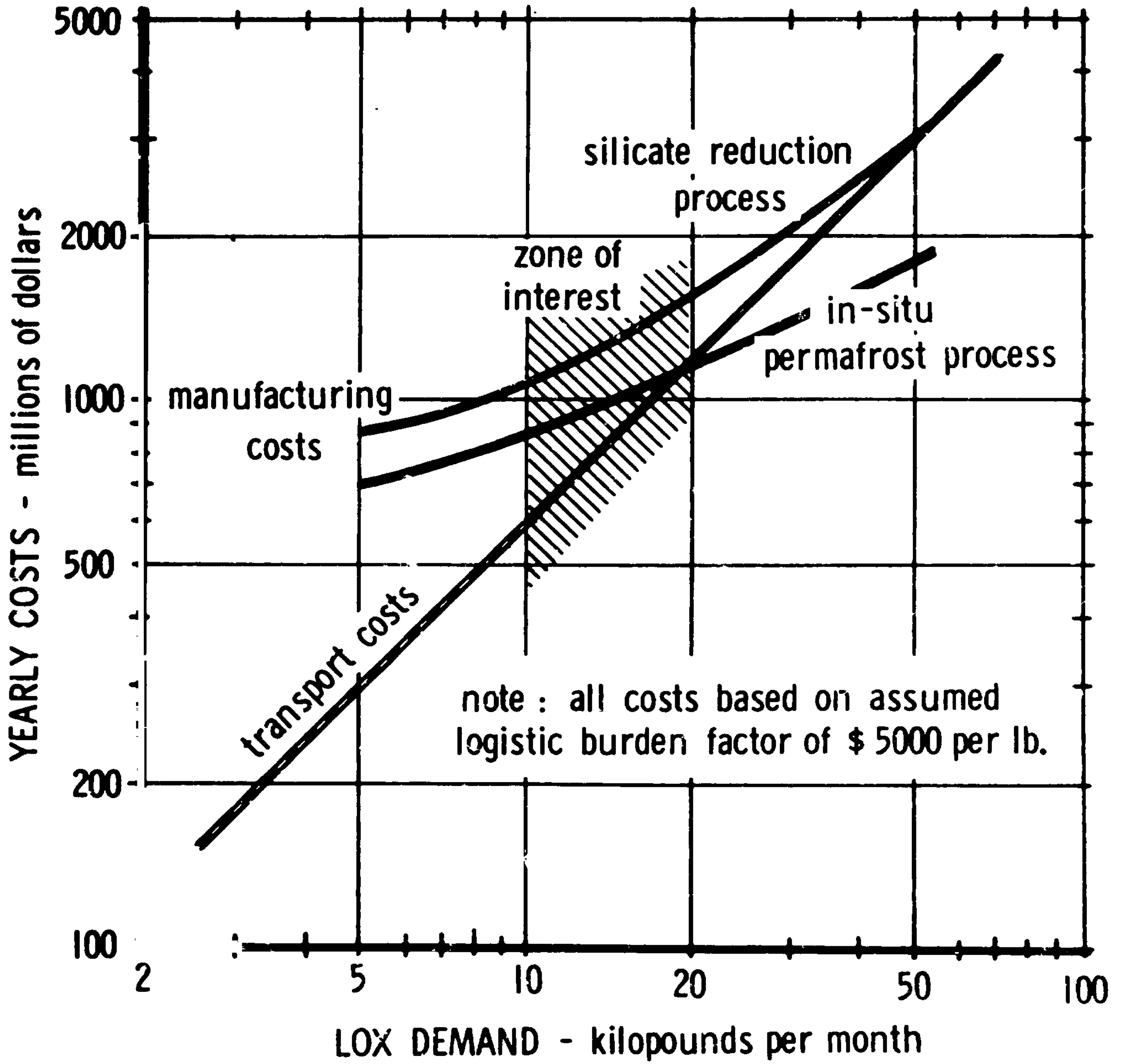
PROCESS FACILITY MANNING REQUIREMENTS



RESOURCE MANUFACTURING LOGISTIC REQUIREMENTS

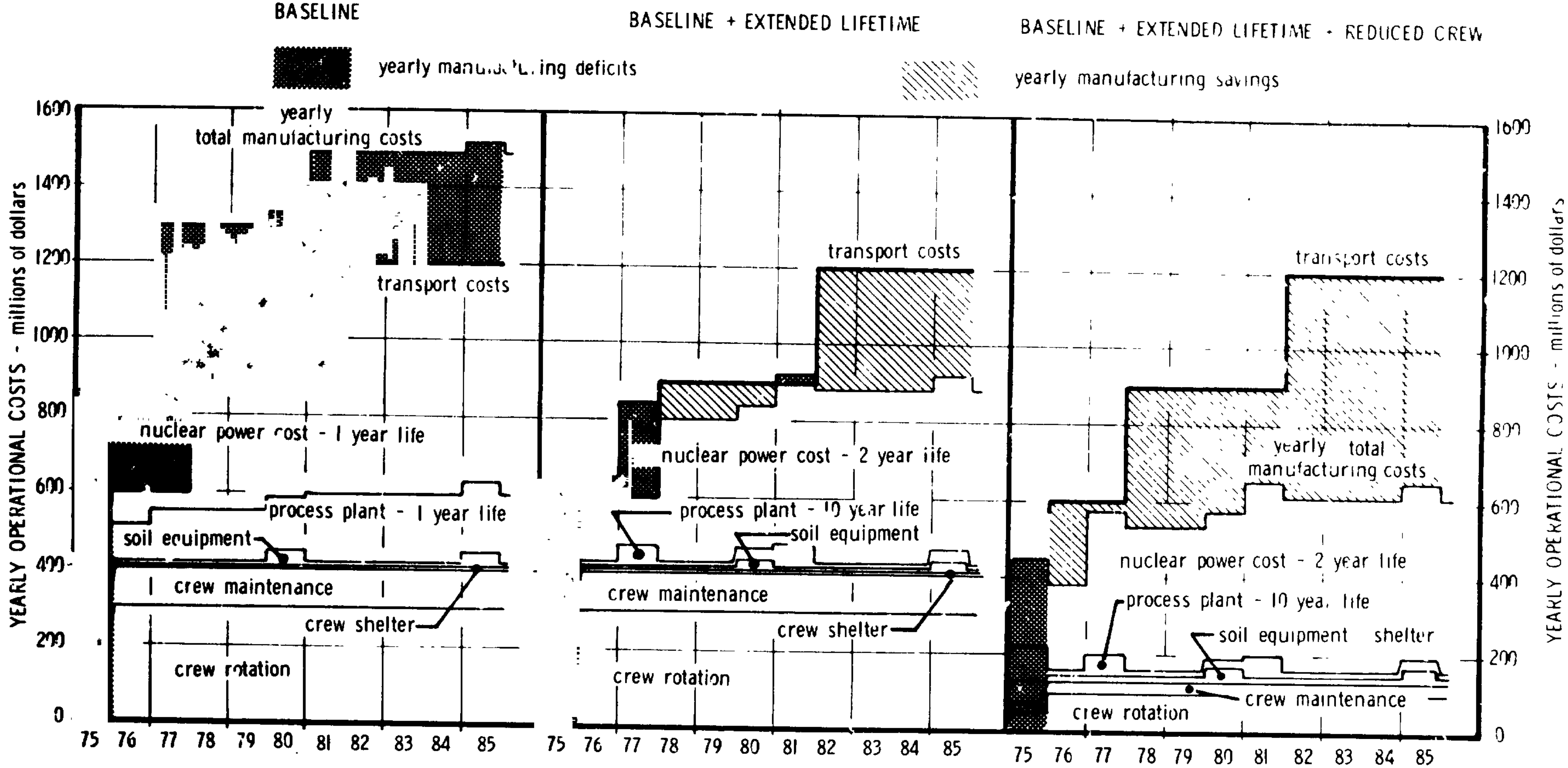


ECONOMIC BREAK-EVEN ASSESSMENT LUNAR OXYGEN MANUFACTURE



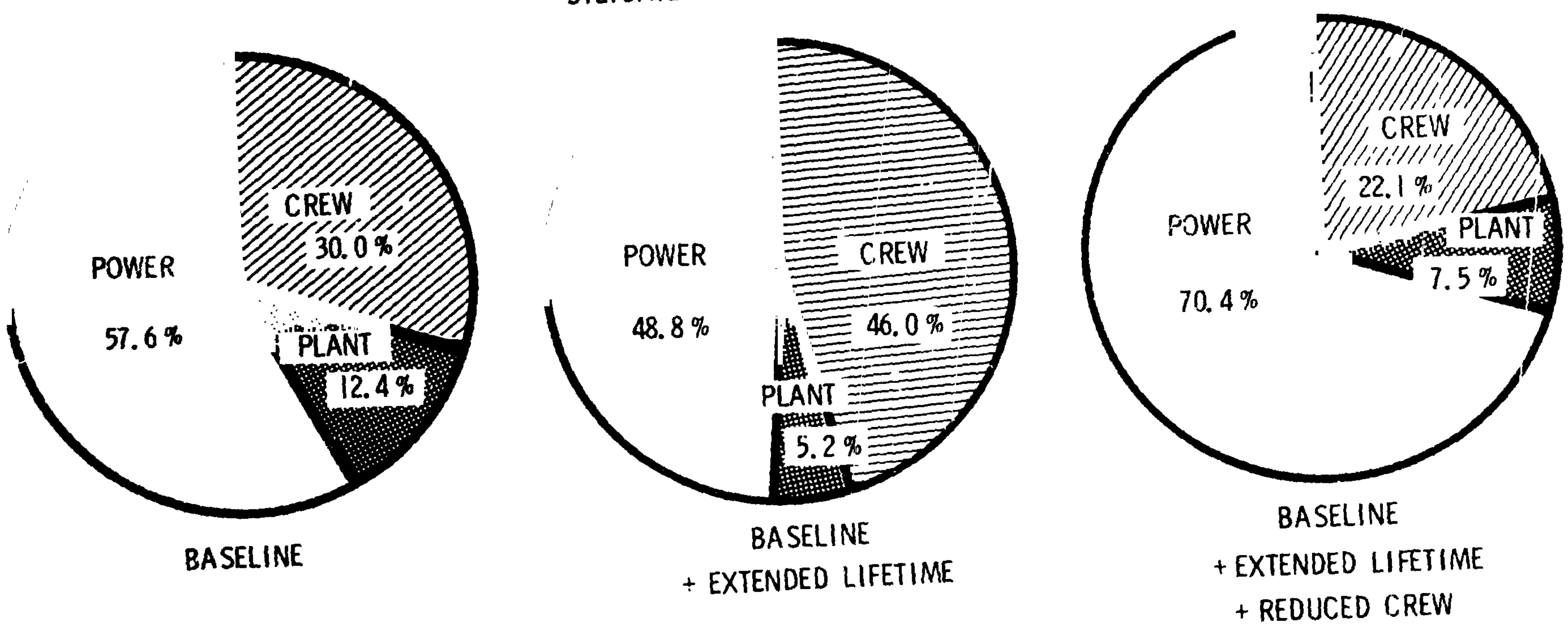
YEARLY OPERATIONAL COST BURDEN

SILICATE REDUCTION PROCESS

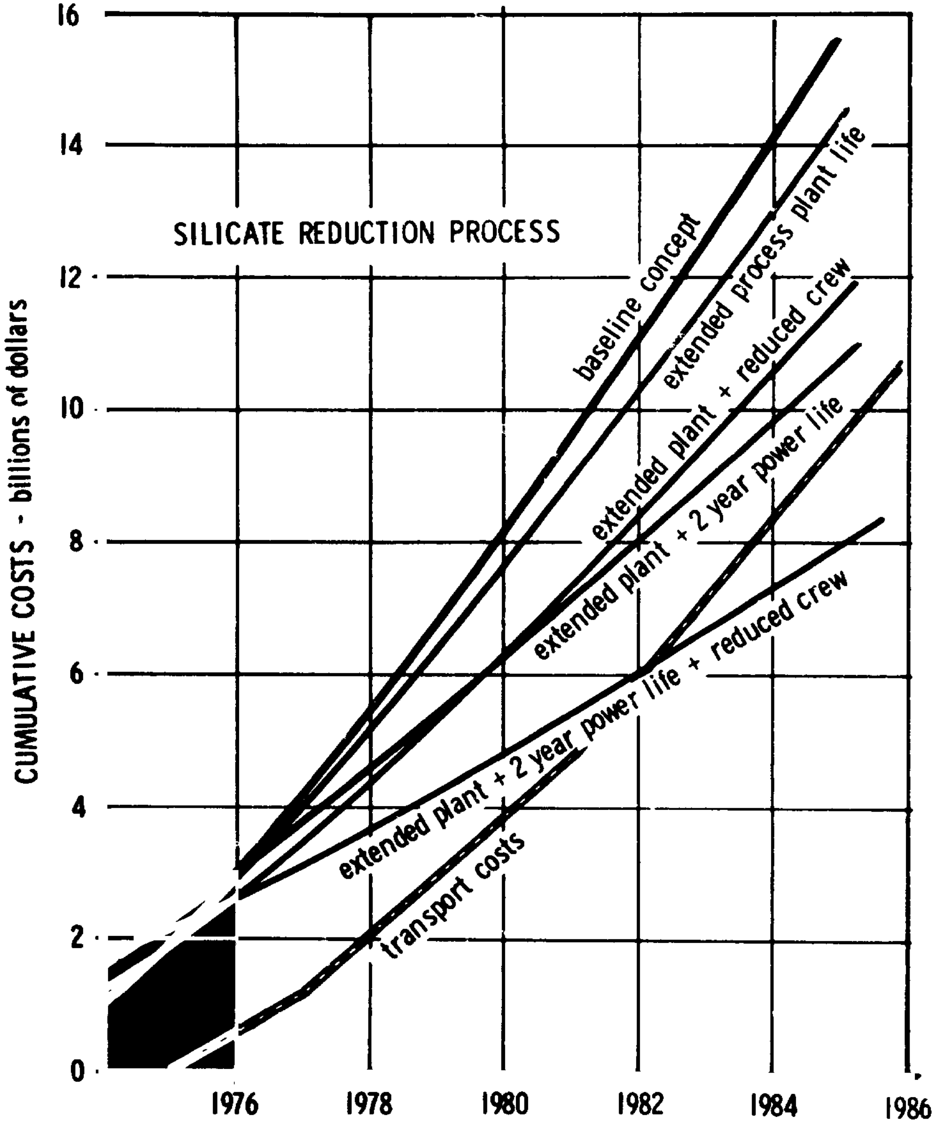


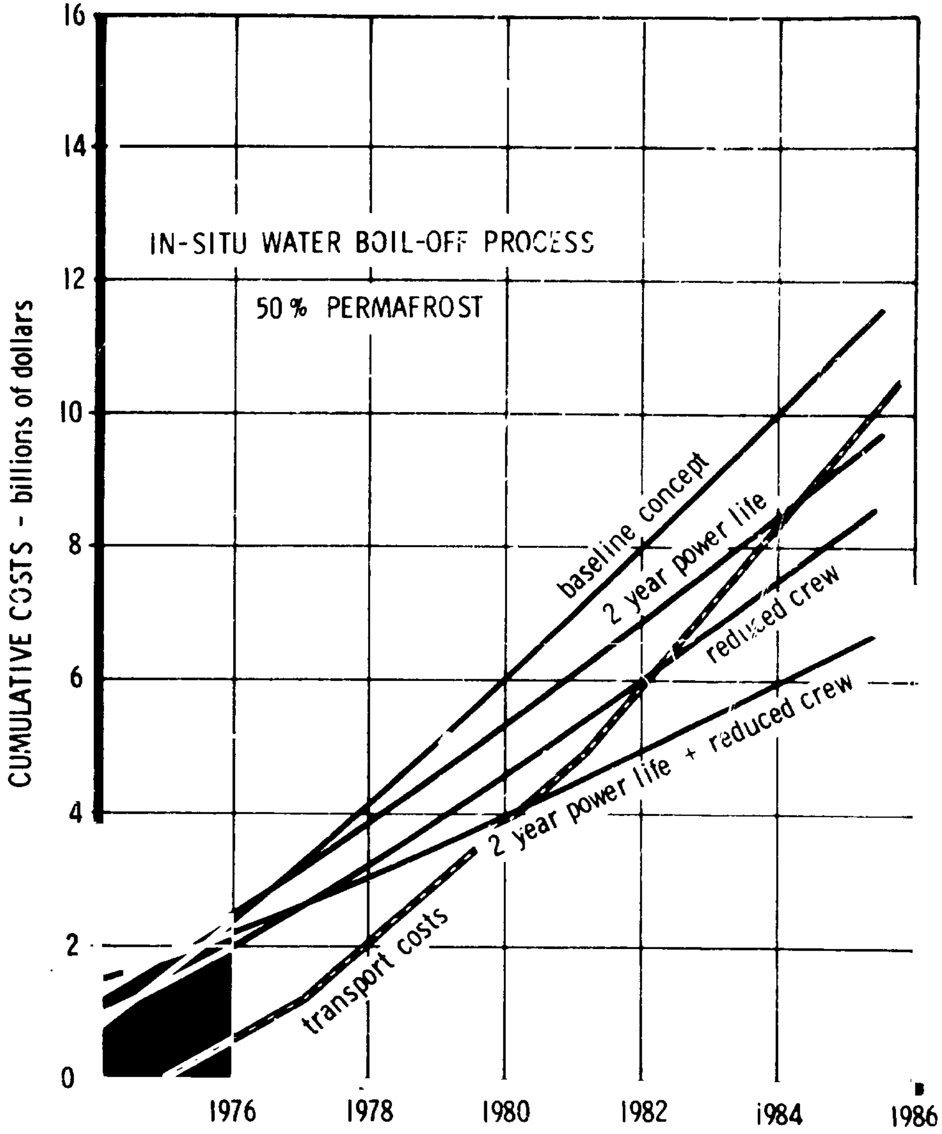
MANUFACTURING COST-BURDEN INCREMENTS

SILICATE REDUCTION PROCESS



NOTE : Based on 10 year cumulative costs


SILICATE REDUCTION PROCESS
CUMULATIVE COSTS - billions of dollars
0
2
4
6
8
10
12
14
16
1976
1978
1980
1982
1984
1986
baseline concept
extended process plant life
extended plant + reduced crew
extended plant + 2 year power life
extended plant + 2 year power life + reduced crew
transport costs


IN-SITU WATER BOIL-OFF PROCESS
50 % PERMAFROST
CUMULATIVE COSTS - billions of dollars
0
2
4
6
8
10
12
14
16
1976
1978
1980
1982
1984
1986
baseline concept
2 year power life
reduced crew
2 year power life + reduced crew
transport costs

N68 33317

SPACE TRANSPORTATION LOGISTIC REQUIREMENTS COMPARISON UTILIZING LUNAR MANUFACTURED PROPELLANTS

R. A. Gorrell and J. B. Deodati

ABSTRACT

The economic feasibility of utilizing lunar produced propellants is considered for Earth orbital, Lunar base, and Mars-lander missions. Various refueling modes in Earth orbit, lunar orbit, and lunar surface are investigated and propellant demand rates for each mission/refueling mode combination are determined. Lunar production and storage facilities requirements are investigated and base personnel and logistics support requirements are assessed.

Saturn V launch vehicles and logistic payload time-sequences for mission support are developed. A comparison is made of the effectiveness of performing the various missions with and without the use of lunar produced propellants in terms of total Earth launch requirements. The improvement in effectiveness as a function of time and the number of missions performed is assessed. Sensitivity effects are evaluated and conclusions are drawn regarding the more promising concepts for utilizing lunar propellants.

INTRODUCTION

A considerable amount of literature has been published on techniques for the mining and processing of lunar resources in order to extract water, oxygen, or propellants in the expectation that these products may be economically employed during space missions. It is the purpose of this study, previously reported in References 1 and 2, to examine the economic feasibility of utilizing lunar-manufactured propellant for potentially the largest requirement of all; namely the transportation requirements of various space missions.

Economic feasibility is evaluated not in terms of dollars, but rather, in terms of Saturn V launch requirements with and without lunar refuel capability. Moreover, in order to determine launch requirements with lunar refuel capability, it is necessary to assess the number of Saturn V launches required to build, man, and maintain the lunar propellant manufacturing plant over several years.

DISCUSSION

In commencing this study it became necessary to make certain assumptions and to establish ground rules, indicated in Figure 1, relating to characteristics of the lunar propellant plant. It is assumed that previous reconnaissance has established a deposit site which is suitable for the extraction of water from ice (near or within coring distance from the lunar surface) or from hydrated minerals or rocks. It is at this point at which plant build-up may commence for the purpose of determining launch support requirements for a specific mission.

Three different space mission types, illustrated in Figure 2, have been studied. Each mission may be refueled by using lunar-produced propellant; however, each mission can best be refueled by a specific refueling mode, and various possibilities are noted in the figure. It is necessary to determine which of the refueling modes should be employed for a given mission.

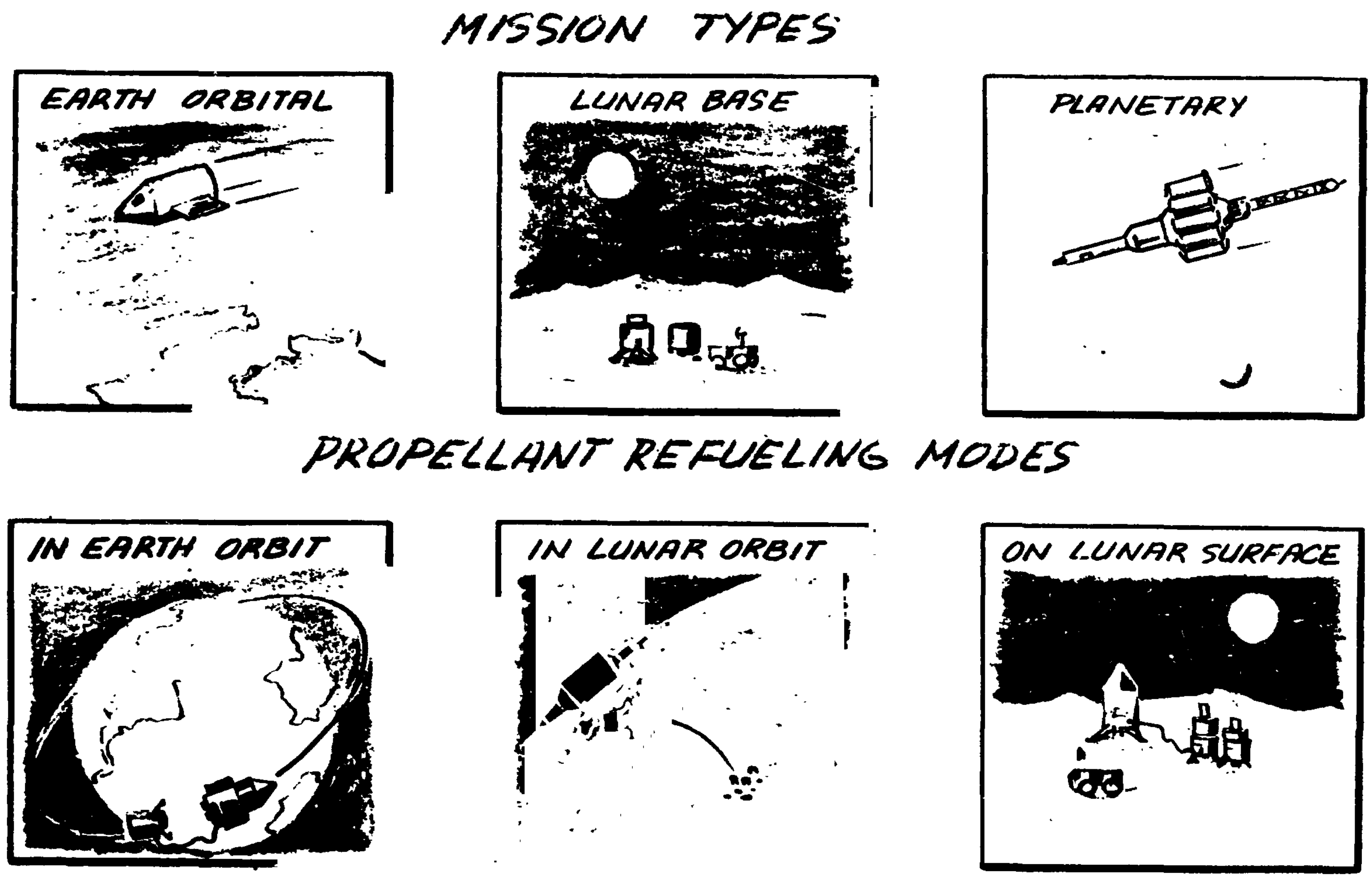
In order to determine the optimum refueling modes and the attendant propellant plant size which would be required to support a space mission, a study approach is formulated as shown in Figure 3. Refueling mode screening is based upon an effectiveness ratio and mode selection is made by a Saturn V launch ratio.

ASSUMPTIONS & GROUND RULES

- PRIOR TO PROPELLANT PLANT BUILDUP, THE WATER SOURCE DEPOSITS (ICE OR MINERALS) ARE ASSUMED TO HAVE BEEN LOCATED BY **PREVIOUS RECONNAISSANCE**.
- SITE PREPARATION, MINING, WATER EXTRACTION, PROPELLANT PROCESSING, AND STORAGE EQUIPMENT ARE SOFT LANDED ON THE MOON IN SELF-CONTAINED **LLV PAYLOADS**.
- CRYOGENIC PROPELLANTS, LOX AND LH_2, ARE PRODUCED FROM THE **ELECTROLYSIS** OF WATER AND SUBSEQUENT **LIQUEFACTION**.
- THE PROPELLANT PLANT IS **PARTIALLY AUTOMATED** TO REDUCE OPERATING COSTS, AND PLANT EQUIPMENT IS **REPLACED PERIODICALLY**.
- PROPELLANT IS STORED IN **PAYLOAD STAGE TANKS** AS WELL AS **SPECIAL TANKS**, WHICH HAVE CARGO-CARRYING CAPABILITY.
- THE SMALL PLANT IS **ADJACENT** TO THE LUNAR EXPLORATION BASE AND SUPPORTS THE BASE WITH PROPELLANT FOR A **LUNAR SHUTTLE VEHICLE** AND FOR OTHER REQUIREMENTS. THE BASE PROVIDES THE **PLANT MANPOWER**.
- THE LARGE PLANT IS A SELF-CONTAINED BASE WHOSE SOLE PURPOSE IS THE PRODUCTION OF PROPELLANT TO **REFUEL PLANETARY VEHICLES**.

FIGURE 1

SPACE TRANSPORTATION
LOGISTICS REQUIREMENT COMPARISONS
UTILIZING LUNAR MANUFACTURED PROPELLANTS



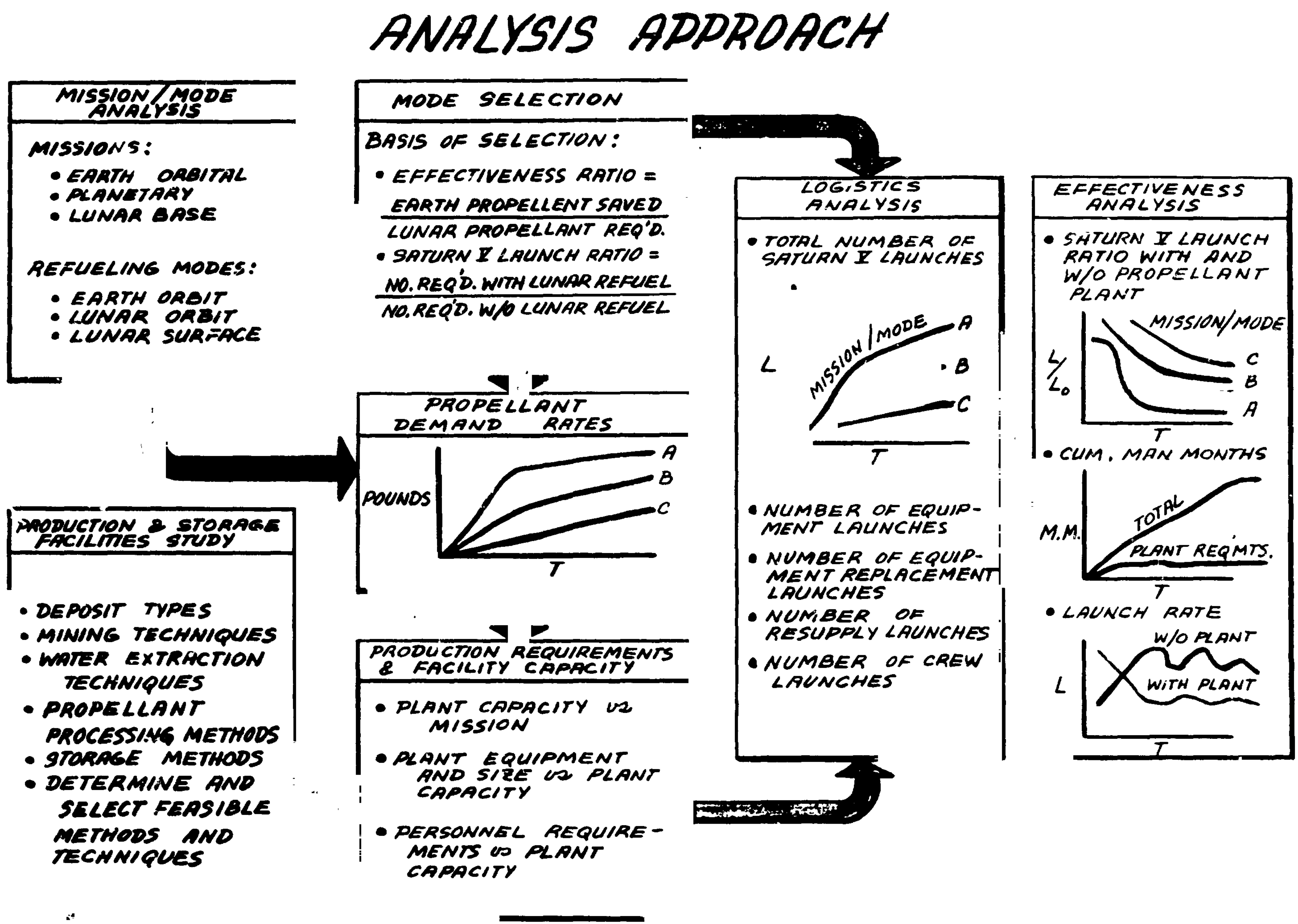

ANALYSIS APPROACH
MISSION/MODE ANALYSIS
MISSIONS:
• EARTH ORBITAL
• PLANETARY
• LUNAR BASE
REFUELING MODES:
• EARTH ORBIT
• LUNAR ORBIT
• LUNAR SURFACE
MODE SELECTION
BASIS OF SELECTION:
• EFFECTIVENESS RATIO = EARTH PROPELLENT SAVED / LUNAR PROPELLANT REQ'D.
• SATURN V LAUNCH RATIO = NO. REQ'D. WITH LUNAR REFUEL / NO. REQ'D. W/O LUNAR REFUEL
PROPELLANT DEMAND RATES
POUNDS
T
A
B
C
PRODUCTION & STORAGE FACILITIES STUDY
• DEPOSIT TYPES
• MINING TECHNIQUES
• WATER EXTRACTION TECHNIQUES
• PROPELLANT PROCESSING METHODS
• STORAGE METHODS
• DETERMINE AND SELECT FEASIBLE METHODS AND TECHNIQUES
PRODUCTION REQUIREMENTS & FACILITY CAPACITY
• PLANT CAPACITY vs MISSION
• PLANT EQUIPMENT AND SIZE vs PLANT CAPACITY
• PERSONNEL REQUIREMENTS vs PLANT CAPACITY
LOGISTICS ANALYSIS
• TOTAL NUMBER OF SATURN V LAUNCHES
L
MISSION/MODE
A
B
C
T
• NUMBER OF EQUIPMENT LAUNCHES
• NUMBER OF EQUIPMENT REPLACEMENT LAUNCHES
• NUMBER OF RESUPPLY LAUNCHES
• NUMBER OF CREW LAUNCHES
EFFECTIVENESS ANALYSIS
• SATURN V LAUNCH RATIO WITH AND W/O PROPELLANT PLANT
L/Lo
MISSION/MODE
C
B
A
T
• CUM. MAN MONTHS
M.M.
TOTAL
PLANT REQ'MTS.
T
• LAUNCH RATE
W/O PLANT
WITH PLANT
L
T

FIGURE 3

Each of the ratios is briefly defined in the diagram. The propellant demand rate can be determined for each refueling mode which in turn permits the determination of plant facility requirements. Earth launch requirements for the plant facility can then be analyzed, as indicated in the logistics analysis. Having determined launch requirements for a given mission, with and without the lunar propellant plant, an effectiveness analysis can then be performed.

Capabilities of the logistic vehicles employed at the lunar plant which are required to support the planetary mission or the lunar base mission are indicated in Figure 4. These vehicles are basically Lunar Logistics Vehicles (LLV) which are modified to perform shuttle service, as noted, between lunar orbit and the lunar surface. Initially, they are Saturn V-launched from Earth, and those cargo vehicles which are used in the propellant plant build-up phase are retained on the lunar surface for storage of lunar-produced propellants.

Planetary Missions

A spectrum of Mars space vehicles was considered for comparing the total number of Saturn V launch vehicles which would be required, with and without the lunar refuel capability. The basic manned Mars landing mission and the space vehicles are defined in Reference 3. Briefly, the mission is of 536 days, 40-day staytime, 3 to 12 man missions employing vehicles with 3 nuclear stages and 1 final chemical stage. In addition, vehicles with all chemical stages were also considered in order to complete the spectrum of possible vehicles. The number of Saturn V launches for each different Mars vehicle was thus determined.

Next, the number of launch vehicles which would be required to accomplish the Mars lander mission with lunar refuel capability was determined. Accordingly, various refueling modes for this refueled mission were analyzed. Figure 5 illustrates these modes and indicates the effectiveness ratio for each mode. It is noted that the best effectiveness is obtained in refuel mode 2, refueling the Mars vehicle on the lunar surface. The second best mode is to refuel in lunar orbit, mode 3. The least effective mode is to refuel the Mars vehicle in Earth orbit - as might be expected, intuitively.

TRANSPORTATION & STORAGE VEHICLES

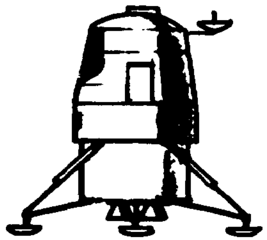
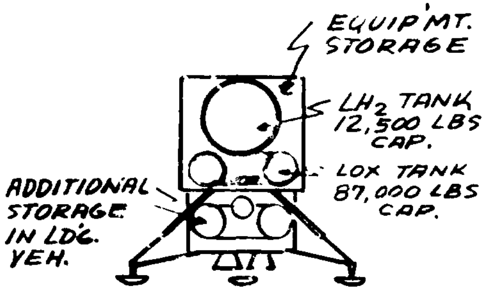
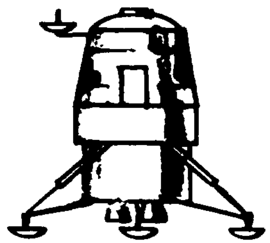
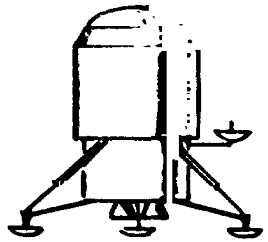
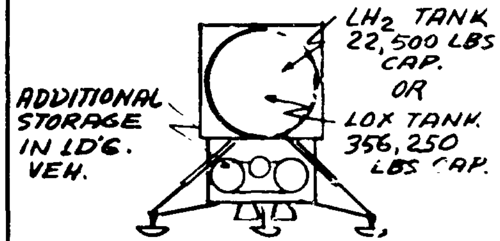
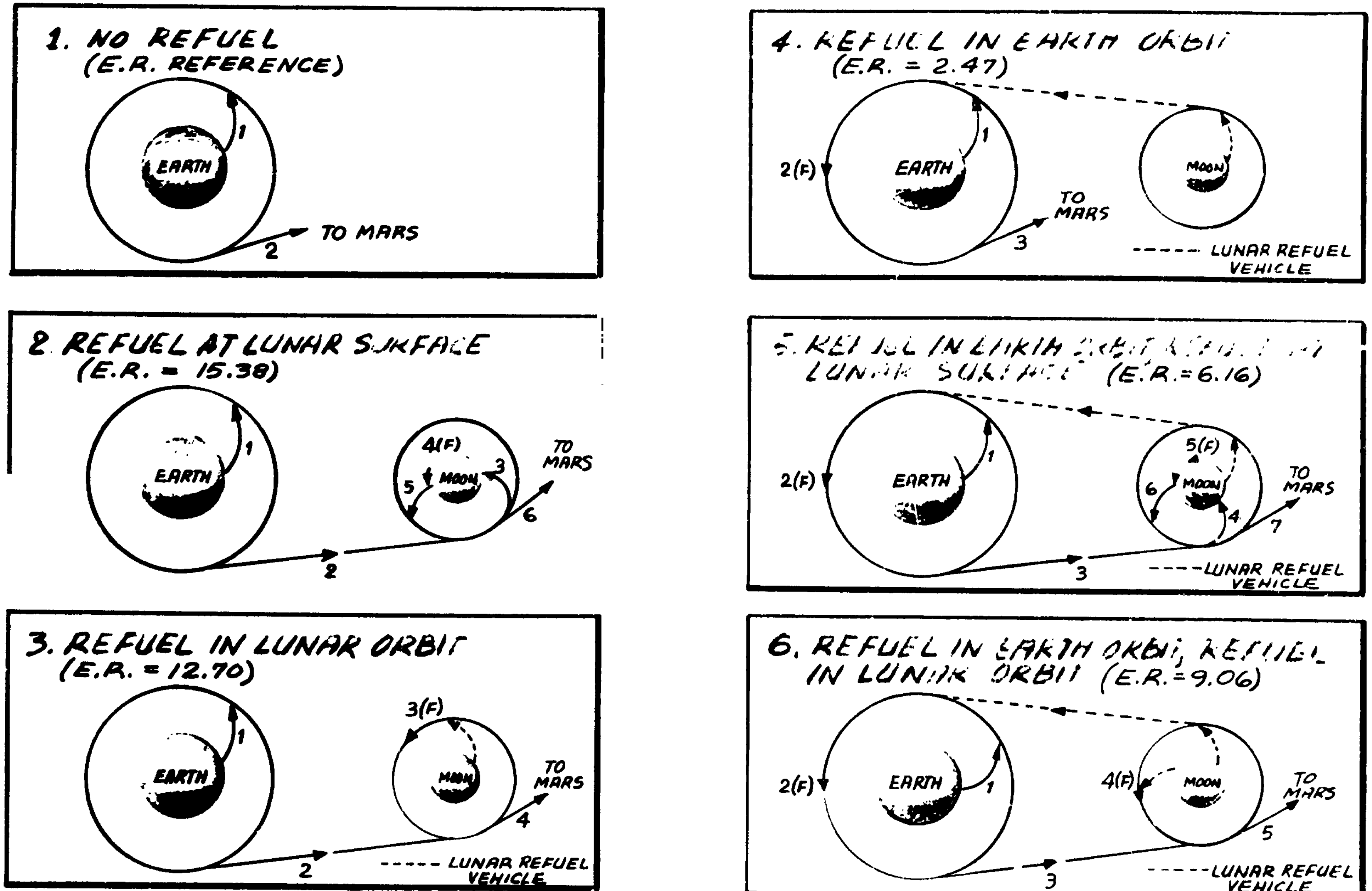
	CREW/CARGO SHUTTLE	PROPELLANT SHUTTLE	PROPELLANT STORAGE
LUNAR BASE MISSION	 CAPABILITY – • 6-MAN ROTATION PLUS 10,000 LBS. CARGO RETURN TRIP • 4 TRIPS REQUIRED/YEAR	NONE	 • LLV CONFIGURATION • 1 LLV REQUIRED FOR LUNAR BASE MISSION
PLANETARY MISSION	 CAPABILITY – • 6-MAN ROTATION PLUS 10,000 LBS. CARGO • 1-2 TRIPS /YEAR	 • 15,500 LBS DRY WEIGHT • DELIVERY CAPABILITY - 66,040 LBS. OF PROPELLANT PER TRIP • SHUTTLE CONSUMPTION RATE 70,260 LBS/TRIP • 15 TRIPS/MARS MISSION	 • LLV CONFIGURATION • 7 LLV'S REQUIRED FOR PLANETARY MISSION

FIGURE 4

MARS LANDING MISSION SPACECRAFT REFUEL MODES



FIGURE

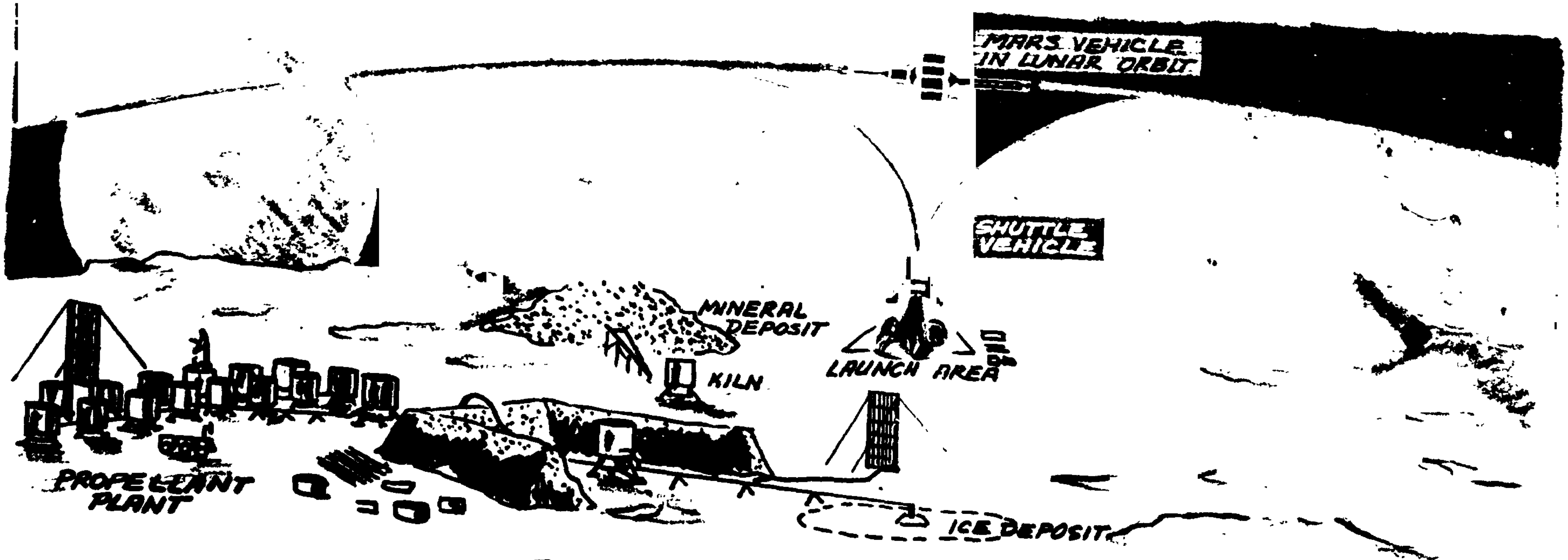
Mode 2, refuel at the lunar surface, was not further examined, owing to the likely extreme complexity of landing and launch pad requirements on the lunar surface. However, mode 3, refuel in lunar orbit, was selected for further analysis. It was then determined that mode 3, using the nuclear/chemical vehicle which would require 6.68 Saturn V launches without lunar refuel, would otherwise require only 2.50 launches if lunar refuel capability were available. This means that the difference in required launches would be 4.18 Saturn V's saved, which could be used for providing a lunar propellant plant in order to "break even". Furthermore, the Mars vehicle with all chemical stages would require 15.9 Saturn V launches without refuel, and only 3.23 launches with lunar refuel. This even greater savings is apparently realized because of the exclusive use of propellants in the latter vehicle. However, as the all chemical vehicle is much larger than the nuclear/chemical vehicle, it would not provide the preferred transportation mode for this mission.

From the foregoing analysis, it is determined that a total of 2,010,000 pounds of cryogenic oxygen and hydrogen propellants are required for the lunar orbit refuel mode in the case of the nuclear/chemical Mars lander vehicle. Assuming one Mars trip per year, a lunar propellant plant is built-up to satisfy a propellant demand rate of 2,010,000 pounds per year. Figure 6 illustrates such a plant and summarizes the number of Saturn V launches of the LLV (cargo capability of 25,000 pounds soft landed on the Moon) required to set the plant into operation. The figure suggests that either an ice deposit source of water or a hydrated mineral deposit may satisfy the resource requirement. In the latter case, however, one additional launch is required to set up a kiln and conveyor system for the extraction of water. In this regard, it is determined that a 1 electrical megawatt nuclear reactor plant was required to meet all power requirements. Moreover, the waste heat from the reactor is sufficient for ice sublimation or for the extraction of water from hydrated minerals which have bonding energies as high as 7000 Kcal/gram and water content as low as 1%. Thus, overall propellant plant weight is quite insensitive to water source deposit, as indicated in the foregoing discussion.

Figure 7 depicts the operational build-up sequence for the foregoing propellant plant which would support the planetary mission. Approximately 15 months from initiation of plant construction would be required to set this size plant into operation.

PLANETARY-VEHICLE REFUELING BASE AT THE MOON

LUNAR MANUFACTURING PROPELLANT PLANT PRODUCTION RATE: 2,010,000 POUNDS PER YEAR

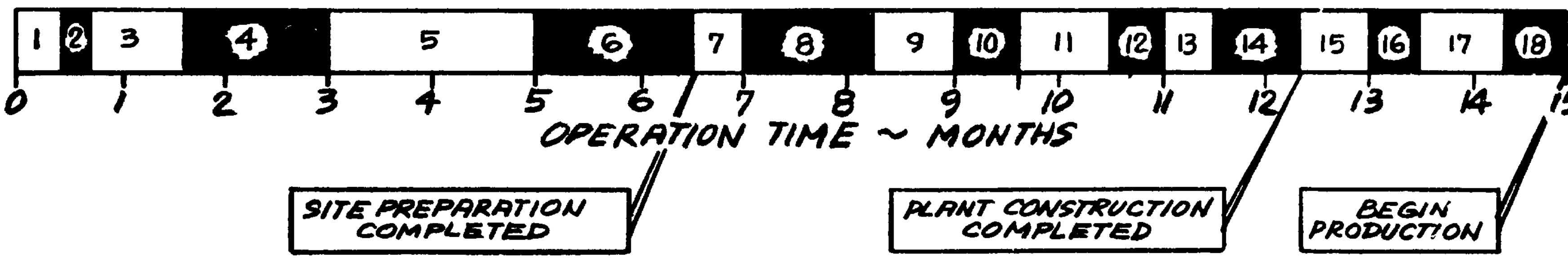


PROPELLANT PLANT

1 6-MAN PERSONNEL SHELTER
2 EQUIPMENT SUPPORT PAYLOADS (SURFACE VEHICLES AND EXCAVATION AND ERECTION EQUIPMENT)
1 NUCLEAR POWER PLANT
4 ELECTROLYTIC AND LIQUEFACTION PROCESSING PLANT
2 EQUIPMENT SUPPORT PAYLOADS (RADIATOR SECTIONS)
7 PROPELLANT STORAGE TANKS
1 PROPELLANT SHUTTLE VEHICLE
18 TOTAL

PLUS 4 3-MAN LEMS FOR PLANT BUILDUP

OPERATIONAL SEQUENCE
PLANETARY SUPPORT BASE



OPR. NO.	OPERATION
1	MANUALLY LOCATE AND VERIFY THE DEPOSIT
2	TRANSPORT AND POSITION THE PERSONNEL SHELTER ON THE SITE
3	SURFACE PREPARATION ON THE SITE
4	TRANSPORT AND ERECT EXCAVATION EQUIPMENT
5	DRILL & BORE HOLE FROM SURFACE TO THE DEPOSIT FOR NAK AND STEAM LINES
6	BACK-FILL LUNAR SOIL FOR PERSONNEL SHELTER SHIELDING AND REVETMENT
7	TRANSPORT AND POSITION NUCLEAR POWER PLANT
8	ASSEMBLE NUCLEAR RADIATOR & INSTALL NAK & STEAM LINES INTO THE HOLE WITH THE DEPOSIT
9	COMPLETE THE PWR. INSTALLATION & WITH AUX. PWR. HEAT THE NAK LINES FOR CIRCULATION FLOW
10	START NUCLEAR POWER-LOW POWER CHECKOUT BY ENERGIZING THE SYSTEM (NO ACTIVATION)
11	TRANSPORT AND POSITION THE 4 ELECTROLYTIC AND LIQUEFACTION PLANTS
12	REMOVE, TRANSPORT AND ERECT THE ELECTROLYTIC AND LIQUEFACTION RADIATOR
13	TRANSPORT AND POSITION THE PROPELLANT STORAGE PAYLOADS
14	TRANSPORT & POSITION ALL EQUIPMT. SUPPT. PYLDS. FOR UTILIZATION OF THE LANDING VEH. STORAGE TANKS
15	COMPLETE ALL THE INTERCONNECTIONS OF LIQUID & ELECTRICAL LINES BETWEEN THE PAYLOADS
16	CHECKOUT THE ELECTROLYTIC & LIQUEFACTION PLANTS - ENERGIZE ALL SYSTEMS
17	PRESSURE CHECK ALL STORAGE TANKS INCLUDING THE LANDING VEH. STORAGE TANKS
18	START ALL SYSTEMS - NUCLEAR POWER PLANT FULL POWER: CHILL-DOWN ALL LIQUID LINES AND TANKS

FIGURE 7

Several years of plant operation were analyzed in order to determine the "break even" point with respect to economic feasibility of such a plant. Accordingly, Figure 8 indicates the estimated manpower requirements for maintenance and operation of the plant, consumable supplies status, and finally a complete Earth launch schedule to support this plant. This schedule allows for crew rotation, supplies replenishment, and periodic replacement of plant facilities as shown in the Figure.

Resulting effectiveness comparisons for the Mars mission are shown in Figure 9. For the nuclear/chemical Mars vehicle, the ratio of total launches with and without the lunar plant does not show economic feasibility as the "break even" point is not realized. This is so, irrespective of a 6-month or 12-month crew rotation frequency of lunar plant personnel. However, for Mars vehicles with all chemical stages, the "break even" point can be realized after four missions have been supported by lunar refuel capability. Thus, it can be concluded that the Mars lander mission using lunar refuel will require very careful examination in order to achieve economic feasibility. It is further noted that a considerable number of missions may be required in order to justify lunar refueling.

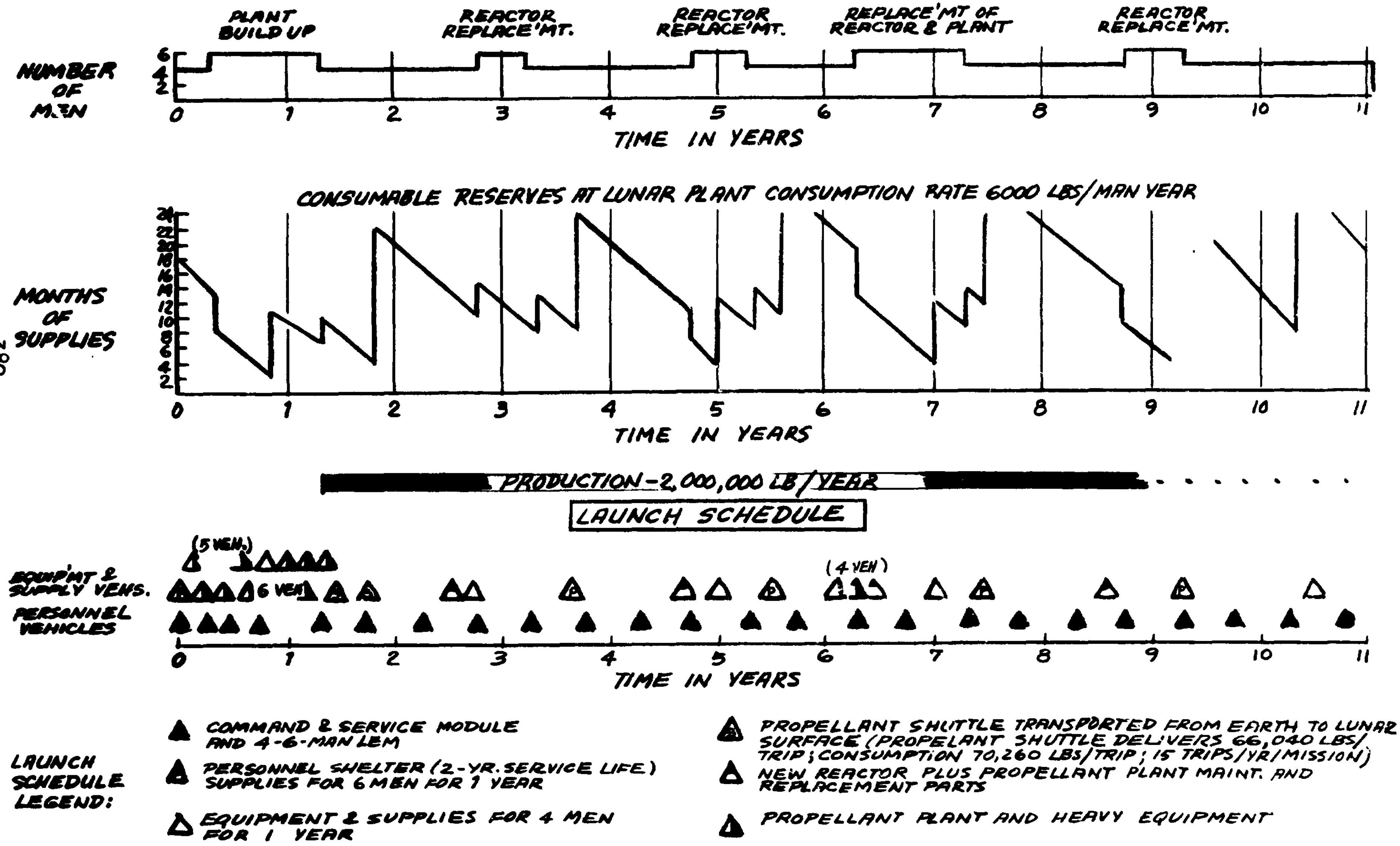
Earth Orbital Missions

Refueling in Earth orbit, mode 4 of Figure 5, indicates a very poor effectiveness ratio as previously indicated. In order to refuel an Earth orbital vehicle from a lunar tanker, approximately seven times as much fuel is consumed in transit by the tanker as compared to the quantity delivered. Consequently, refueling Earth orbital missions with lunar-produced propellant is not economically feasible.

Lunar Base Missions

The support of lunar exploration or exploitation bases is also analyzed in order to determine the economic feasibility of their use of lunar-produced propellant. Figure 10 illustrates a 12-man lunar exploration base (Reference 4) which also has the capability to support itself, partially, with locally-produced cryogenic oxygen and hydrogen propellant. A production rate of

LOGISTICS SEQUENCE
MARS MISSION SUPPORT
BASE COMPLEMENT 6 MONTHS' TOUR OF DUTY



EFFECTIVENESS COMPARISON
MARS MISSION

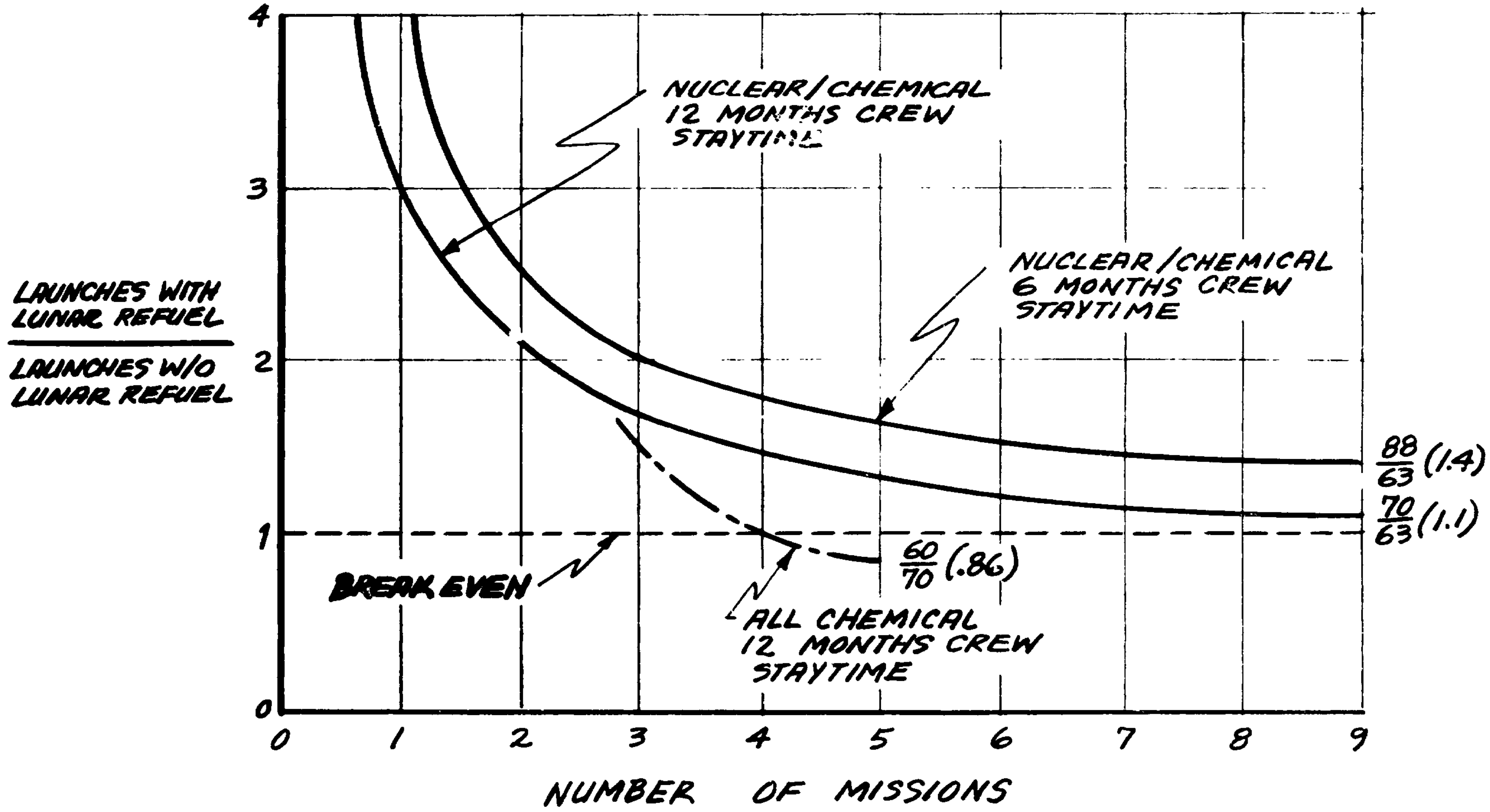
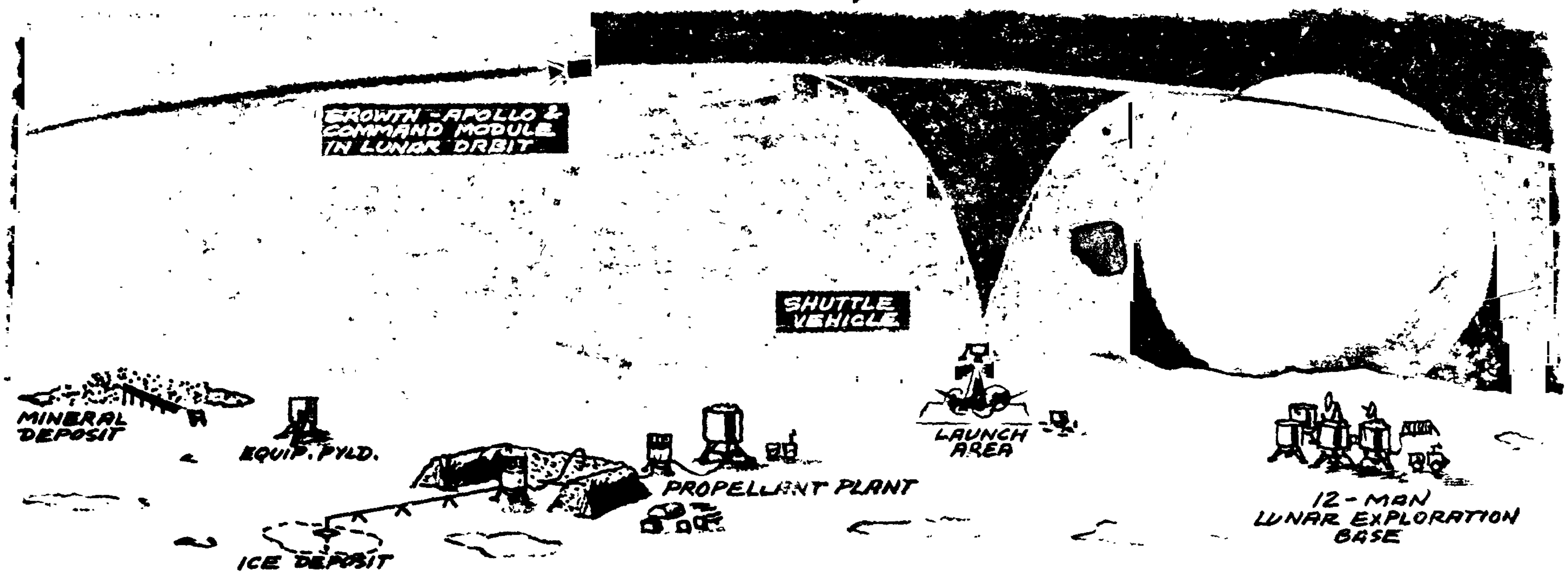


FIGURE 9

12-MAN LUNAR EXPLORATION BASE

SUPPORTED BY LUNAR MANUFACTURED PROPELLANT PLANT
PRODUCTION RATE: 110,000 LBS PER YEAR



PROPELLANT PLANT

1 NUCLEAR POWER PLANT & STEAM CONVERTER (+ INTEGRAL SHIELDING) OR 18,000 LBS OF EQUIPMENT

1 ELECTROLYTIC & LIQUEFACTION PROCESSING PLANT PLUS 17,000 LBS OF EQUIPMENT

1 PROPELLANT STORAGE TANK AND 20,000 LBS OF EQUIPMENT

1 EQUIPMENT SUPPORT PAYLOAD 25,000 LBS

4 TOTAL

12-MAN LUNAR BASE

2 6-MAN PERSONNEL SHELTERS

1 POWER UNIT 12,500 LBS PLUS 12,500 LBS OF SUPPLIES

1 SUPPLY PAYLOAD

4 TOTAL

PLUS 1 CREW/SHUTTLE

FIGURE 10

110,000 pounds per year is sufficient to rotate the entire base crew between lunar orbit and the lunar surface and also to supply 2,000 pounds per year for other purposes (e.g., fuel for the lunar roving vehicle or fuel cell, water, metabolic oxygen, etc.). The lunar shuttle used for rotation of the lunar base crew is indicated in Figure 4, and utilization of propellant for this purpose may yield large savings in the total number of crew vehicles required to support a lunar base. Figure 10 also indicates that 4 Earth launches for the delivery of propellant plant and construction equipment (including one 60 KW nuclear power plant launch) are required to set up the plant for production. The lunar exploration base provides all other assets (i.e., manpower, crew shelter, etc.) required to maintain and operate the base.

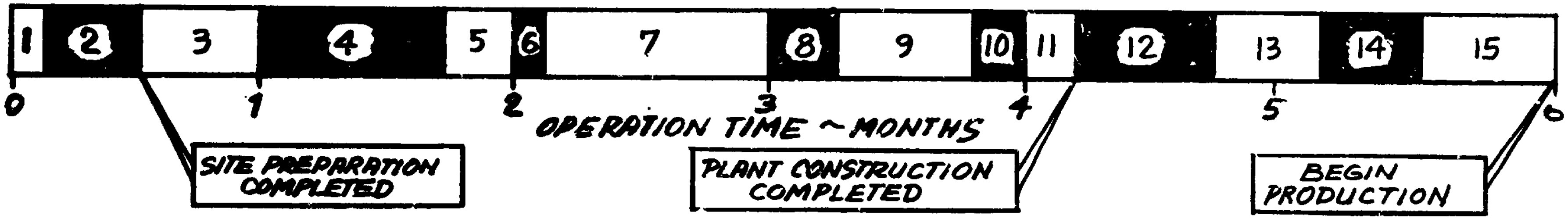
Figure 11 depicts the operational build-up sequence for the foregoing propellant plant which would support the lunar base mission. Approximately 6 months from the initiation of plant construction would be required to set this size plant into operation. Several years of plant operation were analyzed in order to determine the "break even" point with respect to economic feasibility of such a plant. Accordingly, Figure 12 indicates the total base manning level versus time, consumable supplies status, and finally a complete Earth launch schedule to support the base without the propellant plant as well as with the plant. This schedule allows for crew rotation, supplies replenishment, and periodic replacement of plant facilities as depicted in the lower portion of the figure.

Launch requirements for the foregoing analysis are shown in Figure 13. After steady state operation of the plant it is noted that Earth launch rate requirements in support of the entire lunar base are almost halved and total Earth launches are substantially reduced. It is further noted that the propellant plant "pays-off" after approximately 15 months of operation.

Figure 14 indicates that only a small portion of the manhours available in the lunar base are required for propellant plant operation and maintenance (i.e., approximately 1 man of the 12-man base). Consequently, lunar base effectiveness, based on available man-months per Earth launch, is improved by over 40%, as indicated in Figure 15.

Similar analyses were performed for an 18-man and a 24-man lunar base. These analyses indicated very similar effectiveness and economic feasibility results as for the 12-man base. It may therefore be concluded that substantial savings may be anticipated in the number of Earth launches required to support a moderate to large-sized lunar base which employs a propellant plant, at or near the lunar base site.

OPERATIONAL SEQUENCE
12 - MAN LUNAR BASE



OPR. NO.	OPERATION
1	VERIFY THE DEPOSIT
2	SURFACE PREPARATION ON THE SITE
3	TRANSPORT AND ERECT EXCAVATION EQUIPMENT
4	DRILL & BORE HOLE FROM SURFACE TO THE DEPOSIT FOR NAK & STEAM LINES
5	BACK-FILL LUNAR SOIL FOR REVETMENT
6	TRANSPORT AND POSITION NUCLEAR POWER PLANT
7	INSTALL NAK & STEAM LINES INTO THE HOLE WITH THE DEPOSIT & CONNECT TO THE REACTOR
8	COMPLETE THE POWER INSTALLATION & WITH AUX. PWR. HEAT THE NAK LINES FOR CIRCULATION FLOW
9	START NUCLEAR PWR.-LOW PWR. CHECKOUT BY ENERGIZING THE SYSTEM (NO ACTIVATION)
10	TRANSPORT AND POSITION THE ELECTROLYTIC AND LIQUEFACTION PLANT
11	TRANSPORT AND POSITION THE PROPELLANT STORAGE PAYLOAD
12	COMPLETE ALL THE INTERCONNECTIONS OF LIQUID & ELECT. LINES BETWEEN THE PAYLOADS
13	CHECKOUT THE ELECTROLYTIC AND LIQUEFACTION PLANT-ENERGIZE ALL SYSTEMS
14	PRESSURE CHECK ALL STORAGE TANKS
15	START ALL SYSTEMS-NUCLEAR POWER PLANT FULL POWER: CHILL-DOWN ALL LIQUID LINES AND TANKS

FIGURE 11

LOGISTICS SEQUENCE

12-MAN LUNAR BASE

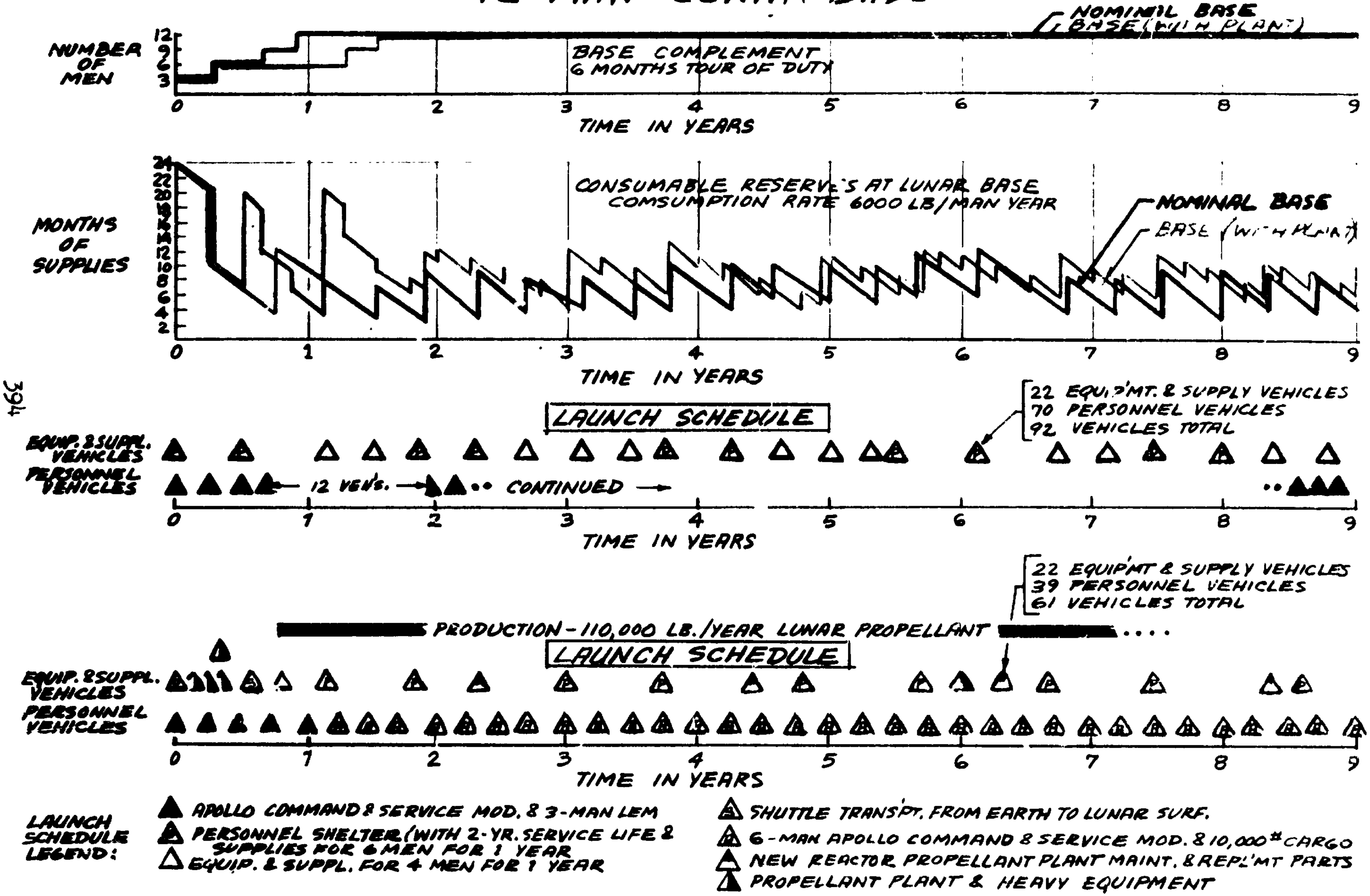
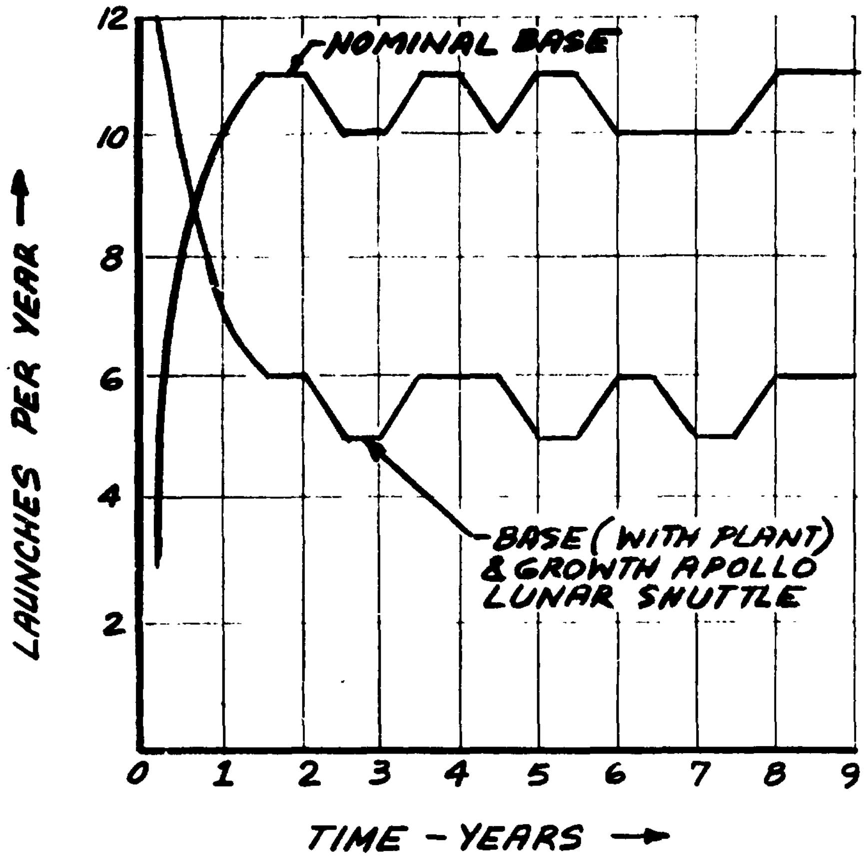


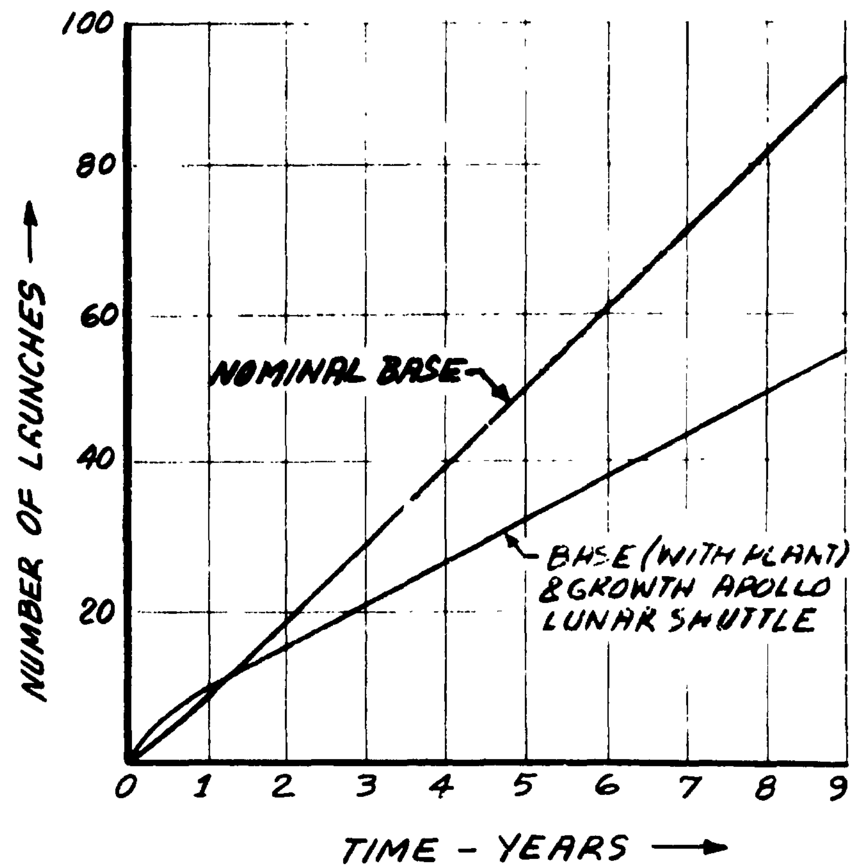
FIGURE 12

LAUNCH REQUIREMENTS

LAUNCH RATES -
12 MAN LUNAR BASE



CUMULATIVE LAUNCHES -
12 MAN LUNAR BASE



MAN MONTHS COMPARISON
12 MAN LUNAR BASE

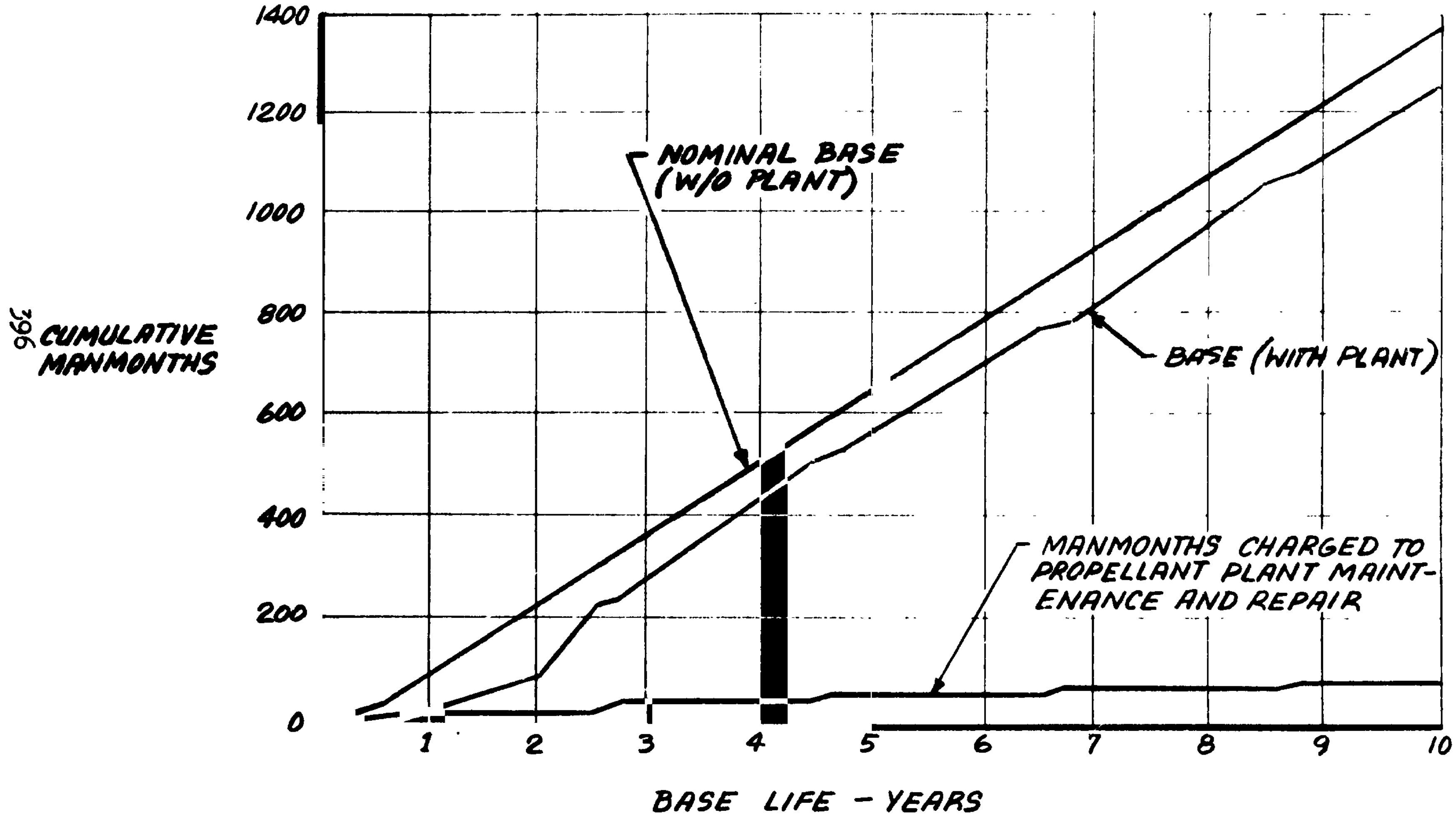


FIGURE 14

EFFECTIVENESS COMPARISON
12-MAN LUNAR BASE

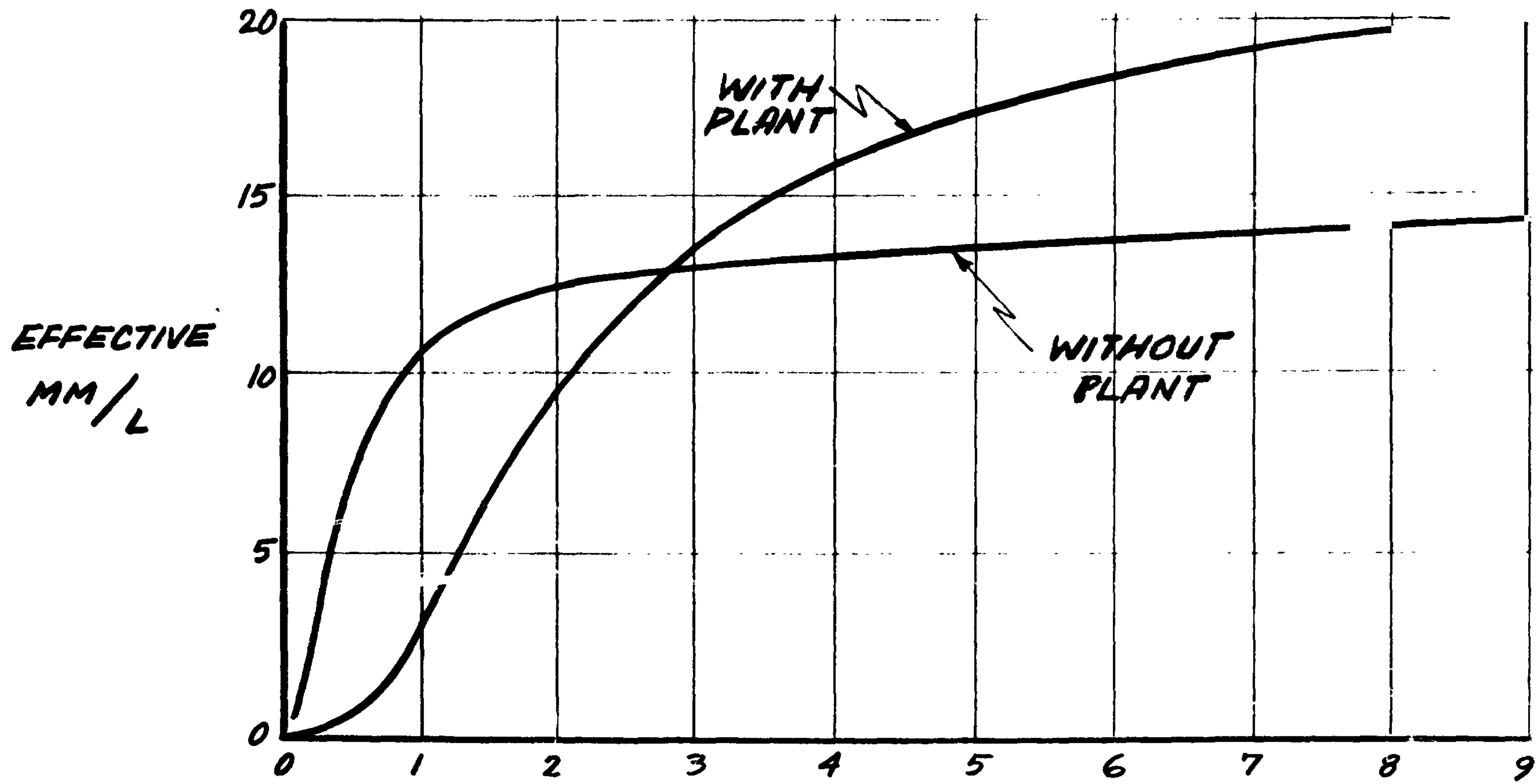


FIGURE 15

CONCLUSIONS

In order to determine the economic feasibility of utilizing lunar-manufactured propellants, three different missions have been investigated employing various refueling modes for the space vehicles.

A typical planetary mission, represented by a manned Mars lander, employing nuclear stages and one final chemical stage vehicle when refueled in lunar orbit is not economically feasible. However, in the case of the Mars vehicle consisting of all chemical stages, lunar orbit refuel did show economic feasibility after four such missions were so refueled.

The Earth orbital mission, when refueled in Earth orbit by a lunar tanker spacecraft, did not indicate economic feasibility - as might be expected, intuitively.

Moderate to large-sized lunar bases (12 to 24 astronauts) can effectively support a propellant plant and thereby experience very attractive savings in the total number of earth launches to support the entire base. A considerable improvement in base effectiveness, in terms of available man-months per Earth launch, can be realized. In the case of a 12-man base, an average of one man was required for plant operation and maintenance, while the base effectiveness improved by over 40 percent.

REFERENCES

1. Gorrell, R. A., Deodati, J. B., et al, General Dynamics/ Fort Worth Division, Utilization of Lunar-Produced Propellants, MR-0-113, 2 April 1965.

2. Ball, H. G., General Dynamics/Fort Worth Division, Memorandum Report on Space-Mission Utilization of Lunar-Produced Propellant, MR-FS-31, 20 August 1964.

3. General Dynamics/Fort Worth Division, A Study of Manned Mars Exploration in the Unfavorable Time Period (1975-1985), FZM-4039-4, 26 February 1964.

4. The Boeing Company, Initial Concept of Lunar Exploration for Apollo, NASA CR-39, March 1964.

N66 35518

THE ROLE OF LUNAR RESOURCES IN POST-APOLLO MISSIONS

Howard Segal

INTRODUCTION

After an astronaut lands on the Moon some of the items he will need are oxygen for breathing and fuel for returning his spacecraft to Earth. Normally, oxygen and fuel are carried as part of the spacecraft's payload, but there may be a better way of providing these materials. Instead of transporting fuel and oxygen directly to the Moon, equipment to process lunar resources could be delivered instead (Figure 1). If H_2O or O_2 are present on the Moon, this equipment could then manufacture lunar material into required quantities of fuel and oxygen. But is this approach economical?

References 1, 2, and 3 emphasize the need for an economic analysis of extra-terrestrial oxygen or fuel production. However, since these references are only generalized studies, it appears appropriate to consider a specialized study in which committed or slightly modified hardware is used.

Sufficient data has been generated by the working group to start comparing the economics of space missions, both with and without lunar resources. Is it cheaper to manufacture a specific fuel on the Moon or manufacture it on the Earth and transport it to the Moon (Figure 1)? What is the break-even point between manufacture and transport? This break-even point is obtained by plotting manufacture and transport curves (Figure 2)* and determining their slope and displacement differences. The slope and displacement of these curves are dependent upon:

1. Mission resource demands
2. Processing costs
3. Fixed costs

This paper will summarize work completed in these three areas and then relate these results to the break-even point between manufacture and transport.

* This is a typical curve for illustration purposes only.

FUEL TRANSPORT VS MANUFACTURE

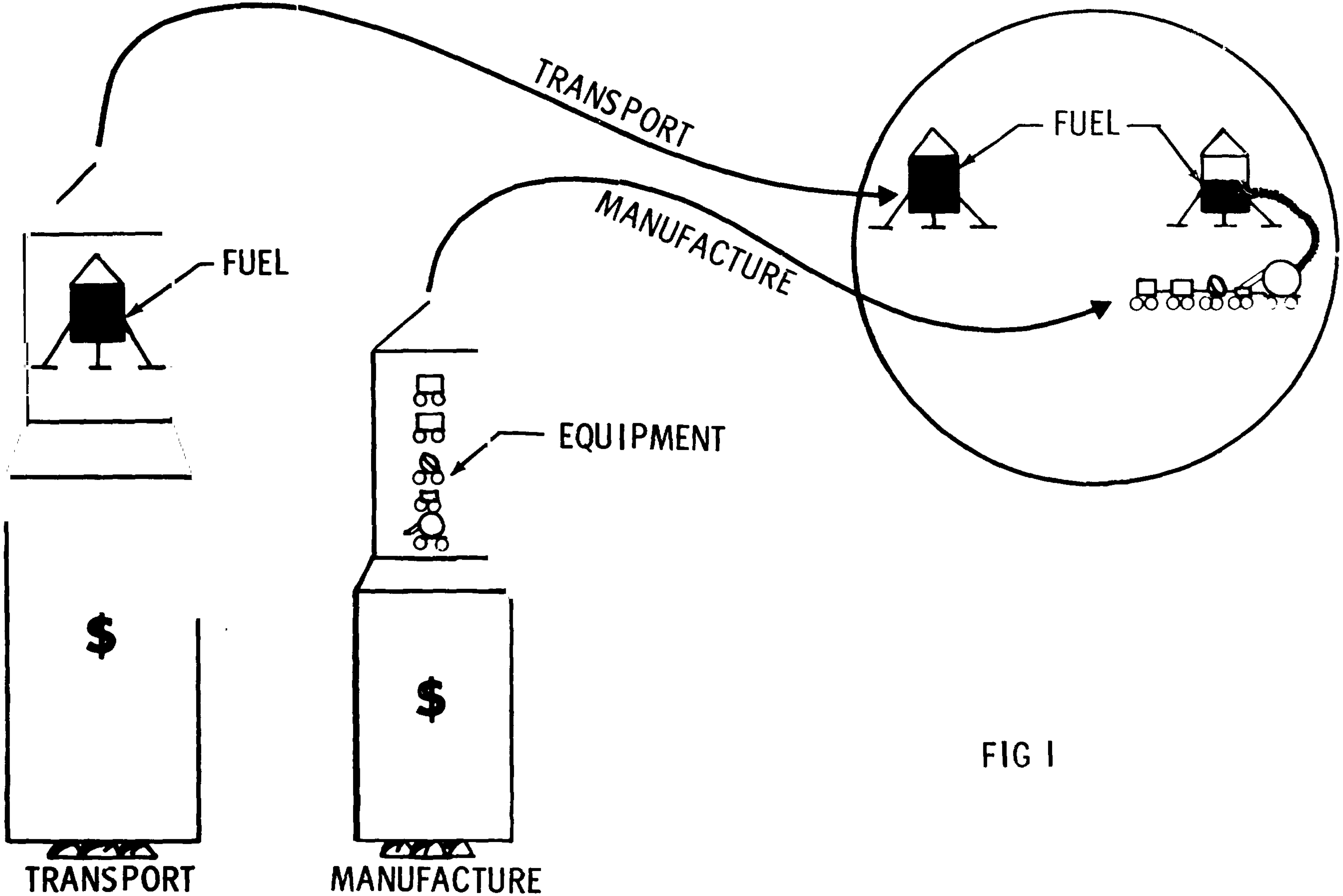


FIG I

ECONOMIC ANALYSIS

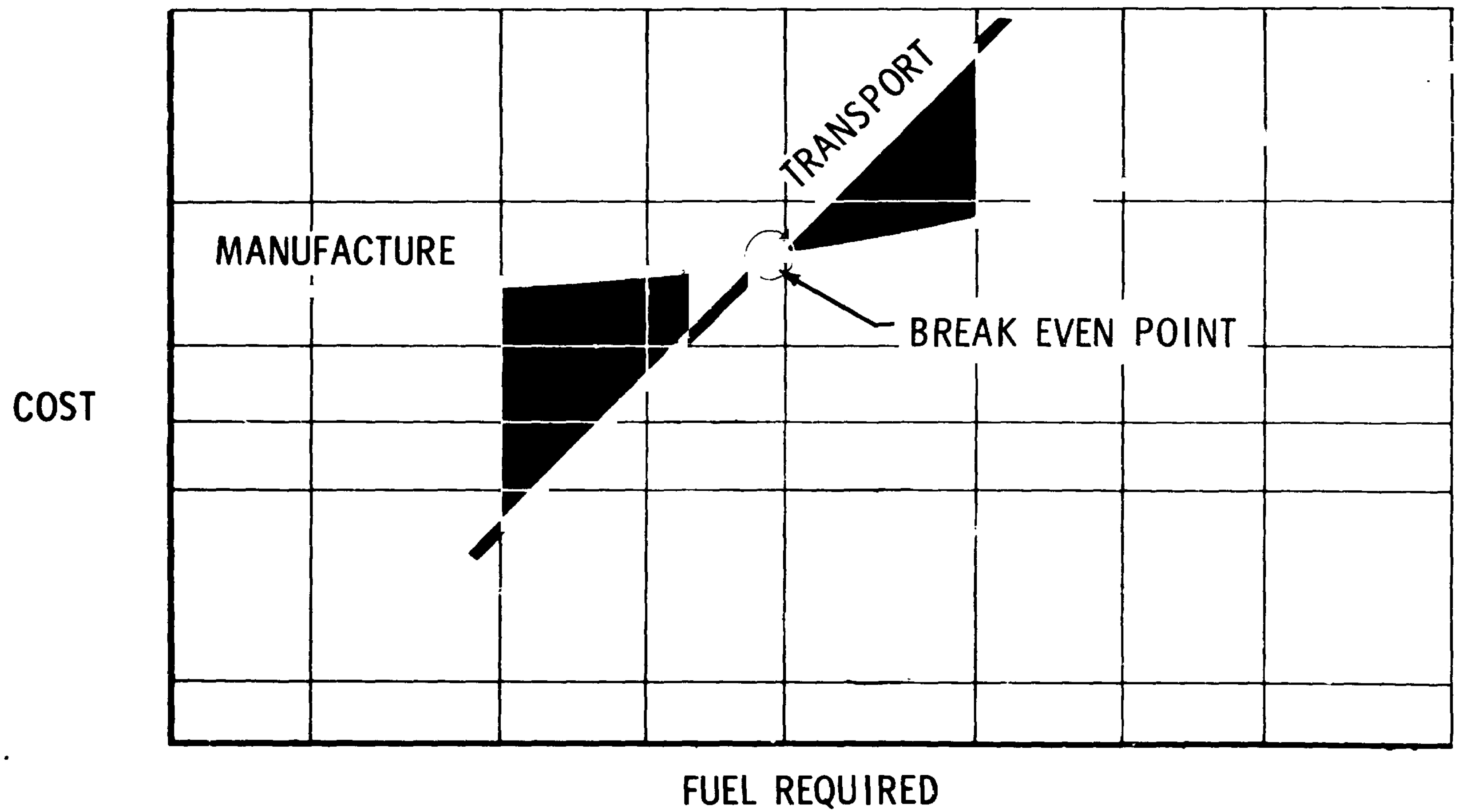


FIG 2

MISSION RESOURCE DEMANDS

The following resource categories were identified in Reference 3. They are:

1. Life support demands
2. Mobility demands
3. Earth return propulsion demands
4. Planetary mission fuel demands

Category 1, which consists of oxygen or water for astronaut life support, will be considered first. Only small quantities of these resources are needed. Even though life support materials can probably be processed from lunar resources, the quantities are so small that their influence upon the economics of space transportation will be negligible. Since economics is the theme of this paper, this category will not be considered further.

As for Category 2, which encompasses fuel needed for lunar rovers, it appears that while lunar fuel would be desirable, it is not essential for lunar mobility. Rovers can utilize wheels or tracks rather than mass flow through reaction jets for their motive force. Since mass does not have to flow to move lunar surface vehicles, molecular fuels which would be consumed are not required; therefore, this category has been eliminated from additional consideration.

Of the two remaining categories, only Category 3 will be considered, since Category 4 is discussed in Reference 4.

LUNAR FUEL DEMANDS FOR CREW ROTATION

The main objective of Category 3 is to return men from the Moon. Since fuel is needed to return these men, Earth-Moon transportation systems must be analyzed to determine return fuel requirements. The basis for this analysis is contained in the following ground rules:

1. Lunar surface refueling
2. A standard Saturn V vehicle which would place 94,000 pounds in a translunar trajectory.
3. Cost per launch of $125,000,000.
4. The operational time period for this system would be prior to 1980.
5. The most favorable resource hypothetically possible, lunar ice, was selected. This resource would be electrolyzed, liquefied, and stored as cryogenic hydrogen and oxygen. Water combined with lunar rock or oxygen in lunar silicates were not considered. The rationale for the selection of ice was that if lunar manufacture was not feasible for the best possible resource, it most assuredly would not be feasible for any less favorable resource.
6. A 100-kilowatt nuclear electric power system weighing 25,000 pounds.

7. The useful life of all equipment is one year.

8. The following two vehicles were considered to be available at the time this system would be operational:

   (A) A modified LEM with an LO_2-LH_2 descent stage

   (B) A lunar logistic vehicle with LO_2-LH_2 lunar descent stage

9. Development or operating costs for both these new upper stages and lunar equipment were not considered and all other costs, i.e., processing equipment delivery costs, were amortized equally over the operational life of the equipment.

10. Earth-Moon transportation costs of $3100/pound for direct flight and $7700/pound for lunar orbit rendezvous (LOR) were used. These figures reflect results from Apollo LOR and direct flight studies which were modified for a LO_2-LH_2 descent stage and total payload rather than useful payload landed on the lunar surface.

Figure 3 shows the men, and return fuel requirements for two transportation systems; direct flight and LOR. Payload is listed for supplementary information.

Referring to the LOR mode and using the ground rules listed above, it is seen that a Saturn V system can deliver two men, their life support bus (the LEM), 5750 pounds of fuel to return the LEM to lunar orbit, and a cargo payload of 2410 pounds to the lunar surface. This cargo payload can be increased by 5750 pounds (the weight of the Earth-return fuel) if 5750 pounds of lunar fuel is substituted for this Earth-return fuel. The new cargo payload then is 8160 pounds (5750 pounds plus 2410 pounds). This is listed as the payload in Figure 3.

For the direct-flight mode, a Saturn V system can deliver 3 men, an Apollo command module, and 7460 pounds of fuel to return the command module to Earth. However, this 7460 pounds of fuel is only a small fraction of the 34,500 pounds of fuel needed to return the command module to Earth. This deficiency must be filled either by fuel delivered to the Moon or else by lunar material processed into fuel. If lunar fuel is used, the entire 34,500-pound return fuel weight can be supplied from a Moon source. The 7,460-pound payload mentioned earlier can then become a cargo payload.

Figure 4 is similar to Figure 3 except that a larger number of men are rotated per flight.

RETURN FUEL REQUIREMENTS
2 and 3 Man Crew Rotations

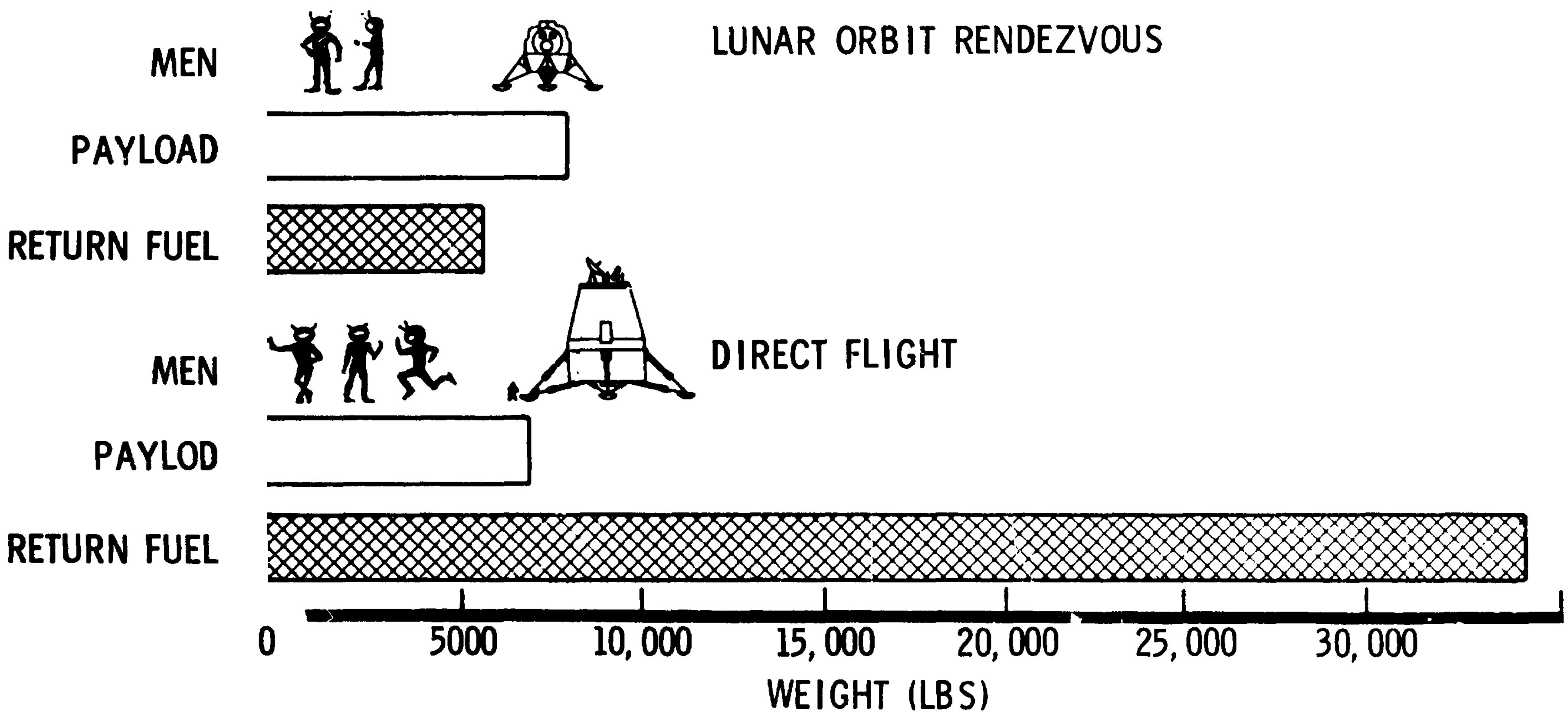


FIG 3

RETURN FUEL REQUIREMENTS
5 and 6 Man Crew Rotations

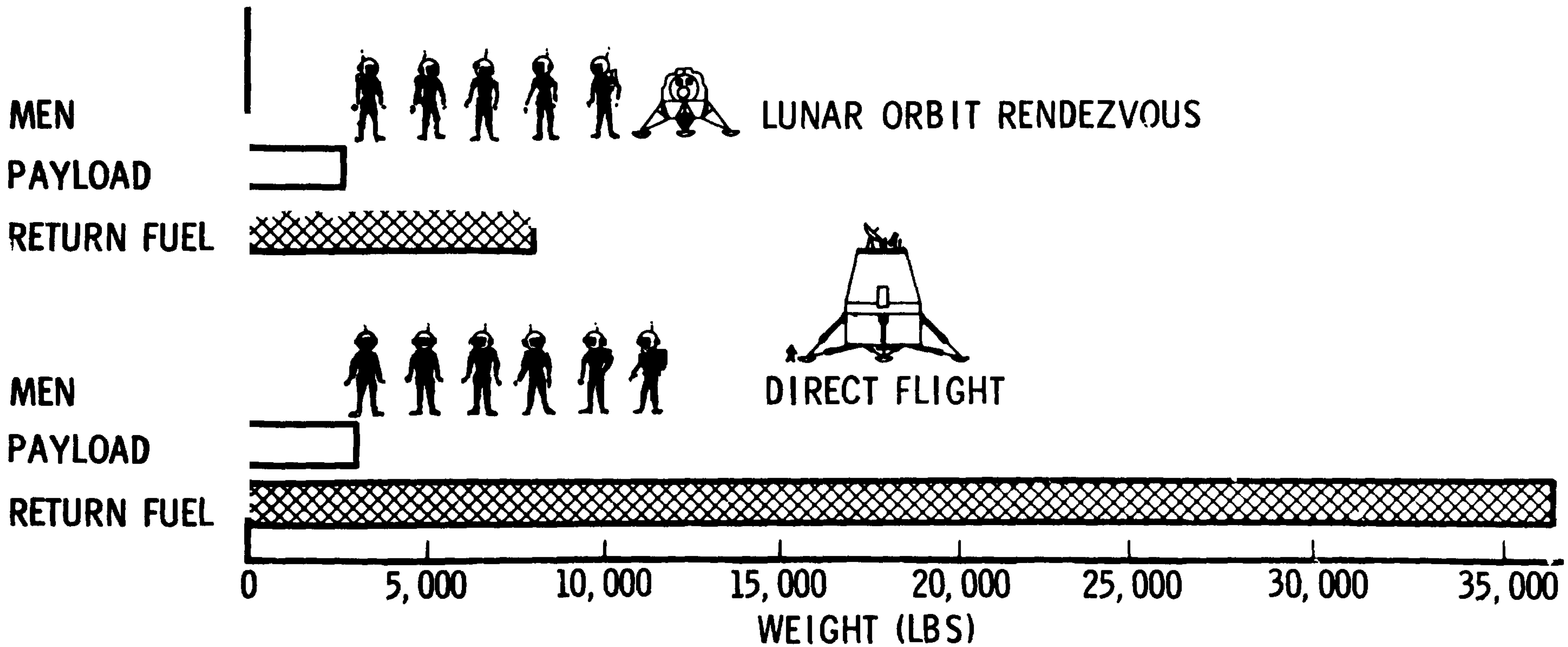


FIG 4

LUNAR FUEL PRODUCTION COSTS

Fuel requirements for rotating crews are now known. The question arises: What will it cost to produce this fuel on the Moon?

Lunar fuel costs are determined by first estimating fuel processing equipment weight and then multiplying this weight by the appropriate Earth-Moon transportation cost. Processing equipment weights were obtained by sizing three plants which were designed to produce 100,000, 500,000, and 1,000,000 pounds of fuel per year, respectively. The 100,000-pound plant is described in this paper because it most closely approaches expected resource demands and has a weight approximately equal to the payload of one Saturn V.

Figure 5 shows the power and equipment weight required to process 100,000 pounds of lunar fuel. It is seen that the power weight is greater than the processing weight. In other words, if we are concerned with reducing weight, the biggest savings would result in reducing power requirements and equipment. As for the equipment weight, it is seen that electrolysis equipment weight overshadows, significantly, the weight of the liquefication and storage equipment. A cursory investigation showed that flight, rather than industrial weight electrolysis equipment would reduce the weight of this equipment. A preliminary weight estimate was then made of a flight weight fuel cell operating in reverse as an electrolysis unit. Weight dropped from 7700 pounds to 1270 pounds. However, since this study is a conservative one, the higher weight figure was used.

Figure 5 also shows that 100,000 pounds of fuel can be produced with 21,700 pounds of equipment. Lunar fuel is cheap in terms of transportation costs; only $\frac{21,700}{100,000}$ or 1/5 of the cost of transporting Earth fuel. But is enough of this cheap fuel used to significantly effect total system costs?

CREW ROTATION COSTS

Crew rotation costs for the LOR mode are obtained by adding two costs; the cost of delivering men to the Moon, and the cost of providing them with fuel to come home. The cost of delivering men to the Moon is calculated by multiplying the crew assigned payload by the average cost of Earth-Moon transportation ($7700/pound for the LOR mode). The cost of supplying return fuel depends on whether the fuel is transported from Earth or manufactured on the Moon. If it comes from the Earth, its cost is computed by multiplying return fuel requirements by the Earth-to-Moon transportation costs ($3,100/pound). If it comes from the Moon, its cost is computed by multiplying the return fuel requirements by the cost of lunar manufacture ($680/pound). These costs were added up and plotted against variable mission requirements in Figure 6.

It is seen that savings are small compared to total system costs. But this is to be expected for the LOR mode since very little return fuel is used per mission and the percentage of return fuel to total payload is small.

EQUIPMENT WEIGHT
100,000 Lb Fuel / Yr

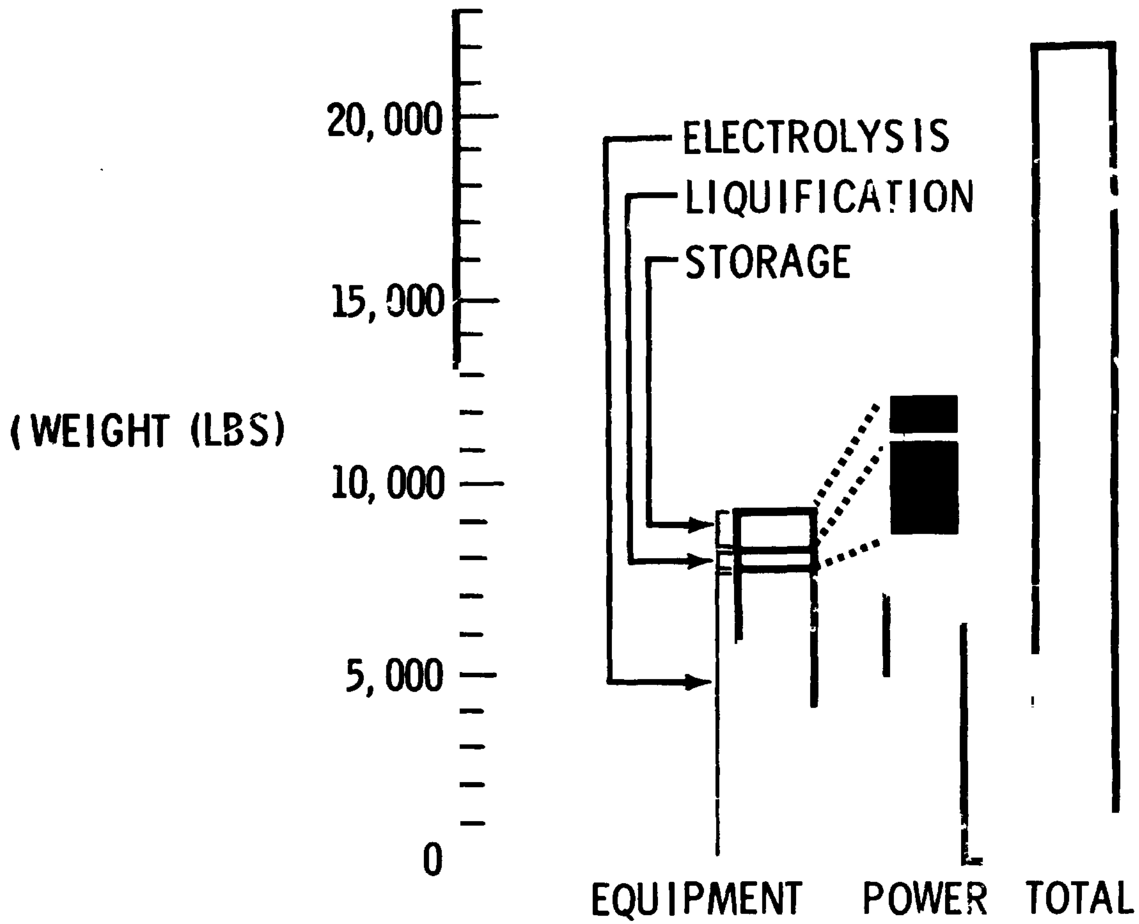


FIG 5

COST FOR CREW ROTATION
Lunar Orbit Rendezvous Mode

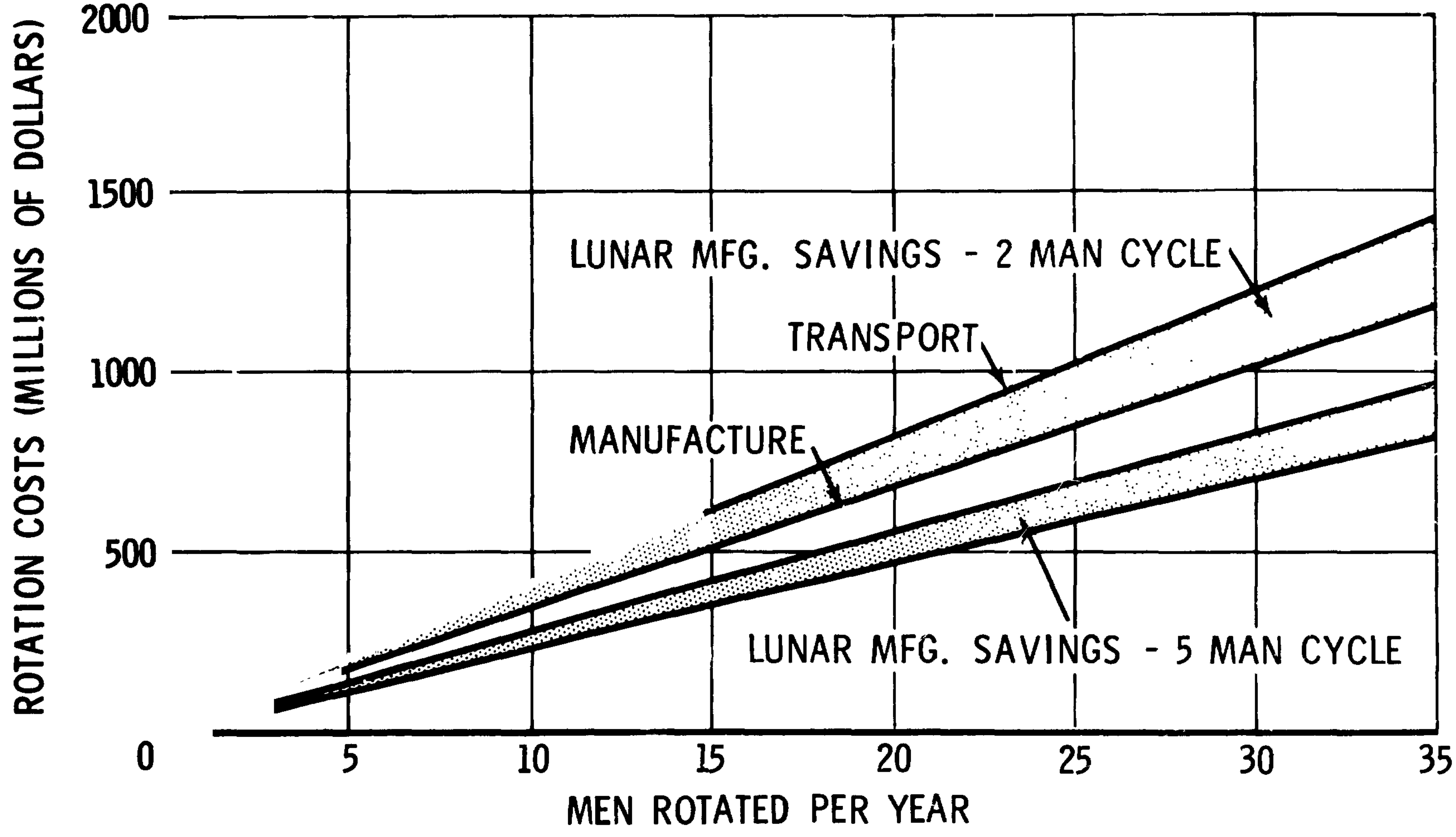


FIG 6

The last item in estimating crew rotation costs is to estimate development costs. Since it is beyond the scope of this paper to consider development costs, parametric relationships were established and the results plotted in Figure 7. It is seen that for a hypothetical development cost of $150,000,000, the break-even point is 22 men rotated per year. Eleven Saturn V/LEM missions would be needed to rotate this number of men. Figure 8 shows how the development costs are absorbed by rotating more men at the break-even point. Then costs are absorbed very slowly because the slopes of the manufacture and transport curves are almost the same.

While it was mentioned that the direct flight mode would not be considered in any depth in this paper, since it was being covered in Reference 5, one curve (Figure 9) was prepared for comparison purposes. It is seen that the included angle between the manufacture and transport curves is greater than the same angle for the LOR mode. Direct flight costs appear to be quite sensitive to available lunar fuel.

CONCLUSIONS

This paper takes into consideration only a small portion of the lunar fuel production problem. It does not address itself to the planetary fueling problem and only considers crew rotation systems using committed hardware or those systems requiring small technology improvements. It has not considered the costs of transporting possible valuable material from the Moon to Earth. A cargo return mission would benefit most from lunar fuel.

This analysis which considered only the most favorable resource, namely lunar ice, showed that:

1. Lunar manufactured fuel used in the LOR mode of crew rotation does not appear to be cost effective unless a large number of crews are rotated.

2. Lunar manufactured fuel used in the direct flight mode may be desirable, and may warrant further consideration after other factors influencing the selection of this mode have been evaluated.

RECOMMENDATIONS

General recommendations for working group action next year are listed below:

1. Determine development and maintenance costs for a lunar fuel producing complex.

2. Investigate techniques for reducing power requirements for this complex.

3. Investigate the probable useful life of lunar based equipment.

4. Encourage programs designed to detect lunar resources.

DEVELOPMENT COSTS AS THEY AFFECT BREAK EVEN POINT

2 Man Rotation Cycle LOR Mode

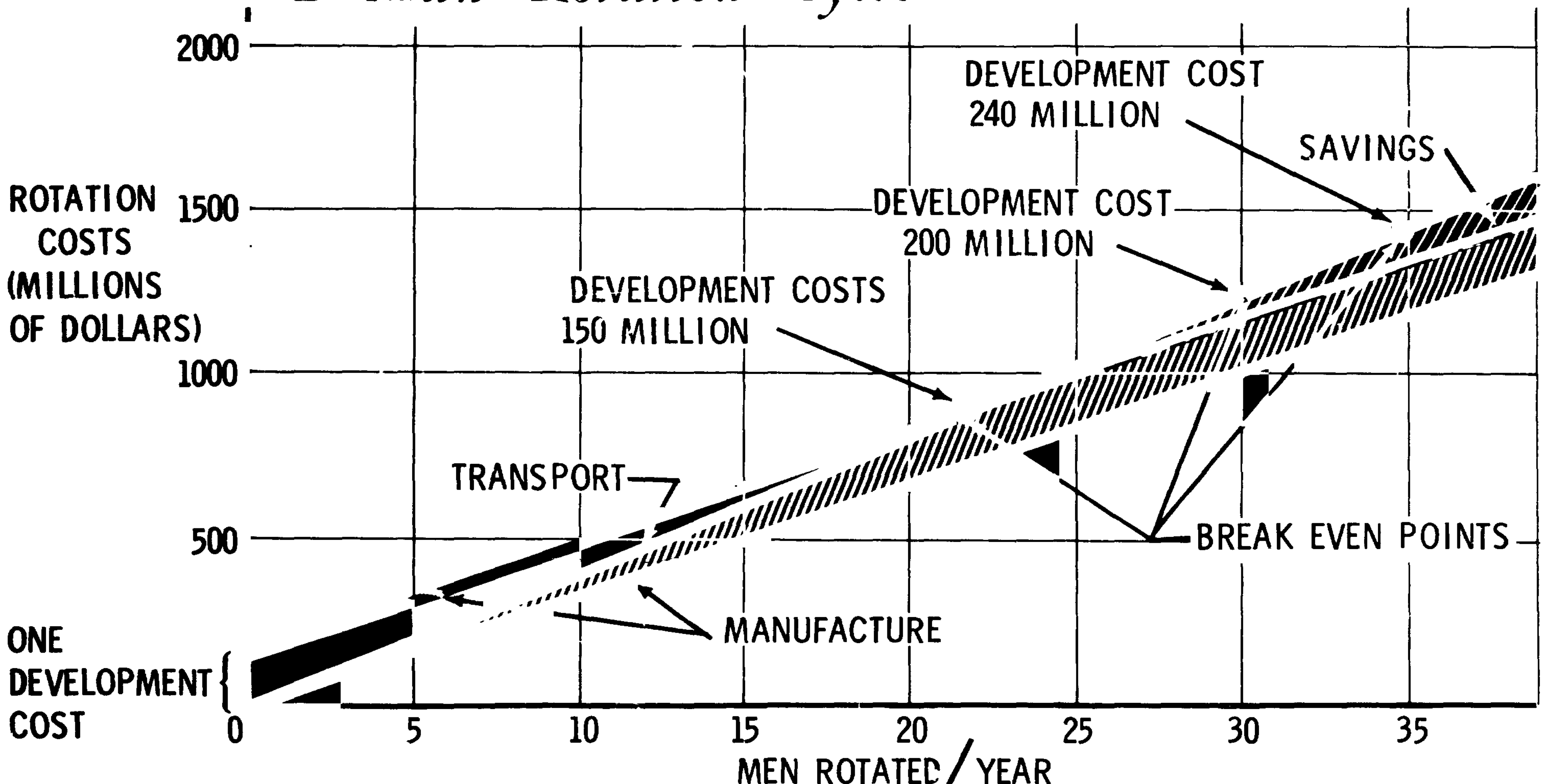


FIG 7

FIXED COSTS AS THEY AFFECT LUNAR FUELING COSTS

2 Man Rotation Cycle

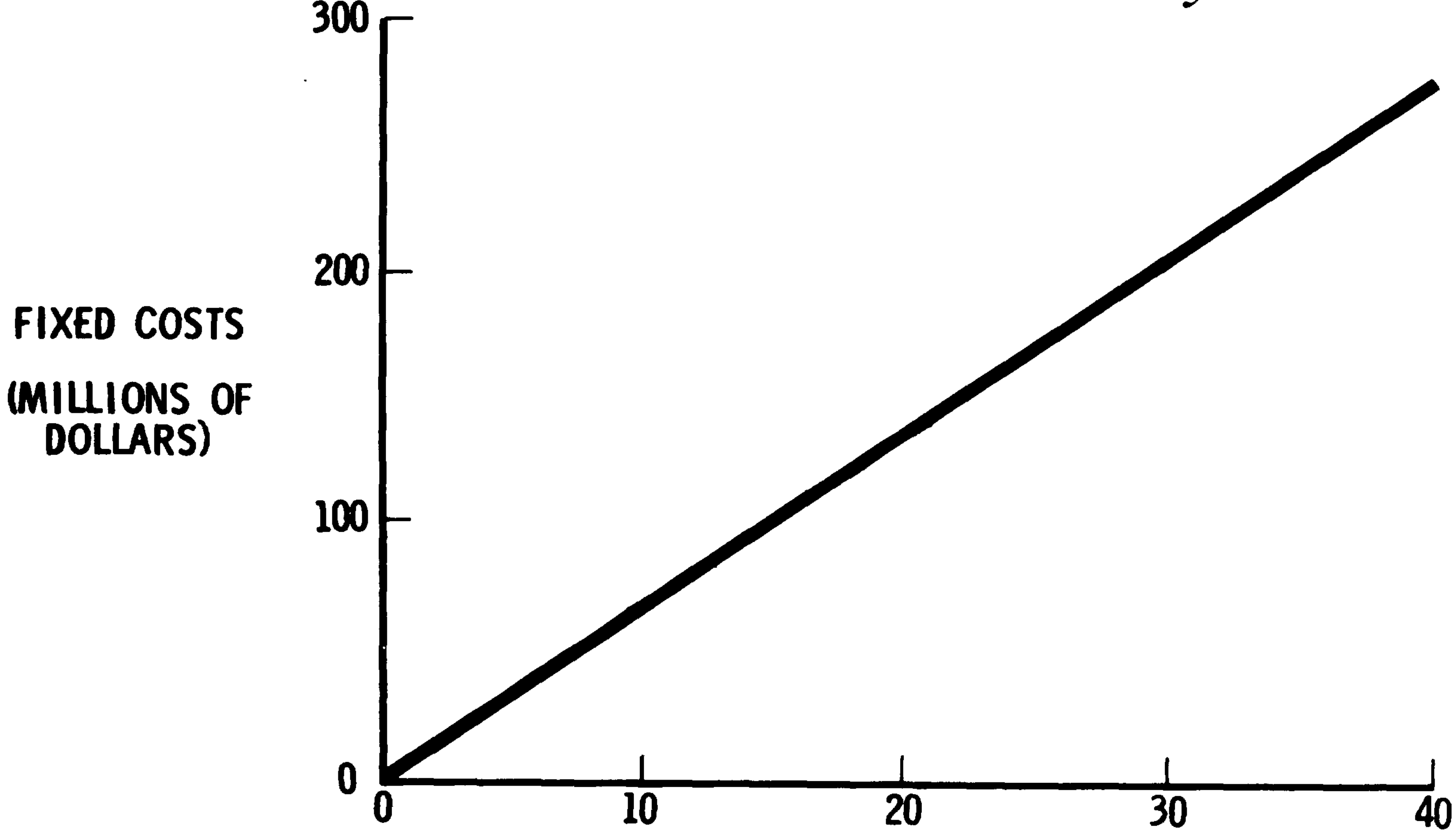


FIG 8

COST FOR CREW ROTATION

Direct Flight Mode

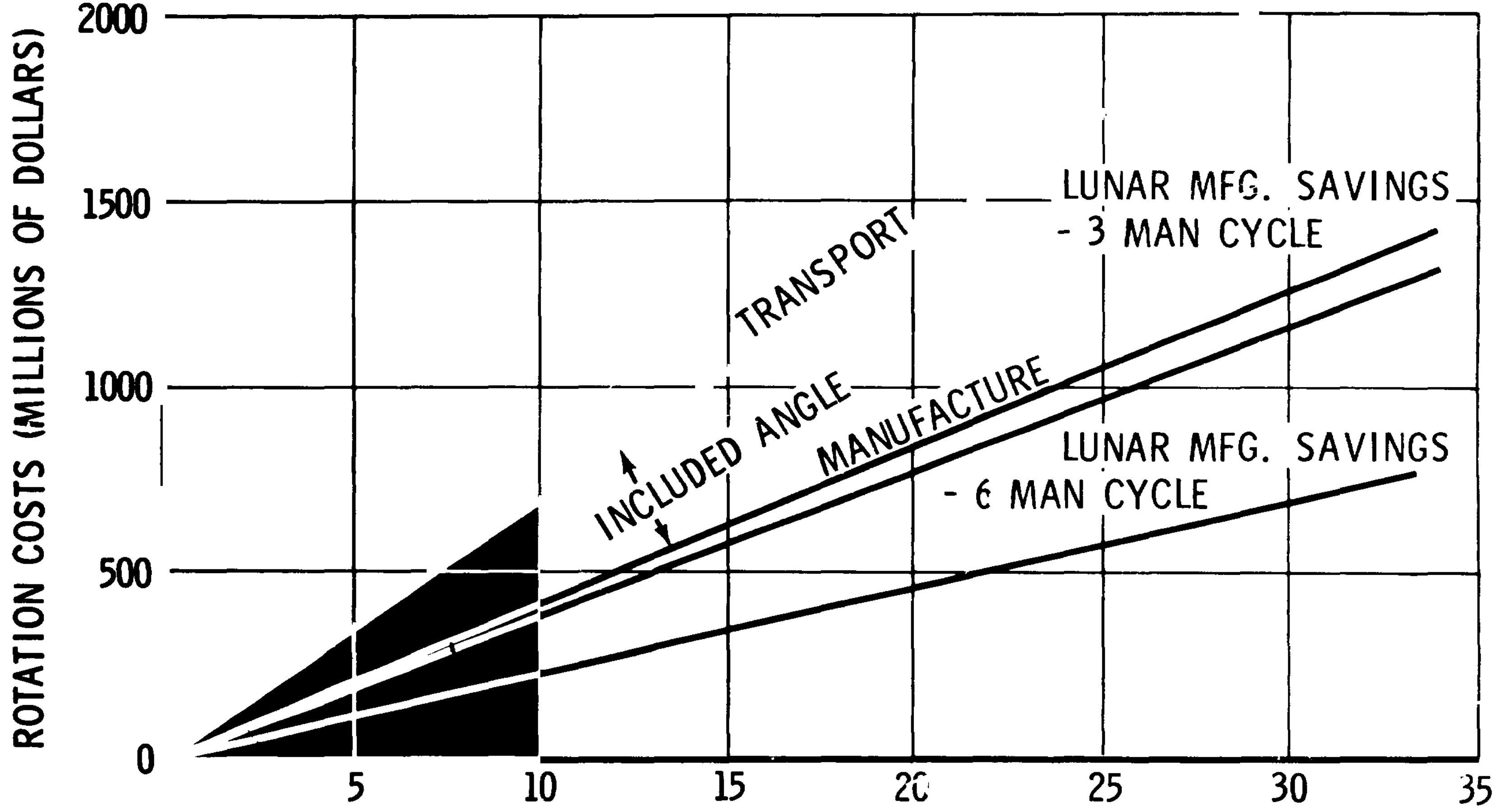


FIG 9

The last recommendation is felt to have the highest priority because, unless we know the location and physical properties of a particular lunar resource, equipment to process this resource cannot be realistically considered. A number of programs have been proposed to detect possible lunar materials at an early date. One such program called Early Lunar Flare (ELF), has as its objective the ignition of a high temperature flare on the lunar surface and the recording of its resulting emission spectrum with remote sensors. It is suggested that this "ground truth" experiment be closely coupled with a gross exploration program to detect lunar resources (in particular, water). Since lunar orbiters, both manned and unmanned, seem to fill this bill, it is recommended that orbital reconnaissance be encouraged. These orbiters, when instrumented with appropriate remote sensors, offer the possibility of early detection of areas where lunar resources may exist.

The author wishes to thank the following Boeing individuals for their help in preparing this paper:

Mr. F. C. Meer	Lunar Facility Analysis
Mr. T. A. Boehme	Weight Analysis
Dr. T. R. Beck	Lightweight Electrolysis Analysis
Mr. D. S. McKellar	Flight Mechanics

The author also wishes to thank two other committee members, Dr. Gordon Hammer of the Rand Corporation, and Major R. W. Pipher of AFSSD for their help in perhaps the most difficult part of this study, defining the problem.

Reference 1: Cole, D. M.
Rocket Propellants from the Moon
Astronautics & Aeronautics
October 1964

Reference 2: Segal, H. M.
Time Phasing of Lunar Events
Second Annual Meeting of the Working Group on Extraterrestrial Resources, Holloman Air Force Base, Alamogordo, N.M., October 22, 1963.

Reference 3: Paul, D.
A Methodology for an Economic Analysis of Transport and Manufacture Strategies for Resupply of Lunar Base Resources.
Third Annual Meeting of the Working Group on Extraterrestrial Resources, Cape Kennedy, Florida. November 19, 1964.

Reference 4: Gorrell, R. D.
Space Transportation and Tanking Systems Utilizing Lunar Manufacture Propellant
Fourth Annual Meeting of the Working Group on Extraterrestrial Resources, Air Force Academy, Colorado, December 1, 1965.

Reference 5: Paul, D.
Economic Analysis of Extraterrestrial Propellant Manufactured in Support of Lunar Exploration
Fourth Annual Meeting of the Working Group on Extraterrestrial Resources, Air Force Academy, Colorado, December 1, 1965.

Mr. Chairman and Fellow Participants:

As an introduction to this session, particularly for the benefit of new participants it may be well to state the interest of Biotechnology in extraterrestrial environments, these interests comprise:

1. Utilization of indigenous materials and energy sources in producing life support elements.

2. Use of biological processes in exploiting extraterrestrial resources.

3. Use of man and other biological systems in exploiting extraterrestrial resources.

4. Support and protection of man in extraterrestrial environments - and better understanding of these environments.

Last year the Biotechnology session consisted primarily of a state-of-the-art summary in the more critical areas of life support technology.

This year we will examine more specifically some of the currently anticipated problems including:

Factors affecting costs, such as system weights, feasibility of manned operations in extraterrestrial environments.

In addition one paper will show the relation between studies of terrestrial problems and those involving extraterrestrial applications.

This latter subject is an example of the manner in which terrestrial applications development supports extraterrestrial developments. It follows for example, that findings in extraterrestrial nutrition management will benefit us in our everyday lives here on earth, which I believe, will become evident as our session progresses.

Our first speaker today is Dr. Walter Kuehnegger, Chief, Biomechanics, Northrop Space Laboratories, Hawthorne, California.

Dr. Kuehnegger received his advanced degree in Mechanical Engineering from the University of Graz, Austria and holds an Aeronautical Engineering Diploma from the British Institute of Engineering Technology. In addition to his work at Northrop, he is a consultant in the field of biomechanics.

Dr. Kuehnegger will report in this invited paper on his work in defining the Physical Capabilities and Logistic Support Requirements for Man on the Moon.

THE PHYSICAL CAPABILITIES AND LOGISTIC SUPPORT REQUIREMENTS FOR MAN ON THE MOON*

by Dr. Walter Kuehnegger**

*This work was conducted under Contract NAS 1-4449 entitled, "A Study of Man's Physical Capabilities on the Moon"
**Chief, Biomechanics, Northrop Space Laboratories, Hawthorne, California

Abstract

The planning of manned lunar surface mission requires prior knowledge of man's physical capabilities and logistic support requirements under these new environmental conditions. When man is sent on this mission, he is sent to do a job. As such, his physical capabilities, including the limits in the subgravity state of 1/6 g as well as the effects of his protective garment, must be known.

This paper describes the application of biomechanical principles in the determination of his physical capabilities and those of work physiology in the determination of his logistic support requirements. A combination of biomechanical and physiological data has been used to derive the efficiency and optimization of man in the performance of simulated lunar working tasks.

The data presented concerns itself primarily with self locomotion experiments.

It is shown how the data developed by this method can be applied as a part of the basic guideline in the preparation of manned lunar surface missions. As such, it will contribute to the safe and successful completion of the mission objective.

I. INTRODUCTION

Reviewing the kind of bases that to date have been used to design life support equipment, we find that we were sitting behind desks planning manned missions knowing really very little whether man will be able to do what we are planning for him or not. We assumed that what we know about him on earth is going to be somewhat similar in space and by that all our design requirements in general had been based on this questionable criterion. Of course, the terrestrial information so far sufficed as a good starting point but we have passed this phase now and are deeply engaged in investigating what man can really do. The session this morning is devoted to man and his role in extraterrestrial work. We are interested in the retrieval of samples of extraterrestrial resources. We expect man to dig up these samples and to bring them back. Taking a critical look at this assignment we find that we know very little. So, today, I will describe to you the work conducted under a NASA contract awarded by the Langley Research Center. The description of this work this morning will only encompass the first portion of the contract and that is the baseline data of man. First, we examine what he can do on earth. Then under simulation of lunar gravity we observe what he can do in a similar shirtsleeve environment. The second portion of this contract concerning the pressure suited activities is currently under investigation, the results of which will be reported to NASA in about two month's time.

II. THE LUNAR GRAVITY SIMULATOR (LGS)

The simulation technique introduced by Hewes and Spady (3) was used in the fabrication of the LGS. The principle of this technique is illustrated in Figure 1 where the subject is suspended on his side at an angle of 9°-36' through his center of gravity. The 1 G gravity vector produces a corresponding 1/6 G vector towards the subject's walkway in this position.

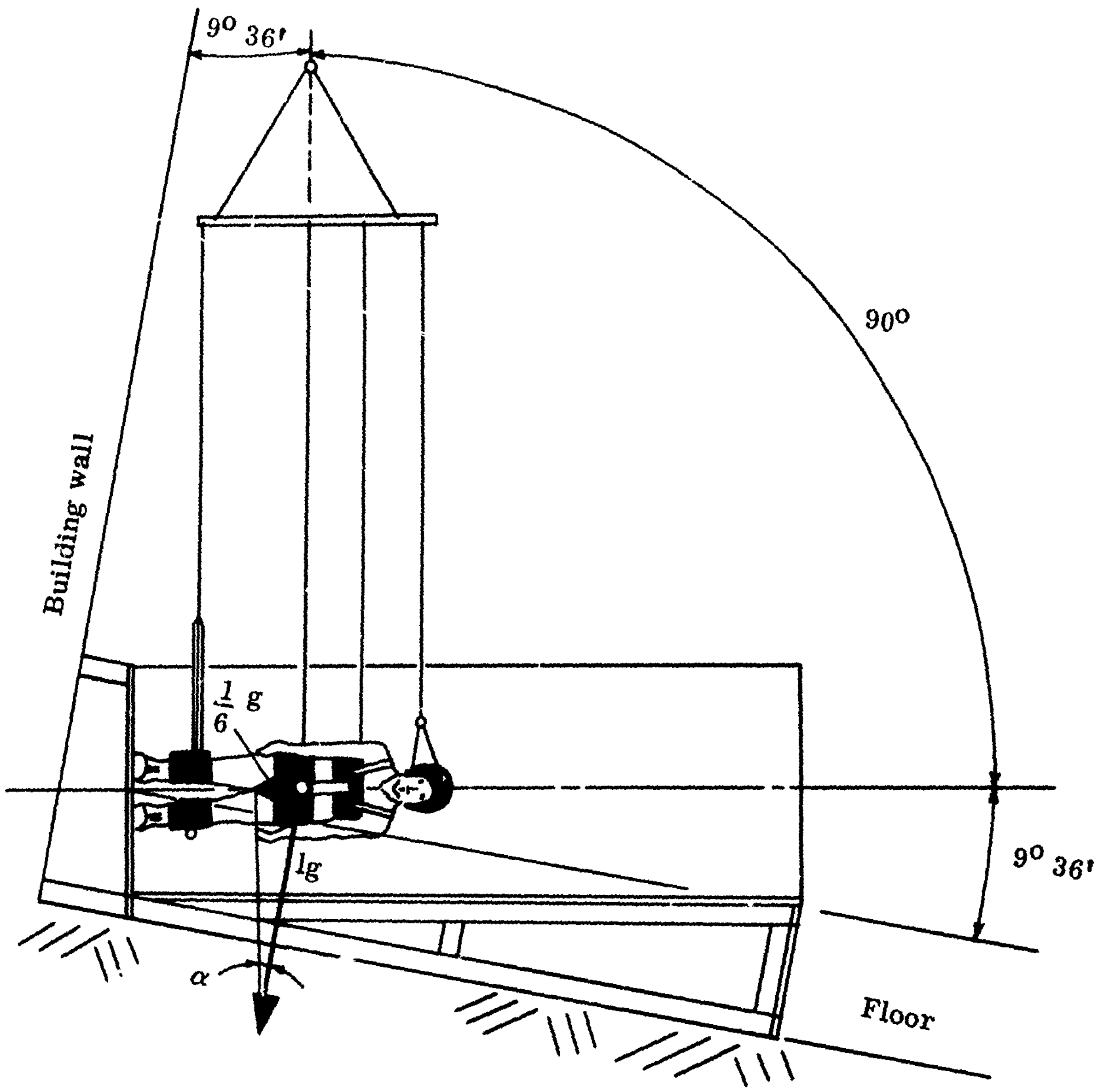


Figure 1

Lunar Gravity Simulation Technique

The subject thus experiences a 1/6 G (lunar gravity) in the maintenance of his body posture. The body is suspended on its side and supported by the helmet, a chest support, a hip support, and two leg supports shown in Figure 2.

Figure 2

Subject Suspension

Each of these body segment suspension cables terminate in a spreader bar (Figure 1) which is suspended by a single cable from a dolly. The dolly is pulled by the subject and travels along a track parallel to the walkway. This can be seen in Figure 3 which shows an overall view of the LGS.

As the subject jumps further out from the walkway along the cable radius the gravity vector becomes larger and a correspondingly required correction had to be incorporated for the prediction of lunar performance data.

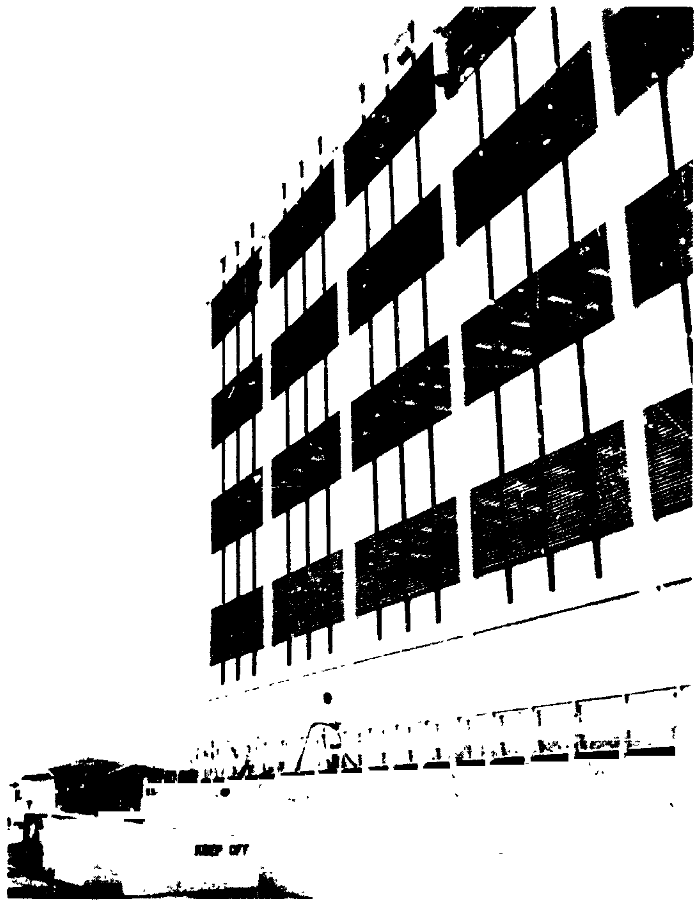


Figure 3

The Lunar Gravity Simulation Facility

The present walkway length is 100 feet enabling the subject to locomote back and forth in three degrees of freedom. The total suspension cable length is 66.4 feet. A gridded backdrop in two test areas is used for the biomechanics data analysis. A 1/6 G treadmill was fabricated and installed for the determination of physiological data. The test control center is located near the end of the walkway and houses physiological monitoring and recording equipment as well as environmental equipment and controls. The subject carries a suspended instrument pack (Figure 4) which holds the biomedical junction box and a respirometer.

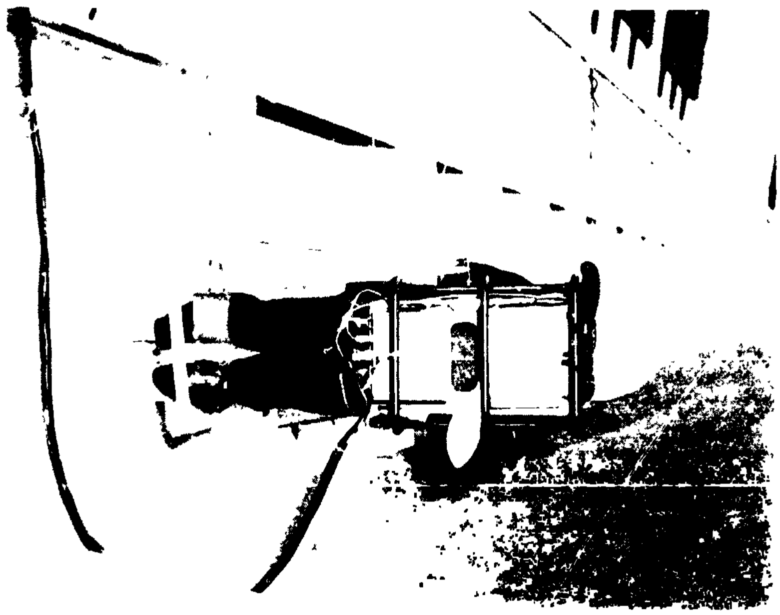


Figure 4

Instrument Pack I

From here a suspended umbilical line held by the escort on the catwalk leads to the test control center. The umbilical contains communications, physiological data lines and a high pressure line for pressure-suited operations. The experiments conducted by the subject are directed and completely controlled by the test director within the control center.

III. APPROACHES

A. The Biomechanical Analysis of Body Motion

This was performed in the sequential steps outlined in References 4-6.

(1) Subject data

(2) Data recording

(3) Data analysis

(1) Subject data - The biomechanical data of the subject refers mainly to his physical properties. It consists of the anthropometry of the test subject which is broken down into body segments according to Figure 5.

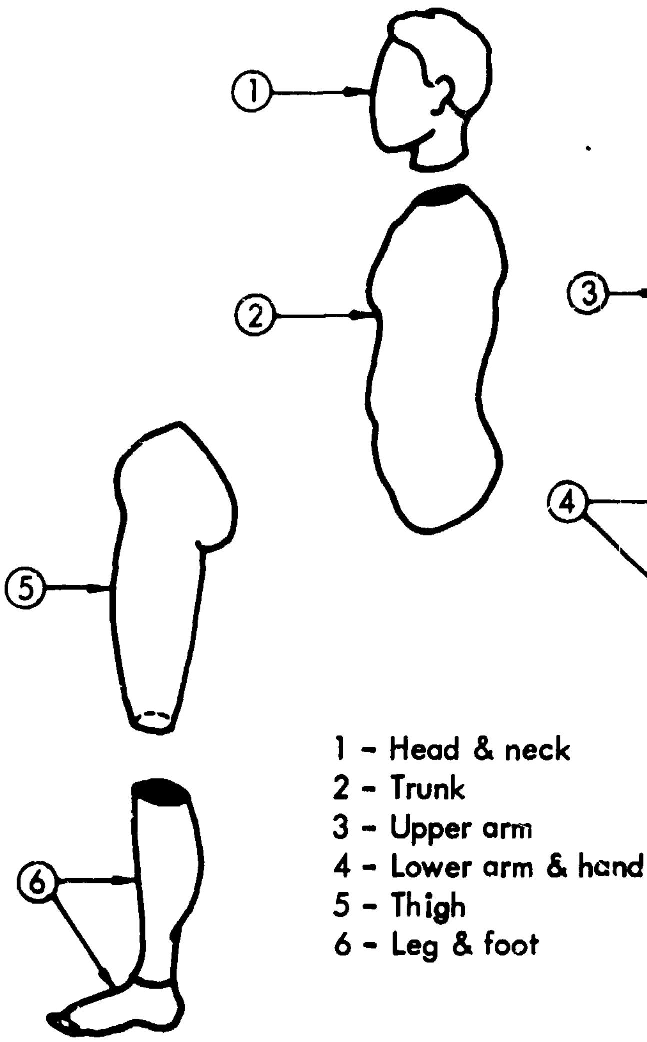


Figure 5

Body Segments

The following parameters of each body segment were measured and computed: the body segment dimension, the density and mass, and the mass moment of inertia. The body segment masses were determined by water immersions as used by Contini, Drillis[1], Dempster[2], et al, while the body density was found and verified by skin fold measurements. Having established the segment mass centers by the differential weighing technique and the joint centers from the corresponding anatomical landmarks, they were transferred onto the subject's suit as shown in Figure 6. The properties of the trunk were found by subtraction of those for the segments from the total body allowing for 1400 ml of residual volume remaining in the lungs.

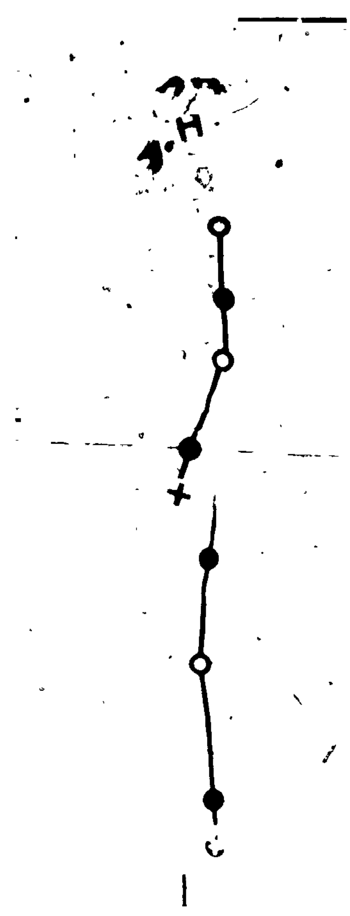


Figure 6

Body Segment Target Locations

The subject was then ready for biomechanics data recording.

(2) <u>Data recording</u> - A biomechanical data recording camera based on the interrupted light method was developed (reference Contini and Drillis[1]). This camera was mounted over the LGS center test section. A detailed view of the camera is shown in the following Figure 7.

Figure 7

Biomechanics Data Camera

After an extensive development and testing period, the quality of biomechanics data shown in Figures 8 and 9 was produced.

Figure 8

Walking

Figure 9

Jumping

The grid system shown in Figure 9 is made up from 2,450 different squares to correct for camera parallax and subject swing-out. This correction produced a 10 x 10 centimeter grid system through the median saggital plane of the subject permitting direct data analysis.

(3) Data analysis - The principles of applied mechanics are used in the analysis of body motion. The analysis is performed by recording the x, z and θ values as a function of time of the data within one motion cycle of the subject. An illustration of this is shown in Figure 10.

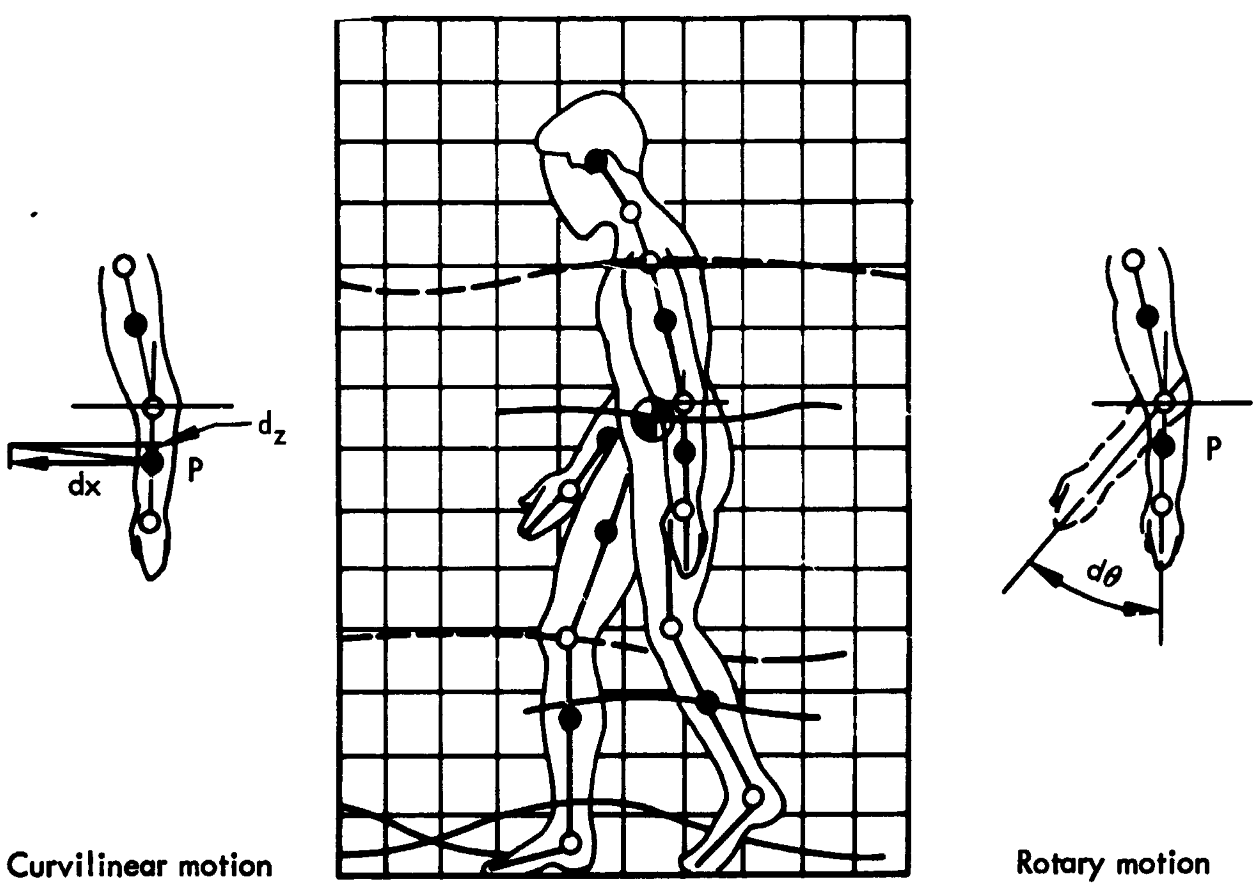


Figure 10

Body Segment Analysis

The velocity and acceleration of each body segment in the curvilinear motion path through x, z were then computed. The rotary motion through angle θ of each segment also provided the angular velocity and acceleration. By computer curve fitting, it was then possible to establish the equation of locomotion of the subject. When the velocities and accelerations are combined with the segment masses, their respective forces and power were determined. Integrating the power as a function of time yielded the external energy expenditure for each body segment for one locomotion cycle. Adding all the expenditures for the body segments together produced the total external energy expenditure of the subject during one cycle. This is then a biomechanical measure of the energy expended in the external body motion.

B. The Work Physiological Analysis of Body Motion

This analysis was based on the following sequence:

(1) Subject selection

(2) Baseline data

(3) Test data

(1) Subject selection -

a. Subject requirements

The number of subjects, their age and anthropometry depended upon their availability and customer requirements.

b. Physical fitness

After compliance with the requirements and an FAA Flight Physical Class II, the subjects were exposed to a Physical Fitness Index Test (PFI) on the 1 G treadmill according to Balke (1960). The test arrangement is shown by Figure 11.

This PFI was not only performed during the subject selection, but also at near constant intervals during the test period to detect any possible conditioning of the subject. No increase in PFI can be reported under the present rate and level of testing.

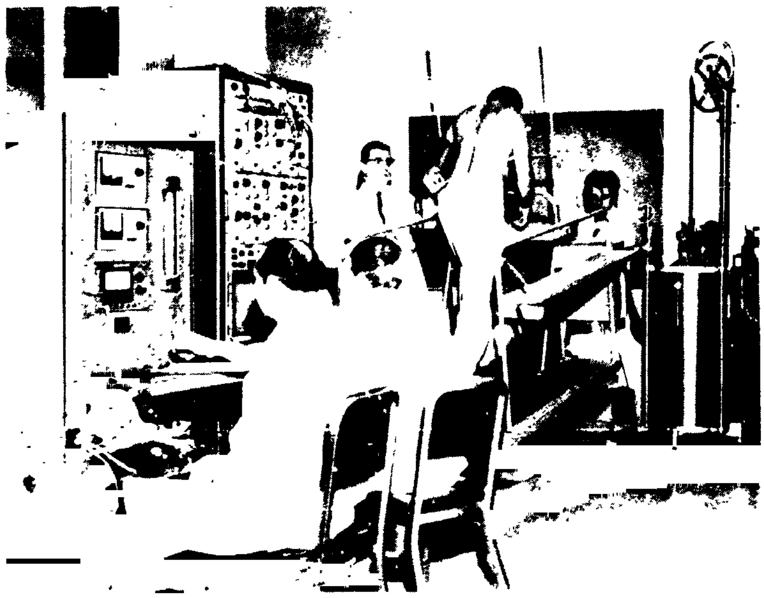


Figure 11

Test Arrangement for PFI Determination

(2) Baseline data - The basal metabolic rate of the subject at complete muscular and mental rest was taken first. The subject then underwent a series of 1 G baseline experiments on a treadmill as in Figure 12.

(3) Test data - The acquisition of test data was carried out in the manner already described under the LGS. The physiological parameters monitored and recorded during each test were:

- Respiratory rate and volume
- Cardiac rate
- Mean body temperature

The respiratory volume and its regular sample were used to determine the metabolic rate of the subject by indirect calorimetry, resulting in the measurement of the physiological energy expenditure of the test subject during a given time interval. It should be noted that the resulting metabolic rate was for the specific time interval of the test only. This metabolic rate did not include the effect of duration and fatigue when such experiments are conducted for prolonged periods of time.

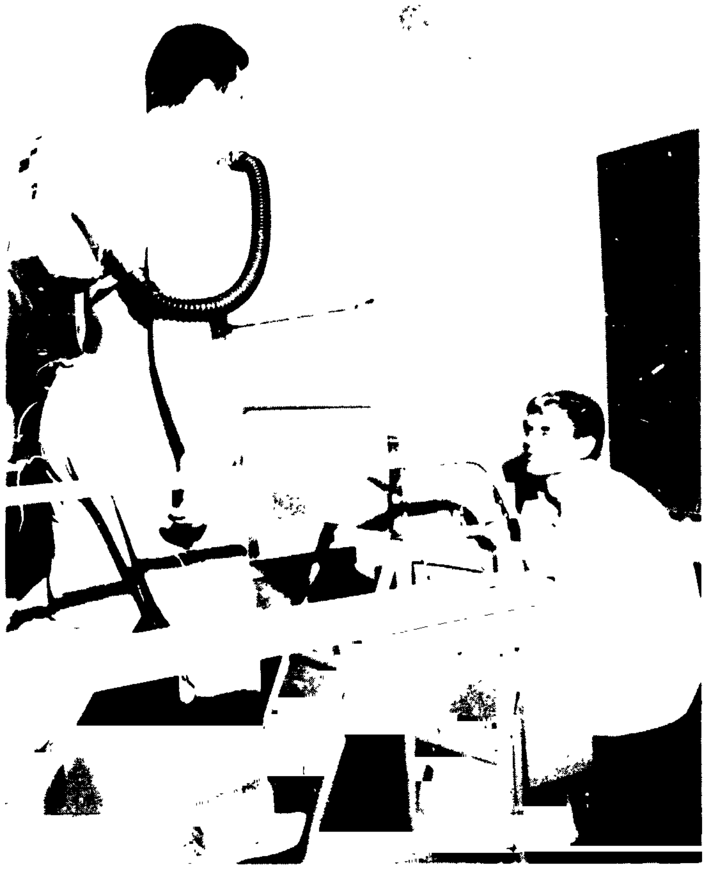


Figure 12

1 G Baseline Experiments

IV. LUNAR GRAVITY SIMULATION DATA

The data derived from this study provides answers to a number of pressing problems in several areas.

A. Information concerning different methods of self locomotion as walking, running, loping and jumping had to be obtained. Investigations were made to determine whether these methods were even physically possible.

B. Once the possibility had been established the next objective was to investigate the differences between the self locomotion of man under simulated lunar gravity and under earth gravity.

Pertinent biomechanical and work physiological data was obtained during the testing program and combined to produce the following important information for the logistic support requirements of man.

C. The total metabolic cost in BTU/h of different methods of self locomotion was determined, this being an important governing factor in the design of environmental control systems not only in their capacity but also in their flow rates.

D. Directly related to the metabolic cost of these experiments is the oxygen consumption and carbon dioxide production which also affects the logistic support of man.

E. Comparing the biomechanical energy expenditure of man in the displacement of his body segments and his load per locomotion cycle to that of the total metabolic cost has given insight into his mechanical efficiency of locomotion.

F. These results were developed further to construct a so-called locomotion envelope to indicate the metabolic cost of different methods and velocities of locomotion per unit length traversed. A typical example of a shirtsleeve locomotion envelope for one test subject is shown in Figure 13. It can be seen that this envelope in addition reveals the optimal locomotion speeds and where the subject should change from one type of locomotion to another as well as the complete spectrum of his physical performance ability.

V. SUMMARY

The described approaches can further be utilized to establish the quantitative trade-offs between the efficiency of man and that of a machine, or at what points it will become necessary and more economical from a logistics point of view to introduce some assistive devices. The energy expenditures of the locomotion envelope represent the logistic support requirements of man in terms of oxygen consumed, carbon dioxide and heat produced. These values can then be used to compute the logistic support required for the locomotion of man on the moon.

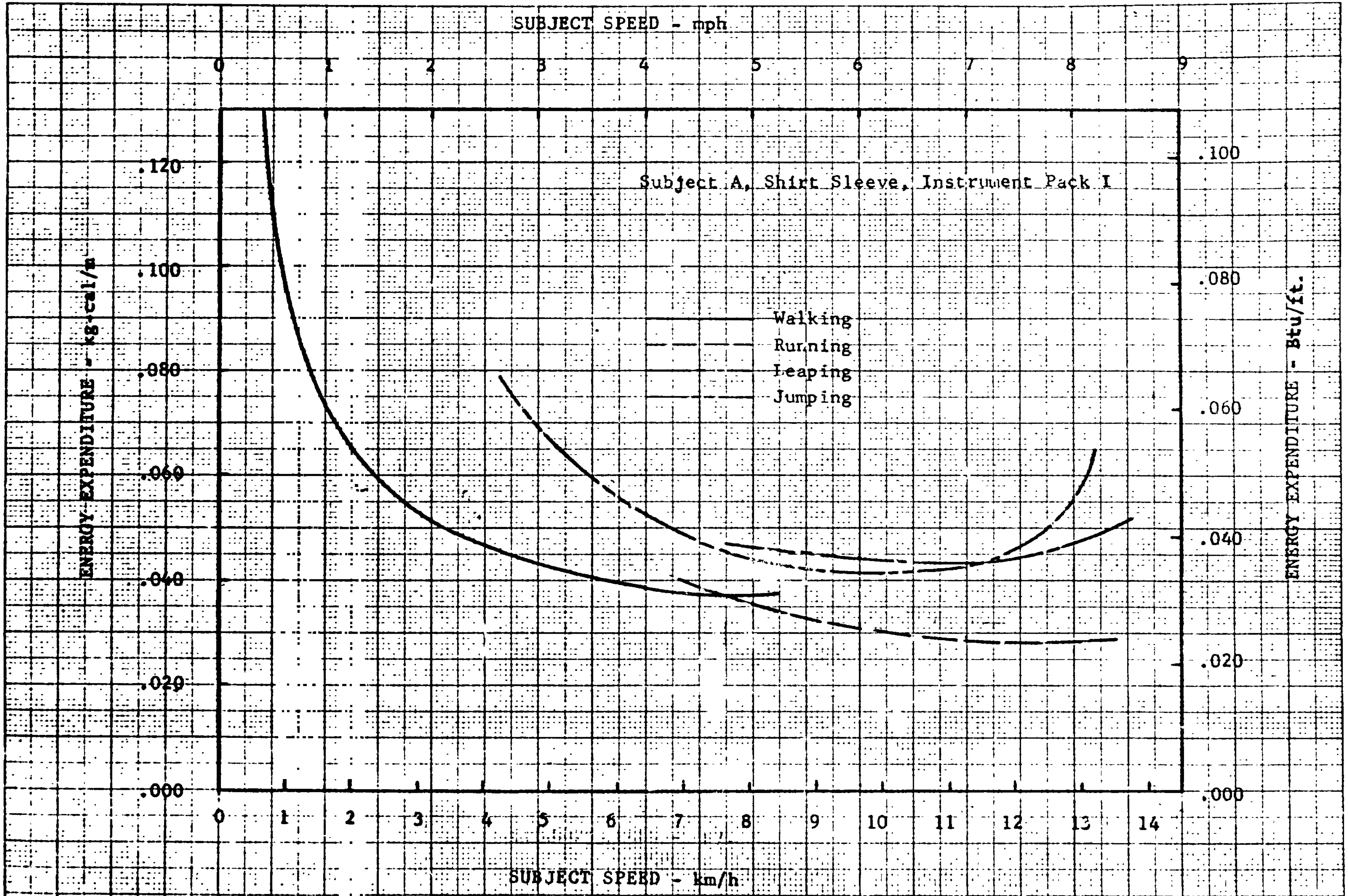


Figure 13 - LOCOMOTION ENVELOPE OF MAN

VI. REFERENCES

1 Contini, R.; Drillis, R.; and Slote, L.: Development of Techniques for the Evaluation of High Altitude Pressure Suits, WADC Technical Report 58-641, 1959

2 Dempster, W.T.: Space Requirements of the Seated Operator, WADC Technical Report 55-159, 1955

3 Hewes, D.E. and Spady, A.A.: Evaluation of a Gravity-Simulation Technique for Studies of Man's Self-Locomotion in Lunar Environment, NASA Technical Note TN D-2176, 1964

4 Kuehnegger, W.: The Work Potential of Man - Elemental Approach and Guide to Research, Northrop Space Laboratories Report NSL 63-256, 1963

5 Kuehnegger, W.: Biomechanical Elements in the Analysis of the Lunar Working Potential of Man, San Diego Symposium for Biomedical Engineering, 1964

6 Kuehnegger, W.: The Ergogram - A Tool for Detail Analysis of Physical Human Performance, Northrop Space Laboratories Technical Report NSL 65-43, 1965

Next we will hear a report on the Cost of Life Support in Manned Lunar Bases presented by Mr. W. L. Burris, who is currently Project Engineer for Special Projects at the AiResearch Manufacturing Company in Los Angeles, California.

Mr. Burriss has his Bachelor's degree in Chemistry, his Masters degree in Chemical Engineering, and a Chemical Engineer's Degree from the California Institute of Technology. He was program manager for the Lunar Exploration Systems for Apollo (LESA) Human Factors and Environmental Control Study which was recently completed, and which led in large part the findings reported in this paper.

Figure Titles for Paper by W. L. Burriss

ABSTRACT

This paper concerns the comparative costs for life support in relatively large lunar bases provided with crews ranging from 3 to 18 men. Early lunar bases will have relatively high expendable usage rates and consequently will be limited to mission durations of less than approximately 3 months (without logistic resupply). The ultimate lunar base, to be achieved by evolution through progressively more sophisticated systems, will incorporate extensive provisions for the reclamation of useful materials from human wastes. The life support system concept described is based upon use of modules to permit growth in mission capability by modular addition of life support equipment and supplies to the systems used in earlier missions. Consideration is given to the operational costs associated with base monitoring, housekeeping, and system support activities to determine the resources available for the performance of the scientific mission tasks.

ACKNOWLEDGEMENT

This paper is based upon work performed by AiResearch under Contract NAS8-11447, "Study of Human Factors and Environmental Control-Life Support Systems for Lunar Exploration Systems for Apollo." The program was monitored by the NASA George C. Marshall Space Flight Center, Huntsville, Alabama. At NASA the monitors were M. J. Vaccaro, Contract Technical Supervisor, and D. Paul of the Future Projects Office.

N66 35520

THE COST OF LIFE SUPPORT IN MANNED LUNAR BASES

W. L. Burriss

INTRODUCTION

The first lunar landings will be accomplished in the Apollo Program with relatively limited resources available in crew staytime and equipment for scientific experimentation and surface exploration. The two-man crews will have a few hours available on the lunar surface. The exploration range will be limited to that accessible by walking in the Apollo extravehicular mobility unit. It can be anticipated that increased lunar surface operational capability will be desired soon after the initial Apollo landings.

Evidently, the most important mission parameter to be extended involves crew staytime. However, the increased mission staytime must be accompanied by a concomitant increase in scientific capability if the increased mission times are to be scientifically meaningful. Lunar surface mobility may be equivalent in importance to staytime, since surface transportation will be essential to provide the data acquisition capability for the surface exploration and geophysical investigations, presently emphasized for early lunar missions.

Manned vs Unmanned Systems

Man's versatility and flexibility in performing functions such as experiment deployment and manipulation, observation and data evaluation, system support and troubleshooting, etc., make man's presence highly desirable in advanced space exploration missions. Unmanned systems, in general, will be relatively simple and inexpensive, but are characteristically less flexible and reliable. In complex missions of the type under consideration here, man may be essential to mission success in providing backup operating modes and alternate procedures. For example, in manned research vehicle programs, such as the X-15, presence of the pilot has been essential to successful recovery of the vehicle after encountering unexpected conditions or major subsystem malfunctions during flight. A vehicle system incorporating human requirement has implications, however, upon the design of all of the vehicle subsystems, in the formulation of missions, and in the establishment of the vehicle configuration. Man provides a high degree of versatility in performing many functions, but imposes a number of requirements and limitations that must be observed for both his survival and his proper functioning. That is, man must be provided with an environment and with the various materials needed to meet his physiological and psychological requirements. Consequently, in particular programs it will be necessary to evaluate man's capabilities relative to the costs for his transportation, maintenance, and recovery.

Because of the high value attached to human life, manned systems are required to provide high reliabilities with respect to crew safety. The safety precautions, reflected in mission abort provisions, crew training, operating procedures, air and sea task forces for personnel recovery, etc., result in increases in program cost considerably in excess of those represented by the flight hardware required for life support. For example, it has been estimated that an overall increase in program cost of $20,000 per mission-hour will be obtained as compared with the cost of an equivalent unmanned vehicle for a 30-day earth orbital mission (Reference 1).

The relative advantage of manned lunar exploration, as opposed to unmanned probes, will depend to some extent upon the nature of the experiments. A large amount of data can be transmitted by an instrument package over a long period of time. An experiment of this type will be relatively inflexible, however, in varying the range of experimental parameters. It can be concluded that both manned and unmanned systems will be essential to the optimum exploitation of the lunar resources.

Missions

Evaluation of the relative scientific worth of various possible experiments and determination of mission priorities are obviously complex problems. It can be concluded that the early lunar missions will be primarily concerned with exploration of the lunar surface and will require use of mobility devices and a number of base sites to provide the desired surface coverage. Thus, the emphasis in the early missions will be on a number of small bases at various locations on the lunar surface that would be occupied for relatively short durations. The scientific capability required for the advanced lunar missions would emphasize fixed-site operations and extended-duration occupancy by relatively large crews. These requirements are consistent with the evolutionary base concept, where advance mission capability is obtained by stepwise progression by incremental addition of equipment modules and logistic vehicle payloads.

This paper is based upon a study (Reference 2) of human factors and environmental control/life support systems for an evolutionary lunar base concept leading to an ultimate 18-man base complex to be continuously occupied for periods in excess of two years. The spectrum of lunar missions was analyzed in terms of the following lunar base models (Reference 3):

Base Model	Duration	Crew
1	3 months	3
2	6 months	6
3	12 months	12
4	+24 months	18

In the discussion following, consideration will be given to the direct costs for life support on the lunar surface.

LIFE SUPPORT REQUIREMENTS

In assessing the cost of maintaining man in the lunar environment, it is first necessary to determine the nature of the systems required for life support. These systems provide the environment and materials needed for sustenance of life.

The special provisions required for life support can be divided into two categories:

- Fixed Equipment: pressure shell structure, furnishings, pressure suits, fixed and portable life support systems, etc.
- Consumables: food, oxygen, water, life support system expendables.

The weight of the fixed equipment is to some extent dependent upon the mission duration, since the waste processing provisions to be used will be determined by the design mission length and the power system. The weight of the consumables will depend strongly upon mission duration and crew size. In the discussion below, the life support requirements will be considered in terms first, of the shelter and, secondly, of support systems used to provide a suitable environment and the necessary materials.

Shelter Design

The design of the shelter required to house the crew depends upon crew size, duration of occupancy, tasks to be performed inside the shelter, and the launch vehicle payload weight and size constraints. A small shelter, based upon either direct utilization of the Apollo Lunar Excursion Module (LEM) without ascent propulsion (LEM Shelter) or use of the LEM descent stage with a new crew compartment (LEM Truck Shelter) could be used to provide early capability for extended lunar surface stay times on the order of 14 days (Reference 4). The present discussion will be primarily concerned with the shelters to be used in the large lunar bases which can be occupied for essentially indefinite periods. Consideration will be given to the material requirements for life support which may be logistically supplied or obtained by utilization of lunar surface resources.

Figure 1 shows the general characteristics of a shelter module designed for the Saturn V Lunar Logistic Vehicle payload (Reference 5). This shelter design consists of a vertical cylinder living compartment surrounded by a toroidal laboratory compartment with an air lock providing external egress. The first contemplated use of lunar resources involves placing lunar fill in a caisson deployed from the shelter to provide radiation and meteoroid protection. Figure 2 depicts the internal arrangement which has been shown to provide adequate accommodations for a 6-man crew for extended periods (Reference 2). Study of alternate arrangements indicates that no significant reduction in shelter size could be obtained without compromising some of the operational features, such as crew size. For example, it has been determined that a 2-man crew could be housed in a 10-ft-diameter shelter that could be landed on the lunar surface by the LEM Truck (Reference 4).

	GROSS VOL CU FT	FLOOR AREA CU FT
LIVING COMPARTMENT	1421	113
LABORATORY COMPARTMENT	1875	161
AIR LOCK	148	14

LUNAR BASE CONCEPT	CREW	MISSION DURATION	NO. OF SHELTERS
NO. 1	3	3 MONTHS	1
NO. 2	6	6 MONTHS	1
NO. 3	12	1 YEAR	2
NO. 4	18	2 YEARS	3

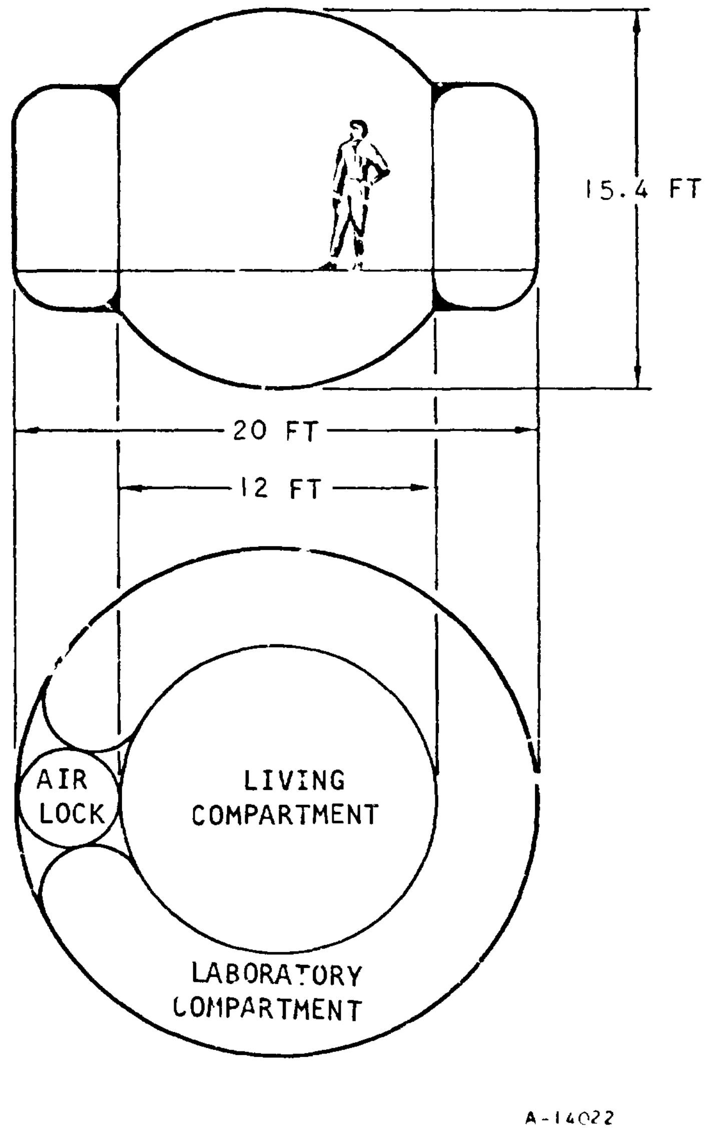


Fig. 1

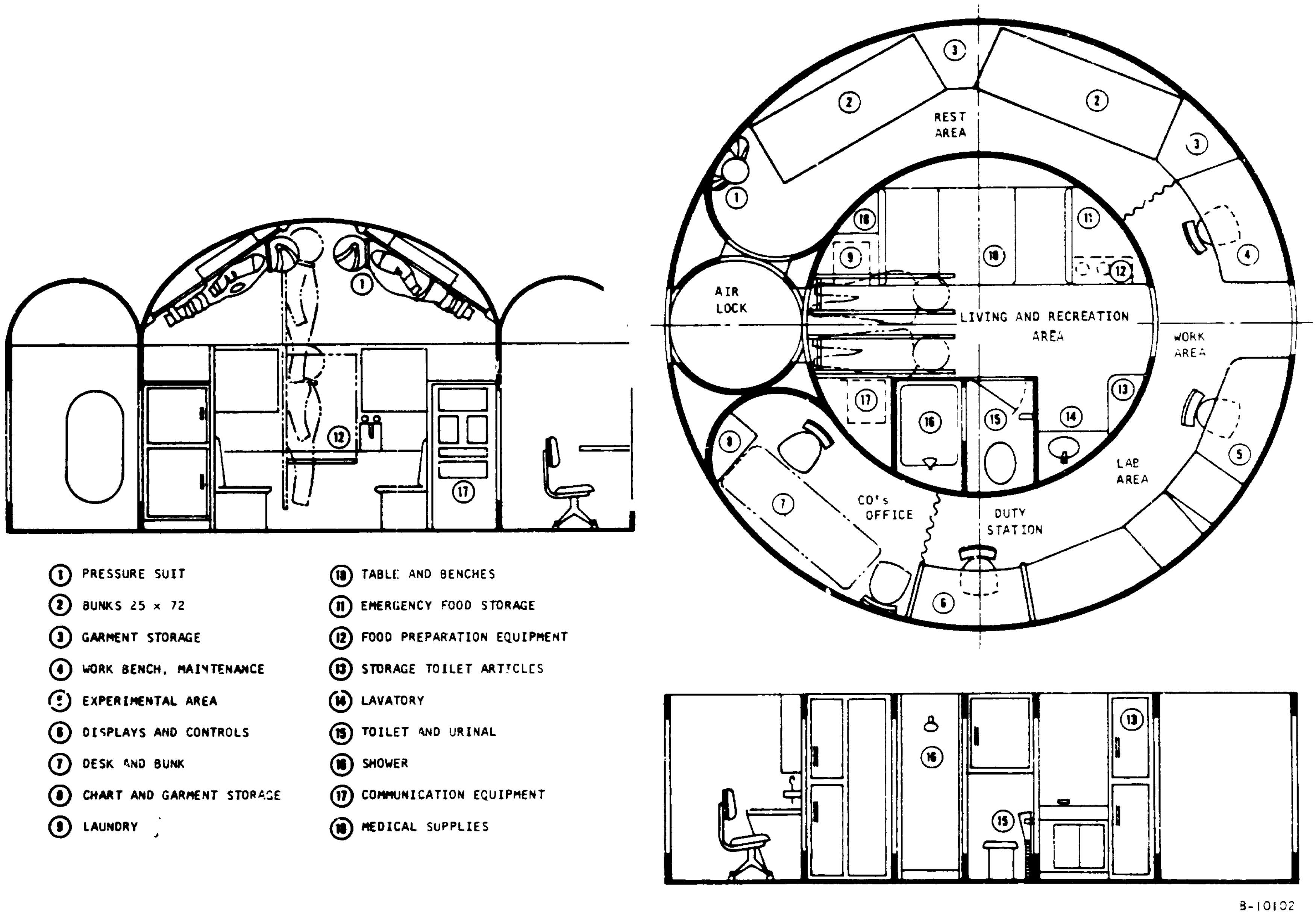

REST AREA
AIR LOCK
LIVING AND RECREATION AREA
WORK AREA
LAB AREA
DUTY STATION
CO's OFFICE
1 PRESSURE SUIT
2 BUNKS 25 x 72
3 GARMENT STORAGE
4 WORK BENCH, MAINTENANCE
5 EXPERIMENTAL AREA
6 DISPLAYS AND CONTROLS
7 DESK AND BUNK
8 CHART AND GARMENT STORAGE
9 LAUNDRY
10 TABLE AND BENCHES
11 EMERGENCY FOOD STORAGE
12 FOOD PREPARATION EQUIPMENT
13 STORAGE TOILET ARTICLES
14 LAVATORY
15 TOILET AND URINAL
16 SHOWER
17 COMMUNICATION EQUIPMENT
18 MEDICAL SUPPLIES
B-10102

Fig. 2

In the larger bases, which involve the use of more than one shelter to house crews larger than six, there may be incentive for shelter specialization. For example, in a 2-shelter base, it may be preferable to use one shelter for housing the 12-man crew and the other shelter for operations. It will be assumed here that the shelter modules are self-contained with respect to essential life support functions.

Life Support Functions

The principal functions of the systems installed in the shelter for life support can be classified into one of three groups, as follows:

- Thermal Control Functions
  - Temperature control
  - Heat transport
  - Heat rejection
- Atmospheric Control Functions
  - Composition control
  - Pressure regulation
  - Contaminant removal
- Life Support Functions
  - Food supply
  - Water supply
  - Waste management
  - Personal hygiene
  - Clothing management

Some of these functions can be accomplished in a variety of ways, with the optimum selection for a particular application dependent upon factors such as mission duration, availability of electrical power and thermal energy, system delivery requirements, availability of logistic resupply, etc. In general, the most important tradeoffs in process selection are between the open-cycle systems and those providing material reclamation. From examination of a material balance for man's life support requirements, it can be seen that the first priority will be associated with water management, because of the relatively large material requirements for drinking, food preparation, personal hygiene, and cooling.

The carbon dioxide removal and oxygen supply functions also involve important tradeoffs between expendable and material recovery systems. Closing the food cycle appears to be in the far distant future, however, and has not been considered in this study for application to the lunar bases.

Table I lists some of the principal tradeoffs obtained in process selection between open and closed-cycle systems:

TABLE I

LIFE SUPPORT SYSTEM PROCESS SELECTION TRADEOFFS

	Open Cycle	Closed Cycle
Water Supply	Byproduct of power generation from fuel cell	Water reclamation by air-evaporation distillation
CO_2 Removal	Dump CO_2 overboard	Process CO_2 in Bosch reaction for O_2 recovery
O_2 Supply	Subcritical cryogenic storage	Water electrolysis

As shown in Figure 3, power system selection will have a number of significant implications upon the design of other shelter systems. It can be concluded that both power system selection and life support system process selection will show an interrelated dependence on design mission duration. That is, long-duration missions are consistent with use of nuclear power systems and life support processes providing material conservation. It has been assumed that the early lunar bases (Models I and 2) will use solar cell/fuel cell power systems and that the advanced lunar bases (Models 3 and 4) will use nuclear power systems.

MATERIAL REQUIREMENTS

Food, water, and oxygen are the primary materials required to sustain life. Whether these materials are obtained from stored supplies or from reclamation of wastes, a substantial part of the life-support system weight will be chargeable to their supply. The material consumption rates will vary with metabolic energy expenditure rates, which in turn depend, to a considerable extent, upon crew activity level and the task schedule. Table 2 shows the material balance for man in terms of the material requirements and waste production rates as a function of average metabolic rate.

	Fuel Cell	Fuel Cell - Solar Cell	Radioisotope	Battery	Nuclear
Water management	**Water in excess of man's life support requirements is available for cooling or other use.**	Water balance is more critical because of reduced water availability.	Water deficit is obtained suggesting use of urine distillation for optimum system	Because of the relatively short missions consistent with use of batteries, stored water supply will be used	Strong incentive for use of water reclamation systems
Thermal control	**Fuel cell waste heat is to be dissipated, excess water for supplemental cooling to reduce radiator area.**	Fuel cell waste heat at night assists in radiator control design	Radioisotope heat available for nighttime radiator thermal control	Minimum heat load imposed on thermal control system	Power converters independent and remote from shelter
CO_2 removal	**Water-dump 2-bed regenerable CO_2 removal system will be optimum.**	Same as fuel cell	Thermal-swing 4-bed regenerable CO_2 removal system will be optimum	Mission time consistent with use of lithium hydroxide	CO_2 processing optimum
Atmospheric supply	**Atmospheric O_2 supply can be integrated with fuel cell reactant storage.**	Same as fuel cell - daytime water electrolysis.	Cryogenic O_2 supply is required	Cryogenic O_2 supply is indicated for minimum weight	Water electrolysis
Shelter storage	**Fuel cell minimum temperature -20°F for inactive storage.**	Fuel cell as before - solar cell protection from dust, radiation, and heat	Radioisotope heat and electrical power available for thermal control during inactive storage	Battery storage temperature range -10 to 80°F	No effect
Shelter activation	**Fuel cell startup procedure.**	Deploy solar cell panels	Deploy heat converter radiator	Minimum deployment activity	Maximum deployment activity may require separate chemical power system for 30-day deployment period
Time limitation	**Boiloff of cryogenic fluids.**	Boiloff of cryogenic fluids, degradation of solar panels.	Decay of radioisotope output	Suitable for long-term storage if adequate temperature control is provided	2 years continuous operation feasible

Fig. 3

TABLE 2

MATERIAL BALANCES

Material (lb/man-day)	Average Metabolic Rate (Btu/hr)		
	350	500	650
Food	1.16	1.50	1.83
Minimum H_2O intake	4.73	4.77	4.80
Oxygen	1.37	1.96	2.55
Total Material Intake	7.26	8.23	9.18
Insensible moisture loss	2.05	2.28	2.50
Carbon dioxide	1.56	2.25	2.92
Urine	3.20	3.20	3.20
Feces and food residue	0.45	0.50	0.56
Total Waste Output	7.26	8.23	9.18

The material balances given in Table 2 are based upon providing man with an environment where minimum sweat rates are obtained. An increase in moisture loss above the insensible level by sweating must be offset by a corresponding increase in water intake to maintain water balance for the body. The provisions required for packaging and supply of the materials and for removal of the wastes will represent additional weight factors.

Metabolic Rate

Metabolic rate has been shown to be an important factor in establishing the material design requirements for the life support system. It is expected that the metabolic rate will vary with the individual, the phase of base operation, and the tasks assigned to the individual crew member.

Although lunar surface operations have been analyzed in some detail, the metabolic energy expenditures required for performance of many work assignments is presently somewhat speculative. This is largely due to the unknown effect of the reduced-traction environment on work rates for performance of such tasks as walking inside the shelter.

Reduced Gravity

The initial data obtained under simulated reduced gravity indicate 34- to 70-percent increases in metabolic rate for performance of a given task in a reduced-gravity environment, as compared with a normal earth-gravitational environment (Reference 6). In recent tests at AiResearch, using the suspension support system shown in Figure 4, significant reductions in metabolic rate were observed for the task of walking on a treadmill at reduced weight.

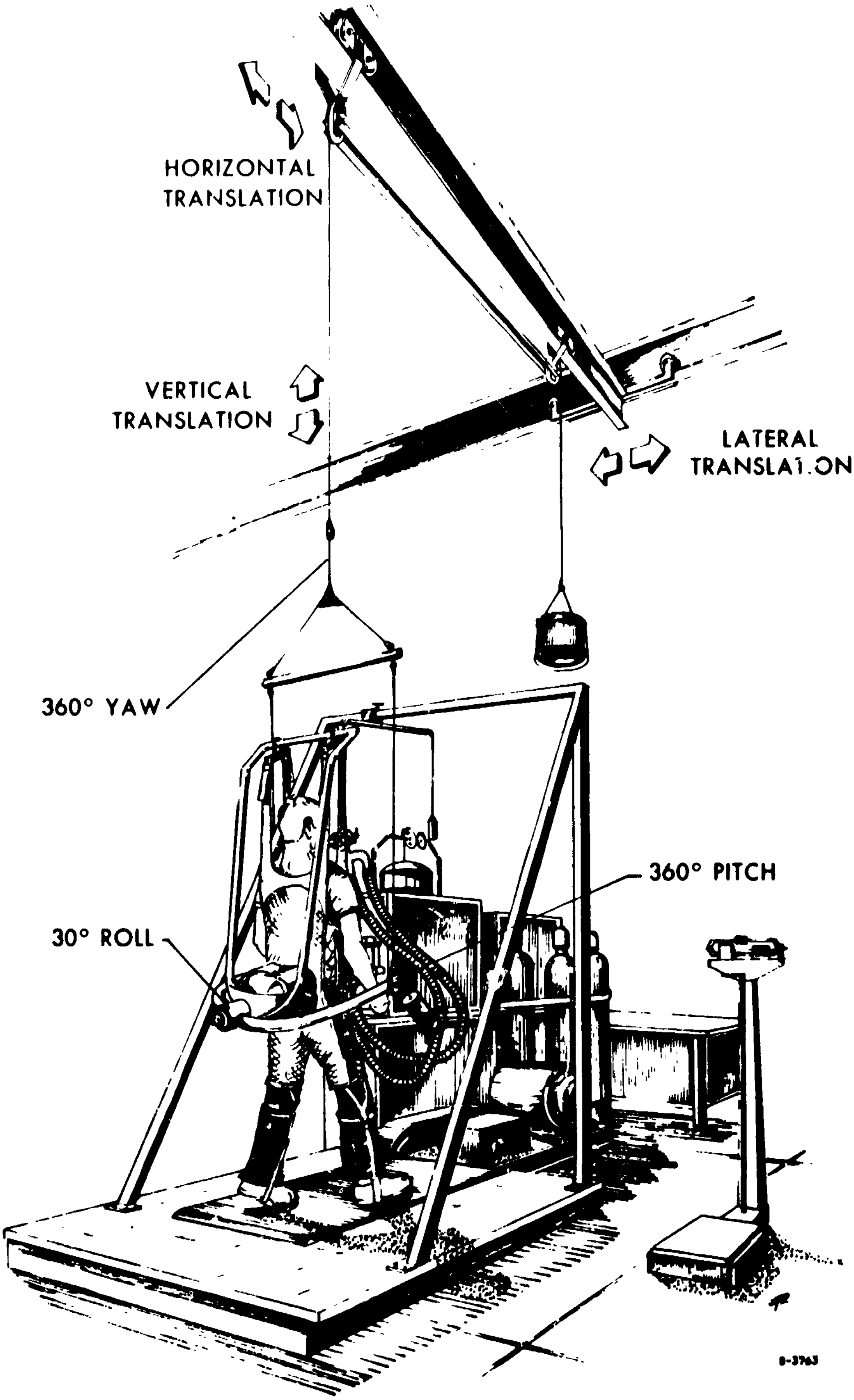

HORIZONTAL TRANSLATION
VERTICAL TRANSLATION
LATERAL TRANSLAT.ON
360° YAW
360° PITCH
30° ROLL

Fig. 4

Figure 5 shows the averaged results of a typical series of experiments with nine test subjects in shirtsleeves (Reference 7). At a treadmill walking speed of 2.0 mph, a reduction in metabolic rate of approximately 300 Btu is obtained for the simulated reduced-gravity condition.

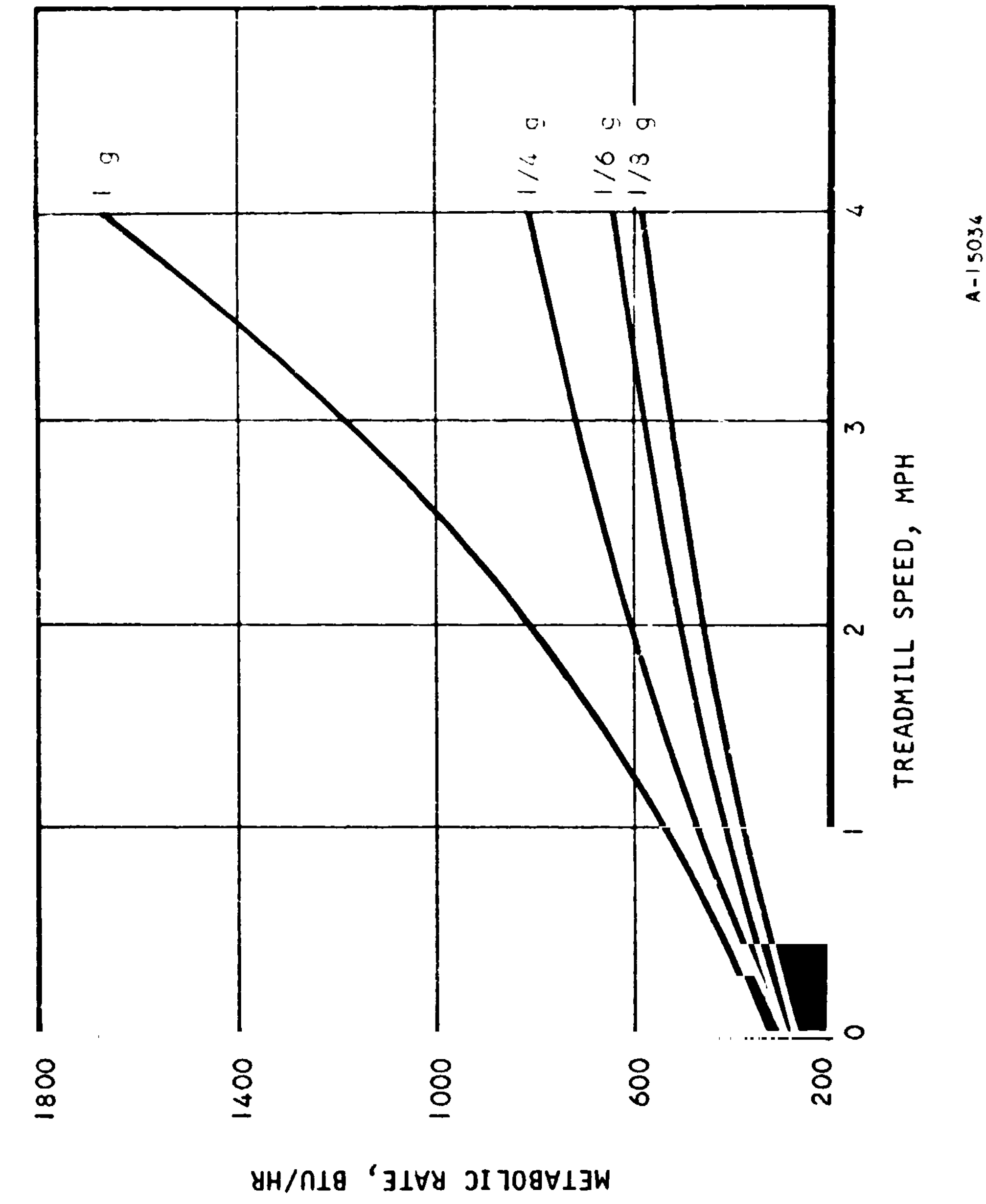
Although these data suggest significant reductions in metabolic rate in walking on the moon, other factors may tend to increase metabolic rate. In the previously cited experiments, the test situation involved the subjects in shirtsleeve clothing moving in a constant direction on a firm surface. Three additional factors should be considered in determination of work rates on the moon. First, the nature of the lunar surface may significantly affect expenditure of metabolic energy. For example, an increase in metabolic rate may occur if consistency of the lunar surface soil produces effects comparable to walking in snow or sand. Second, actual walking inside a lunar shelter (or on the lunar surface in an extravehicular suit) will probably require some maneuvering to avoid obstacles. With changes in direction, the energy required to overcome the inertial effects may offset the reduction in metabolic energy expenditure resulting from decreased body weight. Third, working in pressurized extravehicular suits requires more energy than working in shirtsleeves.

Pressure Suits

The metabolic expenditure required for walking in 1964-65 state-of-the-art extravehicular suits pressurized to 3.5 psid is given in Figure 6. Whether an increase or decrease in metabolic rate is experienced for the lunar gravity, it appears that extravehicular operations in a pressurized suit will be accompanied by high metabolic rates. It may be possible to reduce the work output required of the man through improvement in suit mobility. This development will probably be reflected in an increase in operational capability, and it will, therefore, still be necessary to design for high work rates. The maximum work output that can be sustained by healthy men for 4- to 10-hr periods corresponds to metabolic rates in the range from 1600 to 2000 Btu per hr. This may provide a significant limitation on extravehicular operations in pressurized suits and require extensive use of special-purpose vehicles for extravehicular activities. It appears that, because of the high metabolic heat loads that must be sustained on a continuous basis, future extravehicular suit systems will utilize liquid-loop suit cooling techniques (Reference 6). For routine extravehicular operations in pressurized suits, it may be necessary to design for higher metabolic rates than shown. For example, on a 4-hr extravehicular excursion at an average metabolic rate of 1600 Btu per hr, with the remainder of the day at a comparatively sedentary average metabolic rate of 450 Btu per hr, the average metabolic rate for a 24-hr day becomes 640 Btu per hr.

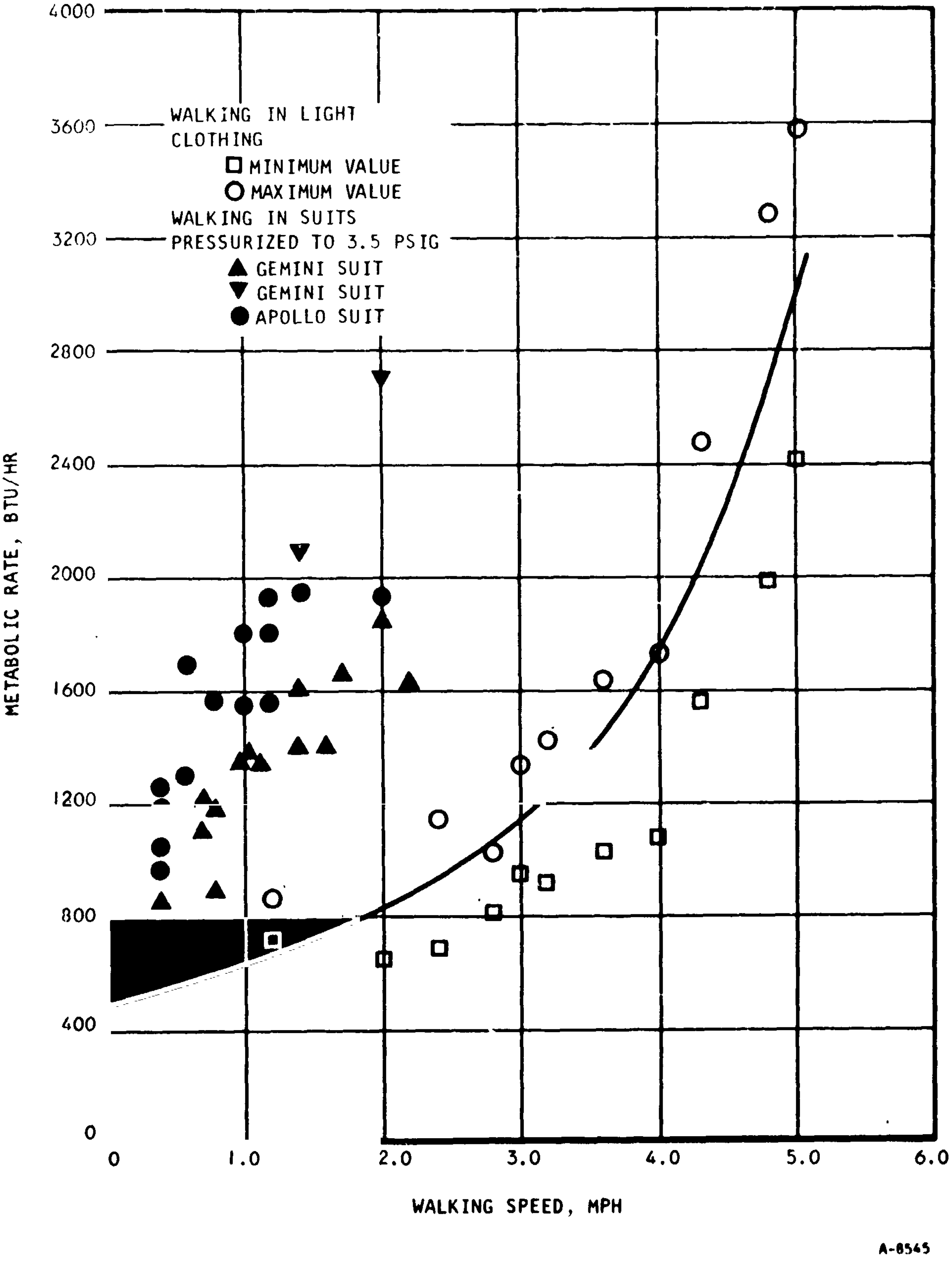
Crew Activity Schedules

Many different crew activity schedules can be postulated for the projected lunar-base operations. The total design energy expenditure will depend largely upon the allowances made for extravehicular operation and the low-traction environment. The extravehicular suit time may exceed 4 hr per man-day during base activation and operation of the roving vehicles used for lunar surface exploration. For the missions characteristic of the advanced lunar bases, the extravehicular suit time will probably average less than one hr per man-day.



METABOLIC RATE, BTU/HR
1800
1400
1000
600
200
TREADMILL SPEED, MPH
0
1
2
3
4
1 g
1/4 g
1/6 g
1/3 g
A-15034

Fig. 5



WALKING IN LIGHT CLOTHING
MINIMUM VALUE
MAXIMUM VALUE
WALKING IN SUITS PRESSURIZED TO 3.5 PSIG
GEMINI SUIT
GEMINI SUIT
APOLLO SUIT
METABOLIC RATE, BTU/HR
WALKING SPEED, MPH
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
0
1.0
2.0
3.0
4.0
5.0
6.0
A-8545

Fig. 6

As a consequence, a design metabolic rate of 500 Btu per hr is recommended for the large lunar bases. A design metabolic rate on the order of 650 Btu per hr is indicated for the roving vehicles and early bases, where pressure suit operation will approach 4 hr per man-day.

Textiles

A variety of textile materials will be required for clothing, bedding, and bathing. One approach involves use of expendable materials for these purposes. Figure 7 gives an estimate of the textile material requirements based upon use of lightweight synthetic fabrics. A total requirement of 1.17 lb per man-day is given for clothing and linens, not including the undergarment used with the extravehicular pressure suit. Figure 7, which shows the tradeoff between expendable textiles (not including pressure suit undergarment) and use of a laundry for washing textile materials, shows the laundry to be used to advantage in the shelters for Base Models 2, 3, and 4. The cleaning requirements for the liquid-cooled garment used with the extravehicular suit are not known at the present time but will probably increase the incentive for use of a laundry in the lunar shelters.

WATER MANAGEMENT

Since water will be the major mat . required for life support, its reclamation and conservation becomes highly important for the long-duration lunar bases. In addition to the water used directly for life support in food preparation, sanitation, and drinking, water will be used for cooling (in the environmental control systems used with the extravehicular suit and the roving vehicles) and as a source of oxygen. Thus, the auxiliary uses of water will be important in the overall water management for the lunar bases. Also, the base deployment procedure may be important since, during base evolution, surplus water will be produced by the fuel cell power system used before the nuclear power system is available. During early phases of base evolution, it will be desired to store the waste water for subsequent processing in the advanced bases, where water deficits will be obtained.

From the analysis of the lunar cabin shirtsleeve environment, it appears that it will be possible to provide a comfortable cabin environment with the sweat rates at the insensible level without excessive fan power or ventilating flow rates. In addition, it appears that it will be possible to remove heat by conduction from the body under zero-sweat-rate conditions using liquid-loop suit cooling methods. It has been previously determined that the total water intake (for drinking and food preparation) will be approximately 4.77 lb per man-day for an average metabolic rate of 500 Btu per hr, dried-food diet, and a minimum sweat rate. Therefore, this water requirement can be used in water balance calculations for the shelters.

	UNIT MASS, LB	CHANGE FREQUENCY	
SHIRT	0.276	DAILY	TOTAL CLOTHING REQUIREMENTS - 0.597 LB/MAN-DAY
TROUSERS	0.775	WEEKLY	
UNDERWEAR	0.166	DAILY	
SOCKS (2)	0.044	DAILY	
SHEETS (2)	1.55	WEEKLY	TOTAL LINEN REQUIREMENTS - 0.575 LB/MAN-DAY
TOWELS	0.353	DAILY	
VENT SUIT UNDERGARMENT	1.0	EACH USE	PRESSURE SUIT UNDERGARMENT REQUIREMENTS DEPEND UPON COOLING METHOD AND SUIT USAGE
LIQUID COOLED GARMENT	2.4	UNKNOWN	

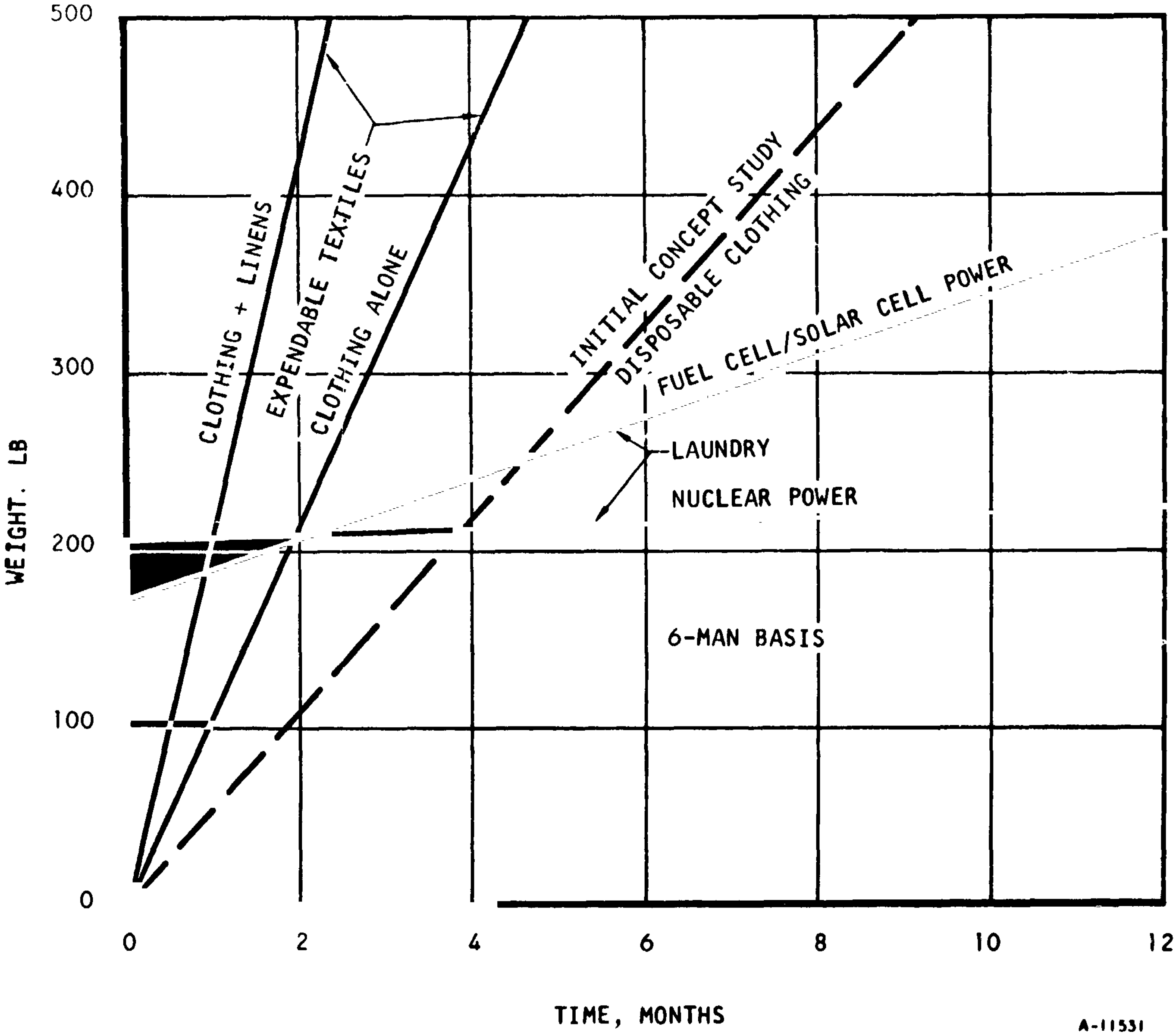


Fig. 7

The overall water balances obtained for the lunar base shelters are as follows:

	Water Balance, lb
Base Model 1	+2980
Base Model 2	+3820
Base Model 3	-4500
Base Model 4	-13500

The plus sign indicates surplus water (which will be obtained primarily in the form of human wastes) for the shelter, as a consequence of water production from the fuel cell power system.

ATMOSPHERIC SUPPLY

The atmospheric supply system provides the makeup gas needed to maintain the cabin atmosphere at the desired pressure level and composition. The atmospheric fluids will be lost in various ways, such as leakage from the cabin, metabolic consumption, air lock depressurization, and shelter depressurization. The atmospheric supply requirements will vary with both total pressure and composition; a 6.0-psia oxygen-nitrogen atmosphere has been assumed for the present discussion for the baseline systems. The Initial Concept Study (Reference 3) gives a shelter leakage rate of 4.0 lb per day. With 90 percent efficient scavenging of the 148-cu-ft shelter air lock, 0.47 lb will be lost overboard with each air lock operation. The [illegible]0-cu-ft shelter total volume (neglecting volume occupied by equipment) requires 51.5 lb of atmospheric fluid for pressurization to a nominal 6.0 psia. Thus, if the number of air lock operations are known and the number of cabin pressurizations is specified, the atmospheric fluid requirements for pressurization can be determined. The Initial Concept Study specifies a design average of two air lock operations per day and one shelter repressurization per month. On this basis, the following gives the atmospheric fluid required per shelter for pressurization in pounds per month (not including metabolic oxygen consumption):

Air lock loss	28.2 lb per month
Leakage	120.0
Repressurization	104.6
Total	252.8 lb per month

It can be seen that these allowances are somewhat arbitrary, particularly those related to leakage loss and the repressurization requirements. The assumed leakage rate is consistent with those obtained on the much smaller Mercury and Gemini spacecraft. No data are available concerning leakage rates with structures this large. It appears feasible, however, to develop sealing methods that will provide extremely low leakage rates. Also, the assumption of one complete repressurization of each shelter per month appears to be conservative. For the advanced lunar bases, an accidental depressurization due to meteoroid penetration should be remote. Deliberate depressurization for either elimination of a toxic atmosphere or suppression of a fire should be an unlikely event at the state of the art projected for the lunar base operational phase. Therefore, it is concluded that previously listed atmospheric fluid requirements are conservative. However, because of the open-ended nature of some of the missions, a certain amount of conservatism in this area may be tolerable because of the possible use of residual expendables in mission extension.

Of the 252.8 lb of atmospheric fluid required per month for shelter pressurization, 97.5 lb is nitrogen and 155.3 lb is oxygen. The oxygen consumed in metabolism amounts to approximately 1.96 lb per man-day. Therefore, the total oxygen requirement for a 6-man shelter is 504.5 lb per month. Subject to the availability of water and electrical power, a substantial part of the oxygen requirement can be provided by the electrolysis of water. Part of the oxygen requirement for Base Model 2 can be provided by water electrolysis during the lunar day, when the solar cell power system is operative. A water surplus in excess of human metabolic requirements will be obtained on Base Models 1 and 2 as a result of water obtained from the fuel cell as a byproduct of power generation. Thus, it will be possible to save weight by generating oxygen by water electrolysis during the day, when electrical power is available at relatively low penalties. However, it will be necessary to supply all of the nitrogen, since it will not be possible to reclaim any significant amount of this material from the wastes.

Because of the large volume of the shelter and the desirability of accomplishing the repressurization within a limited time period, it may not be feasible to provide the oxygen required for repressurization by electrolysis. For example, 64.3 lb of oxygen is required for shelter pressurization. The energy requirement for electrolysis of water will be approximately 2250 watt-hr per lb of water. Therefore, if 3 kw of electrical power is available for water electrolysis, it will take two days to provide the necessary oxygen production for shelter repressurization. Therefore, it appears that the 385 lb oxygen allowance for Base Model 2 shelter repressurization should be provided by the oxygen storage system. Approximately 1/2 of the remaining oxygen requirement for Base Model 2, or 1321 lb, can be obtained by electrolysis of water during the day. Consequently, the Base Model 2 oxygen supply system will be required to provide 1321 + 385 = 1706 lb for the life support and environmental control functions.

The table following summarizes the atmospheric fluid requirements for the various lunar bases:

TABLE 3

LUNAR BASE ATMOSPHERIC FLUID REQUIREMENTS

	Oxygen, lb	Nitrogen, lb
Base Model 1	990	293
Base Model 2	1706	586
Base Model 3	622	2340
Base Model 4	1866	7020

These atmospheric fluid requirements are based upon use of a 6.0-psia oxygen-nitrogen atmosphere selected on the basis of an aeroembolism criterion established to minimize the risk of decompression sickness during extravehicular excursions from the shelters (Reference 3). Subsequent studies indicate that significant engineering advantages will be obtained with a 3.7-psia oxygen atmosphere (Reference 2). If use of an atmospheric diluent is indicated for physiological reasons, helium will show a significant weight advantage over nitrogen for a given total pressure level.

ENVIRONMENTAL CONTROL/LIFE SUPPORT SYSTEMS

Many of the life support subsystems (such as food, personal hygiene, clothing, sanitation, crew provisions, etc.) are not amenable to engineering tradeoffs or optimization. Consequently, the system studies will be primarily concerned with the life support provisions where important tradeoffs exist, reliability problems are found, or large logistic material requirements are obtained. These areas include water management, fluid supply, thermal control, and atmospheric control.

The integration studies forming the basis for system design are concerned with the material and energy balances associated with water management, atmospheric fluid supply, atmosphere control, and thermal management. In performing these studies, it is necessary to consider the requirements for operation of the roving vehicle and for use of the extravehicular suit, in addition to those for the lunar base shelters. Some of the engineering tradeoffs may be strongly dependent upon these auxiliary functions. Some of the lunar mission parameters, particularly those involving the advanced bases, are at present poorly defined. Consequently, the material requirement estimates given previously are applicable to operations in the lunar base and do not consider the requirements imposed by roving vehicle missions from the base.

Basic Systems

The basic system configurations are derived from the integration studies. The "basic" system represents the most simple nonredundant arrangement that will meet the operating modes and functional requirements. Table 4 gives the basic system fixed weight for the four lunar base models.

TABLE 4

EC/LSS WEIGHT

Mission	System Weight, lb	
	Basic	Total
Base Model 1 Shelter	1903	2290
Base Model 2 Shelter	2098	2618
Base Model 3 Shelter	2416	3954
Base Model 4 Shelter	2416	5160

Reliability/Availability/Maintainability

The basic systems have been analyzed from the standpoint of reliability to determine the redundancy and maintainability requirements to attain a given reliability or availability level. For the long-duration missions, where maintenance is an important factor, the analytical methods developed for reliability estimates are inadequate. In this case, system availability is a more valid concept in determining system performance. With the complex system used in the advanced bases, extensive maintenance provisions will be required. Maintenance involves both scheduled operations, as in replacement of filters, and unscheduled procedures resulting from a failure. Analysis of the failure modes and repair methods indicates that the unscheduled maintenance procedure will usually consist of replacement of a component or a subsystem.

The effectiveness studies indicate that for a one-year shelter mission, redundancy and spare parts amounting to approximately 64 percent of the basic system weight should be provided. For shorter missions, the optimum redundancy level will be less. For example, for a 2-week roving vehicle mission, the required redundancy will represent approximately 12 percent of the basic system weight. Table 4 shows the total EC/LSS weight (including redundancy and spare part provisions) for the four lunar base models.

WEIGHT COST CHARGEABLE TO LIFE SUPPORT

Figure 8 shows the assessment of weight penalty in the power system due to the life support functions. The power penalties shown for the different lunar bases are representative of those accruing with power systems of the type that will be used in the respective missions.

Figure 9 is a weight breakdown of fixed equipment and expendables chargeable to life support for the four lunar base models. The weights shown are applicable to the total base (Base Models 1 and 2 represented by a single shelter module; Base Model 3 by two shelter modules; and Base Model 4 by three shelter modules). It is assumed in Base Models 1 and 2 that water in excess of the life support requirements is produced by the fuel cell as a byproduct of power generation. It is additionally assumed that a 6-month crew rotation period is used in the advanced bases and that each crewman is provided with a spare suit and backpack.

Specific Weight Cost

If the life support weight is broken down into fixed and expendable categories in terms of pounds per man and pounds per man-day, some insight can be gained into the factors influencing cost of maintaining man in a lunar environment. Figure 10 shows a comparison of this type based upon the previously discussed data. It will be observed that the fixed weight per man and the expendable weight per man-day remain relatively constant in Base Models 2, 3, and 4. If it is assumed that all of the expendables are supplied logistically, the logistic supply weight for the advanced bases will remain relatively constant in the range from 5.2 to 5.3 lb per man-day. Based upon a lunar logistic cost of $5000 per lb, it can be concluded that it will cost approximately $1100 per man-hr to maintain man on the lunar surface (not including the hardware development and production costs). This logistic cost could be reduced by utilization of extraterrestial resources. These savings must be balanced, however, against the equipment and manpower cost of the processing equipment needed to produce the required materials.

Some interesting conclusions can be derived from Figure 9 concerning the possibility of using extraterrestial resources to manufacture life support materials. The large material requirements in the advanced bases where lunar surface material processing would be considered are represented by food, water, and nitrogen; relatively little oxygen is needed. Of course, all of the water requirement is convertible into oxygen, if a process is available for conversion of lunar rock into oxygen. Food will impose the greatest logistic cost upon operation of a permanent lunar base.

HUMAN FACTORS CONSIDERATIONS

Previous sections of this paper have been concerned with the weight costs of maintaining man in lunar bases. An additional factor essential to the evaluation of man's utility is the crew time available for performing scientific missions. The scientific mission time is the time remaining after performance of the essential personal, base support, and facility monitoring activities.

	Base Model			
	1	2	3	4
Power penalty, lb/w				
Lunar day	0.38	0.38	0.50	0.50
Lunar night	2.00	3.50	0.50	0.50
EC/LSS power consumption, w				
Lunar day	771	2332	7632	11448
Lunar night	771	1012	7632	11448
EC/LSS power penalty, lb	1832	4435	3816	5724

Fig. 8

	Base Model			
	1	2	3	4
Basic EC/LSS fixed weight	1903 lb	2098 lb	4832 lb	7248 lb
EC/LSS spares and redundancy	387	620	3076	7232
Power system weight penalty	1832	4435	3816	5724
Shelter structure	6580	6580	13160	19740
Furnishings	550	550	1100	1650
Fixed weight total	11252 lb	14283 lb	25984 lb	41594 lb
Pressure suits, backpacks, repair kits	300 lb	600 lb	2400 lb	7200 lb
Clothing and personal effects	90	180	720	2160
Water	0	0	4500	13500
Water storage	0	0	450	1350
Oxygen	990	1706	622	1866
Oxygen storage	545	718	435	745
Nitrogen	293	586	2340	7020
Nitrogen storage	440	645	1760	5280
Food	405	1620	6560	19680
Food packaging and storage	203	810	3280	9840
Expendable weight total	3266 lb	6865 lb	23067 lb	68641 lb
Total fixed and expendable weight	14518 lb	21148 lb	49051 lb	110235 lb

Fig. 9

	Base Model			
	1	2	3	4
Fixed weight				
Total, lb	11252	14283	25984	41594
lb/man	3750	2380	2150	2310
lb/man-day	41.7	13.2	5.9	3.2
Expendable weight				
Total, lb	3266	6865	23067	68641
lb/man	1089	1144	1925	3810
lb/man-day	12.1	6.4	5.3	5.2
Life support cost				
Total	14518	21148	49051	110235
lb/man	4839	3524	4075	6120
lb/man-day	53.8	19.6	11.2	8.4

Fig. 10

Personal Activities

The personal activities are presented in Table 5. The daily pressure suit checkout task is important for maintaining this equipment for emergency use. It is anticipated that the pressure suit and portable life support systems will be handled as personal property, with each crew member responsible for his own equipment. Spare suits and backpacks and repair kits are provided for each crew member; they will be supplied by a logistic payload with crew rotation in the advanced lunar bases.

TABLE 5

PERSONAL ACTIVITIES FOR 24-HR CYCLE

	Daily Frequency	Time	
		Minutes	Hours
Toilet	1	20	2.00 (Toilet through Pressure suit checkout)
Urinal	5	15	
Wash basin	5	15	
Shower	1	15	
Grooming	2	15	
Washing machine	1/2	10	
Clothing	1	10	
Pressure suit checkout	1	20	
Exercise	1	20	0.33
Sleeping	1 or 2	480	8.00
Eating	3	90	1.50
Totals	23	710	11.83 = 11 hr 50 min

Crew Support Activities

Table 6 depicts four principal task groups required to support various phases of crew activities. The task groups comprising handling food, physiological monitoring, and housekeeping are essential to the health, safety, and well-being of the crew. Scheduled system support activities are associated with maintaining the facility. Test, checkout, and maintenance activities are based on state-of-the-art hardware and anticipated requirements for future systems. The present analysis indicates that these tasks will be assigned on a regular schedule.

TABLE 6

CREW SUPPORT ACTIVITIES

Task Group	Daily Frequency	Time (24-hr Cycle)
Food		1 hr 30 min
Procure	3	
Prepare	3	
Serve	3	1 hr
Sanitation	3	1 hr
Physiological monitoring		
Base interior	2	
Pressure suit	2	
Housekeeping	2	1 hr
Scheduled system support		3 hr
Test	As required	
Checkout	As required	
Maintenance	As required	
		6 hr 30 min

The task composite total of 6.5 hr represents the time devoted to support activity for a 24-hr cycle. Where skills and scheduling permit, the tasks will be shared equally by the various crew members.

Food handling tasks (meal preparation and serving) are performed by one man. Under this procedure, all crew members will eat together, except for the operator at the communication console. This arrangement has obvious psychological benefits. Physiological data necessary to evaluate crew health including effects of lunar environment upon their physiological well-being, will be required. Although each member will participate in this activity, the three crew members assigned to the facility and communication console will have primary responsibility for these data. Tentative scheduling provides that each of these men will be doing this work at a specific time during each 24-hr cycle.

Housekeeping will require a minimum of one hour each 24-hr cycle, assuming that each individual will normally keep his work station clean and in order.

Communication and Control

Many system functions set up to protect the crew from hostile lunar environment require immediate corrective action in case of malfunction. Such action requires ready knowledge of system performance within established tolerances. This requirement established a monitor and control task for these critical survival parameters. Constant manning of certain communication links is also advantageous. These two task groupings are combined in a monitor and control/communication task composite shown in Table 7. Preliminary analysis indicated that these tasks should be time-shared by one operator for a duty period of 4 hr to appropriately utilize the available manpower.

TABLE 7

FACILITY AND COMMUNICATION MONITORING AND CONTROL

Task Summary			
Facility Display and Control Console		Communication Console	
	Monitor and Control Time, Minutes	Links	Monitor and Control Time, Minutes
Air lock	10	Voice to earth	30
Power	21	Voice to LRV	40
Base exterior	22	Telemetry to earth	20
Thermal		LRV telemetry	10
Radiation		Lunar suit to base	20
Meteoroid			
ECS	18		
Water	18		
	89		120
One operator task shared for 4-hr duty cycle			

Of this 4-hr duty period, a total of 31 min is undesignated time. It can be safely regarded, however, as contingency time since monitoring requirements will more likely increase than decrease. Moreover, the intervals established for this task are regarded as minimal time allocations.

Crew time could be saved with complete automation of the facility monitoring function and display of these parameters as hazard warning for out-of-tolerance performance or malfunctions. This approach, however, would require monitoring equipment with exceptional reliability.

Base Task Composite

Personal activities, crew support activities, and facility and communication control have been combined in a base task composite to depict the crew time expenditure. Time remaining after these essential tasks are accomplished is available to perform the scientific mission. Based upon the previous time allowance, the overall average manpower allotment is as follows (for a 6-man shelter):

	Percent of Time
Sleeping	32
Monitor and control communication	16
Unscheduled (potential mission) time	7
Schedule system support	6
Exercise	1
Physiological monitoring	0.5
Duty	24
Personal activities	7
Eating	5
Meal preparation	1
Housekeeping	0.5

Duty and unscheduled time represents the time available for pursuit of the scientific missions and 31 percent of the total mission time. This estimate is based upon a six-man shelter. In the larger bases involving the use of more than one shelter, it may be possible to increase the available scientific mission time by centralizing the communications and control functions in one shelter. For example, the available scientific mission time will increase to 39 percent in Base Model 3 and 42 percent in Base Model 4. On the other hand, if continuous base monitoring is an operational requirement, the scientific mission time is reduced to 15 percent in Base Model 1.

Simulation Studies

The suitability of the shelter interior configuration shown in Figure 2 was investigated by construction of a full-scale mock-up of the six-man shelter and testing of the design with respect to representative tasks and duty schedules. Figure 11 is an overhead view of the shelter mock-up showing a representative distribution of the crew members during base operation. Figure 12 shows the control and communications console which serves as the duty station for the crew member monitoring base operation.

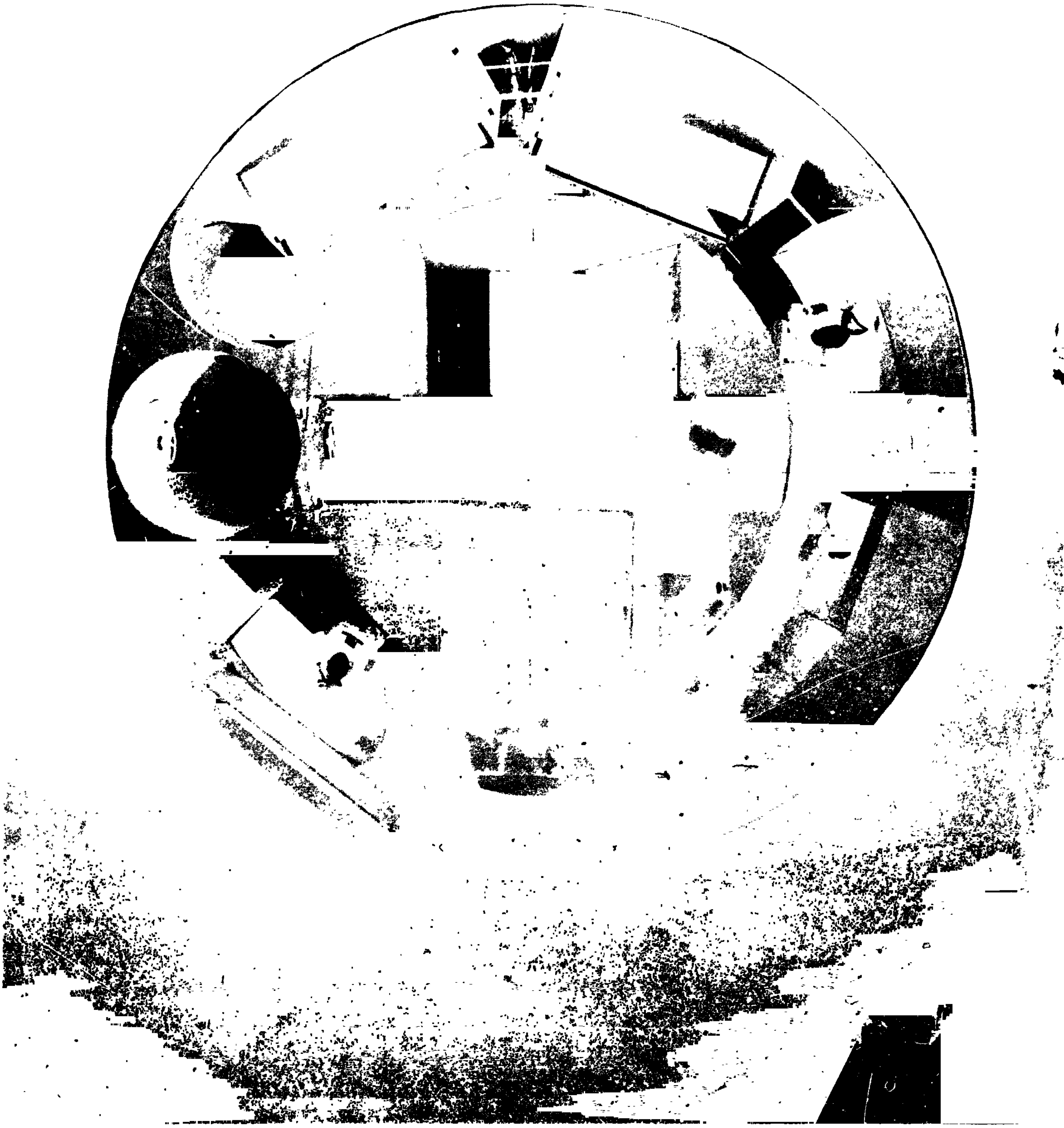
Testing of the mock-up design consisted of two phases: (1) shirtsleeve operations and (2) pressure suit operations. First-phase operations involved six subjects in street clothing who simulated six crewmen performing various tasks and routines. Second-phase operations involved two subjects in Apollo pressure suits who performed ingress-egress procedures and duty station and functional tasks with the suits pressurized, and functional and support tasks with the suits unpressurized. Significant findings of the experimental study are discussed below.

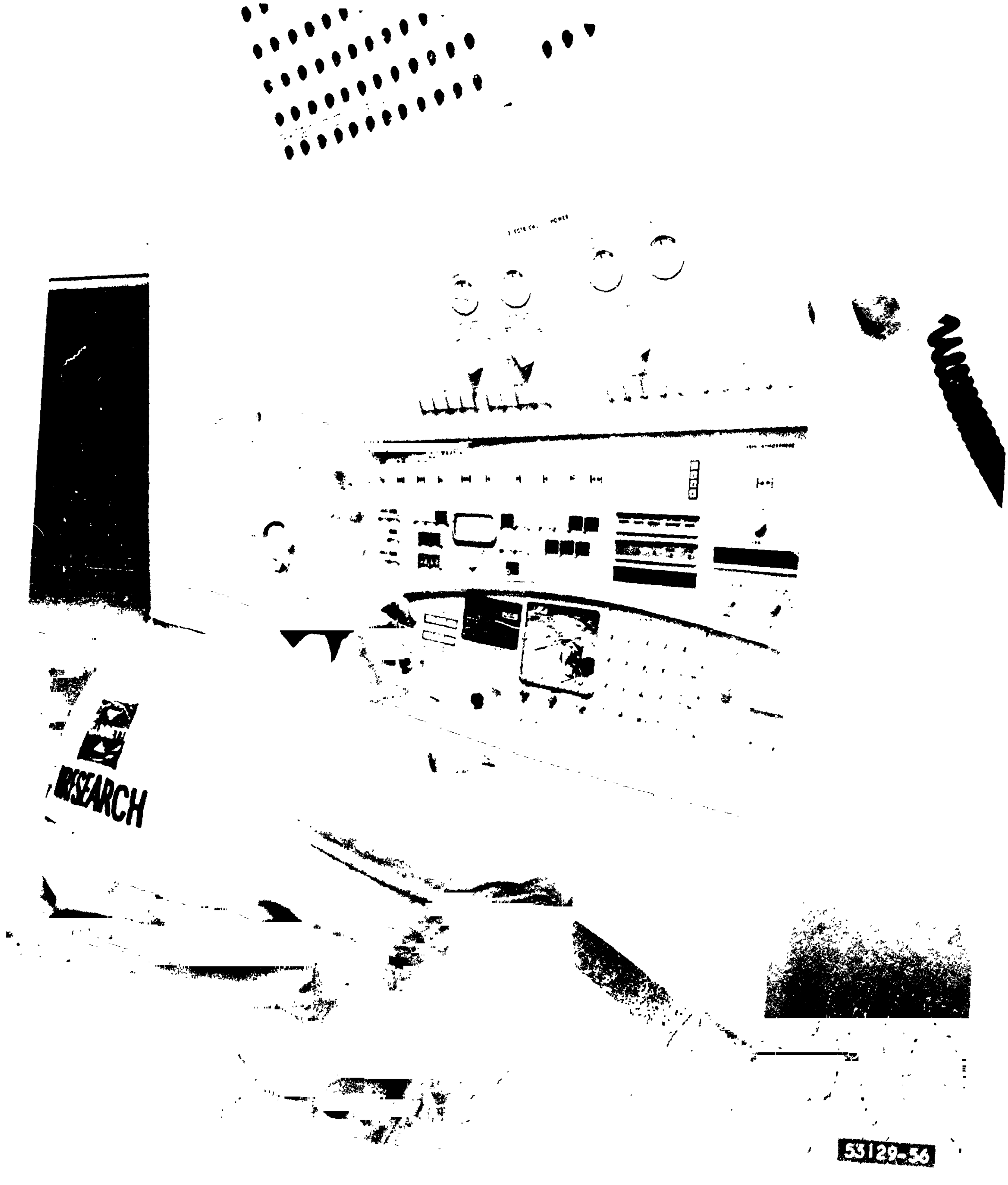
In the shirtsleeve simulation, the analysis revealed no striking conflicts requiring design changes or concept alterations. The dynamic simulation in pressurized suits, however, revealed two problem areas. The first one is the difficulty encountered by pressurized suited personnel in traversing the hatches. The hatch configuration hampered movement because of the dimensions between the hatch sill and the coaming. To alleviate this it is recommended that the hatch configuration be revised to remove the lower sill and increase the overall height of the hatch from 60 to 72 in.

The second problem involves limited access in the aisle of the outer shelter area. Here, the tests indicated only minimal clearance in the passageway for pressure-suited personnel to pass one another or a seated operator. Passage of personnel in this area required that both participants turn sideways to present their narrowest body dimension to one another. However, although the passage was difficult, it did not warrant recommendations for a design change. Factors in this decision included (1) that a design change to widen the outer area could be done only at the sacrifice of space from the inner area and (2) that operations in pressurized suits in this area would occur only in emergency situation. Furthermore, the recently announced reductions in Apollo suit shoulder width should significantly alleviate this problem.

CONCLUSIONS

Figure 13 shows the effect of design mission duration on the overall weight (per crew member) chargeable to life support. The initial decrease in fixed equipment weight with time is attributable to use of a 6-man shelter module for the early 3-man missions. The subsequent increase in fixed equipment weight reflects the increased life support equipment needed for waste processing and spare parts for maintenance of the system.

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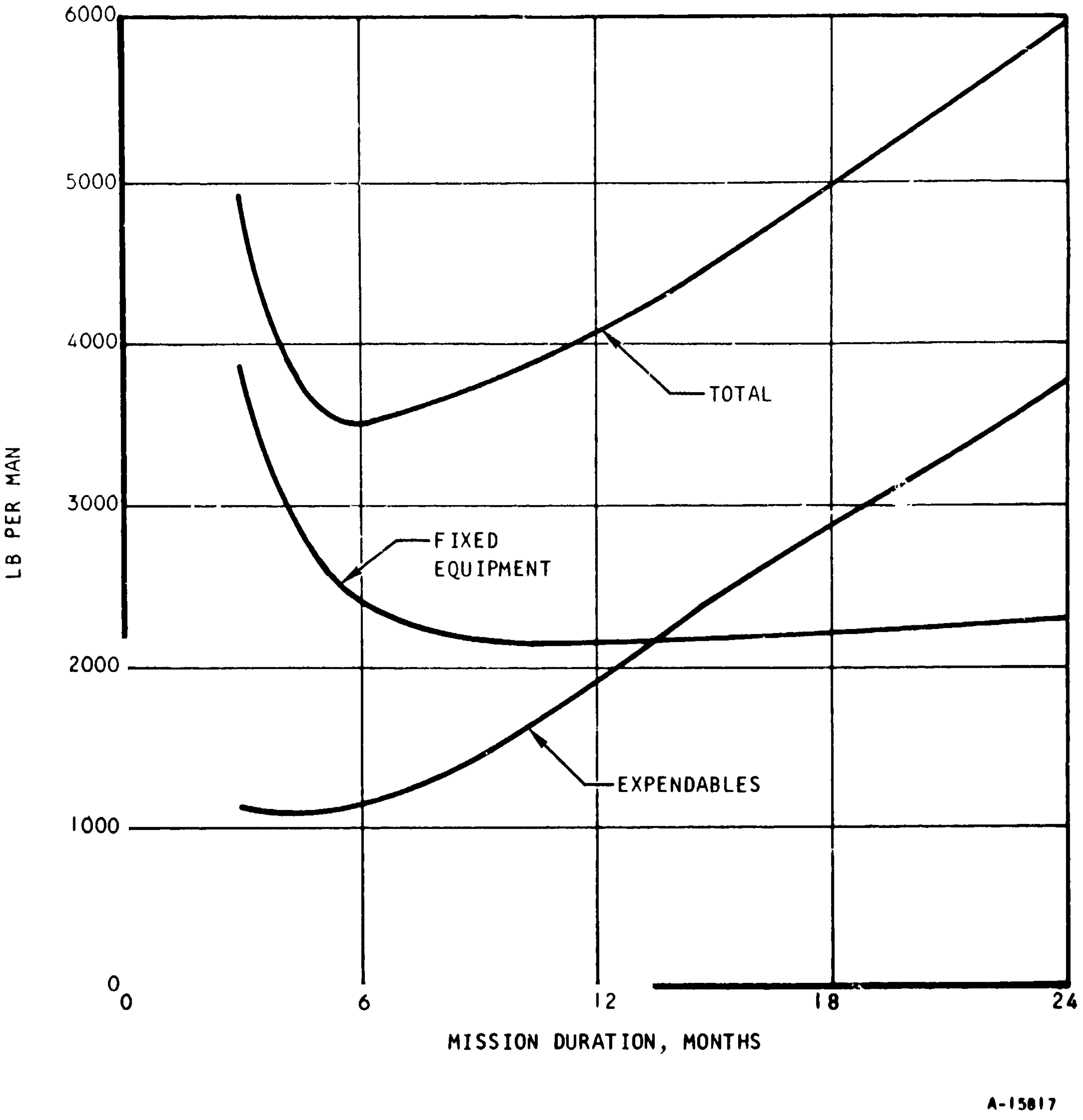
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4000
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LB PER MAN
TOTAL
FIXED
EQUIPMENT
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0
6
12
18
24
MISSION DURATION, MONTHS
A-15817

Fig. 13

Figure 14 depicts the effect of design mission duration on the weight cost (per man-day) for life support. In evolving from a 3-man, 3-month mission (Base Model 1) to an 18-man, 2-year mission (Base Model 4), the overall cost for life support decreases from 53.8 to 8.4 lb per man-day. For the advanced base (mission duration in excess of one year), the logistic support cost will remain relatively constant at approximately 5.3 lb per man-day. Utilization of extraterrestial resources for the production of oxygen provides a potential logistic saving of 1.4 lb per man-day. Food production on the lunar surface could reduce the logistic load by approximately 2.3 lb per man-day.

With the previously determined data for scientific mission time availability and life support weight cost, the overall weight cost for scientific mission time can be determined for the lunar base models, as indicated in Table 8.

TABLE 8

SCIENTIFIC MISSION TIME WEIGHT COST

Base Model	Total Life Support Weight Cost, lb/man-day	Crew Availability for Scientific Mission, percent	Scientific Mission Life Support Cost, lb/man-hr
1	53.8	15	14.9
2	19.6	31	2.62
3	11.2	39	1.20
4	8.4	42	0.83

The scientific mission manpower cost given in Table 8 is based upon the assumption of a continuous base-monitoring task that is nonproductive from the standpoint of performance of the scientific mission. Base Model 1 scientific mission cost can be reduced with an increase in manning of the shelter to the design six-man level. The desirability of increasing the Base Model 1 crew size becomes apparent when the requirements for extravehicular activity for this base are taken into consideration. That is, Base Model 1 may be marginal from a safety standpoint, unless automatic monitoring systems that provide a high degree of reliability can be developed. An alternative approach would involve remote monitoring of the lunar base from the earth to reduce the lunar base manpower commitment to this task. The relatively high scientific mission manpower cost in Base Model 1 may be negligible in the evolutionary lunar base concept under consideration here. Operation of this base would be a step toward development of the ultimate capability represented by the advanced bases.

Table 8 indicates that manpower used in the lunar bases for deployment, operation, or maintenance of supporting systems (such as lunar material processing plants) will be relatively expensive in terms of the materials and equipment required for life support on the lunar surface. It can be seen that if a three-man crew is required for operation of a lunar processing plant in an advanced lunar base, the plant must have a useful production capacity in

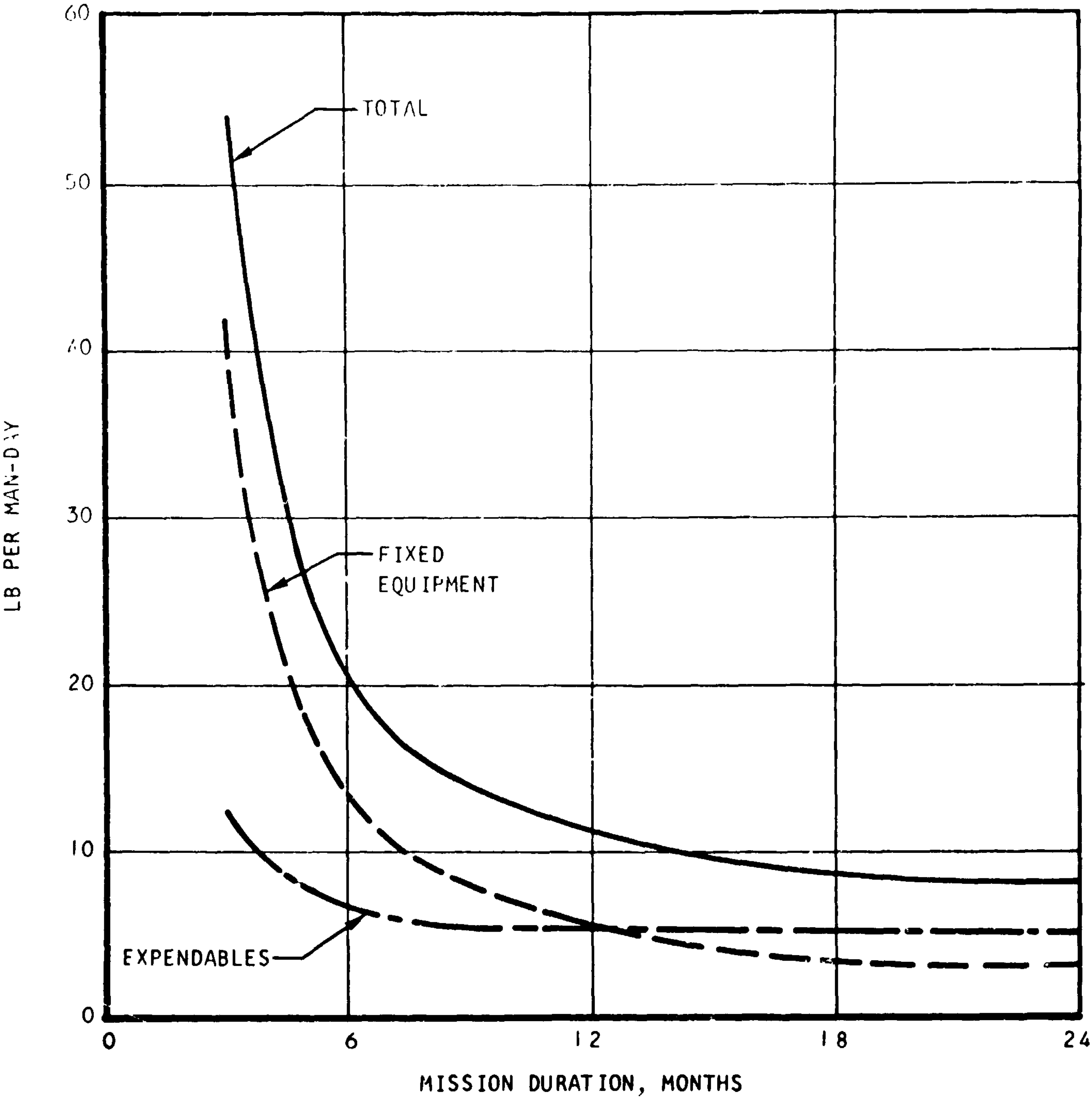

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Fig. 14

excess of approximately 1000 lb per month for it to break even (on the basis of weight cost of life support alone).

REFERENCES

1. Hall. A., from a speech at the American Institute of Aeronautics and Astronautics meeting in San Francisco during August 1965; cited on p. 22, Space/Aeronautics, October 1965.

2. "Study of Human Factors and Environmental Control-Life Support Systems for Lunar Exploration Systems for Apollo," Contract NAS8-11447, Report No. SS-3243, AiResearch Manufacturing Company, Los Angeles, California, 1965.

3. "Initial Concept of Lunar Exploration Systems for Apollo," Contract NASw-792, Report No. D2-100057, The Boeing Company, Seattle, Washington, November 1963.

4. "Payload Performance Study for the Lunar Logistic System (LLS)," Contract NASw-528, Grumman Aircraft Engineering Corp., Bethpage, New York, January 1963.

5. "Lunar Logistic System (LLS) Study," Report No. MTP-M-63-1, George C. Marshall Spaceflight Center, National Aeronautics and Space Administration, Huntsville, Alabama, March 1963.

6. Burriss, W. L., S. H. Lin, and P. J. Berenson, "Study of the Thermal Processes for Man-in-Space," Contract NASw-1015, NASA Contractor Report No. CR-216, National Aeronautics and Space Administration, Washington, D.C., April 1965.

7. Wortz, E. C., and E. J. Prescott, "The Effects of Subgravity Traction Simulation on the Energy Costs of Walking," Report No. EP-8 (To be published in The Journal of Aerospace Medicine), AiResearch Manufacturing Company, Los Angeles, California, September 1965.

Our next speaker is Dr. Robert Yeck, Chief of the Livestock Engineering and Farm Structures Research Branch of the U. S. Department of Agriculture, Agriculture Research Service at Beltsville, Maryland.

Dr. Yeck received his advanced degree from the University of Missouri, where he was also on the staff of the Psychoenergetic Laboratory prior to association with the Department of Agriculture.

Dr. Yeck is chairman of the National Academy of Sciences committee on the Effect of Environment on Animals.

Dr. Yeck will discuss Terrestrial Agriculture Pland and Animal Research as applicable to Extraterrestrial Food Production.

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TERRESTRIAL AGRICULTURE PLANT AND ANIMAL RESEARCH AS APPLICABLE TO EXTRATERRESTRIAL FOOD PRODUCTION

Robert G. Yeck

When discussing research with space scientists, one often is reminded of the value of "spin off" developments in the solution of terrestrial problems. Indeed, this is true. This presentation might be considered as leading toward the "spin off" process in reverse. Its primary purpose is to alert the Working Group on Extraterrestrial Resources to the agricultural research organization in the United States as a resource in meeting extraterrestrial problems. Included are two illustrations of areas of research that might have direct application to some immediate problems facing our group.

As earthlings, we, of course, plan our needs in extraterrestrial environments much in terms of that to which we are accustomed on earth. If we would look to terrestrial food production techniques as a guide to extraterrestrial food production, practically all agricultural plant and animal research would have some application to extraterrestrial needs. The major block to this line of thinking is the difference in environment for plant and animal growth. Present plans in extraterrestrial planning are toward closed ecological systems wherein the environments are artificially controlled. However, complete simulation of earth environments will very probably not be achieved and we will need to know the effects of altered environments on plant and animal growth.

Other agricultural research activities that we might consider are in the areas of: packaging, storing and processing of food; evaluating nutritive qualities of foods and nutritive requirements of man; soil characteristics; traction of vehicles on various types of soil; and fundamental physiological and other studies that might provide leads to the solution of problems which, seemingly, would have little direct relation to extraterrestrial problems.

Agricultural Research Organization in the U.S.

Private industry and philanthropic foundations have agricultural research programs but most agricultural research is conducted or sponsored by either State or Federal agencies. The primary state agency is the State Agricultural Experiment Station of each State. These stations are usually headquartered on the university campuses. Each are under complete State control and operate with funds. These funds are augmented by grants or other agreements with Federal and private agencies. A substantial part of such support comes through Federal-grant research funds which are administered by the Department of Agriculture through the Cooperative State Research Service of the Department.

This Service has the responsibility for seeing that the funds are expended as intended by Congress and providing such technical assistance as may be requested. This assistance includes reviews of Federal-grant research and coordination of research effort among states. Generally, the States also submit non-Federal grant research projects for these reviews.

The agricultural research conducted or directed by U.S.D.A. agencies is divided among several agencies. The Agricultural Research Service accounts for the bulk of the Department's research effort and is the Federal research activity most apt to be of help in extraterrestrial agricultural problems. However, the research program of the Forest Service may also offer some solutions.

There is also considerable agricultural research information exchanged with other countries through participation in international meetings, publications, exchange students, scientists, etc.

Coordination and Information Retrieval

The coordination of Department research is delegated by the Secretary to the Director of Science and Education. Research projects are documented by one- to three-page project outlines which are coordinated by the Central Projects Office of the Department. Recently these projects, along with those of the State Experiment Stations, have been brought together in one file with each project abstracted on a separate card. This file has been reproduced in sufficient quantities for each of the 53 Experiment Stations, some libraries of the Department, and the Science Information Exchange. I have no recent count but I would estimate that there are more than 15,000 cards in this file.

Major headings are listed in Appendix Chart A. Subheadings of some of these will cover a complete page. As might be expected, several subheadings are cross-referenced to subheadings of other areas. All but 7 of the 32 major areas are starred as having the possibility of contributing something to the solution of extraterrestrial problems. Entomological research for instance, might be questioned but one's imagination does not have to be too great to detect the possibility (perhaps remote for now) that basic physiological studies of how insects respond to sound may lead to a new method of extraterrestrial communication.

Agriculture has successfully worked with Defense in the development of flameproof clothing and the development of dehydrated and compressed foods. The Soil Tillage Laboratory within the Engineering group has been used in research in predicting soil trafficability for military vehicles and more recently for predicting traction on the moon. Crop and Animal research has attained the degree of refinement where close attention is being given to the role of environmental factors on growth, and the methods by which plants and animals adapt to environment. The following examples of CO_2 research with plants is an example of the former and that of animal dissipation loss as an example of the latter.

Effect of CO_2 on Plants

Miller (1) attributes early work with CO_2 and plants as beginning in 1772 by Priestly, Ingen-Housz, Senebier, and DeSaussure but that there was no further activity until 1860 when Sachs (2) was given credit as the first to report chloroplasts as the organs concerned with the appropriation of CO_2.

Interest in CO_2 enrichment of greenhouse atmospheres appears to have begun in Europe in the early 1900's. It has only been relatively recently that U.S. activity has increased in this specific area of interest. My attention was drawn to it through a project at the State of Washington Agricultural Experiment Station (3) where Federal research engineers were brought into the research effort. Their results showed head weights of lettuce to increase progressively with each successive level of increased CO_2 concentration. At 400 ppm (0.04% CO_2) head weights averaged 73 grams; at 800 ppm, 143 grams; 1200 ppm, 189 grams, and at 1600 ppm, 207 grams. Dry ice was placed in high pressure tanks as a source of CO_2 and metered into plastic greenhouses. Gas concentrations were monitored and controlled through an infrared gas analyzer (4). In other tests at this station the average weight of okra plants was about four times greater in beds with 1600 ppm than in beds with 400 ppm exposure.

Wittwer and Robb at Michigan State University have been very active in this area of work, too. They prepared an excellent historical review of CO_2 enrichment studies (5). They conducted experiments with lettuce, tomatoes, and cucumbers. The range of CO_2 was 125 to 500 ppm in one greenhouse and 800 to 2000 ppm in the other. Two levels of light intensity were used (500 foot candles and 1500 foot candles). The higher level of CO_2 resulted in a 50% greater weight of lettuce at the lower level of light and more than doubled weights at the higher level of light. Tomatoes were also raised under these two ranges of CO_2 concentration with increased yields of 25 to 58 percent reported. As might be expected, there were definite varietal differences among the responses. However, that which is of interest to me is that these gains were made with varieties developed under a selection process with the lower level of CO_2. We should be able to attain even greater increases if we make genetic selections in atmospheres of high CO_2. Cucumbers, although not a probable candidate for extraterrestrial propagation, also showed marked productive gains with increased CO_2(6). Other literature reveals that the following plants have also shown increased productivity through CO_2 enhancement of atmospheres; peas, potatoes, strawberries, Kohlrabi and several species of flowers. As I reviewed the literature in this area, I wondered what the upper limits would be. One text suggested that 10,000 ppm (1.0% CO_2) would be the upper limit. However, Lake (7) reported no harmful effects on tomatoes at 30,000 ppm (3.0% CO_2).

Heat Dissipation of Animals

Although I am not currently a proponent of using animals as a food source in an extraterrestrial environment, the possibility does exist. All farm animals and poultry that are used as a source of food are homeothermic and their ability to dissipate (or conserve) heat under various environmental conditions is a key to their productive efficiency. Recently, considerable agricultural research effort has been placed on the effect of environment on animal growth and the means by which animals adjust to their environment. Dairy cows when under full feed dissipate between 4100 and 2900 Btu/hr./1000 lbs. of body weight with the greater values at 10°F air temperature, and smaller values at 80°F (8). At 100°F, they have been found capable of dissipating nearly 100% of their heat production by evaporative means with up to 70% from external body surfaces (9).

Swine heat production when under full feed has been reported (10). Current research at Davis, California is determining the role of evaporative cooling in swine heat dissipation process.

Information on poultry heat production with a variety of environmental conditions are now available (11). Values vary considerably with temperature as well as among strains and breeds. Limited research indicates that chickens may be rather effective in the dissipation of their body heat through radiation.

Summary

The intent of this presentation is to alert the space scientist to agricultural research as a resource for solving problems of extraterrestrial food production. The general organization for agricultural research within the United States and a discussion of the range of activities that are being conducted is given. Included are some specific examples of research that might have direct application to space problems. For example, recent studies on the effect of CO_2 concentration on vegetables have shown head weight of lettuce to increase progressively with each successive level of CO_2 concentration. The levels of exposure were 500, 800, 1200, and 1600 ppm. The average weight of okra plants were about four times greater in beds with 1600 ppm of CO_2 than in beds with 400 ppm exposure. Rates of heat dissipation and the identification of the method in which it is dissipated are subjects of some of the animal research. Skin vaporization has been identified as an important means of heat dissipation among animals previously considered as "non-sweating."

Appendix Chart A

Agricultural Research Areas as Recorded in
Central Projects Office File

Area Nos.	
11*	Agronomy - Field Crops
13*	Agronomy - Forage Crops
15*	Agronomy - Range
21*	Animal Science
23*	Botany
25*	Botany - Plant Pathology and Microbiology
27*	Botany - Plant Physiology and Nutrition
31*	Chemistry and Physics
35	Communications
37*	Dairy Science
39*	Economic Zoology
41	Economics - Consumption and Household
43	Economics - Income Resources and Adjustment
45	Economics - Marketing
47*	Engineering
51*	Entomology
53	Family Housing, Household Equipment and Processes
55*	Food Science and Technology
63*	Forestry
65*	Genetics
67*	Horticulture - Fruits and Nuts
69*	Horticulture - Ornamental, Drug and Special Crops
71*	Horticulture - Vegetables
75*	Human Nutrition

77*	Meterology and Climatology
81*	Poultry Science
85	Rural Sociology and Family Life
87*	Soil Science
89*	Textiles and Clothing
93*	Veterinary Science
95*	Weeds
98	Administration

* Starred items are those that may contain projects having some application to extraterrestrial problems.

Area Nos.

65*	Genetics
67*	Horticulture - Fruits and Nuts
69*	Horticulture - Ornamental, Drug and Special Crops
71*	Horticulture - Vegetables
75*	Human Nutrition
77*	Meteorology and Climatology
81*	Poultry Science
85	Rural Sociology and Family Life
87*	Soil Science
89*	Textiles and Clothing
93*	Veterinary Science
95*	Weeds
98	Administration

* Starred items are those that may contain projects having some application to extraterrestrial problems.

References

1. Miller, Edwin C., 1938, Plant Physiology, p. 155. McGraw-Hill, New York

2. Sachs, J., 1862, Uber die Auflosung und Wiederbildung des Amylums in den Chlorophyllkornern, Bot. Ztg., 20: 365-373

3. Matson, W.E., Pettibone, C. Alan. Ackley, W. B. and Haynes, Gary D., Control of Carbon Dioxide Content in an Air Supported Plastic Greenhouse, Dec. 1964, Progress Report, Washington Farm Electrification Committee.

4. Pettibone, C.A., Matson, W E., and Ackley, Control of Carbon Dioxide Content in an Air-Supported Plastic Greenhouse, Jan. 1964, ARS 42-92, U. S. Department of Agric.

5. Wittwer, S. H. and Robb, Wm., Carbon Dioxide Enrichment of Greenhouse Atmospheres for Food Crop Production, Jan.-March 1964, Vol. 18, Economic Botany.

6. Hopen, Herbert J., Environmental Factors Affecting the Growth of Cucumis Sativus L., with Special Reference to Carbon Dioxide, 1962, PhD Thesis, Michigan State University

7. Lake, J.V., Try CO_2 for the Summer Crop, 1963, The Grower, 59 (15), pp. 765-766

8. Yeck, R.G., and Stewart, R.E., A Ten-Year Summary of the Psychroenergetic Laboratory Dairy Cattle Research at the University of Missouri, 1959, Transactions, American Society of Agricultural Engineers

9. Thompson, H.J., McCroskey, R.M., and Brody, Samuel, VIII. Influence of Ambient Temperature, 0° to 105°F on Insensible Weight Loss and Moisture Vaporization in Holstein and Jersey Cattle, Oct. 19'9, Res. Bul 451, University of Missouri, p. 13

10. Bond, T.E., Kelly, C F., and Heitman, Jr., Hubert, Heat and Moisture Loss from Swine, Mar. 1952, Journ. Agricultural Engineering, pp. 148-152, 154

11. ASHRAE Guide and Data Book, Chapter 8: Environmental Control for Animals and Plants--Physiological Considerations, p. 122, 1965-1966

Next we have two technical notes, covering specific topics of interest to this session. The first reports the findings of a study conducted by Mr. Stephen Dole, Head of the Human Engineering Group with the Rand Corporation, Santa Monica, California. This study concerned the Weights of Environmental Control Systems proposed for Extraterrestrial Applications.

Mr. Dole is well known for his published study reports on environments suitable for human occupation, both natural and synthesized. One of his latter publications concerned habitable planets for man.

WEIGHTS OF ENVIRONMENTAL-CONTROL SYSTEMS

S. H. Dole

The purpose of this paper is to present some generalized relationships that can be used for estimating the weights of environmental-control equipment and expendables required for supporting human beings on space missions.

It may not be obvious how this information relates to the exploitation of extraterrestrial resources. However, most of the kinds of operations with which we are concerned in the Working Group require the active participation of human beings. And of course human beings need life support. So it is important to know what weight penalties are associated directly with the use of people. In other words, how much does it cost in weight to keep a man going--and how would this affect the economics, for example, of extracting useful products from lunar surface materials.

The weight relationships I am going to present are based on a recently completed analysis of practically all of the principal spacecraft studies conducted by aerospace companies during the past three or four years. In each case for which data could be obtained we attempted to extract from contractors' reports the weights of the environmental-control systems. These were further broken down into dry weights and weights of expendables. In our terminology dry weights consist of weights of equipment used in environmental-control systems, while wet weights are total weights of equipment plus expendables such as food, oxygen, atmospheric nitrogen, water, and emergency supplies. Dry weights are useful in making cost estimates, and wet weights are necessary inputs for preliminary design and for determining overall mission requirements.

In any such analysis of weights from a large number of different contractors, it is very important that all the data be placed on the same basis. To this end a set of definitions were adopted and adhered to strictly as possible.

ECS Dry Weights

Under our definition, the dry weight of the environmental-control system includes those specific items of equipment employed in (1) breathing-gas supply, (2) carbon dioxide removal, (3) humidity control, (4) trace contaminants removal, (5) fresh water supply, (6) thermal control, and (7) waste management. It also includes spare parts, equipment and tankage for replacing materials lost through leakage and for providing contingency supplies. Our dry weight does not include the weight of radiation shields or external radiators, nor does it include a prorated weight penalty for electrical power.

Although our survey of environmental-control-system weights covered a wide variety of types ranging from open systems for short missions up to nearly-closed systems for long interplanetary flights, we found that dry weights could be correlated by using a single mathematical expression.

This expression had the form:

$$W_D = A\, N^{\alpha}\, T^{BN^{\beta}}$$

where A, α, B, and β are constants

N = number of men in the crew

T = unresupplied duration of mission in days

and W_D = dry weight in pounds

The constants in the above expression were determined by using a computer program in which calculated values were compared with values obtained from reports. Combinations of the constants were changed until the relative variance reached a minimum, resulting in the equation:

$$W_D = 117\, N^{0.58}\, T^{0.33N^{0.11}}$$

A plot of the final relationship is shown in Fig. 1. It should be emphasized that this is purely empirical and was based primarily on missions involving crews of 2 to 6 men (for which the data were most plentiful), but it also produces dry weight estimates within useful limits for missions requiring larger crews. The range of mission duration is from 1 to 1,000 days and a great variety of mission types were represented--from both brief and extended earth orbital flights, through lunar missions, planetary fly-bys, planetary excursions, lunar base models and reentry. Finally, the range of mission types extends from completely open systems to nearly-closed systems employing oxygen and water regeneration.

This relationship enables one to estimate the dry weight of an environmental-control system from the duration of the mission and the crew size, independent of system type. Implicit in the empirical formula is the assumption that the system has been conscientiously selected to be consistent with the mission, and that total system weight has been minimized.

For the data we had available (23 cases) the mathematical expression produced system dry weights within ± 20 percent of those obtained from contractors' reports in all but 2 instances.

ECS TOTAL WEIGHTS

Total weights of environmental-control systems can be estimated by adding weights of expendables to the dry weights. The expendables include metabolic supplies, reactants, make-up for leakage of atmospheric gases, and metabolic stores for contingencies. For estimating purposes we assumed a leakage rate of 1 lb per man-day and that the length of the contingency period was proportional to the square root of the mission duration.

The final estimating relationship for total ECS weight became

$$W_T = W_D + N(19\ T^{\frac{1}{2}} + 2\ T)$$

where W_D is system dry weight (a function of N and T) as indicated earlier.

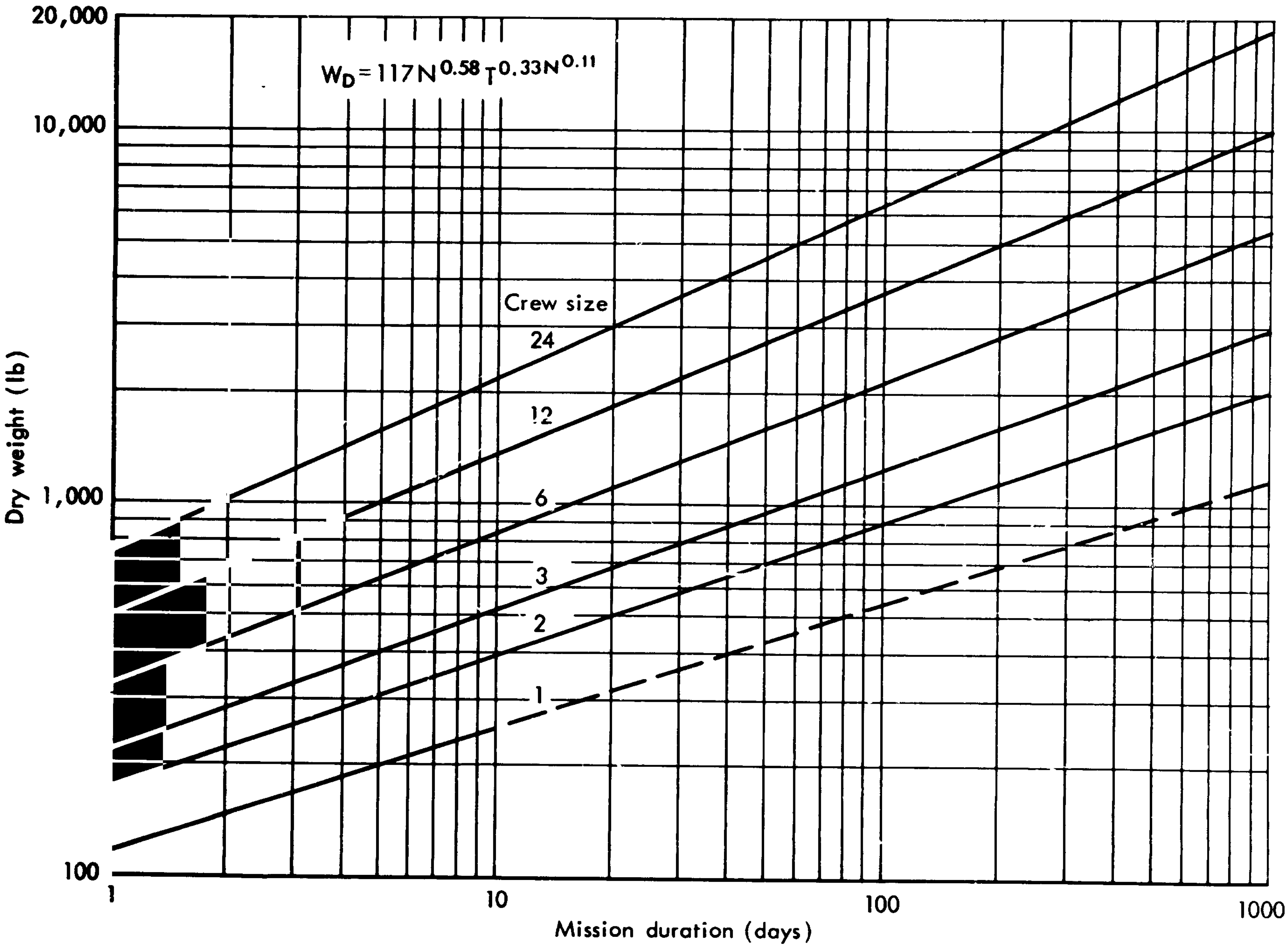
This expression, shown graphically in Fig. 2, produced total weight estimates generally within ± 40 percent of those obtained from contractors' reports in our survey. This is not unreasonable when one considers the great variety of design philosophies embodied in the reported weights, the different assumptions made about leakage rates and contingency provisions, and the fact that some of the reported weights may have contained components, not itemized, that would not be placed in the environmental-control system under our definition.

These relationships are presented for quick estimating purposes when all the details are not available. Clearly because these are empirical correlations they can be no better than the data on which they are based. And at the moment we have no way of knowing whether the weights so estimated are generally optimistic or pessimistic.

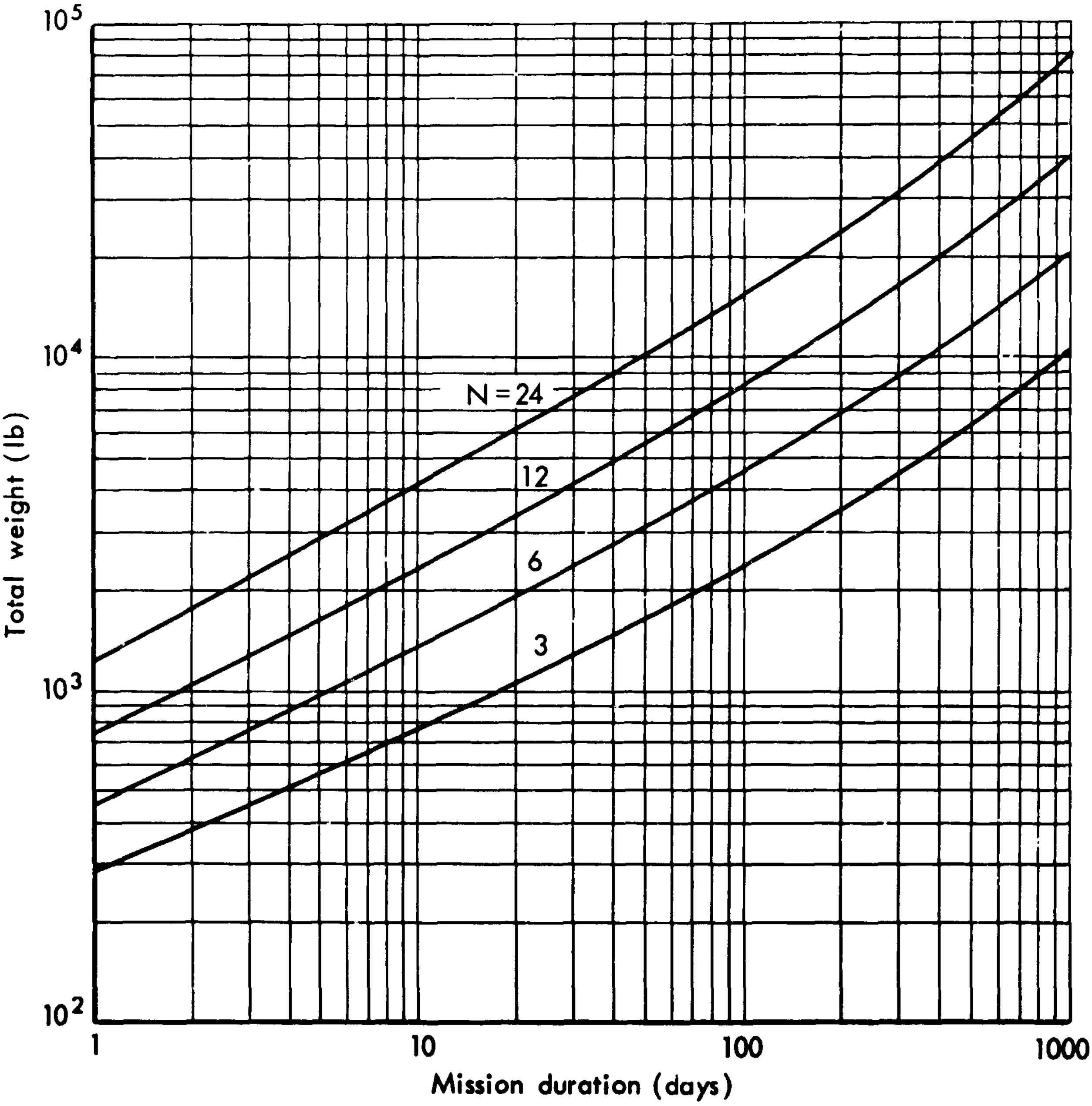
Captions

Fig. 1. Dry Weights of Environmental-Control Systems

Fig. 2. Total Weights of Environmental-Control Systems



$W_D = 117 N^{0.58} T^{0.33 N^{0.11}}$
Crew size
24
12
6
3
2
1
20,000
10,000
1,000
100
Dry weight (lb)
1
10
100
1000
Mission duration (days)



10^5
10^4
10^3
10^2
Total weight (lb)
N = 24
12
6
3
1
10
100
1000
Mission duration (days)

The last presentation, an invited technical note by Mr. Arthur Sullivan will discuss Leakage in Life Support Systems, as a problem in extraterrestrial operations, and proposed solutions insofar as personal protective systems are concerned.

Mr. Sullivan is Assistant Director of the Litton Industries' Space Sciences Laboratories, located in Beverly Hills, California, and is the Acting Manager for Litton's Space Suit program.

Mr. Sullivan is a Mechanical Engineer, having received his Bachelor's degree from Worcester Polytechnic Institute. His background had included work in a large spectrum of problems, from cryogenic processes to control systems logic.

N66 35523

LEAKAGE IN LIFE SUPPORT SYSTEMS

by

Arthur F. Sullivan

This paper briefly considers a small, but nevertheless essential, element of any extraterrestrial exploration activity - - the leakage of gases from life support systems. In particular, we will examine both the logistic and the design consequences of leakage from space suits during extraterrestrial activity.

To date space suits have been characterized by very high leak rates. In spite of the moderate, 3.7 psi, operating pressures employed by the current generation of operational suits, leak rates in excess of 160 scc/min are typical. To a reasonable approximation one can, in fact, assume that all of the life support system leakage occurs in the suit. Further, marked increases in suit leakage with wear, and as the result of don/doff manipulations, have come to be accepted as inevitable. Increases in gas losses resulting from wear generally range from 50 to 100% during the useful life of current suit types.

LOGISTICS

To place in realistic perspective the logistics problem posed by leakage of such magnitude consider a mission comprising a total of 25 extraterrestrial sorties, each of 6-hour duration. Although intended to represent no particular mission, these numbers are certainly typical of early lunar exploration efforts. If we further assume an average leak rate as high as 360 scc/min from the suits used in this exploration, (based on an estimate of leakage increase due to wear) a loss of more than half a pound of oxygen can be expected for each 6-hour mission.

There are several ways by which the overall effects of this loss may be placed in perspective. The most direct consequence of such leakage is manifested in the primary oxygen storage subsystem. Nearly 9 pounds of additional oxygen will be required to compensate for the leakage during twenty missions. If the primary oxygen system stores a total of 150 lbs of oxygen in the supercritical state, the tankage weight can be expected to increase by approximately 3 lbs to contain the added oxygen. When this 12-lb penalty is reflected back to the first stage boost vehicle, a one to two-ton increase in lift off weight can be identified.

Certainly the problem is not really as straightforward as the previous weight bookkeeping suggests. The lunar explorer must carry oxygen, or a means of producing oxygen, with him during his explorations. Metabolic oxygen consumption averages 0.20 lbs/hr, and peaks at 0.26 lbs/hr. The current Apollo back packs have been designed for 3-hour operation (plus a 1-hour contingency, plus a 20-minute emergency O_2 supply). Most of us are sufficiently familiar with the weight and bulk of these back packs as to be impressed by the difficulty involved in simply extending this capability to six hours. When one considers the fact that a 360 scc/min gas loss is the equivalent in oxygen consumption of more than two hours of normal extravehicular operation, an appreciation emerges for the added difficulty imposed by suit leakage.

In the absence of more detailed insight into the specifics of the actual life support system to be used for the lunar mission, these difficulties can only be expressed in general terms. Our current experience suggests that overall bulk limitations and center of gravity considerations will continue to govern the design of extravehicular life support systems. If suit leakage, coupled with metabolic penalties imposed by pressure suit characteristics[1] makes it impossible to conduct sorties of 6-hour duration, the impact of this restriction will be of greater overall consequence than the previously cited arithmetic has indicated. Taken to the most pessimistic extreme, the compounding of such negative factors can lead to the requirement for two separate missions to perform the exploration task initially assigned to one.[2,3]

With this brief description of the logistics problem, let me now state that the ongoing hardsuit development has progressed so that leakage has been reduced below that of contemporary space suits by an order of magnitude. The 1963 vintage RX-1 Litton suit employed a soft hip section and exhibited a 52 scc/min leakage which degraded to 68 scc/min after three months of extensive use. The following generation, RX-2, suit incorporated a hardened (rolling convolute) hip section, with consequent reduction of total leakage to 24 scc/minute. Reproducibility of these results is indicated by the fact that a second RX-2 model, produced by retrofitting the RX-1 with a hard hip section, displayed a 25 scc/min total leakage.

In these hard suit prototypes several design approaches have been combined to produce such gratifyingly low gas loss rates, as well as the ability to sustain considerable use and wear without appreciably increasing leakage. In brief, this performance can be variously attributed to: extended areas of hard, impervious, shell sections; controlled, rolling deployment and retraction of fabric articulations supported against smooth structural members; pre-loaded pressure-actuated rotary seals; fixed-geometry, compression-type body closure devices.

Performance of suit components in life tests has been excellent, as typified by the RX-2A knee assembly whose leakage increased from 1.7 scc/min to 2.0 scc/min following 19,000 cycles of simulated operation.

DESIGN

The articulations and dynamic seals required for any space suit will assure the existence of some leakage. With good engineering practice the logistic implications of such leakage can be minimized. But, if biological contamination of a planetary environment must be avoided, one cannot look toward the attainment of zero suit leakage as a reasonable approach. With Mars in the process of being declared a biological preserve, it is appropriate to speculate on the possible configuration of a Mars exploration suit.

Clearly, if micro-biological contamination of the Martian environment by suit leakage is to be avoided, it will be necessary to collect the effluent and sterilize it prior to discharge, or store it for later treatment. Thus, as shown in Figure 1, an overgarment will be required. Out-leakage can be eliminated by evacuating the volume between the overgarment and the space suit outer surface below the local atmospheric pressure. The garment must be nonporous, articulated to minimize restraint, resistant to sterilizing chemicals and the high-velocity windborne particles characteristic of the Martian surface. While the overgarment presents appreciable design and development difficulties, it should be apparent that the most demanding problem arises from the necessity to continuously evacuate the volume within the overgarment.

As the result of a current study of the various means by which such evacuation could be accomplished, Litton favors a cryopumping approach. Figure 2 schematically outlines this pumping concept; and Figure 3 presents typical performance parameters for a closed-cycle cryogenic refrigerator employed in this service. The cryopump concept is attractive because; pump and storage functions are combined in a simple device; all portions of the system are sub-atmospheric; and pressure beneath the undergarment can easily be regulated by temperature adjustment.

Recent developments in the field of small reliable cryogenic refrigerators are sufficiently encouraging to suggest their use in this application. Figure 3 presents an extrapolation from the current performance of a 77°K Arthur D. Little, Inc. prototype unit. It should be clear from this tabulation that a severe weight and power penalty would be imposed on a Mars suit system if a closed cycle refrigeration subsystem were used in the effluent cryopump.

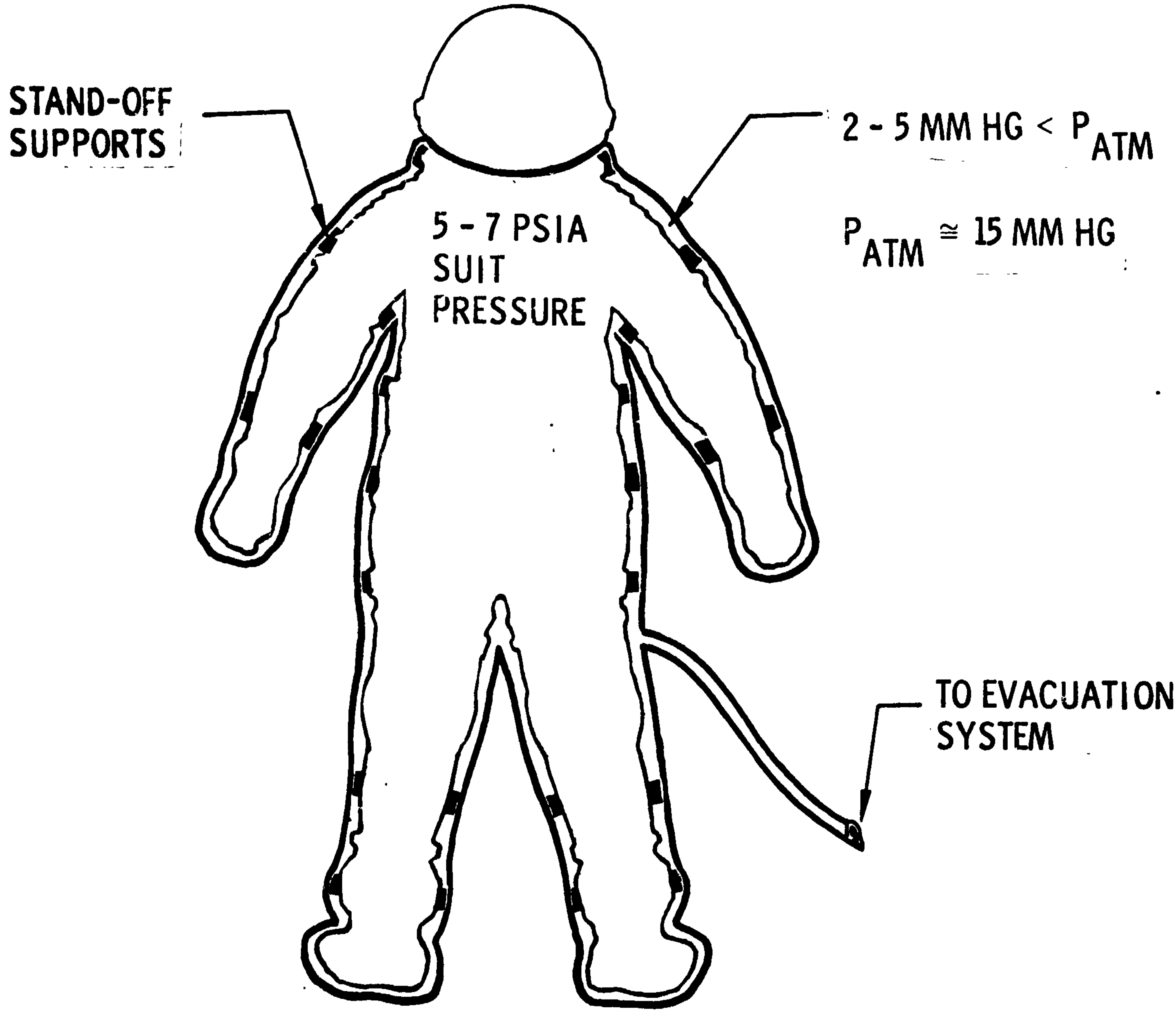


Figure 1. MARS Suit Overgarment

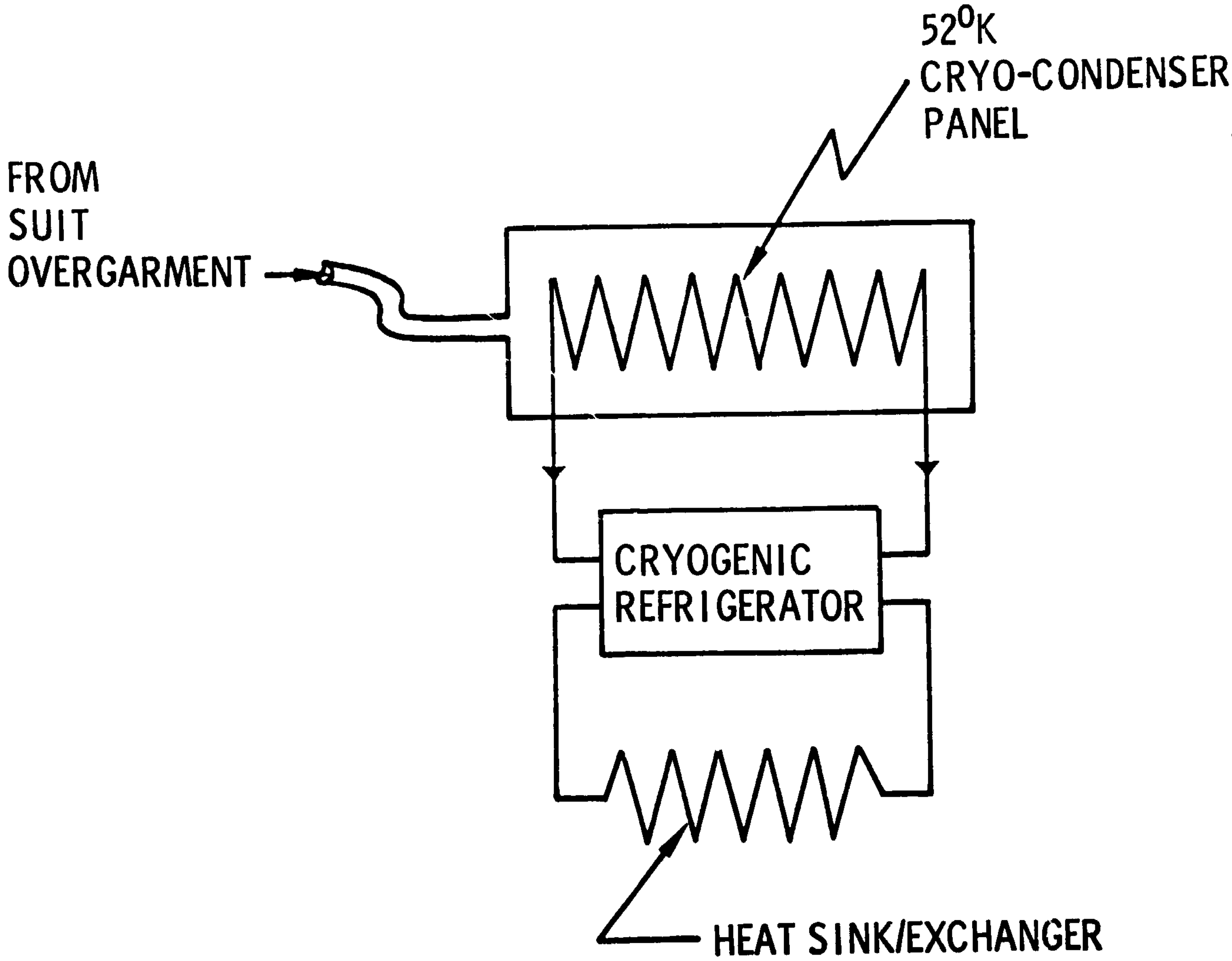


Figure 2. Cryogenic Gas Collection System

ASSUME — PRESSURE = 10 MM Hg

TOTAL LEAKAGE = CONDENSATION RATE = 50 SCC/MIN (N_2)

REQUIRED REFRIGERATION = 2 WATTS AT 52^{O}K

EST. REFRIGERATOR WT. = 20 LBS

EST. WT. OF HEAT SINK = 5 lbs

INPUT POWER REQUIREMENTS = 175 WATTS

Figure 3. Crycgenic System Description

Fortunately an alternative is available, and open cycle refrigeration techniques are well suited to this service. For example, 1 lb of liquid hydrogen - which occupies less than 1/4-ft^3 - will provide more than 200 BTU heat sink capability in vaporizing at 22°K. In a reasonably well insulated system this heat absorption capability corresponds to the solidification and storage of 50 scc/min of suit effluent for a period in excess of one day. When one considers the high probability that, by the time Mars exploration is initiated, hydrogen will be required to supply a suit-mounted fuel cell, the use of hydrogen for open-cycle refrigeration in an effluent pumping and storage subsystem becomes quite reasonable and efficient.

In summary, the leakage of gas through space suits presents very real contraints on extraterrestrial missions if the performance of contemporary or "soft" suits is used as a criterion. Whether viewed from the standpoint of logistics, or related to the problem of preventing planetary contamination, the leakage characteristics of space suits is an important consideration in planning extraterrestrial missions. The hard suit prototypes, despite their pressurization to nearly 70% higher pressures than contemporary suits, have demonstrated an order of magnitude reduction in leakage. It seems clear that the need for maintaining these low leak rates will persist well into the planetary exploration phase of our space program.

References:

1. deGraeve, E., "Applications of the Constant Volume Hard Pressure Suit to Future Space Programs ,"third annual meeting, Working Group on Extraterrestrial Resources, Nov. 1964.

2. Streimer, I., and Wendrow, B. "The Implications of Space Crew Physical Fitness Maintenance to System Design," Jour. of the Astronautical Sci. Vol. XII, No. 1, pp 27-29, Spring 1965.

3. Streimer, I., and Wendrow B. "Effects of Variations in Operator Output Characteristics on Space Logistics," SID 64-1425, July 1964.

N66 35524

PROJECT SUPER

By

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Presented At

Fourth Annual Meeting
of the Working Group on Extraterrestrial Resources
Air Force Academy
Colorado Springs, Colorado

1 December 1965

PROJECT SUPER

1stLt Michael V. Vasilik, USAF

Introduction

The purpose of this paper is to describe a program which should be of extreme interest to United States Air Force and National Aeronautics and Space Administration personnel involved in extraterrestrial research. The name of the program is SUPER, which stands for Support Program for Extraterrestrial Research. Basically, it is a joint effort between the NASA-Marshall Space Flight Center (MSFC) at Huntsville, Alabama, and the Air Force to more effectively utilize Air Force and NASA research and development capabilities for extraterrestrial and space-oriented research.

Objectives

The objectives of SUPER are threefold:

1. To assist NASA through Air Force participation in advanced extraterrestrial studies and research programs. For example, in many cases the Air Force is conducting projects in its labs which are of interest to NASA. With a slight reorientation of the project, and a minimum of additional funds and manpower, NASA objectives could also be met.

2. To increase Air Force technology by remaining abreast of NASA research programs, and thus facilitate identification of extraterrestrial military potentials. In many cases, the Air Force may not yet have a definite mission in a certain area, but in the future a military potential may be defined.

3. To more effectively utilize the nation's resources in the national space program. By allowing utilization of the resources of both agencies, the program will fulfill both NASA and Air Force requirements at a lower cost, thereby allowing more research per dollar.

General Concept

At present, there are two types of SUPER projects: those conducted in Air Force labs with NASA supplying funds, and those conducted in NASA labs with the Air Force supplying funds. As an example of the former, NASA provides funds to Air Force laboratories and centers for the following items:

1. Supplemental contract costs (consultant fees, computer services, outside contracts to supplement in-house work, etc.)
2. Materials and supplies
3. Facility modifications peculiar to a project
4. New equipment peculiar to a project
5. Travel costs

The Air Force provides costs associated with manpower and existing facility and equipment utilization.

The funding arrangement described here is reversed if the Air Force provides funds for work conducted in NASA labs.

Background and Organization

Project SUPER was conceived by the Air Force in late 1962 following a Department of Defense directive covering Air Force support to NASA for space programs. In July and August, 1963, Dr. Von Braun and his technical staff at MSFC visited various Air Force centers and labs in order to ascertain the capabilities and availability of Air Force facilities. At the same time, his staff briefed the Air Force on MSFC interests and capabilities. Following these visits, an agreement was reached with MSFC, and on 4 Oct 63, a letter from Air Force Systems Command (AFSC) established the project.

A Coordinating Board was initiated with overall responsibility for establishment and direction of the project. The board consists of three Air Force and three NASA members and is jointly chaired by an Air Force and a NASA member. Research and Technology Division (RTD) was designated as the lead division for AFSC and was responsible for managing the project. Because of its proximity to MSFC and extensive aerospace environmental facilities, Arnold Engineering Development Center (AEDC) was designated as the focal point for RTD. In this capacity AEDC is responsible for daily management of the project and maintains liaison of contact points at all participating AFSC and Office of Aerospace Research units with MSFC (see Fig. 1).

Project Procedures

Figure 2 illustrates the cycle normally used for initiation of a SUPER project. Either the Air Force or NASA may propose a project. In the case illustrated, a preliminary proposal is made by MSFC and submitted to the Cochairmen acting for the board or can be submitted directly to the SUPER office at AEDC, who will in turn coordinate it with the Cochairmen. After review by the Cochairmen, the AEDC SUPER office forwards the proposal to the appropriate Air Force organization. If the laboratory is interested and the project is approved, a proposal including staffing plans, funding requirements, scheduling, etc. is forwarded to the SUPER office at AEDC. The proposal is then forwarded to the Air Force Cochairman of the SUPER board, who, after reviewing the proposal, refers it to MSFC (NASA Cochairman) for acceptance and preparation of a final statement of work with a purchase request in the amount of funds agreed upon. Any difference between the final statement of work and the proposal are resolved by the Air Force/NASA technical personnel concerned before issuing the final statement of work. The SUPER office at AEDC keeps abreast of the projects and renders assistance in resolving problems of an administrative nature.

Projects

Figure 3 lists the original nine SUPER projects which were initiated in FY 64. Seven of these projects have been extended and are still being conducted today, thus attesting to the satisfaction of both the Air Force and NASA.

Figure 5 gives an overall summary of the present status of SUPER projects. The total funds involved are about

$900,000 for the Air Force and $300,000 for NASA. However, these figures are misleading since many of the projects were already being conducted and funded by the Air Force when NASA became interested.

None of the present projects listed in Figure 5 are being conducted in MSFC laboratories. However, in the past the Manufacturing Engineering Lab at MSFC has coated nozzles and MHD accelerator walls for AEDC. The anodization and plating processes required were highly advanced, and in accomplishing this work NASA experimentally developed their coating techniques while the Air Force also gained.

Future Trends

In order to more effectively carry out the SUPER program and to provide means for its expansion, several approaches are currently being studied or implemented. There are:

1. Exchange of Research Programs - A formal means of exchanging research programs and interests between the Air Force and NASA is needed. One possibility is the computer program currently being implemented by Defense Documentation Center which will allow retrieval of any research project being conducted by the Air Force on a work unit level (DD Form 1498, "Research and Technology Resume).

2. Annual SUPER Meeting - Each year an Annual Air Force/NASA SUPER Meeting is held. The objectives are to:

a. present proposed extraterrestrial research projects

b. create interest in areas for future Air Force/NASA participation on possible SUPER projects.

The next meeting will be held early in May, 1966, at AEDC. A month prior to the meeting the Air Force and NASA extraterrestrial research projects proposed for FY 67 will be exchanged, if possible. Also, laboratory information about mission and interests will be circulated in order that presentations may be tailored to specific interests.

3. Research Reviews - MSFC has initiated a monthly lecture series whereby each laboratory reviews its progress and research achievements for the past year. The Air Force has been invited to attend these lectures.

4. Jointly Funded Outside Research - Methods are being investigated whereby when NASA and the Air Force have a common interest in an area, but do not have the capability to accomplish the effort in-house, it will be conducted by an outside organization (industry or university) and jointly funded and directed by the Air Force and NASA. An example is a project currently under study for solar simulation source development which is of interest to NASA-Manned Spacecraft Center and AEDC.

5. Other NASA Center Participation - Consideration is being given to extending the SUPER Program to other NASA centers which have shown interest in the project. One possibility is to organize the NASA units parallel to those of the Air Force, where Headquarters NASA would be the lead NASA organization for SUPER, and MSFC would be the focal point for contact with the Air Force.

Conclusions

Project SUPER can never become a vast program because of the nature of the ground rules under which it was established. The Air Force and NASA interests and objectives must overlap such that mutual objectives can be achieved at a lower cost than if the projects were conducted separately. In this way, SUPER enables both the Air Force and NASA to carry out more extraterrestrial research per dollar, and this economic factor is becoming increasingly important as the war in Vietnam escalates and research money becomes more scarce.

The importance of SUPER is that it is a national effort to provide maximum utilization of the nation's resources in support of the national space program.

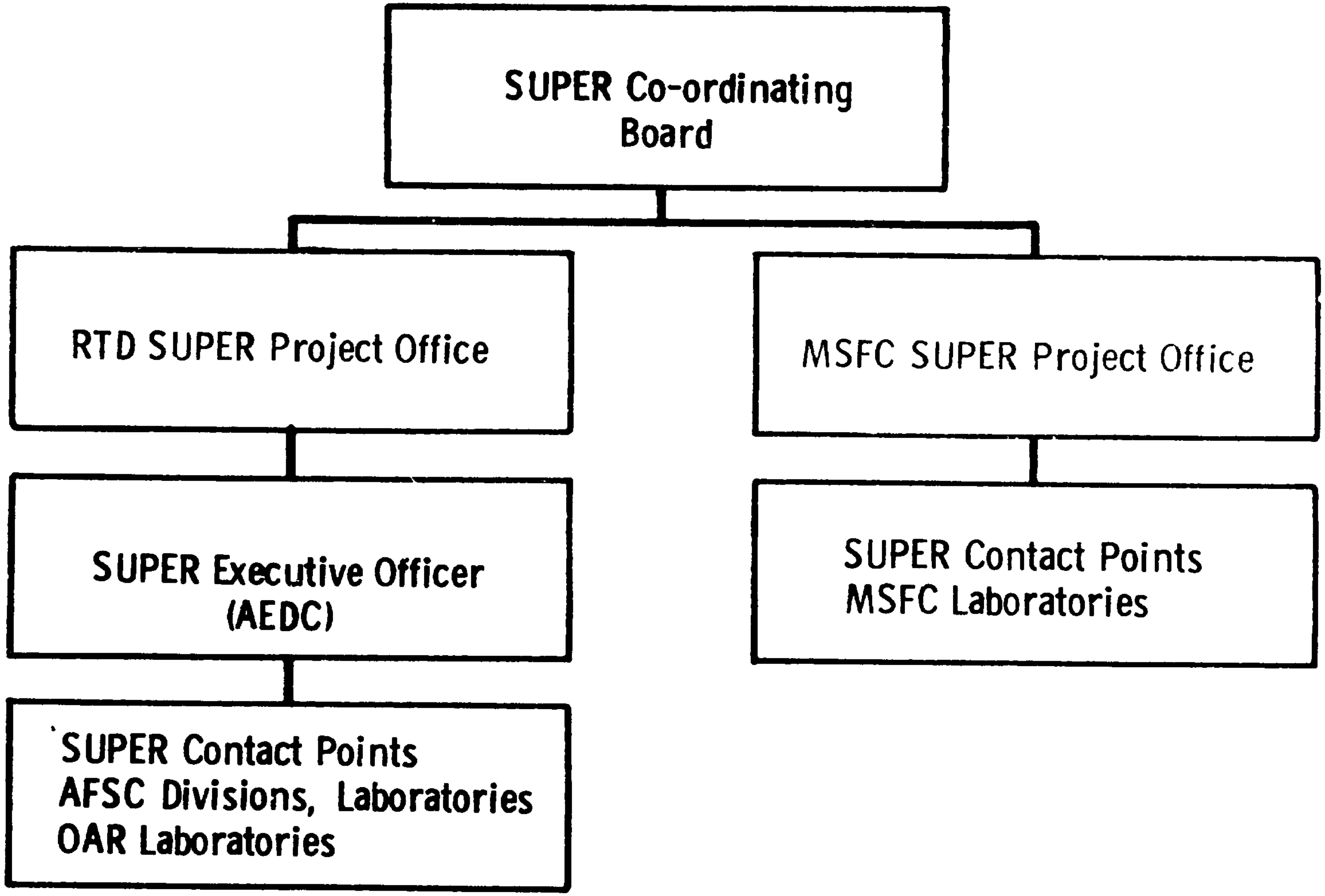

Fig. 1 SUPER ORGANIZATION

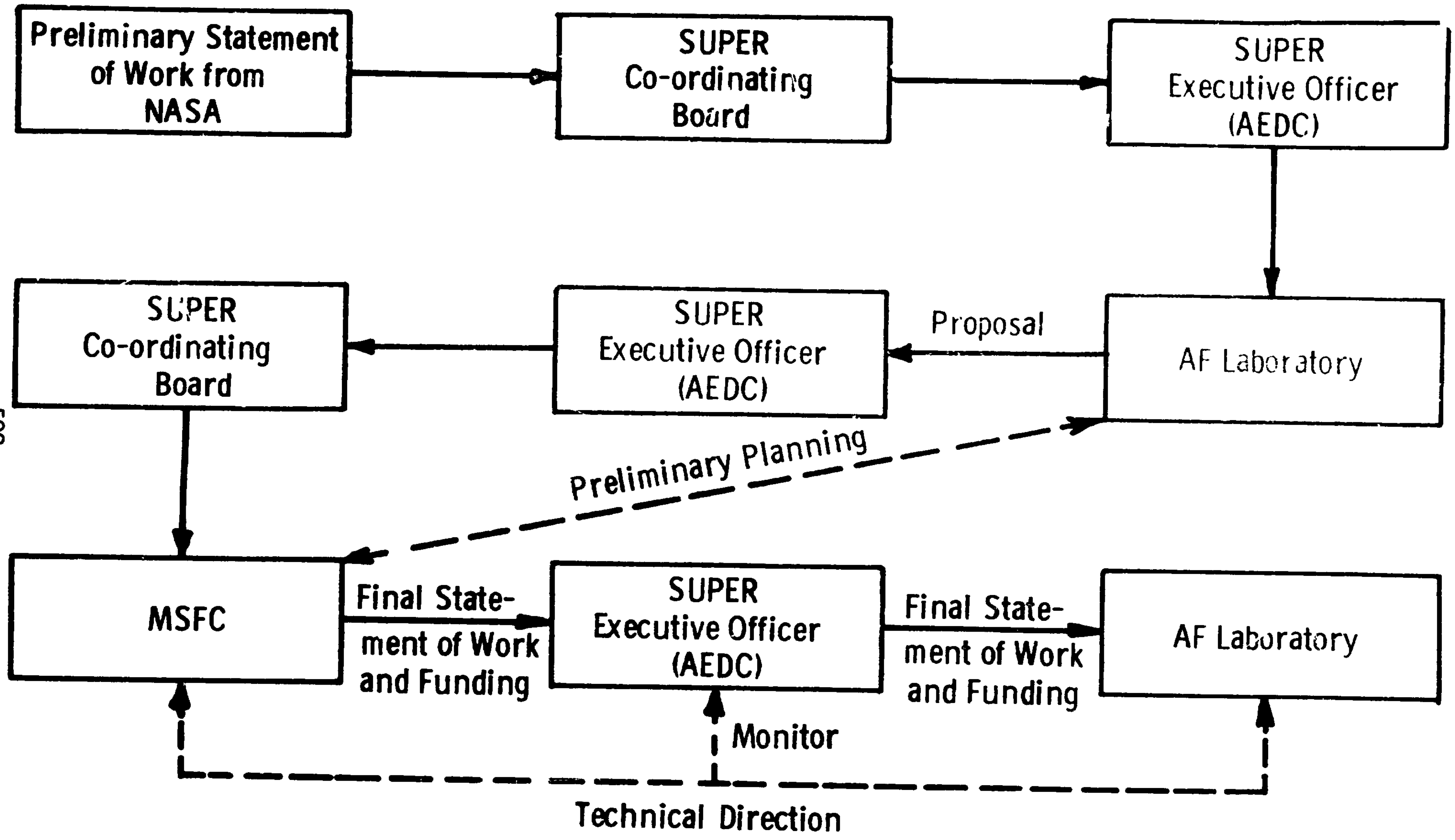

Fig. 2 SUPER OPERATIONAL PROCEDURE

Research Project	Performing Organization
- Hypervelocity Impact Data for Cratering	Arnold Engineering Development Center
- Measurement of Gas Density by Radiation Scattering	Arnold Engineering Development Center
- Thermal Radiation Measurement Technology	Arnold Engineering Development Center
- Thermal Similitude Testing	Arnold Engineering Development Center
- Thermal Testing Techniques	Arnold Engineering Development Center
- Conceptual Study for Model Test Facility	Arnold Engineering Development Center
- High Vacuum Adhesion Investigations	AF Cambridge Research Lab
- Self-Sealants for Spacecraft	AF Materials Lab
- Thermal Control Surfaces for Spacecraft	AF Materials Lab

Fig. 3 SUPER RESEARCH PROJECTS INITIATED IN FY 64

Research Projects	Performing Organization
- Crew Seating and Restraint Systems for Lunar Surface Vehicles	AF Flight Dynamics Lab
- Vehicle Systems Failure Analysis	Space Systems Division

* Most of the FY 64 projects were extended in time, scope, and funds by AF and NASA.

Fig. 4 SUPER RESEARCH PROJECTS INITIATED IN FY 65

FIG. 5 **STATUS OF ACTIVE SUPER PROJECTS (AS OF 1 NOV 1965)**

SUPER PROJECT AND TASK NO.	MIPR NO. (AEDC PROJ. NO.)	LOCATION	AF PROJECT CONTACT	NASA-MSFC TECHNICAL SUPERVISOR	NASA DOLLARS ALLOCATED	AF DOLLARS ALLOCATED	% COMPLETE	PERIOD OF PROJECT	REMARKS
Hypervelocity Impact Data for Cratering 951404	H-66022 (VS-1443)	AEDC-VKF	J. J. Payne VKF-A	Robert J. Naumann or O. K. Hudson R-RP-P	$22,825.	$104,175.	48	FEB 64 - 4 FEB 66	Provide cratering data on materials useful for space applications and develop a theoretical model for impact and cratering processes.
Thermal Similitude Testing (Use of Thermal Models for Environmental Testing) 951406	H-71483 (SAO-412)	AEDC-AEF	D. L. Adkins AEFR	J. K. Harrison or B. P. Jones R-RP-T	$30,000.	$76,680.	65	APR 64 - 31 DEC 66	Investigate use of thermal scale models by which temperature measurements obtained in space environmental chambers on the models can be interpreted to determine thermal conditions in actual size space vehicles.
Spectral Measurement of Radiation in Space Chambers 951407	H-71459 (SW-2515)	AEDC-AEF	D. Frazine AEFI	Billy J. Duncan R-RP-J or B. P. Jones R-RP-T	$16,000.	$53,968.	15	1 APR 65- 30 AUG 66	Improve techniques of thermal radiation in space environmental chambers in order to adequately monitor spectral and total intensity radiation to test articles.
Thermal Testing Techniques 951408	H-71460 (SW-3406)	AEDC-AEF	H. Latture AEFR	Billy J. Duncan R-RP-J or B. P. Jones R-RP-T	$15,000.	$140,000.	80	OCT 63 - 30 APR 66	Provide techniques for simulating correct radiant heat flux on test vehicle areas in order to conduct thermal environmental testing without a solar simulator.
Experimental Verification of CNTF Secondary Mach No. 951411	H-92190 (TW-4355)	AEDC-ESF	F. H. Smith ESF	O. K. Goetz or E. J. Conner R-Test-C	$4,000.	$52,825.	60	20 JUN 65- 28 FEB 66	The relationship between steam requirements and secondary Mach number will be experimentally established for design and operation of multistage steam ejector systems.
Thermal Control Surfaces for the Extraterrestrial Environment 951401	H-71465	AFML WPAFB	Harold Hormann or James Mattice AFML (MANE)	E. R. Miller R-RP-T	$42,000.	$150,000.	65	JUN 64 - 31 MAR 66	Develop surfaces with high solar absorptance, α_s, to thermal emittance (ϵ_T) ratio, (about 1-3); develop universal reflector coating ($\alpha_s \approx \epsilon_T < 0.1$).
High Vacuum Adhesion Investigations 951402	H-66039	AFCRL Hanscom Field	J. W. Salisbury AFCRL (CRFL)	H. P. Gierow R-RP-J	$2,900.	----	95	DEC 63 - 1 DEC 65	Investigate the phenomena of dust adhesion, the nature of the bonding forces, and the influence of various parameters such as grainsize and cleanliness.
Investigation of Addition Polymerization of Self Sealants 951403	H-71461	AFML WPAFB	Lt John Spence or R. Headrick AFML (MANE)	L. R. Moffett R-P&VE-MNM	$57,000.	$140,000.	75	MAR 64 - 15 MAR 66	Develop, synthesize, determine reaction mechanics, and test compounds for self-sealing a void created by a moderate velocity particle both at ambient and cryogenic temperatures.
Vehicle Systems Failure Analysis 951410	H-92159	SSD LAAFS	LtCol J.R. Golden R. A. Rodriguez (SSSI)	R. Ray Hitch Jr. or M.P. Miller R-QUAL-OC	$44,369.	$114,573.	45	1 JAN 65 -1 FEB 66	Flight data from space vehicle failures (in-flight and pre-flight) will be analyzed to determine what component caused the mission or system to fail, how the component affected the system, and which check-out procedures should have detected the defect.
Crew Seating and Restraint Sys for Lunar Surface Veh. 951412	H-2101A	AFFDL WPAFB	R. L. Peterson AFFDL	H. T. Grubbs or C. A. Larsen R-P&VE-AL	$80,000.	$80,000.	10	1 JUL 65- 31 AUG 66	Evaluate various crew seating and restraint systems from which crew-station design will be evolved for applications to AES vehicles including the Local Scientific Survey Module (LSSM), the Lunar Flying Vehicle (LFV), and the Mobile Laboratory (MOLAB).
				TOTAL	$314,094	$912,221			

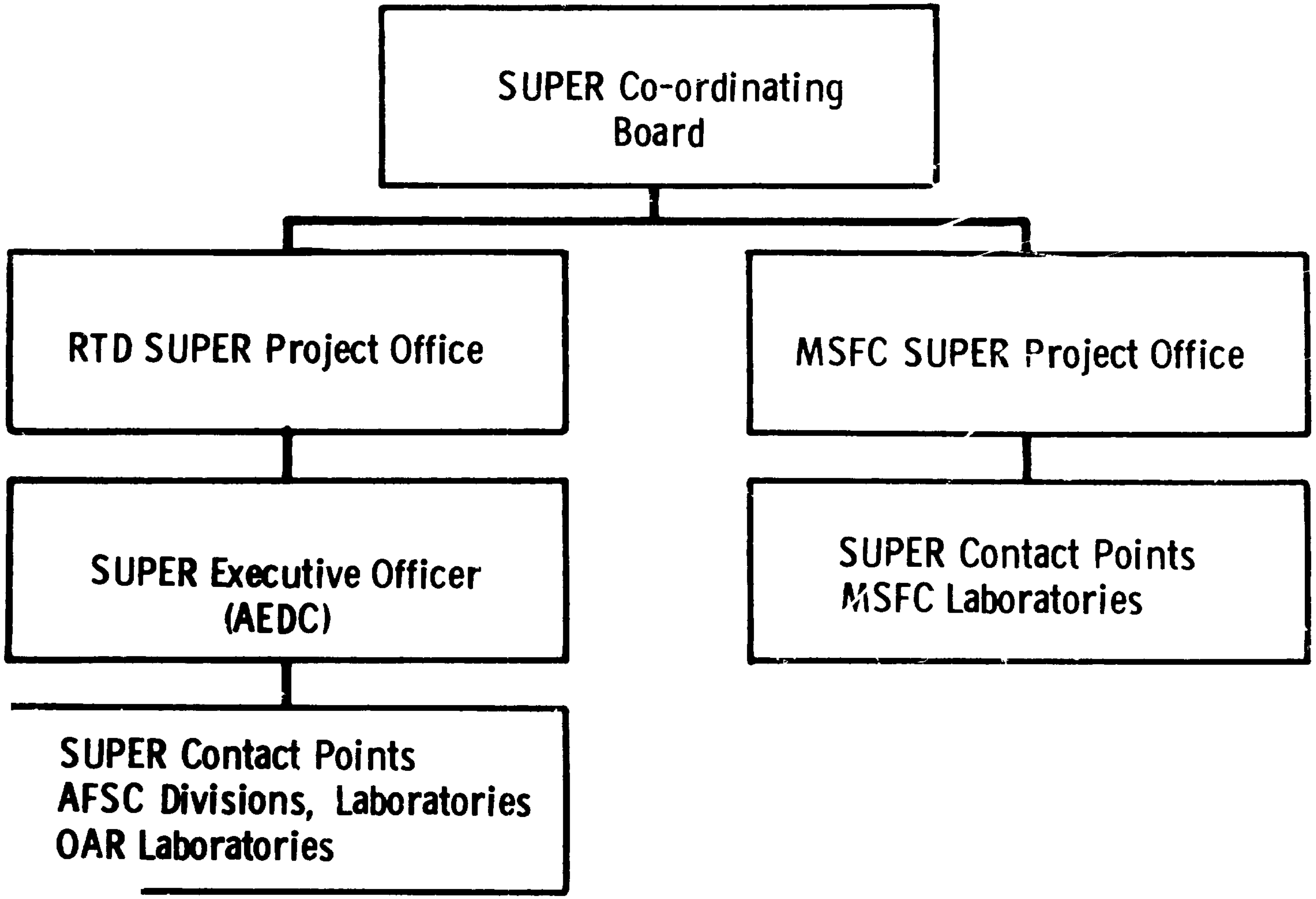

Fig. 1 SUPER ORGANIZATION

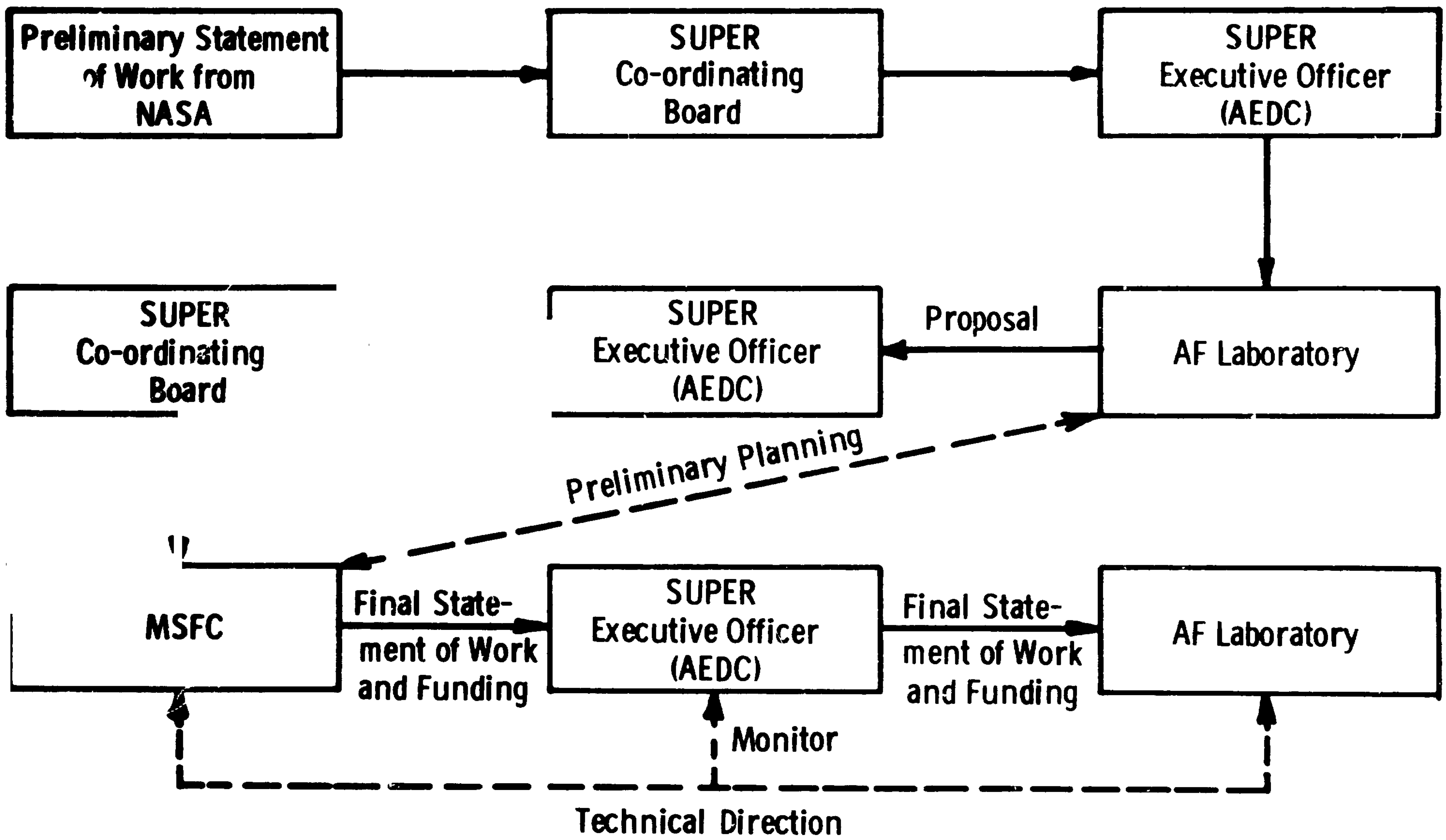

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Fig. 3 SUPER RESEARCH PROJECTS INITIATED IN FY 64

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* Most of the FY 64 projects were extended in time, scope, and funds by AF and NASA.

Fig. 4 SUPER RESEARCH PROJECTS INITIATED IN FY 65

APPENDIX A

ATTENDEES,

WORKING GROUP ON EXTRATERRESTRIAL RESOURCES
FOURTH ANNUAL MEETING
29 NOV - 2 DEC 1965

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APPENDIX B

TECHNICAL PAPERS PRESENTED AT THE FOURTH ANNUAL MEETING WORKING GROUP ON EXTRATERRESTRIAL RESOURCES

29 NOV - 2 DEC 1965

	Presented By
ENVIRONMENT & RESOURCES SUBGROUP	
A Survey of Observed Changes on the Moon - Mrs. Jaylee Burley	Lowman
Geometry of Backscattering Surfaces as Applied to the Moon - Mr. John Halajian	Halajian
Evidence of Lunar Ignimbrites - Dr. Paul D. Lowman	Lowman
Scientific Missions for a Lunar Base (LESA) - Dr. Paul D. Lowman	Lowman
Chemical Bonding and Shear Strength of Silicate Systems under Lunar Conditions - Dr. Rodney W. Johnson and Mr. John M. Greiner	Johnson
MINING & PROCESSING SUBGROUP	
Lunar Water Resources - Dr. Jon M. Weber, Dr. G. W. Brindley, Dr. Rustum Roy, and Mr. J. H. Sharp	Not Presented
Cryogenic Storage on the Moon - Dr. Peter Glaser	Glaser
Petrologic Processes and Lunar Logistics - Dr. E. Azmon	Azmon

	Presented By
Some Problems and Potential of Lunar Geothermal Power - Dr. Carl F. Austin, Dr. J. Kenneth Pringle, and Mr. Richard D. Fulmer	Pringle

LOGISTICS REQUIREMENTS SUBGROUP

Propulsion Gains From Free Tanking in the Vicinity of the Earth, Moon, and Planets - Mr. Rollin W. Gillespie	Gillespie
Economic Analysis of Extraterrestrial Propellant Manufactured in Support of Lunar Exploration - Mr. David Paul III	Paul
Space Transportation and Tanking Systems Utilizing Lunar Manufactured Propellants - Mr. R. A. Gorrell and Mr. Joseph B. Deodati	Gorrell
The Role of Lunar Resources in Post Apollo Missions - Mr. Howard Segal	Segal

BIOTECHNOLOGY SUBGROUP

The Physical Capabilities and Logistic Support Requirements for Man on the Moon - Dr. Walter Kuehnegger	Kuehnegger
Cost of Life Support in Manned Lunar Bases - Mr. W. L. Burriss	Burriss
Terrestrial Agriculture Plant and Animal Research as Applicable to Extraterrestrial Food Production - Dr. Robert Yeck	Yeck
Weights of Environmental Control Systems - Mr. Stephen H. Dole	Dole