

NASA-CR-167756



National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center

Houston, Texas 77058

31 January 1980

(NASA-CR-167756) EXTRATERRESTRIAL MATERIALS
PROCESSING AND CONSTRUCTION Final Report
(Lunar and Planetary Inst.) 655 p
HC A9, MF A01

N83-12109

CSCI 22A

Jncias

G3/12 00851

**EXTRATERRESTRIAL MATERIALS
PROCESSING AND
CONSTRUCTION**

FINAL REPORT

NSR 09-051-001 Mod. No. 24



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LUNAR AND PLANETARY INSTITUTE

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713/488-5200

PROGRAM DIRECTOR

Dr. David R. Criswell

31 January 1980

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STUDY PERSONNEL

Dr. David R. Criswell -- is the Director on the "Extraterrestrial Materials Processing and Construction Program." He was the Associate Scientist with the Lunar and Planetary Institute which is operated by the Universities Space Research Association (1970-1980). He conducts research in the fields of plasma physics as applied to the interaction of the moon and the solar wind, the electrodynamic transportation of dust about the moon with emphasis on both observational and theoretical analyses of the processes, microseismic effects operating in granular media, cyclotron amplification of hydromagnetic waves in the magnetosphere and optical and particle observations of the aurora by sounding rockets and satellites. He has been active in the conceptual analysis of the development of space industrialization since 1968. He served as the Executive Director (1971-1978) of the Lunar Science Review Panel and was the Director of the Proposal Evaluation Program of the Universities Space Research Association (1976-1977) which conducted the review of all proposals for experiments to fly on board the development flights of the space shuttle and the first two missions of the Space lab. He received his Bachelor of Science and Master of Science Degrees in Physics from North Texas State University in 1963 and 1964 and the Doctor of Philosophy from Rice University in 1968 for work in the Department of Space Physics and Astronomy. He worked for two years with the Houston Operations of TRW Systems following graduation from Rice University with special focus on the support of Apollo science experiments and advanced planning. He is a consultant and president of Cis-Lunar, Inc., a Texas Corporation.

Dr. Robert D. Waldron -- was a research scientist with the Lunar and Planetary Institute and was the lead research engineer on the analysis of processes for the chemical processing of lunar and asteroidal materials in space. He started on the program in September 1977. He received a Bachelor of Chemistry degree from the University of Minnesota in 1948 and the Doctor of Philosophy in Physical Chemistry from California Institute of Technology in 1952. He was engaged in postdoctoral and staff research studies at Brown University and the Massachusetts Institute of Technology in the early 1950's. He was a staff scientist for the Garrett Corporation from 1959 to 1967. Since 1967 he has been an independent consultant in chemistry and the physical sciences and has been involved in chemistry of reactive metal processing, coal gasification, solar energy research and magnetic levitation. He holds several patents in these fields.

Mr. J. Meier was supported by an Undergraduate Research Fellowship (15 April - 30 December 1979) to assist in the development and documentation of chemical processing procedures for lunar materials. Mr. Meier used the work in part to complete the Senior Individualized Project (SIP) for a B.A. Degree in Chemistry from Kalamazoo College in Michigan. His Fellowship was funded 50% out of this contract (Mod. 24) and 50% out of the basic funding of the Lunar and Planetary Institute.

Mr. Aaron Goldberg was supported by an Undergraduate Research Fellowship (10 June 1979 - 30 December 1979) to develop a computer model on the economics of bootstrapping space industries using lunar materials. He graduated from Yale University in May 1979 with a Bachelor of Science in Chemistry and a minor in Economics. He was responsible for the development of Chapter IX

of this report.

Professor John D. Mackenzie was a consultant to the contract and participated as an organizer and co-chairman of the workshop, "Glass and Ceramic Industries in Space Based on Lunar Materials." He is professor of Engineering and Applied Science at the University of California at Los Angeles. He is an internationally recognized expert in the science and technology of glasses and ceramics, and has published over 120 papers and edited six books in this general area and has been awarded eleven U. S. patents on glass and ceramics. Honors received include the S. B. Mayer Award of the American Ceramic Society in 1964, the Lebeau Medal of the French Society for High Temperature Materials in 1969, and the Toledo Award of the American Ceramic Society in 1973. He has been an officer in the International Glass Commission, was elected to the U. S. National Academy of Engineering in 1976, and is Editor-in-Chief of the International Journal of Non-crystalline Solids.

Professor J. R. Selman was a consultant to the contract and participated as an organizer and Co-chairman of the workshop on "Electrochemistry Applied to the Processing of Lunar Materials." He is chairman of the Department of Chemical Engineering at the Illinois Institute of Technology and is active in the Industrial Electrolytics Division of the Electrochemical Society which co-sponsored the workshop.

Chapter I

EXECUTIVE SUMMARY

Executive Summary (Chapter I)

Major motivations for the use of lunar materials in support of space missions and future large scale space industry are easy to summarize: (1) The moon exists; (2) The moon is a very large and accessible source of matter appropriate to a majority of the material needs of industry on the moon and in space; (3) We have visited the moon and returned samples to earth of the surface material which can be used in final demonstrations of processing equipment; (4) We possess considerable general knowledge of the entire moon and how to operate modest operations with tens of people on the moon; (5) We possess extremely detailed knowledge of the specific landing sites of the Apollo landing sites; and (6) Methods and devices have been identified which would allow the acquisition of lunar materials for use in space and on the moon at low unit costs and which can be fully proven prior to a return to the moon.

A broad range of technologies have been developed by industry for use on earth which are applicable to initial small scale (possibly prototype level) industrial operations on the moon for the production of industrial feedstocks and production of devices. Table 1 summarizes the approximate order of magnitudes of machinery mass and expendables and power necessary to complete various industrial processes. Notice that the use of rockets to lift products or even bulk mass from earth is far more capital, energy and especially consumable intensive than most other industrial operations in terms of the tons/hour of goods delivered to a point in space or on the moon (factor of 2 greater requirements). This table indicates that terrestrial support industries can be considerably smaller on earth for a given level of industrial activity in space if the center of space industrialization is shifted to the moon.

Implied in Table 1 is the fact that more industrial options and capabilities will be generated by the use of lunar materials to support space industries at an earlier time than will occur if only materials transported from the earth into space are used. Figure 1 attempts to convey the spirit of this expectation. At this point in time the national efforts which have gone into space exploration (manned and unmanned) and into the defense aspects of space hardware and operations have accumulated approximately 100 billion dollars (B\$) of worth of experience. The original Apollo investment required the order of 800,000 to one million work-years (WY) of carefully documented efforts. These activities are represented by the "Space Community" region in Fig. 1. This "Space Community" has drawn on the far larger resources of the overall United States "Raw Materials" and "Industrial Manufacturing" segments for the specialized goods (rockets, computers, sensors, communication equipment, etc.) necessary to support the space operations.

Approximately 8 B\$ is expended annually by the "space community" to draw on these larger industrial resources. The "Space Community" exchanges some information or expertise with this larger community in the form of technical reports, research and development efforts and serendipitous mutual discoveries of needed capabilities. "Spin-off" is one term often used to describe the transfer of technology from the "Space Community" to industry. However, there has been virtually no exchange from the materials industry to the "Space Community" with respect to the use of non-terrestrial and specifically lunar materials. The lack of motivation by the "space community" is summarized by the mental statement common to many technical members of the aerospace community -- "Since the moon is far away and there is no present lunar program, it will be fifty years before we return and can use the materials. Therefore, there is no need to even consider planning for the use of lunar materials." In addition,

there are the perceptions that the lunar materials will be very difficult to process into any useful form and that a return to the moon will be necessary before work can even begin on lunar materials processing. This last statement has gone unchallenged in the "Space Community" simply because the "Space Community" traditionally has had very few members, especially in major administrative positions, who have any extensive experience or knowledge of the materials industries on earth and simultaneously of the lunar materials. Traditionally, the "Space Community" has dealt with finished rather than raw materials industries. Thus, widespread administrative insight and interest into this critical interfacial area have been missing.

This present study on the processing of non-terrestrial materials was begun in 1977 under contract to NASA to determine whether or not available procedures in the chemical process industries, chemical engineering, the glass and ceramics industry and associated industries dealing with excavation and mineral beneficiation could be applied to the generation of various types of industrial feedstocks from lunar surface materials. The initial positive evaluations have been published in a 1978 contract report (1) and in the numerous papers reprinted in the final section of this report. Other parallel studies conducted by the Massachusetts Institute of Technology and the General Dynamics Corporation (2,3) concerning the production of final components for space power stations and systems studies for the production of space power stations from lunar materials have also reached the conclusion that in-space use of lunar feedstocks to make a very wide range of products is possible and reasonable. These results are true even if the "means of manufacturing" are brought from earth rather than created in part from non-terrestrial materials.

These conclusions are augmented by a recent review (9) of the potential for the application of robotics and advanced computer technologies in space. It was

concluded that NASA is far behind the state-of-the-art in the application of robotics, teleoperators and semi-independent computers to virtually all space operations. In particular, NASA has not vigorously pursued the large potentials of this technology for application to space industry using non-terrestrial materials and the build-up of non-terrestrial industries.

Thus, there is considerable reason of optimism that a diverse and essentially open-ended industrial system can be created which initially utilizes lunar materials as the primary source of feedstock. The next stage of consideration is how large the annual tonnage of such an initial industry must be and what the major products should be. Current considerations of this question have been dominated by the concept that large space power stations would be the initial product. However, it is appropriate to carefully consider this initial scaling and the range of products which might be profitably developed in space at a much lower scale of annual tonnage and original equipment mass than required for the space power stations (i.e., much less than 100,000 tons year). Some limited work has been conducted on this question (3,5,6). Much more work is needed on this problem.

In the limit of development of lunar and asteroidal industries, it has been suggested that a machine could be made on earth and sent to the moon, one of the earth-like planets or to an asteroid. This machine could use sunlight and local materials to replicate many times. The new suite of machines could then create major industrial facilities by remote control from earth (7,8). Such an approach is not being explicitly explored in this report. However, in any approach to the use of local materials it is necessary to be able to process the local materials. Work in this report will be applicable and certainly necessary prior to developing self-replicating.

Considerable effort should be expended by NASA and other segments of the

"Space Community" in identifying new and synergistic products and systems which can be built from lunar materials in this robotic or "bootstrapping" manner and which can provide the means of generating a growing industrial capacity in Cis-lunar space.

The major accomplishments of the first portion of the LPI study of Processing of Extraterrestrial Materials were:

1. Three different chemical processing schemes were identified for separating lunar soils into the major oxides and elements by means of separation techniques which require very little expenditure of working fluids or reagents per unit of output. A large fraction of the chemical processors and reagents could be derived from lunar materials. A two year terrestrial program of development could demonstrate the process systems at a throughput level only a factor of ten less than would be useful for initial operations on the moon. The major process operations are based primarily on technologies demonstrated in industrial or laboratory operations.
2. Lunar soils, soil fractions and separated oxides can definitely be used as feedstocks to a glass and ceramic industry on the moon and in space. Most of the exploration of the product characteristics and production systems could be completed on earth.
3. Physical, electrostatic and magnetic separation schemes for the beneficiation of lunar soils by non-fluid processes appear to be applicable to lunar soils. It is likely that they can be developed to an adequate level by experiments on lunar soil prior to a return to the moon.

4. Lunar mining operations and construction of facilities in which excavation operations are required should be completely reasonable to accomplish with adaptations of terrestrial technologies.
5. Only two technology areas were identified where it might be necessary to return to the moon to demonstrate the operational limits of the proposed devices: electrostatic separation and large scale sintering of lunar soil.
6. Future lunar exploration, from orbit and in-situ, will certainly enhance the range of opportunities for lunar industries. The discovery of ice concentrations near the poles would be very valuable. Our work in 1979 focused on three general areas: continued extension of the definition of process flow sheets generated in the first portion of the contract effort; the convening of workshops which would involve researchers in the glass and ceramic industries and industrial electrochemistry in the evaluation and exploration of the uses of lunar materials; and the publication in the open literature of the results of both the first part of our study and as much as possible of the results of the current portion of the study. Chapter II through X of this current work is summarized in the following descriptions.

Technology Readiness Plan (Chapter II)

One fact stands out clearly in considering the development of processing technologies to use lunar materials. It is completely reasonable to start immediately on ground-based experimental and development programs which would result in demonstration systems. Rapid progress can be expected.

A surprising second fact was revealed during the work in 1979. Much of the technology which will be developed and demonstrated for lunar soils will

directly support the development of schemes for the processing of common and low grade terrestrial minerals as feedstocks for terrestrial industry. This is not a matter of accidental "spin-off". The research and development needs in both fields are very similar and mutually supportive. Due in part to the limited number of major minerals and vitric products found in the lunar soils, it is apparent that the initial development program can proceed rapidly and require only modest resources of money and people. Table 2 summarizes the research and development needs perceived for a lunar materials program.

Table 3 summarizes the research needs of a program for the development of means of processing the common terrestrial materials. Most of the technology developments in this listing would be synergistic to the development of lunar resource processing. We note that there are many opportunities for the development of new cooperative programs between government research agencies such as NASA, DoE, DoD, NSF and the Bureau of Mines and with industrial and university laboratories, to explore in a new context their traditional materials challenges.

Chemical and electrolytic processing schemes applicable to the processing of lunar materials must intrinsically be conservative of their working fluids through very efficiently recycling. Therefore, the earth version of such systems would be non-polluting and would be capable of utilizing traditionally more expensive working fluids or reagents. Other aspects of lunar processing which might find economically attractive uses in terrestrial processing are: more efficient use of energy, less mass of plant per unit of throughput and, therefore, more capital efficient, plants which increase throughput by scaling up volume and rate of materials movement rather than surface area; plants which can concentrate minor and trace elements from the main materials stream for more convenient recovery of strategic or rare elements; plants which produce more

than one significant chemical value; and plants which can accept inputs of less rigorously defined raw or semi-processed materials streams. It may be that some of these plants can process premixed or preprocessed materials (i.e., oil shale, fly ash and coal ash, slags) and in this manner use materials for which the gathering and transportation costs and energy are paid for by other front end uses. Refer to Section II for detailed discussions of these points and the specific projects which could be pursued in the development of lunar processing schemes.

Generalized Description and Classification of Materials Acquisition and Processing Steps for Production of Native, Semi-refined and Refined Feedstocks for Space Industry (Chapter III)

The lunar soil consists of seven major elements (O, Si, Al, Ca, Mg, Fe, Ti >1%) and minor (<1%) and trace (<.1%) elements. Considerable attention has been given in previous work to increasing the concentration of minor and trace elements by means of various non-fluid schemes which beneficiate mineral or vitric grains rich in a particular element or suite of elements. Electrostatic and magnetic processes were specifically considered. Other materials processing operations are examined in Chapter III which require little or no incremental energy or mass of lunar deficient elements but which may substantially increase the recovery of minor or trace elements from the lunar soil fraction. These thermal operations could be incorporated into glass making or other operations where the soil or fractions thereof are melted. The schemes can be especially attractive if a native materials products stream is ten times or more greater than chemically refined streams of primary interest. Controlled solidification of a molten soil can be used to concentrate barium, potassium and rare earth elements from soil fractions selected by other low energy process schemes. Immiscible fluids (iron, silicon, sulfides, etc.) can be circulated through

magmas to take out over 30 minor elements. Some of these schemes would mimic the natural processes which were presumed to have operated on the moon to produce observed separations of trace and minor elements in lunar basalts. Other techniques may be superposed on these molten operations such as electrochemical processing, centrifugation, and recirculation of particular elements such as sulfur and phosphorus in the melt. These and other approaches may be useable on the moon with direct solar heating as the main energy input. Considerable progress may be expected in increasing the inventory of useful elements by continued studies of these "natural" separation approaches.

HF Acid Leach Process (Chapter IV)

The HF acid leach process was developed in 1978, and presented in considerable detail in Ref. 1 (pp. 44 to 47) and Appendix I (pp. 157 to 175). In the previous study a number of process options were presented for various primary reactions and recycle or regeneration steps. Subsequent work has led to a narrowing of practical options; i.e., steps which are both technically feasible and with high specific output. More detailed considerations of reagent attrition have led to alternative systems which can substantially reduce the amount of reagent which must be resupplied from earth. This is primarily due to reduction in fluoride loss in oxide mass streams exiting the process by conversion to sulfoxy compounds -- the latter being pyrolyzed to oxides. Although this may be expected to lead to residual sulfur in the oxides, this make up sulfur can be supplied from lunar sources and thus reduce requirements for earth reagent supply. We consider that these systems could be demonstrated at the bench-top scale in two years. The development program would also produce fundamental engineering data of direct use to many other approaches to chemical processing of lunar materials.

Electrorefining Process for Lunar Free Metal and Metal Derived from Chemical Processing of Lunar Soils (Chapter V)

Lunar soils contain a small fraction of metallic particles or grains, either free-standing or welded to glassy or crystalline material. The grains are predominantly iron but contain minor amounts of nickel and cobalt and trace amounts of other elements. Metal contents of typical soils may range from less than 0.1% by weight to more than 1%. Impure metal (again, mostly iron) may also become available as a result of chemical beneficiation or processing of lunar soils, primarily as a result of electrowinning operations in aqueous or fused magmatic liquids. The principal impurities for these metals will likely be manganese, chromium, and traces of more noble metals such as copper, lead, etc.

For metal products intended primarily for mechanical properties applications, it may be unimportant to purify or refine the alloys derived from these sources, save for reduction of sulfur and/or phosphorus levels through slagging operations during initial melting of lunar metal grains. For electrical conductor or magnetic applications, however, it may become important to be able to reduce impurity levels in iron. The electrical resistivity of iron nearly doubles for 5 to 6% Ni content compared to pure iron. Five to 10% Ni is typically present in lunar free metal. Thus, a relatively straightforward purification step could probably reduce the mass requirement for iron wire used as an electrical conductor by approximately 50% over that needed with impure metal.

Electrorefining would also be advantageous in offering a source of nickel and cobalt which would be virtually inaccessible from other lunar sources.

We have studied and present in Chapter V possible means of separating and purifying ferrous based metals of this type and have designed a water based electrorefining process of the two compartment cell type in which the anode and

cathode are separated by a membrane and the impure anode solution (anolyte) produced by dissolution of the impure cast anodes is withdrawn and the metal values transferred to the purified cathode solution (catholyte) by the use of ion exchange techniques. In the process a third solution loop, a purification loop, is used to aid separation and transfer. In addition, a certain amount of water must be transferred from loop to loop to maintain water balance. A schematic flow chart for the process is presented (Fig. 2) as a function of HCl concentration for transition metal ions, and limited information on the distribution in neutral chloride and self equilibration has been reported (see Ref. 1, 2, 3 in Chapter V).

Production of Silanes (Chapter VI)

Silanes are the silicon analogs of hydrocarbons. The silicon molecules serve as the backbone of linear chains of atoms in the same manner as does carbon in hydrocarbons. Silanes (chlorosilanes) are of interest to many workers concerned with the ultrapurification of silicon for use in solar cells. In these compounds the silicon can be separated in extremely clean and efficient manners. Considerable engineering experience is available from industrial uses of boron and aluminum hydrides which are analogous to silanes. Silanes have been studied extensively on the laboratory scale. It has been established that the lower weight silane molecules have many of the physical and thermodynamic properties of the corresponding hydrocarbons (methane, ethane, etc.). However, they are not used industrially on earth because they ignite spontaneously on contact with air or oxygen. The problem of spontaneous ignition would be far less severe when used in space or on the moon.

Silanes are of considerable interest for chemical propellant transportation in the earth-moon system. It may be possible to substitute silanes for traditional fuels such as hydrogen or kerosine in liquid propellant rockets with

little or no loss in overall rocket performance. If this is the case, then approximately 90 to 95% of the propellant needs of chemical rockets could be supplied as convenient liquid propellants derived from lunar materials and only 5% of the propellant in the form of hydrogen might have to be brought from earth. Chapter VI explores this possibility in greater detail, reviews the literature on silane and estimates the specific impulse range that might be achievable with silane/oxygen propulsion systems (310 to 380 seconds). What is especially interesting is that there are three different approaches to the production of silanes which can be incorporated into the HF acid leach process for chemically processing bulk lunar soils. Thus, it appears that a major fraction of the propellant needs for chemical rockets operating in the earth-moon system might be derived from common lunar materials.

If concentrations of hydrogen can be located in the lunar polar regions or derived from concentrated lunar ore fractions, then all of the propellant requirements could be met from lunar materials for major transportation operations between earth orbit and the lunar surface. Silanes would sharply increase (factor of 3 to 6) the fraction of useful payload which could be transported to the lunar surface for each flight of the space shuttle into earth orbit.

Production and Use of Spectrally Selective Materials (Chapter VII)

In space and on the lunar surface the management of waste heat flows to space from physical systems (factories, process plants, habitats) will be via radiation. Radiation from a material surface at a given temperature and illumination level is determined by the ratio of absorptivity to emissivity (α/ϵ). Cool surfaces have low ratios and warm surfaces have high ratios. It is desirable to have access to both cool and warm surfaces in many process and life-support systems. Chapter VII reviews data on materials which can be

derived from lunar soil fractions and derived oxides and elements. Calcium, magnesium, aluminum oxides or silicates plus silica itself, could be readily produced and spread in a thin powder over the surface of the moon to produce light colored and highly emissive layers. Equilibrium temperatures, even at noon, under the layer would be considerably below ambient. Very high performance "cool" layers may be especially useful in reducing refrigeration requirements for oxygen and other cryogenic storage applications.

Aluminum or iron with a dark anodized or sputtered film containing transition metal oxides such as FeO , Fe_3O_4 , Cr_2O_3 , NiO or CoO or their complex compounds with Al_2O_3 can produce warm surfaces. High temperatures can be reached even without solar concentrators. Plots of temperature versus illumination angle are given for various solar exposures in Chapter VII.

Workshops on "Glass and Ceramics" and "Electrochemistry" and the Processing of Lunar Materials (Chapter VIII)

Two workshops were held at the Lunar and Planetary Institute under the support of NASA contracts. These were to involve professionals from the glass-and-ceramics and electrochemistry industries in the evaluation of the prospects of processing lunar materials, commenting on proposed processing schemes previously generated in the Extraterrestrial Processing program, and to evoke suggestions of new approaches toward lunar processing and identify new industrial opportunities. Chapter VIII details the workshops, and presents contributed abstracts and papers.

The first workshop was entitled, "Glass and Ceramic Industries in Space Based on Lunar Materials." It was held 16-18 April 1979 and was co-organized by Professor J. D. Mackenzie of the Materials Science Department of the University of California at Los Angeles. The second workshop, "Electrochemistry Applied to the Processing of Lunar Materials," was held 12-13 September 1979 and was

co-sponsored by the Industrial Electrolytics Division of the Electrochemical Society. Professor J. R. Selman, of the Department of Chemical Engineering of the Illinois Institute of Technology, was the co-organizer. Approximately sixty people attended the two meetings. Of these, twenty had no previous experience with lunar research; ten others had worked with lunar materials and had industrial experience in related fields.

Details of the discussions and recommendations are given in Chapter VIII. What is extremely significant is the broad agreement which existed at both meetings. THE STATE OF THE ARTS AND BASIC KNOWLEDGE IN THESE FIELDS OF INDUSTRIAL PRACTICE ARE COMPLETELY ADEQUATE TO IMMEDIATELY BEGIN PROGRAMS OF RESEARCH AND DEVELOPMENT OF PROCESSES TO USE LUNAR MATERIALS INDUSTRIAL ON THE MOON.

Other broad conclusions were also reached at these workshops and in subsequent discussions.

1. Time and expenses necessary to develop moderate sized production processes on earth which could be transferred to the moon should be significantly less expensive than the development of major spacecraft systems such as the space shuttle or very large boosters.
2. There are many direct applications of the processes, technologies and basic knowledge which will be developed in lunar processing to the processing on earth of common and low grade terrestrial resources. The lunar related research and development should directly speed up technology areas of vital importance to the industrial health of the United States.
3. It is reasonable to start systems studies of the operation of feedstock industries in space both to understand more fully the constraints and

advantages of lunar based industries and to place the use of lunar materials into the planning strategies of the "Space Community" (Fig. 1).

4. Many members of the industrial materials community consider the prospects of developing lunar and space based industries worthy of consideration and professionally extremely interesting.

Many specific possibilities for products and processes were discussed in the workshops and are presented in Chapter VIII. Highlights include: the preliminary schematic lay-out of a lunar based plant to produce 37,000 tons/year of glass parts for a space power station and iron for use on the moon which would be constructed primarily from lunar materials; the use of molybdenum probes heated by solar energy to fuse habitats and working volumes directly into the lunar soil; discussion of methods to directly electrolyze lunar soils to obtain separate elements and oxides; and several different chemical approaches toward lunar processing.

The Economics of Bootstrapping Space Industries -- Development of Analytical Tools and Formalisms (Chapter IX)

Three basic strategies for space industrialization have been proposed: lift of all materials and equipment from earth; lift of productive equipment from earth which is used to process lunar materials; and lift of the minimal mass of productive equipment to the moon and then use of lunar materials to build the remaining machines of production, and process lunar materials into the final products (bootstrapping). Due to the high costs of lift of mass from earth and the initially high costs of maintaining industrial operations on the moon and in space, there is a strong intuitive drive to consider various

bootstrapping schemes. A computer code has been created which maximizes the present discounted value (PDV) of a bootstrapped approach toward the construction in space of space power satellites from lunar materials. Approximations are made of the productivity of capital equipment (tons of equipment per ton/hour of output products) used to make the machines of production and to produce the space power satellites. Estimates are also made of the terrestrial and lunar expendables which must be supplied in both the build-up of productive capacity and final production. Net cash flows (CF) were determined by associating the mass of equipment and materials and expendables supplied from earth with their purchase prices on earth. The optimal value of the present discounted value (PDV) was calculated over the time horizon of the program (T) in terms of cash flow (CF), total initial research and development (R&D) and the initialization costs (INT) of the system.

Several obstacles exist to the modeling of the complete range of bootstrapping options within the limited scope of this effort. There are many possible degrees of freedom that should be considered. Therefore, a simplified approach was adopted. It was assumed that manufacture of the final output product is delayed until all of the capital -- whether produced in space or merely transported there -- is operational. Simplified equations for this approach are derived from the general equations. Five graphs are presented which display the dependences of total costs (isocosts), time to completion of the space power satellites (isotime), for all space operations, the PDV minus R&D costs and finally, PDV minus R&D and INT costs. These curves are plotted versus the shipping rates of materials from earth (tons per year) and mass of the initial capital. The optimal PDV-values lay along a straight line in each graph. The slope of this line depends on overall productivity.

This particular model reveals that producing capital with lunar resources

(bootstrapping) not only reduces the cost of transport of materials into space, but as significantly it reduces the time needed to assemble a space manufacturing facility using a given fleet size. Full bootstrapping may be even more attractive, since it would postpone many of the costs and start delivering benefits sooner. Bootstrapping may also decrease research time and risks by transferring more development to the productive phase of operations. A listing of the computer program and the capital and expendable ratios and other physical and monetary values are included. We hope that this modeling may stimulate other more detailed efforts.

Reprints and Preprints in the Open Literature (Chapter X)

A major thrust of the final portion of the "Extraterrestrial Materials Processing Program" at the Lunar and Planetary Institute was the publication of the results of these studies in as broad a cross-section of the literature as possible. It was hoped that in this manner the possibilities for the application of a wide spectrum of industrial operations to the creation of space industries would be realized by many more people at an earlier date than if these especially interdisciplinary efforts were confined primarily to a NASA contract report. Substantial progress has been made. Ten articles have been prepared and published in the open literature by the participants in the study on all phases of the effort up to mid-1979. One article on construction of lunar base habitats and an abstract submitted to a forthcoming meeting of the American Chemical Society are also included. We expect to publish seven to eight additional papers as a group on the results of the two workshops held in 1979 on Glass and Ceramic Processing, and Electrochemistry. Half the included articles have been published in the proceedings of aerospace-related conferences (Princeton/AIAA 1979 Meeting on Space Manufacturing; Proceedings of the XXXth Congress of the International Aeronautical Federation; October 1978 meeting of

the American Astronautical Society). Long articles have appeared in trade publications such as Chemical Engineering and Journal of Contemporary Business, and in a Proceedings of a United Nations Conference on Technology for Third World Countries.

We believe it is of significance that the 1978 contract report and various articles are being reported independent of our efforts in various trade publications. Some aspects of lunar mining were discussed in Civil Engineering (July 1979) in an issue devoted to civil engineering in space. 33 Metal Products (January 1980, McGraw-Hill, NY) has an eighteen-page article on the future of the iron industry in the Twenty-first Century. Approximately half the section discusses the lunar iron industry and emphasizes the potential contributions that terrestrial industry can make. We are aware of two foreign language reports on the work. Reference A. (Chemical Engineering article) was translated in its entirety to Chinese, for publication in a U. S./Republic of China journal on current technologies. A semi-popular report of the work and space industrialization appeared in Japanese in Kagaku Asahi, which is similar to National Geographic. Over 500 copies of the 1978 contract report have been requested and distributed.

Two very extensive articles will be published on lunar utilization and materials processing in space in 1981 as chapters in a CRC Handbook on Space Industrialization. Preprints of these articles are in the Appendix. We anticipate the publication of several other articles based on the new work in this report in chapters II through VII and IX. However, the time table for this is not clear, due to the lack of follow-on funding of the project.

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GENERAL MOTIVATION

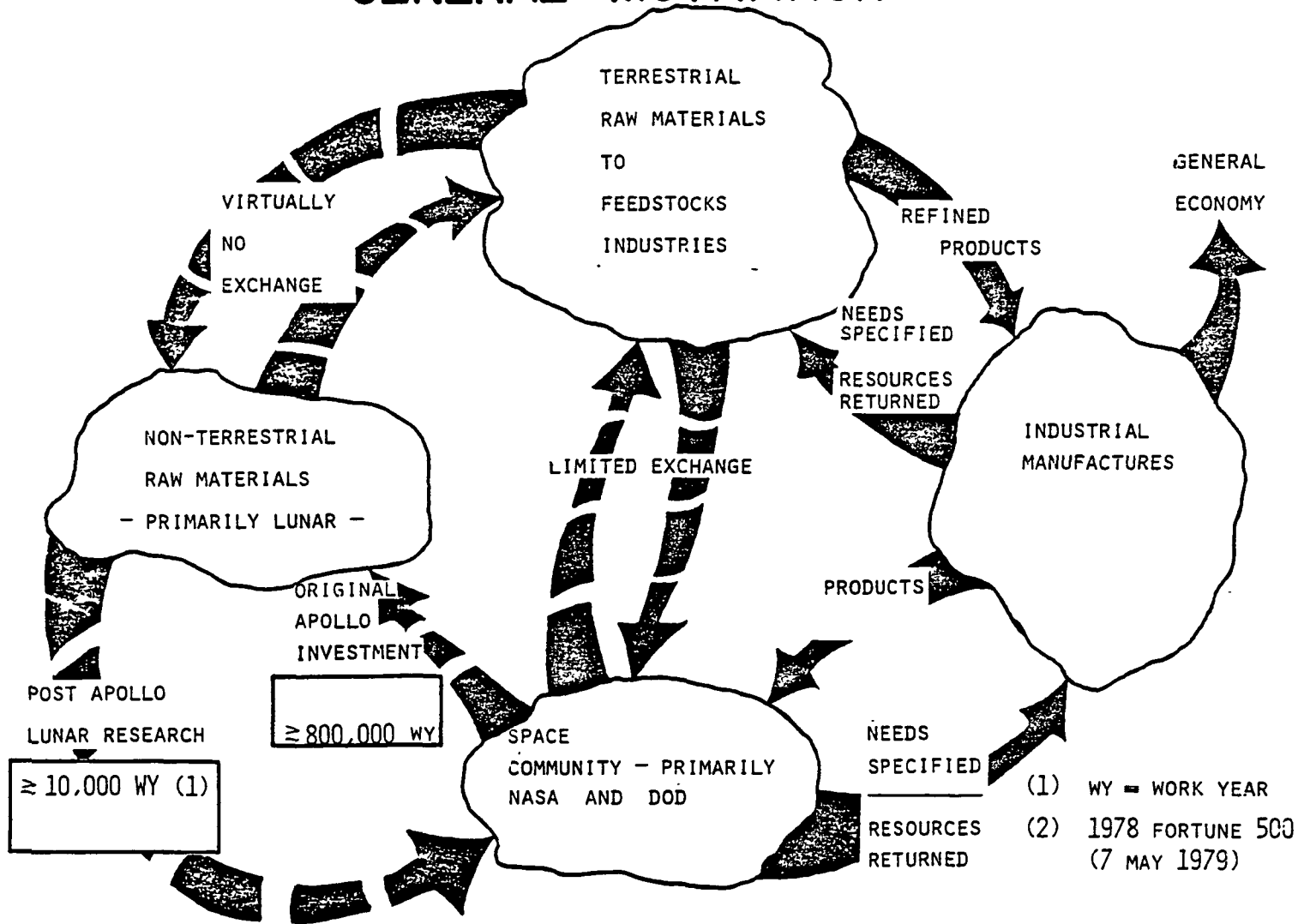


Figure 1

APPROXIMATE CONVERSION RATES FOR MECHANICAL PROCESSES (3)

<u>FUNCTION</u>	<u>TONS CAPITAL</u>	<u>MEGAWATTS</u>	<u>TONS CONSUMABLES</u>
	TON/HOUR	TON/HOUR	TON/HOUR
SOIL EXCAVATION OR BENEFICIATION	0.1 - 1 ⁽¹⁾	10 ⁻⁴	<10 ⁻⁷
COLD DRAWING	10	0.1	SMALL
LUNAR MASS DRIVER	50	1	0.01
COLD MACRO ASSEMBLY	100	0.1	SMALL
WELDING, HOT FUSION FORMING	1 - 10	10 ² - (10 ³)	SMALL
CHEMICAL REFINING	100 ⁽²⁾	10	0.01
LUNAR CHEMICAL ROCKET	150	10 - 20*	2
SOLID STATE - MICRO COMPONENTS	3000	50	0.1
TERRESTRIAL CHEMICAL ROCKET	>2000	>100*	20

* WITH PROPELLANT PRODUCTION

- (1) HIGHER VALUE APPLIES FOR LONG HAULAGE
 (2) RATIOS DECREASE FOR PARTIAL SEPARATION OF LUNAR ELEMENTS
 (3) SEVERAL OF THE RATIOS EXTRACTED FROM STUDIES BY MIT AND
 GENERAL DYNAMICS ON PRODUCTION OF SPACE POWER
 COMPONENTS FROM LUNAR MATERIALS IN-SPACE, OTHERS
 FROM AVAILABLE ENGINEERING LITERATURE AND SPECIAL
 STUDIES FOR THE PROCESSING STUDY AT THE LUNAR AND
 PLANETARY INSTITUTE.

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Chapter II

TECHNOLOGY READINESS PLAN

An overview discussion of an R&D development plan for space technology development based on lunar materials utilization was presented in R1, Chapter I, pp. 34-51, and a more detailed discussion of R&D projects recommended in support of the chemical processing of lunar materials was given in R1, Chapter II, pp. 58-79. Most of the recommendations advanced in those sections appear to be still important in the light of the additional studies performed in the intervening period and results of discussions and workshops with outside consultants and experts.

The original thrust of the contract effort [and parallel contracts on systems analysis of lunar materials utilization (General Dynamics NAS-15560) and space manufacturing studies (Mass. Inst. of Technology NAS 08-32925)] were based on requirements for an alternative system for fabricating solar power satellites or similar large orbiting systems. While the mining, beneficiation and chemical processing operations would probably be very similar to those required in other engineering projects utilizing lunar materials, the systems study and manufacturing requirements are, of course, substantially dependent on the specific details of the desired engineering projects. Unfortunately, the manufacturing study (MST) could not examine generalized features of a broad range of earth manufacturing operations to identify particular operational problems which might arise in space vacuum or zero gravity due to time and budget limitations. Thus, a more generalized technology readiness plan applicable to a broader range of space industrialization scenarios will require additional studies of manufacturing and assembly operations as well as detailed consideration of mining, beneficiation and chemical processing development

requirements.

Results of workshops, in-house contract studies and independent analyses have led to probable scenarios for many major space industrialization activities based on lunar materials utilization somewhat different from those foreseen at the initiation of the contract or at the time of the first year final report. These scenarios or forecasts can be described by the following sequence of events:

- (1) Deployment of small crew manned missions and facilities to one or more locations on the moon.
- (2) Facilities will be substantially automated and capable of expanding their capacity to mine, separate and refine lunar soil fractions by creation of new equipment.
- (3) A substantial fraction of the material mined on the moon will be used in native or semi-refined form, thus greatly reducing the requirement for chemically processed feedstocks. In this regard, technologies to process and form soil fractions into glass and ceramic products, and a metallurgical industry based on the use of lunar free metal to develop steels and related alloys will assume a major importance.
- (4) Technology to develop substantial levels of solar electric and thermal power on the lunar surface will permit the establishment of major industrial facilities on the moon.
- (5) Establishment of this major industrial base will support the construction and operation of electromagnetic launch systems to permit inexpensive transport of raw and refined lunar materials and lunar

manufactured parts to lunar and earth orbital locations and, by dynamic deceleration methods, return to the earth's surface.

- (6) Moderate to large scale orbital processing or manufacturing will probably not become operational until after medium to large scale lunar surface industrial operations are in place and equipped to deliver a steady supply of raw, semi-refined or refined feedstocks to orbital facilities.

Based on this scenario, several conclusions follow:

- (a) Initial processing will proceed mainly on the lunar surface and problems of weightlessness and lack of massive inertial platform on processing and manufacturing systems can be deferred. Studies of the effects of reduced gravity operation (lunar surface) will continue to be of high priority.
- (b) Addition of operations classified as preconditioning and chemical beneficiation (Ch. III) can potentially greatly extend the range of recoverable elements from lunar soils. Electrorefining of lunar free metal (Ch. V) can recover nickel and cobalt as well as additional trace metals which can improve the capability of the lunar metallurgical industry. Additional studies to more thoroughly evaluate the potential of these techniques are indicated.
- (c) Lunar surface solar-electric power converters using in-situ support structures and/or active elements should be studied. Such power systems promise to be much easier to fabricate and install than orbital solar photovoltaic systems.

(d) A very generalized study of manufacturing and assembly operations applicable to a broad or diverse range of products should be undertaken. These should be examined for requirements and/or problems for reduced gravity operations initially, and later for zero gravity operations.

(e) Continued development of mass driver and novel launch systems (such as chemical propellants involving lunar materials such as silanes (Ch. VI) should be conducted to permit implementation of Step 5.

The manufacturing operations study in Item D could be based on common features of classes of operations as currently performed on earth. Table I below represents a suggested classification of manufacturing processes.

Table I

Classification of Manufacturing Processes

1. Kinematic

K1 Fiber operations (felted, paper, textiles, etc.)

K2 Particulate operations (mixing, conveying, clustering, dispersing, etc.)

K3 Fluid operations (mixing, pumping, heating, cooling, phase separations, etc.)

K4 Discrete operations (small scale assembly, etc.)

2. Forming

F1 Hot forming (casting, forging, powder metallurgy, sintering, hot rolling, bending, etc.)

F2 Cold forming (extruding, bending, punching, drawing, machining, grinding, cold molding, etc.)

F3 Unconventional forming (electromagnetic, etc.)

3. Surface Treatment

S1 Removal (washing, etching, electropolishing, etc.)

S2 Addition (coating, plating, anodizing, etc.)

S3 Modification (bonding, hardening, shot peening, etc.)

4. Internal Treatment

I1 Internal heating (resistance, induction, dielectric, etc.)

I2 Irradiation (X-ray, gamma ray, electron beam, UV, etc.)

I3 Miscellaneous (magnetic poling, ultrasonic, etc.)

5. Bonding

B1 Hot processes (welding, brazing, soldering, etc.)

B2 Cold processes (adhesives, chemical bonding, ultrasonic welding, etc.)

B3 Unconventional processes (explosive, electromagnetic, etc.)

6. Large Scale Assembly

L1 Reduced gravity (lunar surface)

L2 Microgravity (orbital assembly)

*of interest and importance to chemical processing technology, also.

Detailed Revisions to First Year's Report

In the first year Final Report, a series of recommendations were presented under the class headings, IDENTIFICATION/SYNTHESIS, ANALYSES/MODELS, and EXPERIMENTS. The first group consisted of five recommended steps to insure the continuity of effort and recognition and identification of opportunity for cost effective industrial operations in space. These steps are considered still valid and strongly recommended in the light of results of the past year. One might well add a sixth step:

- (f) Identification of useful adaptations and modifications of lunar processing technology to terrestrial materials industries for utilization of low grade waste and by-product source materials.

Some progress in Steps 4 and 5 appears to have occurred in the past year and more could be anticipated upon continued support of this activity.

Under the groupings of ANALYSES/MODELS and EXPERIMENTS, priorities and initial levels of R&D efforts were recommended. For the former class, we would recommend lowering the priority of Item 5 to 3 or 4. In the latter class, Item 3 has been under investigation by a group at SRI International for silicon and titanium. Continued support and extension to aluminum and magnesium is recommended. Item 6 should be lowered in priority to 3 or 4, since it appears that ion exchange separations of major elements may not be necessary. Additional items should be added as:

- (g) A study of the solution chemistry of sulfites/bisulfites of the major lunar elements and the pyrolysis reactions of solid bisulfites should be undertaken to determine reaction kinetics and residual sulfur levels of reaction products. This should have a priority of 1, and a two to three work year effort initially.

- (h) A study of magmatic extraction processes using silicon, sulfides, and/or phosphides to better define the potential utility of chemical beneficiation methods for extraction of minor and trace elements should be undertaken. We recommend a priority of 2 or 3, and a three work year effort.

SUMMARY

The development of space industry with a broad operational capability can be furthered with an organizational plan along the lines recommended. The primary purposes of the initial phase of the work should be to fill in missing data for process steps and identify critical technology steps requiring flight testing to verify operation under reduced gravity and combined vacuum-low gravity environments.

The interactive nature of lunar and terrestrial materials processing will inevitably lead to mutual advances in both fields. The great similarity in composition and texture between lunar soil and fly ash has significant implications in the terrestrial economy. Methods of nurturing and fostering technology development to maximize benefits to both fields must be explored.

As a result of the "Electrochemical Workshop" (see Chapter VIII) and a subsequent presentation to a multi-agency group, a consensus of near term research needs was developed for both lunar and terrestrial materials processing. These are listed in Tables II and III.

Table II
IMMEDIATE RESEARCH NEEDS FOR
UTILIZATION PLANNING OF LUNAR MATERIALS

1. *Physical Separations:*

- Verify degrees and rates of physical separabilities of distinctive components (major minerals, free-iron grains, amorphous combinations) by direct and combined means (magnetic, electrostatic, sieving, crushing, vibration, others). Use analog materials and very limited quantities of lunar samples. [Note — these investigations are of scientific value in the lunar research program.]
[WY \equiv work years].

2. *Glass and Ceramics:*

- Apply the extensively developed technologies and basic materials knowledge of terrestrial glasses and ceramics to determine the products and production characteristics for the direct and early use on the moon and in space of bulk lunar soils, physical separates (mineral, vitreous and metallic), and chemical separates of the soils.
- Verify the indicated degree and rate of recovery of gasses from lunar soils which will be released by heating in melting operations and by means of low energy desorption processes (extreme oxidizing and reducing conditions at low gas pressures). [20 WY].

3. *Chemical Processing:*

- Demonstrate the electrorefining and alloying of metallic "free" iron. [2 WY].
- Demonstrate with simulated lunar soils on the bench-scale level the HF acid leach, ammonium salt fusion and mixed acid leaching based on adaptations of well known terrestrial industrial and laboratory procedures for extracting the major oxides and elements (O, Si, Al, Mg, Ti, Ca, Fe) from a wide range of bulk lunar soils. Rates of throughputs, recycle efficiencies, and separability data will be determined in these demonstration experiments. Implications of reagent make-up from native lunar materials will be determined. [10 WY].
- Investigation of sodium or electrochemical reduction of a) raw or beneficiated lunar soil fractions, or b) chemical intermediates from hydrochemical processing of lunar soils [20 WY].
- Literature studies of methods to recover minor and trace element fractions obtainable from immiscible liquid extraction of magmas (molten fluids) such as would occur in glass production. [1.5 WY].

4. *Systems Analyses and Operations Tests:*

- Examine economic attractiveness of the manufacturing of machines of production (including materials processing devices) and products by a minimal mass facility from native lunar iron, glass and ceramics and derived products. Facility should be based on current state-of-the-art of semi-automatic numerical production and remote monitoring. [6 WY].
- Theoretically examine the use of silane based fuels for use in moon-earth liquid rockets. Determine whether or not lunar hydrogen can be obtained in adequate quantities to transport lunar materials back to low earth orbit, significantly reduce earth-lift requirements of propellants, and provide feedstock in low earth orbit for materials industries. [1 WY].
- Examine construction of large volume living and manufacturing chambers under the lunar surface by melting of the lunar soil into self-sealed lava tubes. [1 WY].

*Final recommendations*KEY R&D TOPICAL AREAS FOR TERRESTRIAL
PROCESSING OF LOW GRADE MINERAL SOURCES

1. *Physical Processing:* Investigation of dry magnetic and/or dielectric beneficiation of source materials currently considered too low grade for economic recovery.
Examples: Black sands, various mine tailings, clays, silts, gravels and other divided silicate sources including spent oil shales.

Investigation of fluid suspended sources (usually water) by magnetic beneficiation and using insulating liquids for dielectric beneficiation.
2. *Chemical Processing:* Investigation of hydrochemical leaching or dissolution processes based on acid fluoride systems in which recycle recovery of acid and fluoride values approaches or exceeds 90% of input equivalents.

Topics: Comparison of excess fluoride vs. fluoride deficient processes. Use of mixed acid HF-HCl, HF-H₂SO₃, and HF-H₂SiF₆ systems. Use of NH₄FHF salt fusion methods, etc.

Investigation of application of acid fluoride dissolution processes to sodium reduction or electrochemical reduction of silicon, aluminum, titanium and other metal fluorides.
3. *Electrochemical Processing:* Investigation of direct high temperature electrolysis of silicates or other semirefractory source materials, either as molten systems or dissolved in high temperature fused salt systems such as fluorides or carbonates.

Topics: A. Science — Solubility and miscibility limits in specific systems. Distribution coefficients between magmatic and fused salt phases where liquid immiscibility exists. Potentiometric studies of specific elements in molten, fluoride and carbonate systems.

B. Engineering — Preliminary economic and engineering feasibility studies. Cell materials compatibility studies for magmatic, fluoride and carbonate systems, including container and anode materials.

C. Establishment of kg scale electrochemical feasibility tests for molten silicate and fused salt (fluoride and carbonate) systems.
4. *Glass and Ceramic Processing:* Investigation of physical, chemical and manufacturing or handling properties of glasses and microcrystalline solids with compositions characteristic of residual material following various extraction procedures applied to low grade sources.

Topics: Temperature-viscosity Properties — Quench vs. annealed materials. Suitability for cast (basalt) fabrication.

Investigation of properties and engineering applications of particulate silica or silicate material derivable from solution and hydrolysis products of silicate ores.

Topics: Recovery and conversion of silica gels, sols and combined systems for unfired binder systems, adhesives, low energy fabrication of building products, etc.
5. *Recycle Chemistry:* Investigation of alternative methods of salt splitting or recycling acid and fluoride values.

Topics: Pyrolysis of NH₄F. Conversion of metal fluorides to compounds more readily pyrolyzed — sulfites, formates, oxalates, etc. Conversion to hydroxides with NH₃. Conversion of NaF (from sodium reduction) to Na, HF and O₂ via NaOH and Castner cell, or from fused fluorides using consumable anodes.
6. *Economic Analyses:* Survey of large scale low grade mineral sources to identify candidates for general technology areas covered by processing and probable price/profitability parameters.

Chapter III

GENERALIZED DESCRIPTION AND CLASSIFICATION OF MATERIALS ACQUISITION
AND PROCESSING STEPS FOR PRODUCTION OF
NATIVE, SEMI-REFINED AND REFINED FEEDSTOCKS FOR SPACE INDUSTRIES

Previous reports under this contract were primarily concerned with the production of refined feedstocks using chemical processing of lunar soil fractions along with the mining operations to supply such activities and the projected performance of one class of physical beneficiation involving electrostatic surface charging of soil grains. Chapter V (R1) "Lunar Glass and Ceramic Products" discussed some of the potential advantages which might accrue from using glass and ceramic technology based on native, beneficiated, semi-refined or chemically refined input materials, but the primary emphasis was toward a native product materials industry largely independent of a chemical processing (refining) facility. In a later article (P1), the broader options of native vs refined products were outlined and the potential advantages of magnetic recovery of free metal from the lunar soil were mentioned.

Succeeding studies and workshops have suggested that integration of the various native/refined materials processing operations may permit additional processing steps requiring little or no incremental energy or mass of lunar deficient elements but which may substantially increase the recovery of minor or trace elements from the lunar soil fractions. This may be particularly important if the mass flow rates of native and semi-refined feedstocks exceed that of chemically processed feedstocks by an order of magnitude or greater. Since most of the former classes will require high temperature processing to temperatures close to or exceeding the melting point, additional operations which may be conducted without multiple cooling or reheating but which can

permit recovery of valuable minor and trace elements can greatly extend the number and quantity of recoverable elements and may substantially reduce the earth transport requirement for replacement of reagents.

Figure 1 (reproduced from R1) shows the simplified flow diagram previously presented for producing chemically refined feedstocks. In the expanded scope of (integrated) total materials processing operations, we may replace Fig. 1 with Fig. 2 which introduces two new classes of processing operations which we designate preconditioning and chemical beneficiation respectively; the latter constituting reactive counterparts to the physical beneficiation previously studied.

Preconditioning

We may define preconditioning to include size fractionation and modification and other operational steps which do not require external chemical reagents or solvents and which do not, in themselves, achieve a macroscopic compositional separation of soil fractions (other than volatile components) but which are intended to improve the performance of a subsequent separation step. This latter group includes various composition or property modifying heat treating operations such as solid-solid phase transitions (devitrification, recrystallization, magnetic or electric ordering, etc.), simple annealing, and surface modification by sputtering or vacuum pyrolysis or degassing.

The last process may be desirable for separation of volatile constituents from the principal mineral fractions and will be treated in greater detail under chemical beneficiation, but may additionally be of value in its specific heat treatment effects on the residual mineral material and will be listed as a potential preconditioning step. Figure 3 shows a classification of preconditioning operations which may be of value in the overall processing of lunar materials.

We shall not discuss in detail representative operations for all of the respective classes, but rather indicate some of the potential features and advantages of selected groups.

Low to ambient temperature fluids (both as liquids or gases) for dispersion, fluidization or other materials handling operations may include O_2 , SO_2 or scarce element containing fluids such as H_2O , H_2 , He, N_2 , etc. One would particularly like to avoid widespread use of water in preconditioning operations due to inevitable loss of its contained hydrogen by surface adsorption and chemisorption on mineral grains. Superficial loss of oxygen or sulfur appears much less troublesome. Rates of oxidation of reduced grains of free metal or other sensitive compounds would probably not be of concern at temperatures below the critical point of oxygen ($-118^\circ C$).

Devitrification of lunar glassy or semicrystalline material or fusion and recrystallization are potential routes to convert a significant weight fraction of many lunar soils to crystalline form which can then be beneficiated by electrostatic or other means (1). This would normally involve an extra heating and cooling cycle (to allow for regrinding of the crystallized material) in comparison with untreated material used for cast basalt or glassy products. Recovery of volatile components by vacuum degassing or various magmatic extraction processes (to to be described under chemical beneficiation) can generally be performed in a single heating cycle along with the fabrication operations. Whether the benefits to be gained by dual heating devitrification/separation cycles requiring increased energy and equipment masses exceed those obtainable by an increase in mining volume to obtain an equivalent mineralic crystalline output must await additional system studies.

Uhlmann et al., (2) derive the following expression for the volume fraction, V_c/V , crystallized at time t for an initially vitreous sample if the

crystal growth rate, u , and nucleation rate per unit volume, I_V , are independent of time:

$$V_c/V = 1 - \exp(-(\pi/3)I_V u^3 t^4)$$

where the units are: (I_V) $\text{cm}^{-3}\text{sec}^{-1}$, (u) cm/sec and (t) sec . For glasses of lunar composition, isothermal heat treatment at optimum temperatures of the order of 10^4 to 10^5 seconds can achieve 50 - 90% or more volume crystallization (Fig. 4).

Lofgren (3) has studied the textures of crystallized magmas as a function of cooling rates, degree of partial melting and thermal prehistory. His results indicate that cooling of completely melted samples for a week or longer ($\sim 2^\circ\text{C}/\text{hr}$) resulted in appreciable residual very fine grained microcrystalline or glassy matrix content, while partially crystallized (nucleated) samples could be cooled at much higher rates ($5 - 33^\circ\text{C}/\text{hr}$) with fractional coarse crystallinity and mean crystal size increasing as the cooling rate decreased.

An industrial process could presumably be tailored to give an optimum density of crystal nuclei by controlled heating cycles or by external inoculation, and the crystallization process optimized by various non-linear time-temperature cooling cycles with total time cycles of the order of 100 hours probably required for high yields. An interesting option which may be of value in recovery of various trace elements is to arrest the crystallization process at 80 to 90% completion and withdraw the residual magma (if viscosity permits) by centrifugal means. The liquid fraction should be substantially enriched in those elements which do not readily substitute in normal lattice sites of the common silicate minerals -- in particular, elements which form large cations such as barium, thorium and most of the rare earth elements (the so-called large ion lithophile elements). Partition coefficients in excess of 10^2 have been

reported for barium, potassium and rare earths elements for silicate systems during crystallization of silicate phases that do not contain significant Ca (e.g., olivine, low Ca pyroxenes, etc.) (4). Magmatic concentration of these large cations will ultimately be limited by crystallization of calcic phases. Such a residual magma may then be treated by various chemical beneficiation steps to recover these and other elements of interest.

Chemical Beneficiation

Chemical beneficiation will be defined for our purposes as those processing steps in the overall materials processing operations that achieve partial separation or enrichment of selected fractions from single or multiphase systems as a result of chemical reactions (oxidation, reduction, substitution or pyrolysis, etc., but which do not require reagents or extractants involving use of lunar deficient elements and for which the substantial mass ratios of reagent or extractant (solvent) to materials stream being treated is much less than unity. We shall include vacuum or low pressure gas-solid reactions of lunar soils in this category, although it is apparent that desorption of some solar wind elements, particularly the noble gases, is more in the nature of a physical desorption. The evolution of hydrogen, carbon and sulfur compounds usually involves formation of stable molecules by interaction of light element atoms with other solar wind atoms or the mineralic matter or in some cases by direct pyrolysis of the mineral constituents. Some possible methods of chemical beneficiation include treatment of fused magmas with immiscible fluids (iron, silicon, sulfides, etc.), vapor extraction of magmas, vacuum pyrolysis, and low pressure gas-solid reactions (with optional electric discharge generation of reactive species).

Chemical beneficiation may be particularly useful in beneficial recovery of materials process streams which would not otherwise be chemically processed as,

for example, where substantial quantities of lunar soil fractions may be used to make cast basalt parts, glass products or sintered ceramic products. One may then usefully recover the volatile and other minor or trace elements with little or no additional energy than that required for the high temperature processing step. Conversely, the chemical beneficiation of material to be later used in chemical refining operations may be less effective than other recovery methods such as ion exchange, precipitation or other options available to material in solution or partially refined.

Figure 5 shows a proposed classification of chemical beneficiation processes. Of the various classes, only the vacuum pyrolysis and some electrochemical experiments have been conducted with lunar or simulated lunar materials. The liquid-liquid extraction processes, particularly those involving molten metals and sulfides, mimic the behavior of some natural geologic processes. This is particularly significant where the predominant components of the extractant fluids are iron and FeS respectively. For chemical beneficiation, it may be more advantageous to use more strongly reducing extractants -- for example, a fluid phase which is predominantly molten silicon, or molten sulfide or phosphide phases containing higher proportions of reactive metal compounds. Electrochemical processing may be superimposed on liquid-liquid extraction to achieve preremoval of iron or removal of selected ions.

We shall not attempt a detailed discussion of all possible process classes, but shall rather list those elements in the major, minor and trace element groups which are present in sufficient quantities to make chemical beneficiation possible and for which there appear to be possible useful routes for their recovery.

In R1, we proposed an element classification in which Al, Ca, Fe, Mg, Si,

Ti and O were grouped as major elements; Cr, Mn, Na, K, S and P as minor elements and the balance as trace elements. We concluded that one could reasonably attempt to recover any of the major elements by chemical means, and that the minor elements could be recovered in the course of major element processing but would probably not be practical to recover by chemical means solely for the minor element content. Of the trace elements, we only considered recovery of the four light solar wind elements, H, He, C and N, by vacuum pyrolysis.

More detailed considerations of the possibility of magnetic extraction of lunar free metal combined with a proposed electrorefining process for the Fe-Ni-Co alloy leads to the expectation that significant amounts of nickel and cobalt are potentially recoverable and should be added to the list of elements which can be recovered from lunar soil. Electrochemical experiments by Lindstrom and Haskin (5) have demonstrated the feasibility of extracting iron and oxygen from simulated lunar magmas. This is probably a required step in several of the reducing liquid-liquid extraction methods of chemical beneficiation to achieve reasonable enrichments of other trace elements without excessive dilution by molten iron. For this purpose it may be essential that the iron be removed in the solid rather than the molten state which may impose constraints on the level of eutectic forming elements such as Si or Al in the cathode and the melting temperature of the residual magma, especially as the iron content is depleted.

As previously stated, the adoption of chemical beneficiation steps (other than vacuum pyrolysis) is predicated on the establishment of a substantial mass handling facility for native or physically beneficiated products manufacturing in the glass or ceramics fields. Given such a scenario, we may reexamine the potential for recovery of various major, minor or trace elements by means which

do not require significant quantities of reagents -- especially those incorporating lunar deficient elements.

Table 1 lists the six minor elements along with 29 trace elements (13 of which are in the Ba, Sr, rare earth, Sc and Y groups) which often occur at levels above ten parts per million in lunar soils. Their average levels in Apollo 12 and 14 soils are also given (6). In addition another ten elements (five of which are rare earths) which are generally present in the 1 to 10 ppm range, but which are chemically related or of special importance, are also listed.

The combined content of the lunar soil for the 39 trace elements is .244 and .38% respectively which, added to the minor element contents of 1.23 and 1.55%, give combined minor and select trace element contents of 1.47 or 1.93% for the Apollo 12 and 14 soils. Even 50% recovery efficiencies could lead to 1% total yields of these elements.

In addition to these minor and trace elements, efficient extraction processes may require or permit the recovery of iron, titanium and oxygen from the input material. In a scenario in which the mass flow rate of nonchemically refined ore were ten times that of ore subject to total chemical processing, recovery of iron which typically occurs near the 10% level in lunar soils by (electro)chemical beneficiation could equal the mass throughput of all chemically refined products, while the recovery of other minor and trace elements might total 10% or more of the throughput of the chemically refined streams.

Recovery Methods for Trace Element Groups

The 39 trace elements discussed above were grouped into classes described as volatiles (5), technical metals (12), BSREEYS (barium, strontium, rare earth elements, yttrium and scandium) (18) and LEH light elements and halogens (4).

In addition three of the minor elements, Na, K and S, appear to be recoverable as volatiles while P may also be recoverable under controlled reducing conditions. Zn, Pb and Ga from the technical metal group, and Cl and F from LEH, may also be recoverable in the vapor phase under favorable conditions.

The recovery of any element which is a minor or trace constituent of a solid or liquid phase in more concentrated form depends on the establishment of a favorable partition coefficient (or equivalent) between two phases. The partition coefficient may result from differences in valence state in the two phases as for oxidation-reduction equilibria, or for chemical affinity between two phases for the same valence state as for immiscible sulfide-silicate or phosphide-silicate liquids. Partition coefficients of 1000 or more for Ni or other siderophile elements between metallic and silicate phases have been determined and if present, could extract 50% of an element initially present at a 10 ppm level to a minor phase at the 0.5% level.

The partition coefficient may be expressed as the ratio of mole fractions $X_{A1}:X_{A2}$ of A in phases 1 and 2. The mole fractions in turn may be expressed as activities divided by activity coefficients; i.e., $X_{Ai} = a_{Ai}/\gamma_{Ai}$. The ratios of activities of a constituent in two phases may often be calculated from published thermodynamic data and the activity coefficients may sometimes be estimated from similar systems when direct thermochemical information is lacking.

Vacuum Pyrolysis (Degassing)

Studies by Gibson and others (7) on the thermal degassing of lunar samples in high vacuum both from solid and melted states has established that H, He, C, N, S and the alkali metals can be extracted in yields of over 50% to near 100% by heating to temperatures up to 1400°C (see Fig. 6). Zn and Pb can also be driven off, but these elements are also recoverable by reduction methods. One may also anticipate that under more strongly reducing conditions Ga and/or P may

also be recoverable in volatile form.

The total content of light element volatiles on a volumetric basis is surprisingly large. For example, for an average H content of 70 ppm and an average mineral density of 3 gram/cm^3 , there would be 0.21 mg(H)/cm^3 of lunar soils which is equivalent to 2.35 cm^3 NTP (as H_2). Collection of the volatiles would be favored by operating under self-pressurized conditions to reduce pumping compression requirements for most of the cycle. A multiple stage process could further increase yield, but may not be warranted. If hydrogen, carbon and nitrogen recovery is the most important requirement, the degassing cycle could be concluded by flushing with low pressure oxygen which would yield H_2O , CO_2 which may be readily trapped at cryogenic temperatures and N_2 which may be converted to oxides of nitrogen in plasma discharges and chemically removed. Most of the volatiles would be recovered prior to introduction of oxygen -- for example, progressive pressure reduction of a vessel containing 50 volume percent lunar soil down to 0.1 atmosphere would result in removal of more than 95% of the volatile gases from the vessel. The gases removed at this stage would consist of H_2O , H_2 , CO_2 , CH_4 , He, N_2 , CO, H_2S , SO_2 and alkali metal compounds. Separation may be accomplished by a combination of cold trapping and fractional distillation. The more volatile fraction containing He, H_2 , CO, N_2 and CH_4 may also be simplified by plasma or catalytic oxidation to yield He, N_2 (or nitrogen oxides), H_2O and CO_2 which may improve the separability and storability of the H and C compounds. Helium may also be easily separated from all other constituents by condensation of the gas stream and/or diffusion through glass or metallic membranes.

The efficiency of removal of sodium and potassium may be improved by reductive extraction from a system buffered by silicon-silicate. In such a system with an appreciable content of magnesium in the magma (or as a coexistent

MgO phase) there will exist a measurable partial pressure of magnesium vapor. Under such conditions, flushing with Mg vapor or Mg-He mixtures will efficiently extract alkali metals from the magma including Li, which is substantially nonvolatile under more oxidizing conditions. This system will be discussed in more detail under vapor-liquid extraction methods.

One may generally presume that extraction of volatiles would be desirable and require a minimum of external facilities in addition to those normally required to process the native soil products by high temperature fusion or sintering methods. It would appear that degassing in some form may be virtually mandatory to achieve sound, dense sintered or fused products except where foamed glass or similar products are desired.

In addition to the elements described above, extended heating at elevated temperatures may also volatilize additional elements, including Zn, Pb and Cl. Furthermore, under more strongly reducing conditions, such elements as Mg, Na, K, Li, Mn, P and others may volatilize more easily than for untreated soils. Some of these elements may be recovered more practically by liquid extraction or other methods, however.

I. EXTRACTION FROM SOLID SOIL FRACTIONS

Extraction of constituent fractions from solid crystalline or glassy phases of lunar soils may be expected to be adversely affected by low diffusion rates of atoms or atomic groups within solid phases. Diffusion constants, D , are usually very temperature dependent in the solid state in contrast to liquids reflecting a high activation energy, but even approaching the melting point are invariably one to several orders of magnitude lower than in liquids where they may typically fall near $10^{-5} \text{ cm}^2/\text{sec}$ for liquids of normal viscosity (see Fig. 7).

Extraction from the solid phase, accordingly, will generally require

extremely fine particle size, both to afford access to interstitial crystalline phases and to permit reasonable extraction efficiencies in practical times.

Extraction from the solid phase may be favorably employed when one or more of the following considerations apply:

- (1) Recovery of surface volatiles or condensates is desired.
- (2) Recovery of elements substantially concentrated in scarce (trace) crystalline or glassy phases (examples P, F, Cl, Cr, etc.).
- (3) Recoveries requiring extractants using lunar deficient elements which might otherwise dissolve in molten soil fractions in intolerable amounts provided the surface can be readily stripped or desorbed of the extractant and for which no practical way of recovery from dissolved molten phases is known.

The volatile solar wind elements are known to be concentrated near the surface layers, and special lunar soils such as the orange and green glass soils have been demonstrated to have enhanced surface content of volatile elements. Recovery of these constituents may be particularly favored by vacuum degassing at temperatures below the melting points of the soil fractions. Processing may, of course, be conducted in two stages in a single apparatus by raising the temperature to fuse the charge after initial degassing or extraction.

II. EXTRACTION FROM LIQUID SOIL FRACTIONS

Recovery of desired constituent major, minor or trace elements from molten magmas places additional constraints upon the chemical compatibility of the gaseous or liquid phase as well as container materials in contact with the magma. In this regard, the oxidation potential or equivalent oxygen fugacity is one of the most important factors in determining the possible extractant systems

which may be used. In addition, the acidity or basicity of silicate melts (corresponding to high or low silica contents) is of considerable importance in determining coexistence ranges of two liquid immiscibility zones. We shall discuss several reducing systems in some detail to examine the potential for extraction of specific elements.

Extraction in Reducing Systems

Fusion of lunar samples containing some free iron and a measurable ferrous iron content will buffer the oxygen fugacity or partial pressure in a range near that shown by curve Fe-FeO in Fig. 8. Establishment of more strongly reducing conditions in the magma will normally require removal (reduction) of substantially all of the ferrous iron. This appears to have occurred in the enstatite chondrite meteorites where the silicate phases are virtually iron free (8).

The next range of oxygen partial pressures which can be buffered with the major element constituents involves the elemental silicon-silica (or silicate) system. These are shown in the lower curves of Fig. 8 for the systems: C_2S (or C_3S)-CaO-Si-O₂, M_2S -MgO-Si-O₂, and A_3S_2 -Al₂O₃-Si-O₂ where the silicate phases are expressed in the cement chemist's shorthand notation, (C = CaO, M = MgO, A = Al₂O₃ and S = SiO₂). The melting points of the silicate phases and the binary and ternary mixtures are also shown on the curves.

Establishment of even more strongly reducing systems as, for example, where molten titanium, aluminum, calcium or magnesium (under pressure) is a coexistent phase would normally require substantially complete reduction of silicon. This would drastically elevate the melting points of the magmas and by requiring reduction of 50% or more of the input equivalents constitute a major chemical process rather than chemical beneficiation as we have defined the term. We shall not discuss such steps here other than to note that this constraint

constitutes a problem of considerable magnitude in the direct electrochemical recovery of aluminum from lunar soils.

The silicon-silicate redox buffer may be used in several ways to aid extraction of minor and trace elements from lunar soils. These include vapor phase extraction of magnesium and other metals such as sodium and potassium, recovery of nonvolatile elements more easily reducible than silicon, and recovery of certain reactive elements capable of forming highly stable silicides. These will be discussed below.

II-1. VAPOR PHASE EXTRACTION FROM LIQUID MAGMAS

A. (Vapor phase extraction -- Si-SiO₂ redox buffer)

If one treats a magma by electrochemically reducing and removing iron, preferably in the solid state to minimize codeposition of certain minor and trace elements, one may then establish a very small fraction of elemental silicon by incremental reduction. The silicon may be metastable toward silica in very acidic magmas at temperatures above 1180°C, but should be capable of coexistence with basic magmas to 1400°-1500°C without forming SiO. If the magma has sufficient MgO content, the buffered oxygen partial pressure will yield a partial pressure of Mg vapor dependent on the activity of MgO. For the three previous buffer systems described, the equilibrium pressure of Mg over solid MgO is given by the appropriate curves in Fig. 8. The condensation (vapor) pressure of magnesium is also shown. The equilibrium may be used to recover magnesium from the magma, or alternatively as a carrier gas to recover other metals. Of particular importance, one may anticipate reasonable efficiencies in recovery of the alkali metals, Na and K. The dissociative reduction of sodium proceeds according to the equation: $1/2 \text{Na}_2\text{O} \rightleftharpoons \text{Na}(v) + 1/4 \text{O}_2(v)$ with an equilibrium constant

$$K_{eq} = \frac{P_{Na} \cdot P_{O_2}^{1/4}}{a_{Na_2O}^{1/2}}$$

If the activity or pressure of O_2 is buffered by the Si-SiO₂ system, an apparent equilibrium constant $K'_{eq} = K_{eq}/P_{O_2}^{1/4} = P_{Na}/a_{Na_2O}^{1/2}$ exists. If we assume that the activity of Na₂O is typically 10^{-6} in molten lunar magmas, the equilibrium pressures of Na for the calcic and aluminous Si-SiO₂ buffers are shown by the uppermost curves on Fig. 8. It appears probable that Na and K can be removed more effectively by reductive vaporization than by simple vacuum pyrolysis.

B. (Vapor phase extraction at other reduction potentials)

Sulfur and phosphorus, uniquely among the minor elements, possess volatiles which do not increase monotonically as the reduction potential increases. In wet or acidic systems, sulfur is moderately volatile over a wide range of potentials as H₂S, S₂, SO₂, SO₃, etc., but in dry basic magmas the formation of stable metallic sulfides under strongly reducing conditions suppresses volatilization of contained sulfur. Experiments by Katsura and Nagashima (9) on vapor phase extraction of magmas with dilute SO₂ redox buffered by CO:CO₂ (from H₂:CO₂) show a general reduction of residual S content to about 10 ppm for the compositions studied at 1250°-1300°C. Although these experiments were conducted with higher hydrogen or water contents than appears practical for lunar extractions, it would appear likely that comparable results could be achieved for dry magmas. Lowest residual S levels were achieved with oxygen partial pressures near 10^{-6} atm (Fig. 9) with SO₂ the principal volatile species.

The efficient recovery of sulfur from magmas may be especially important if molten sulfide extraction procedures for other elements were desired.

The volatile behavior of phosphorus in magmas has been much less studied than the corresponding case of sulfur. Phosphorus appears in lunar soils primarily in the +5 valence state in the minerals whitlockite and apatite, but also to a limited degree as iron phosphides (negative valence) associated with the meteoric metal particles.

Under oxidizing conditions, the greater thermal stability of calcium phosphates than calcium sulfates would lead one to expect even greater retention of phosphorus than sulfur in oxidized magmas. While the vapor pressures of phosphorus oxides are lower than those for sulfur oxides, they are sufficiently great (1 atm) at magmatic temperatures to present no particular barrier to volatile recovery. Elemental phosphorus is more volatile than elemental sulfur and is recovered as a vapor in large quantities in arc furnace production of phosphorus from phosphate rock. Under strongly reducing conditions for which phosphide formation is possible, one would again anticipate reduced volatility. The stabilities of metallic phosphides would generally be lower than for the corresponding sulfides, however.

Like sulfur, it would appear possible to efficiently extract phosphorus from magmas as volatile species under controlled redox conditions. Experimental studies would have to be initiated on simulated lunar soil compositions to establish proper conditions and residual magma levels to determine process feasibility.

II-2. LIQUID PHASE EXTRACTION FROM LIQUID MAGMAS

C. Metals, Alloys and Silicide Fluids

(Liquid phase extraction -- Si-SiO₂ redox buffer)

The extraction of a number of additional minor and trace elements is

possible by development of favorable partition coefficients between the reduced and silicate phases. Elements which are classed as siderophilic in meteoric or geochemical systems will preferentially concentrate in the reduced phase. If the volume ratio of reduced (silicon) phase to silicate phase is kept in the range of 10^{-3} to 10^{-2} , concentration ratios of elements such as Cu, Cr, Mn and perhaps Nb and V can be increased from two to three orders of magnitude or more in the extractant phase.

In a manner analogous to the case of sodium discussed above, we may express the dissociative reduction of an arbitrary metal oxide, MO_z by the equation:

$MO_z \rightleftharpoons M(rp) + (z/2) O_2 (v)$ with an equilibrium constant

$$K_{eq} = \frac{a_M \cdot P_{O_2}^{z/2}}{a_{MO_z}} \text{ and an apparent equilibrium constant}$$

$$K'_{eq} = K_{eq} / P_{O_2}^{z/2} = a_M / a_{MO_z} \text{ (rp = reduced phase).}$$

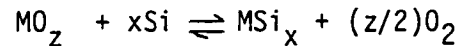
Using available thermodynamic properties data (10,11), we may calculate the activity ratios between the metal in reduced phase (rp) and the oxide in the magma for a number of elements. The results are shown in Fig. 10. If the activity coefficients for the metal in the silicon or silicide phase is the same as for the oxide in the silicate phase, the activity ratio will essentially be equivalent to the partition coefficient expressed as a mole fraction ratio. Curves lying above zero on the log ratio scale will have partition coefficients greater than unity and will be concentrated in the reduced phase. Thus Cu, Cr, Mn, Nb and V will be expected to concentrate in the reduced phase by factors of 20 or more over the temperature range shown.

Conversely, the elements below zero, Ti, Ba, Sr, Zr, Hf and Th, will not concentrate in the reduced phase based on ease of reduction alone. In some of

the cases, however, the enhanced stability of silicide formation may be sufficient to permit useful beneficiation.

D. (Liquid phase extraction -- silicide enhancement)

For those elements which form highly stable silicides, we may express the dissociative formation of silicides by the equation:



This equation is the sum of the oxide dissociation step plus the silicide formation equation: $M + xSi = MSi_x$. Full thermodynamic data is not available for most silicides, but the free energies of formation may be expected to be nearly the same as heats of formation since the entropy corrections are small. Table II summarizes some thermodynamic data on silicides. The equilibrium constant of the combined equation is given by the product of the equilibrium constants for oxide dissociation and silicide formation, and $\log K$ is given by the sum of the individual $\log K'_{eq}$ s. This has the effect of raising the activity ratio curves by an amount characteristic of the silicide equation -- the curves then representing activity ratios of silicide to oxide: i.e., a_{MSi_x}/a_{MO_z} . For elements that form highly stable silicides such as Ti, Zr, Nb, V, etc., this may serve to increase the partition coefficients by three to five orders of magnitude. Based on these data, one may anticipate that Ti and Zr may develop partition coefficients in the range of 10 to 100 at temperatures near 1600°K in silicon rich extractants, and elements such as V and Nb would develop much higher partition coefficients than indicated by the activity ratios on Fig. 10.

NONMETALLIC (AND NONSILICONIC) LIQUID EXTRACTANTS

E. (Sulfide systems)

Molten sulfides and sulfide-oxide fluids constitute a class of liquid

extractants of potential interest for chemical beneficiation of lunar magmas. Two major problems exist for liquid-liquid extraction processes based on these systems; these are: (1) extensive loss of sulfide phase due to saturation in magma (silicate) phase, and (2) very high melting points of alkaline earth sulfides.

The first problem is not completely intractable, but for many situations, it may require a rather sizable desulfurization step (by vapor phase extraction) following the liquid extraction operation. Fig. 11 shows the ternary phase diagram FeS-FeO-SiO₂ and indicates the enormous effect of oxide content on silica-sulfide immiscibility at the liquidus surface. It is presumed substitution of other oxides for FeO would still show a similar trend. For a practical process it would be imperative to reduce the residual content of sulfur below that present in the input source to avoid independent sulfur recovery operations.

The reported melting points for a number of sulfides are shown in Table III.

The first two columns for the sulfides represent highly refractory sulfides which are probably extensive mutually soluble with molten silicates at temperatures at or above 2000°C. Probably the most useful sulfide phases for extractive work might be FeS, the aluminum sulfides, or the Fe-FeS eutectic. For extraction from solid lunar charges, the Ni-Ni₃S₂ system may have special utility, since it can be operated at such a low temperature. Of course, efficient recovery of the nickel from the surface of the solid phase would be necessary.

The partition coefficients between sulfide and silicate phases are difficult to estimate in many cases, but in addition to the elements usually classified as chalcophile (e.g., Cu, Zn, Ga, and Pb) one may anticipate

partition coefficients greater than unity for a number of elements which form exceptionally stable sulfides. In strongly reducing conditions, certain elements such as Cr, Mn, Ti, V and Fe are chalcophilic and have partition coefficients greater than unity (with respect to silicate phases) (12). Examination of Table II leads one to expect that elements in the BSREEYS group (which form lower sulfides of exceptional stability) may be extractable with sulfide or sulfide-oxide fluids. Extraction efficiency may be particularly enhanced by a prior stage of melting and partial crystallization, since these large ion lithophiles (LIL) are strongly rejected from most silicate phases and can be substantially enriched by freezing 80 to 90% or more of the magma.

In the sulfide and phosphide systems some of the metal poor compounds may be unstable at magmatic temperatures except under very high partial pressures of S (or P). This may restrict the range of composition of the extractant fluid and limit the stabilization achievable to that characteristic of the most metal rich compound for a given element.

F. (Phosphide systems)

Examination of the thermodynamic data suggests that phosphide systems may be effective extractants for alkaline earth, Ti and related elements (Zr, Hf) and possibly for trivalent elements such as the rare earths, although the latter group may not be particularly stabilized for large metal atoms (c.f., AlP vs GaP). Clearly, additional experimental work is required to evaluate the potential these systems.

Recovery of the extracted elements from silicide, sulfide or phosphide phases may be accomplished by a variety of chemical or electrochemical methods. Total concentrations of minor and trace elements in given extractant fluids may be elevated to the 5 to 10% range or higher in many cases. These may be stored as unseparated concentrates for batch processing after sufficient accumulation.

G. (Oxidizing liquids)

Na_2SO_4 and its solutions with K_2SO_4 are highly stable fused salts which melt below 900 - 1100°C and have dissociation pressures below 1 atm at magmatic temperatures. Although solubility information is scant, it appears to have low mutual solubility with acidic silicates. Little appears to be known about the partition behavior between sulfate and silicate phases, but this appears to be an interesting field for future investigation.

SiO_2 , TiO_2 and mixtures are possible oxidizing extractants, but their melting points are high, although a eutectic at ca 89% SiO_2 melts near 1550°C. Addition of Na_2SiO_3 (or Na_2O) can produce a strong melting point depression (to as low as 799°C) and may offer a useful extractant. These can, of course, only be used with acidic or silica saturated magmas. Furthermore, their viscosities are so high as to pose a major operational problem (Fig. 12). Of the principal chemical groups, only the alkali metals appear to have favorable partition coefficients, but a number of the elements have not been investigated.

Fe_3O_4 , Mn_3O_4 and mixtures are potential oxidizing extractants, but they are high melting point systems (1550°- 1600°C) and their solubility in silicate melts appears to be too high to be useful. Compounds of Fe_2O_3 with CaO , CuO , PbO , etc., have fairly low melting points and may have low enough solubilities in strongly basic magmas to be useful as liquid extractants. More information on the phase diagrams is clearly needed.

III. ELECTROCHEMICAL EXTRACTION

Electrochemical extraction can be practiced as a general chemical processing step, or as a chemical beneficiation step to remove iron from magmas intended for glass production or as a preliminary step for establishment of strongly reducing buffer systems as previously described. In addition, it may be possible to extract some selected trace elements which may be difficult or

impossible to extract by other available methods. Because of their importance in other chemical operations, it would be particularly desirable to be able to recover F and Cl from the lunar soils. These may be concentrated in principle by electromigration since they, along with oxide ion (and possibly residual sulfide or phosphide) are the only chemical species which should migrate to the anode in strongly reducing silicate magmas.

H. (Cathodic processes)

Cathodic processes may be used for reduction and removal of iron and other more noble elements or removal of other elements which may migrate to the cathode and may be reacted with or dissolved in liquid or solid cathode systems. For iron removal, it may be preferable to separate it in solid form to avoid excessive uptake of certain other (siderophilic) elements which would more effectively be recovered in silicon extraction steps. This may arise simply because of the amount of iron which must be removed to establish more strongly reducing conditions. For example, the Apollo 12 and 14 average soils treated in Table I contain 11.98 and 8.05% Fe, respectively. Regardless of the partition coefficients, the concentration increase (on a weight basis) for any element could not total more than factors of 8.35 and 12.42 over that in the original soils if all of the iron were reduced due to excessive amounts of molten iron phase.

If iron is deposited in solid form, one may expect codeposition of some more noble metals (Cu, Ni, Pb, etc.) as well as some Mn, Cr, and Zn along with traces of more reactive elements. These elements may for the most part be recovered by electrorefining the iron, or alternatively by melting the cathodes and reextracting the iron with various extractants such as sulfides, oxides or iron silicates ("slagging").

Secondary extraction of minor and trace elements may also be performed on

iron alloys originally deposited in liquid form, but one would expect substantial amounts of aluminum and silicon to be incorporated in the cathodic layer, which will again limit the amount of enrichment otherwise possible. Depending on the melting points of the original soils and their changes with composition as iron is removed, it may become progressively more difficult to prevent incipient melting in solid iron cathodes in view of potential eutectic melting systems for possible codepositional elements. The melting point of pure iron (1537°C) is well above that of iron free Ca-Al-Mg silicates over an extended range of composition with minimum silicate eutectics melting near 1230°C.

Removal of all of the iron from the Apollo 12 and 14 soils cited corresponds to reduction of 8 and 5.3% of the total equivalents in the soil samples. At 100% current efficiencies, this would require 4,290 and 2,884 equivalents per metric ton, respectively, or 114,980 and 77,297 ampere hrs/metric ton.

Silicon may be produced by continued reduction of the melt after iron removal to generate the extractant needed for silicide extraction, or simply to provide the oxygen buffer needed in the vapor phase extraction systems previously discussed.

In addition to the solid or liquid metal (or silicon) cathode systems, one may also employ fused salt or salt-like liquid layers which are cathodic with respect to the fused magmas. This liquid layer may be an ionic conductor, electronic conductor, or possess mixed conductivity. Ionic resistivities (inverse conductivities) of some fused salts and silicate fluids are shown in Fig. 12. For electronic conductors, one develops reducing conditions at the interface, which may be accompanied by chemical reaction or solvent behavior between the discharged cations and one or both of the interfacial liquid phases.

For ionic conductors, one may develop changes of concentrations of ionic species at the interface, depending on concentrations and transference numbers of ions in the respective phases. These concentration changes may produce local supersaturations with precipitation of additional phases at the interfaces. For cathodic liquid layers, one must avoid easily reducible fluids, since these will be unstable at the true cathode or internally for electronic or mixed conductors. (It should be mentioned that most transition metal compounds become effective electronic conductors at elevated temperatures, even when they are substantially insulators near room temperature.) Sulfides, phosphides and halides are potential candidates for cathodic liquid electrodes. Of these, the halides may present the greatest operational problems since the anions will tend to migrate and dissolve in the silicate phase, and would have to be recovered with high efficiency.

I. (Anodic processes)

Anodes are particularly susceptible to oxidative corrosion, especially in cells operating above 1000°C. Migration of cations away from the anode in silicate magmas may render the anodic layer more acidic and raise the melting point as pure silica is approached. This may be counteracted by using a liquid anodic system, provided its electronic conductivity is not too high. Fused salts containing Ca, Mg, or Na ions are possibilities.

During removal of iron or other reduction processes, one will generally discharge oxygen or form a higher oxide at the anode from which oxygen may later be recovered. During oxygen evolution, any Cl^- present may be expected to be oxidized to elemental chlorine. After cooling the oxygen down to temperatures prior to liquefaction and storage, the residual chlorine content can be cold trapped or scrubbed with alkaline absorbents and recovered. Unfortunately, the method is not useable with fluoride.

F and Cl may be recoverable by using a fused $\text{CaCl}_2\text{:MgCl}_2$ anodic layer. One would anticipate deposition of CaO and/or MgO along the interface, while Cl^- and F^- should enter the salt layer. Chlorine would be discharged at the true anode. If the magmatic layer were saturated in CaO and/or MgO, the precipitated film may incorporate elevated levels of halide ion, but, if so, could serve as an enriched source for secondary halide recovery.

The halogens may also form volatile anodic products if SiO or TiO are used as anode materials.

In contrast to cathodic liquid layers, the anodic layers should remain oxidation resistant or be used in a manner where partial oxidation could be tolerated. Fused sodium hydroxide or sodium sulfate are also possible useful anodic liquid layers.

SUMMARY

Chemical beneficiation can probably be conducted by heating lunar soils to perhaps only slightly higher temperatures and/or longer times than might be required to form sintered or cast products. One may expect to recover the trace volatiles including Na and S easily, and by processing to remove the iron (which may be desirable for some glass applications) one may expect to recover Cr, Mn, P and various trace elements which may be valuable to space industry. The enriched extractants may then be processed by conventional chemical means to achieve pure products. Total recoveries based on unit mass of lunar soils may fall in the 1 to 2% range, not counting iron (4 to 15%) and titanium (.3 to 6%).

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Table I
 POTENTIALLY RECOVERABLE MINOR AND TRACE ELEMENTS

	Volatiles	Technical Metals	BSREEYS*	LEH
Minor	Na(.36, .52)	Cr(.24, .15)		
Elements	K(.22, .46)	Mn(.17, .11)		weight percent
	P(.14, .22)			(Apollo 12, Apollo 14)
	S(.10, .088)			
Trace	C(104, 130)	Cu(10.3, 11.1)	Ba(413, 767.5)	Cl(31, 44)
Elements	H(45, 79.6)	Co(43, 35.8)	Sr(138.9, 183.8)	F(132, 219)
	N(84, 92)	Ni(189, 321)	Ce(104, 185)	Li(19.5, 29.8)
	He(10, 8)	Pb(4.8, 10.0)	Dy(24.6, 39)	B(9.3, 19)
	Ne(2, 2)	Zn(6.3, 28)	Er(15.35, 23.5)	
		Ga(4.3, 6.8)	Gd(25.7, 34.8)	
		Zr(503, 842)	La(38.8, 69.4)	
		Hf(12.7, 22.2)	Nd(75.6, 105)	
		Th(6.63, 13.5)	Pr(10.1, 23)	
		V(110, 49)	Sm(20.3, 30.9)	
Parts per				
million (weight)		Nb(34, 56)	Yb(13.7, 22.7)	
		Ta(1.58, 4.1)	Sc(39.2, 21.9)	
			Y(145, 242)	
			Eu(1.9, 2.64)	
			Ho(5.3, 7.8)	
			Lu(1.93, 3.1)	
			Tb(4.07, 6.4)	
			Tm(2.02, 3.9)	

Cumulative weights:

Minor Elements	(1.23%, 1.548%)	
Volatiles (5)	(245, 311.6)	ppm
Technical Metals	(925.61, 1399.5)	ppm
BSREEYS (18)	(1079.47, 1772.34)	ppm
LEH (4)	(191.8, 311.8)	ppm
Totals	(1.474%, 1.928%)	

* barium, strontium, rare earth elements, yttrium and scandium

† light elements and halogens

Table II

THERMODYNAMIC PROPERTIES OF SILICIDES, SULFIDES AND PHOSPHIDES

Compound	ΔH_f Kcal/mole	ΔG_f	Log K*	Log K
			(1000°K)	(1600°K)
CoSi ₂	-24.6		5.38	3.36
NiSi	-20.6		4.50	2.81
MoSi ₂	-28		6.12	3.82
ZrSi ₂	-36.1		7.89	4.93
TaSi ₂	-27.7		6.05	3.78
CaSi ₂	-36.1		7.89	4.93
TiSi ₂	-32.3		7.06	4.41
VSi ₂	-29.9	($\Delta G = -26.9$)	5.88	3.67
1/2 Mg ₂ Si	-9.3	($\Delta G = -9.0$)	1.97	1.23
CrSi ₂	-23		5.03	3.14
FeSi	-19.4	($\Delta G = -18.7$)	4.09	2.55
MnSi	-14.1	($\Delta G = -14.6$)	3.19	1.99
Metal-rich Systems				
	ΔH_f	ΔG_f	Log K*	Log K
			(1000°K)	(1600°K)
BaS	-110.0	($\Delta G = -109$)	23.8	14.9
CeS	-111		24.3	15.2
CaS	-113.5	($\Delta G = -112.3$)	24.5	15.3
LaS	-109	($\Delta G = -107.9$)	23.6	14.7
SrS	-108.3	($\Delta G = -107.1$)	23.4	14.6
TiS	-57		12.5	7.79
ZnS	-49.2	($\Delta G = -48.1$)	10.5	6.57
ThS	-105		22.9	14.3
1/2 Ce ₂ S ₃	-142		31	19.4
1/2 Al ₂ S ₃	-86.5		18.9	11.8

	ΔG_f				ΔH_f		Log K*	Log K
							(1000°K)	(1600°K)
FeS	-23.9 ($\Delta G = -24$)	5.25	3.28					
1/2 La ₂ S ₃	-144.5	31.6	19.7					
MgS	-82.7 ($\Delta G = -81.7$)	17.9	11.2					
MnS	-51.2 ($\Delta G = -52.2$)	11.4	7.13					
1/2 Nd ₂ S ₃	-142 ($\Delta G = -140.1$)	30.6	19.1					
NiS	-19.6 ($\Delta G = -19$)	4.15	2.60					
TiS ₂	-80	17.5	10.9					
ThS ₂	-140	30.6	19.1					
1/2 B ₂ S ₃	-28.8	6.29	3.93					
(1/3)Ca ₃ P ₂	-40.3	8.81	5.50	(1/3)Fe ₃ P	-13		2.84	1.77
CuP ₂	-29	6.34	3.96	1/3 Mn ₃ P	-17		3.72	2.82
1/2 Co ₂ P	-22.5	4.92	3.07	(1/3)Cu ₃ P	-12.1		2.64	1.65
AlP	-39.8	8.70	5.44					
GaP	-21	4.59	2.87					
BP	-19	4.15	2.60					
FeP ₂	-46	10.1	6.28					
MnP ₃	-27	5.90	3.69					
(1/5)Ni ₅ P ₂	-19.5	4.26	2.66					
(1/3)Sr ₃ P ₂	-50.7	11.1	6.93					
TiP	-67.6	14.8	9.23					
(1/3)Zn ₃ P ₂	-37.7	8.24	5.15					

*Estimated assuming $\Delta G_f = \Delta H_f$ except where direct values are given

$$\log K = \log \frac{a_{MN_r}}{a_M \cdot a_N^r}$$

where N = non metal (Si, S, P)

and formation equation is: $M + rN \rightleftharpoons MN_r$

Table III
MELTING POINTS OF SULFIDES, SILICIDES AND PHOSPHIDES

	MP°C		MP°C		MP°C
BaS	2227	La ₂ S ₃	2127	FeS	1195
CaS	2400	Ce ₂ S ₃	1887	NiS	~ 950
MgS	> 2000	Ce ₃ S ₄	2050	MnS	1530
SrS	2002	ThS ₂	1905	CrS	1567
CeS	2450			AlS	1197
LaS	2327			Al ₂ S ₃	1097
TiS	1927			Ni ₃ S ₂	810
ThS	> 2200			Cr ₂ S ₃	1350
ZrS	> 2050				
	Fe-FeS eutectic 988°C		FeO-FeS eutectic 923°C		
	Ni-Ni ₃ S ₂ eutectic 645°C		(Fe)-FeS-FeO-SiO ₂ eutectic 917°C		
TiSi ₂	1540			Ti ₅ Si ₃	2120
-ZrSi ₂	1680 d			Zr ₅ Si ₃	2250
VSi ₂	1670			V ₅ Si ₃	2150
NbSi ₂	1930			Nb ₅ Si ₃	2480
TaSi ₂	2200			Ta ₅ Si ₃	2495
CrSi ₃	1550			Mo ₅ Si ₃	2100
MoSi ₂	2030			GaSi	1245
CaSi ₂	1020			FeSi	1420
Mg ₂ Si	1102				
FeSi ₂	1212				

p > 1 atm

BP > 2000
AlP > 1000
Ca₃P₂ ~ 1600
FeP₂ }
NiP₃ } p > 1 atm
CrP > 1200
MoP > 1700
MnP 1147
PuP ~ 2000

Fe₂P 1365
Mn₂P 1327
Cr₃P 1510
Ni₅P₂ 1175

FIGURE TITLES

- Fig. 1. Flow Chart for Lunar Materials Processing
- Fig. 2. Simplified Flow Diagram for Integrated Materials Processing
- Fig. 3. Preconditioning
- Fig. 4. T-t- τ Diagram (temperature-time-transformation) for lunar glasses
- Fig. 5. Chemical Beneficiation
- Fig. 6. Vacuum Degassing of Lunar Soil 12022
- Fig. 7. Cation Diffusion in Solid Silicates and Oxides
- Fig. 8. Equilibrium Pressures of Oxygen, Magnesium and Sodium Vapor in Buffered Reducing Systems
- Fig. 9. Equilibrium Sulfur Content of Magmas
- a. @1250°C, 2.1% SO₂ (vapor) phase vs. magma composition
○ tholeiite basalt, ◐ Hawaiite, ● rhyodacite
 - b. Tholeiite basalt @ 1250°C vs. SO₂ content of gas phase
○ 2.1%, Δ 1.3%, □ 0.5%
- Fig. 10. Equilibrium Activity Ratios of Metal:
Metal oxide in reduced silicon-silicate buffered systems
z value: Cu = 1/2, 1 Mn, V, Ti, Ba, Sr = 1; Cr = 1.5; Zr, Hf, Th = 2
- Fig. 11. Phase Diagram FeO-FeS-SiO₂
- Fig. 12. Viscosities and Electrical Resistivities of Silicates and Fused Salts

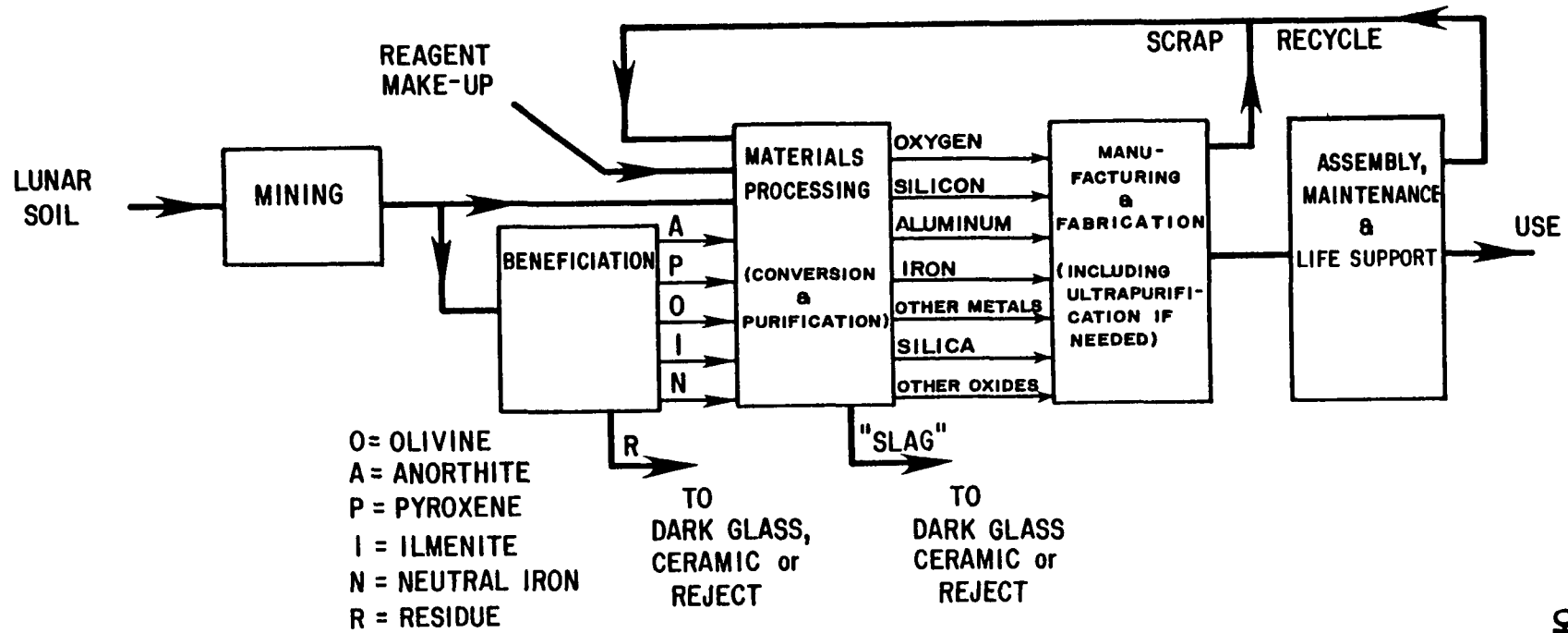
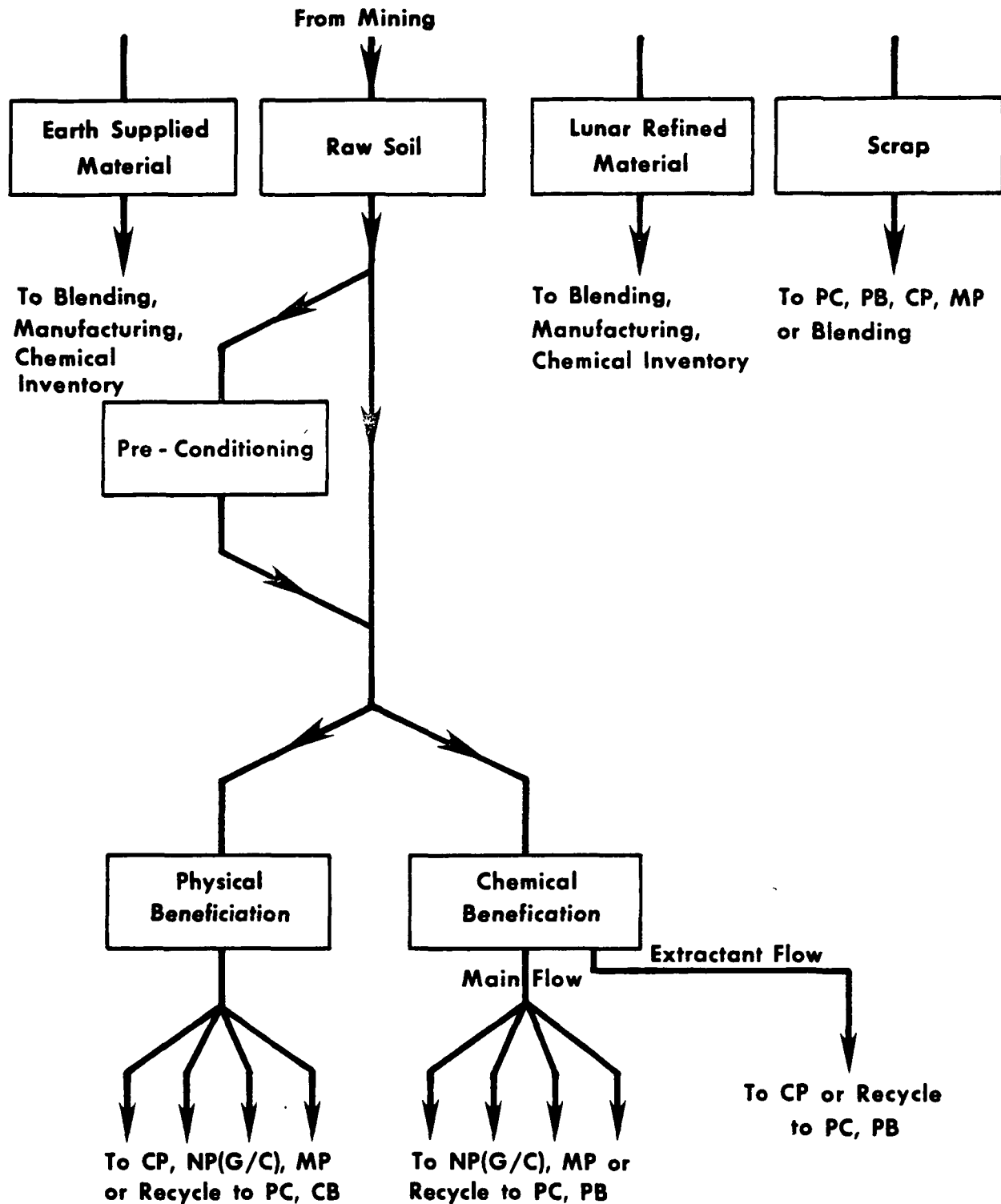


Figure 1

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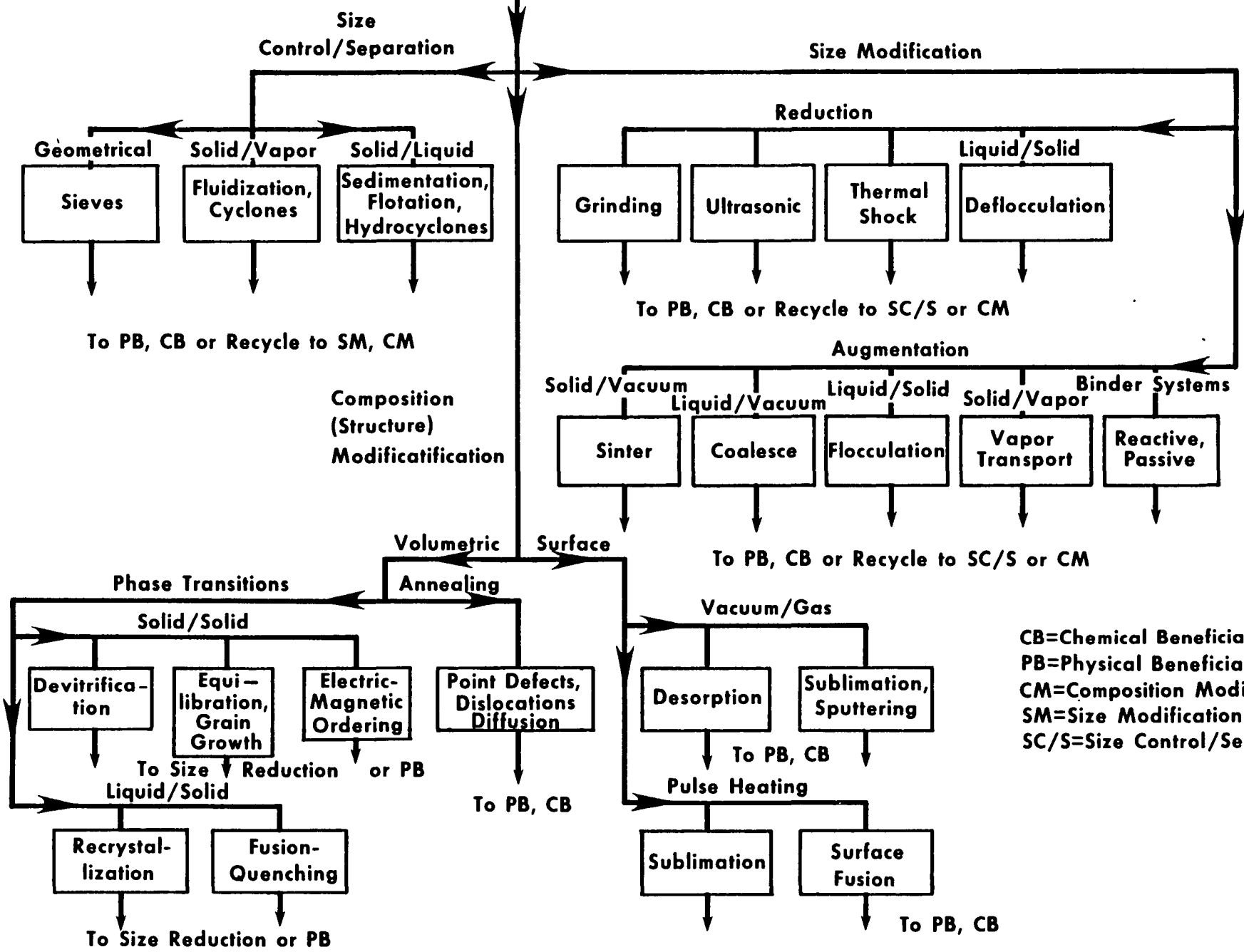
SIMPLIFIED FLOW DIAGRAM FOR INTEGRATED MATERIALS PROCESSING



CP=Chemical Processing
NP(G/C)=Native Products (Glass/Ceramic)
MP=Metals Processing
PC=Preconditioning
CB=Chemical Beneficiation
PB=Physical Beneficiation

Figure 2

PRECONDITIONING



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Figure 3

CB=Chemical Beneficiation
 PB=Physical Beneficiation
 CM=Composition Modification
 SM=Size Modification
 SC/S=Size Control/Separation

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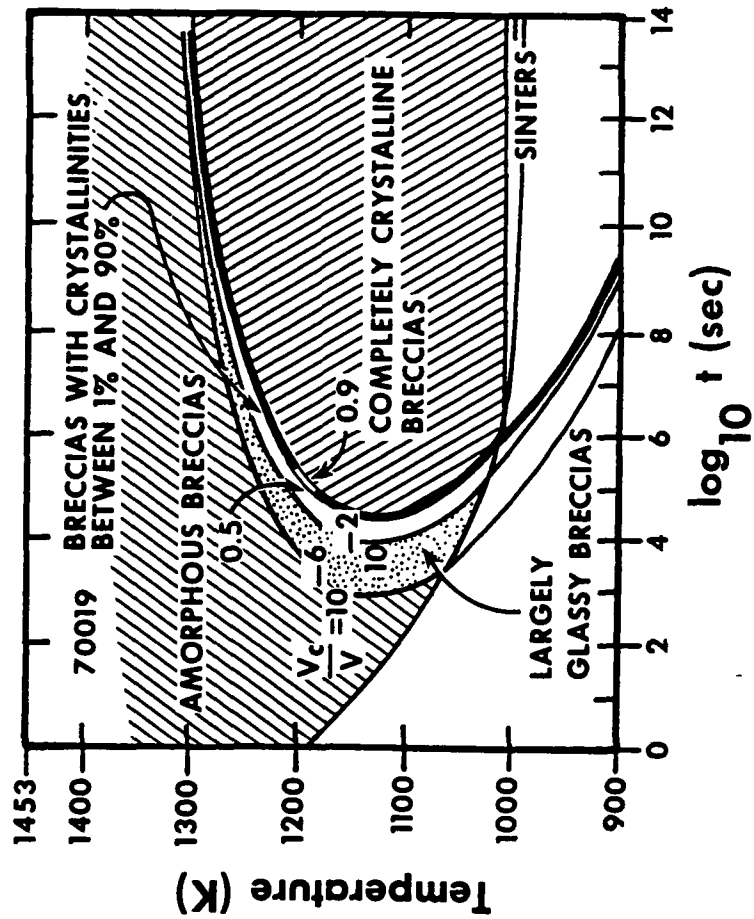


Figure 4

CHEMICAL BENEFICIATION

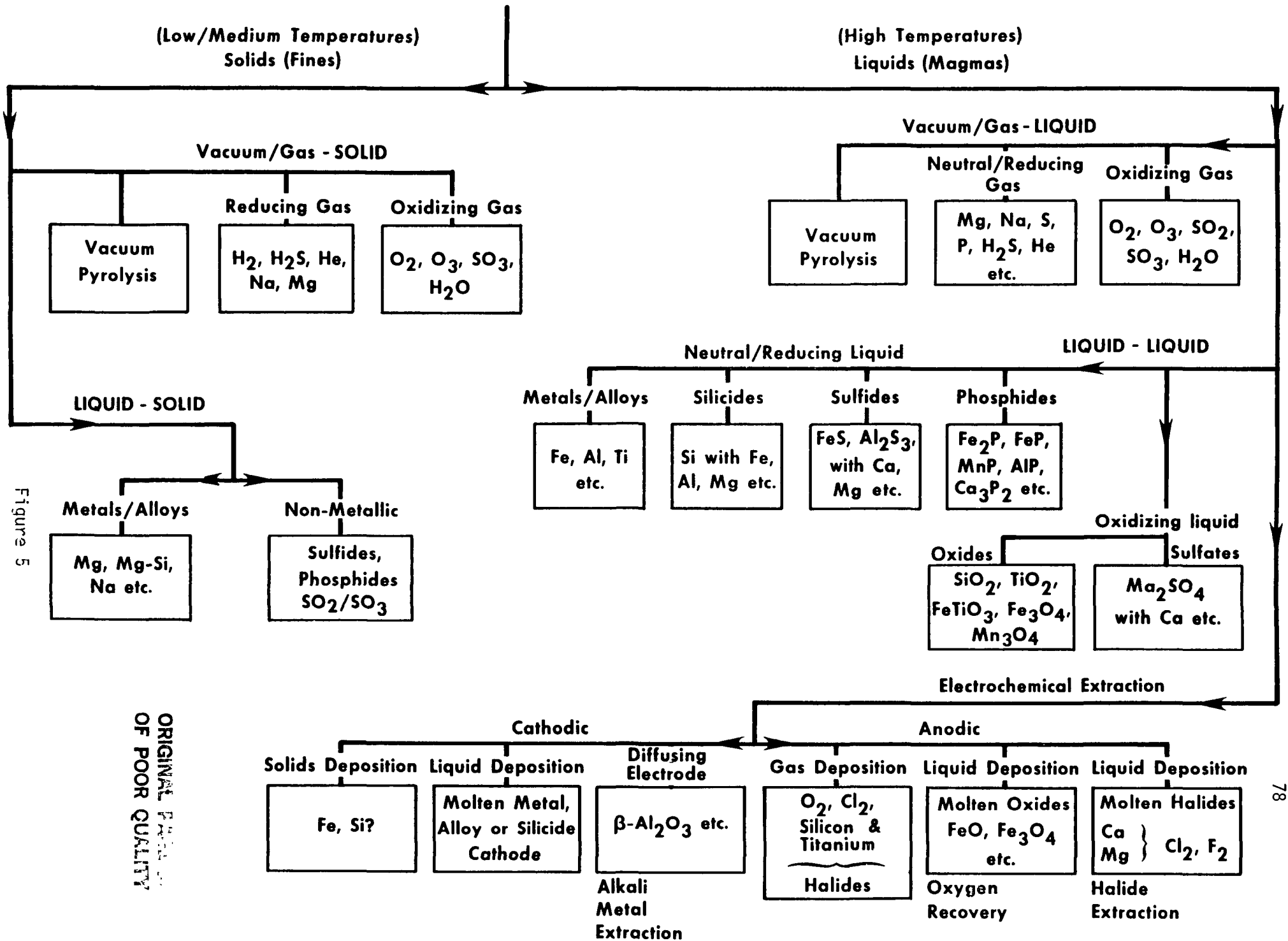


Figure 5

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PERCENT OF ORIGINAL CONTENT NOT VOLATIZED

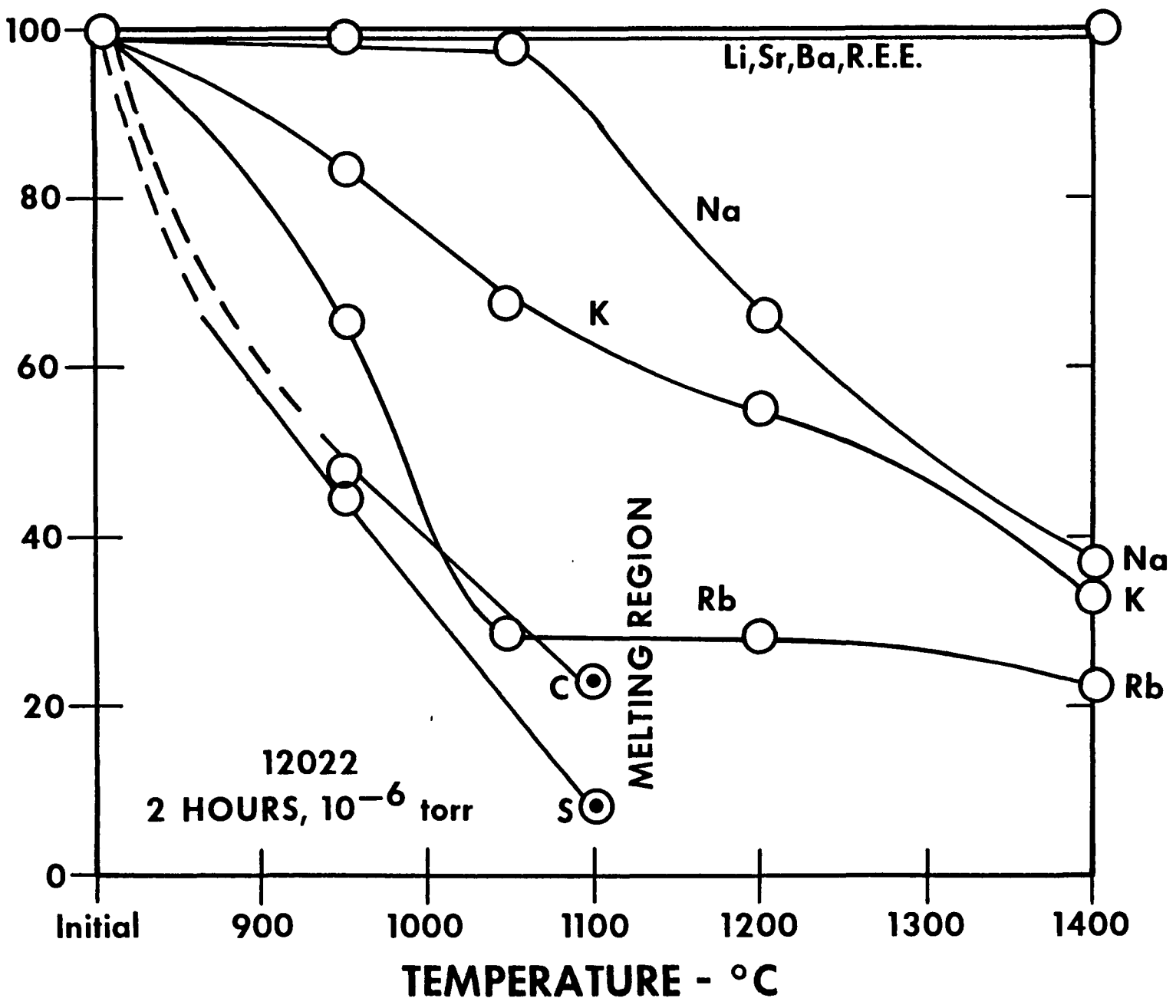


Figure 6

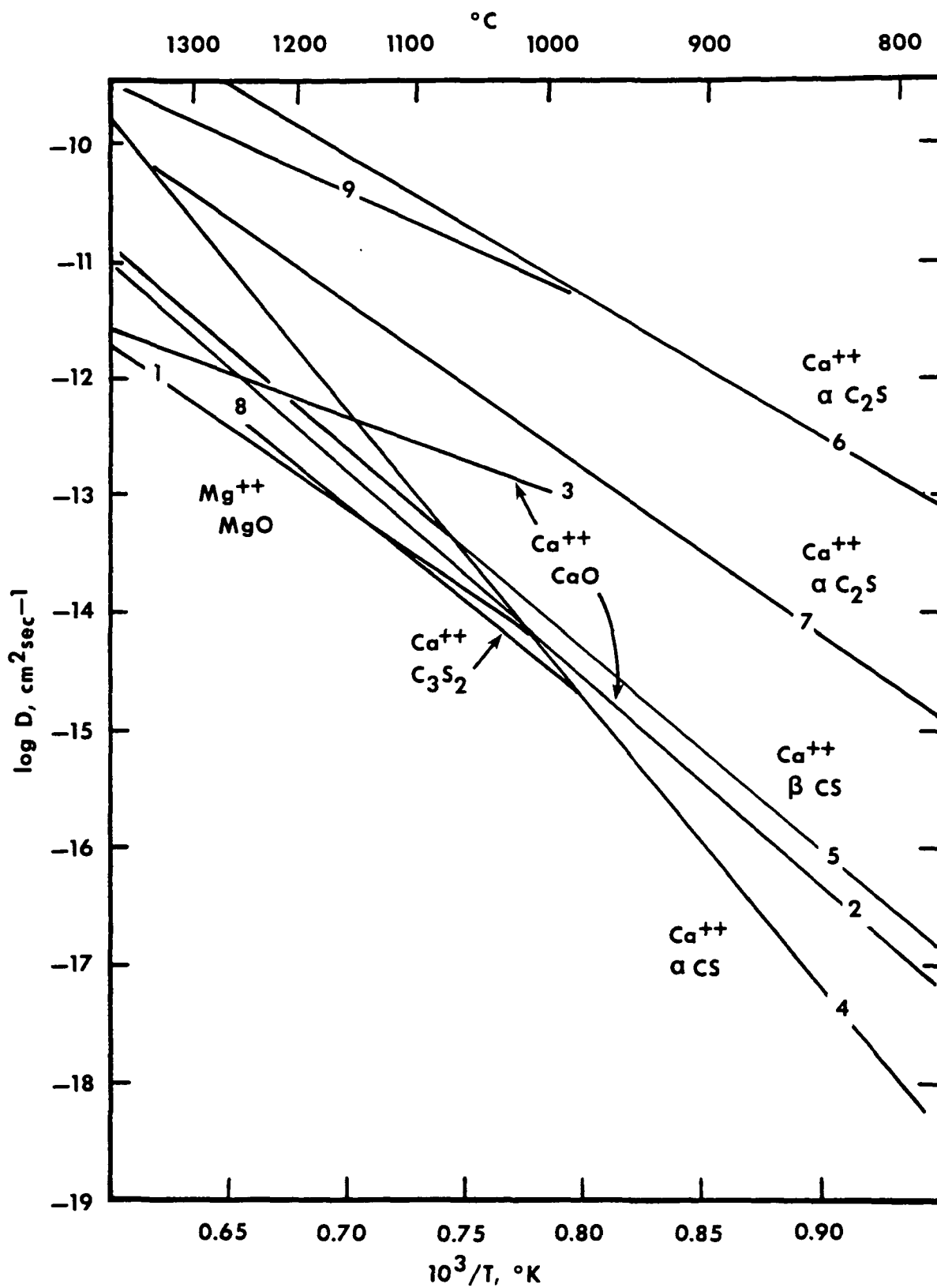


Figure 7

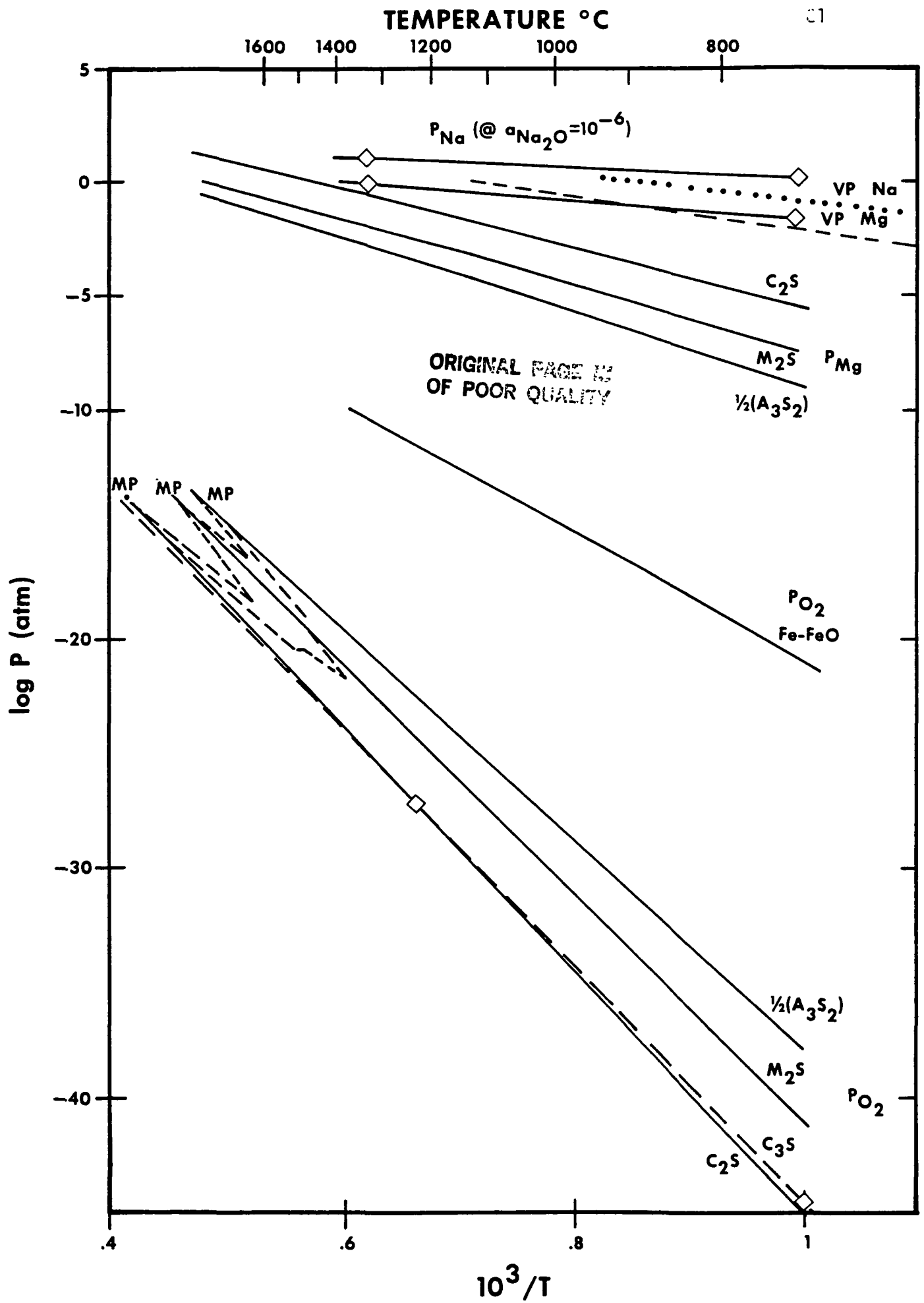


Figure 8

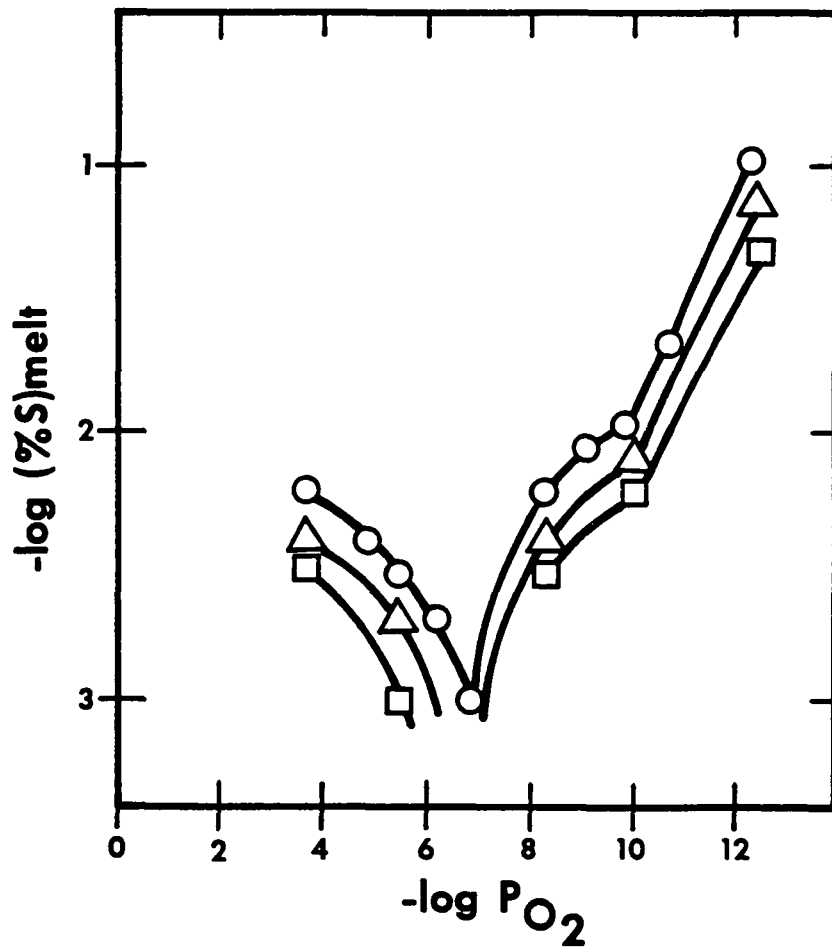
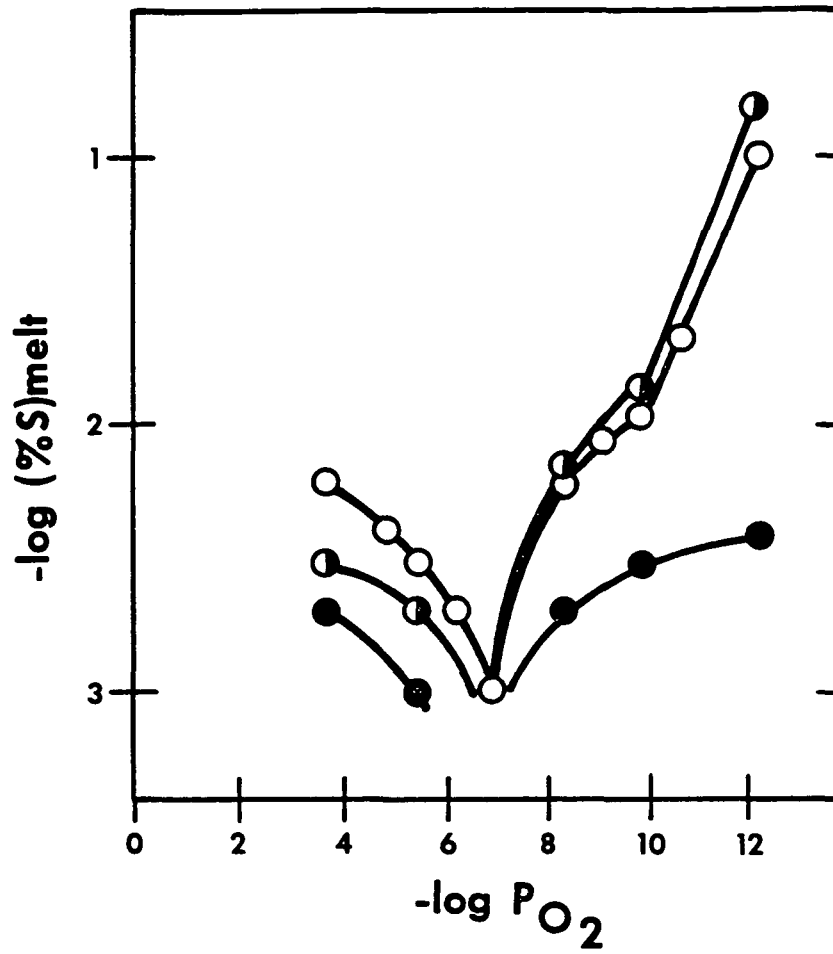
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Figure 9

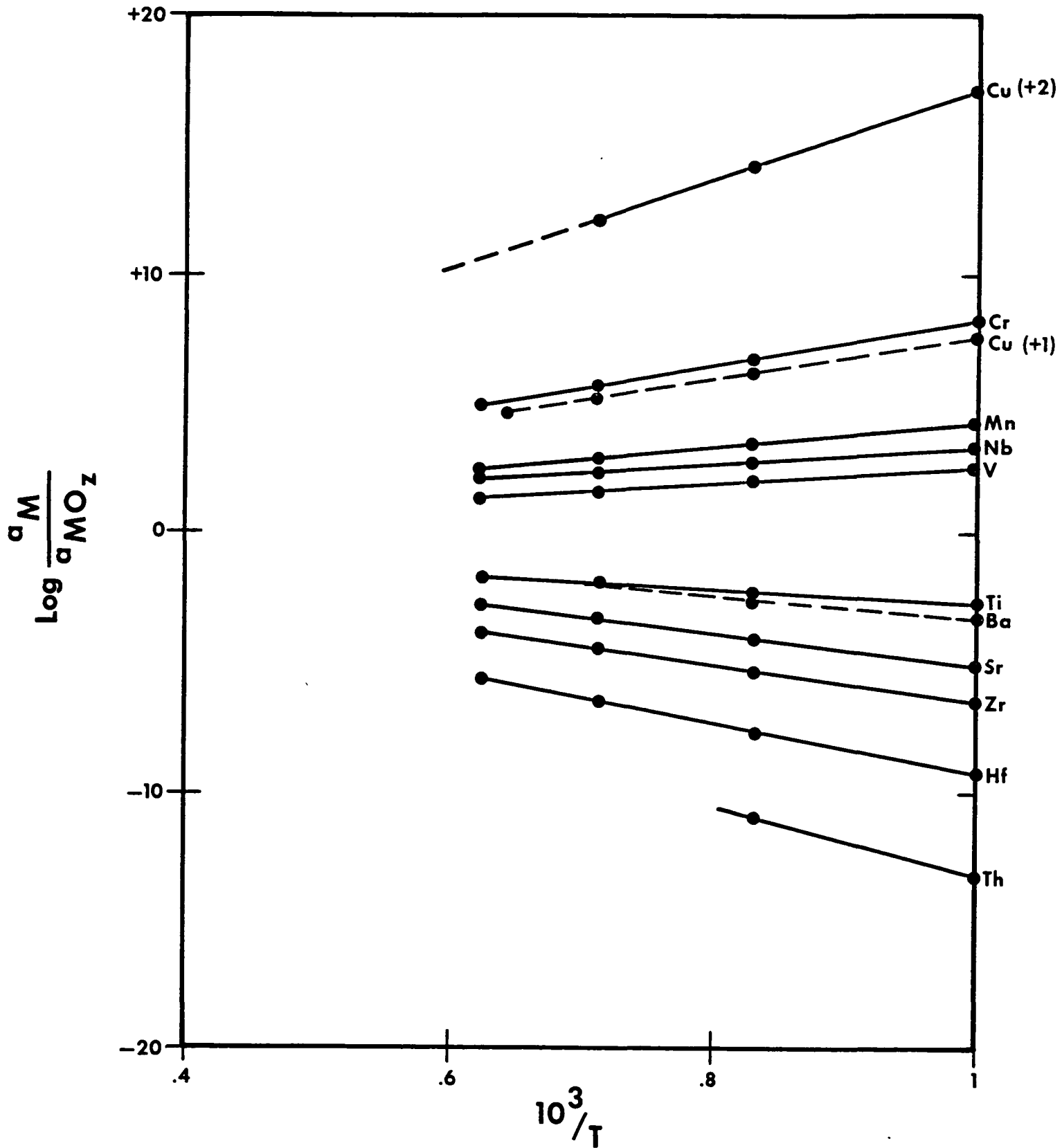
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Figure 10

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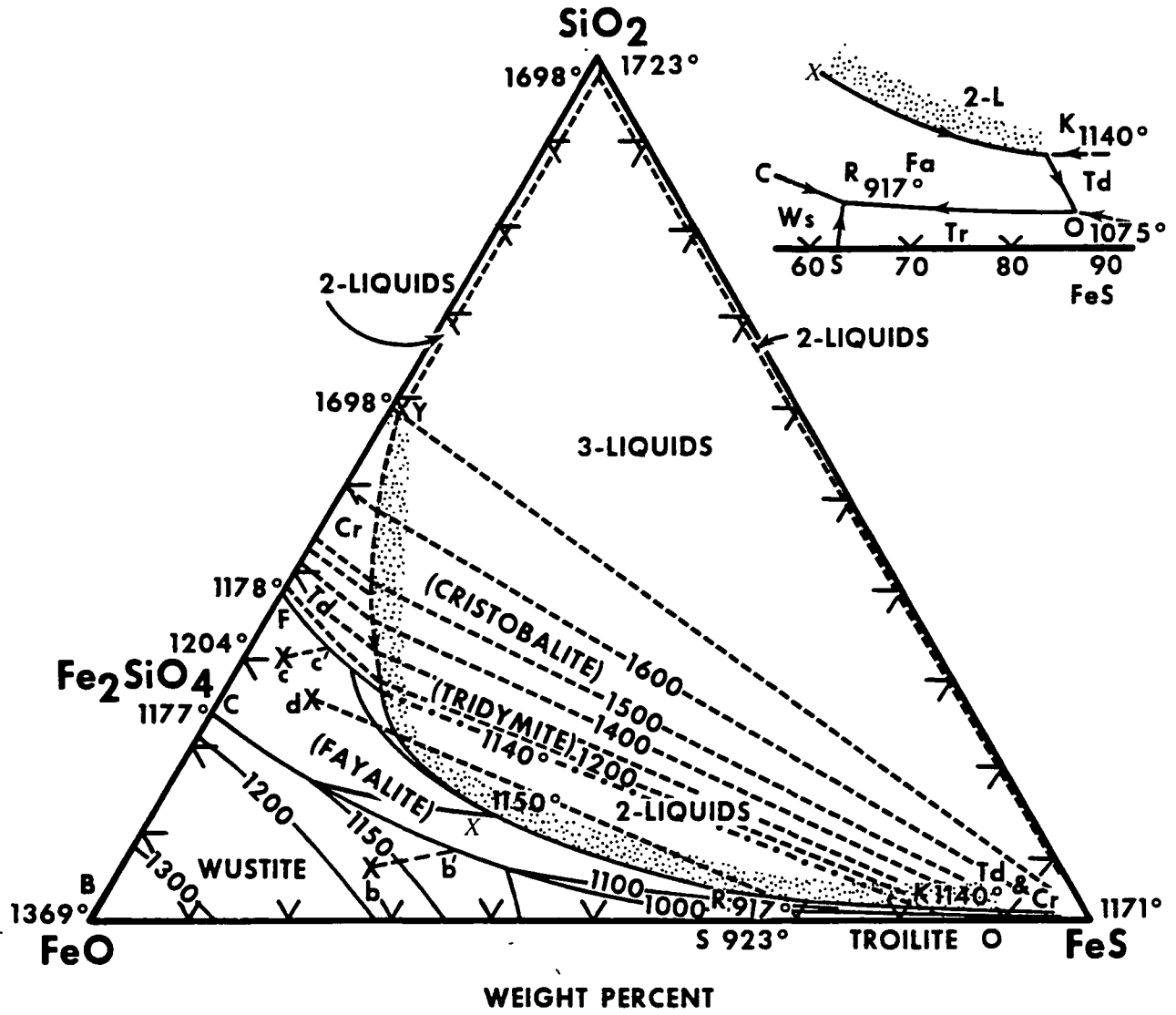


Figure 11

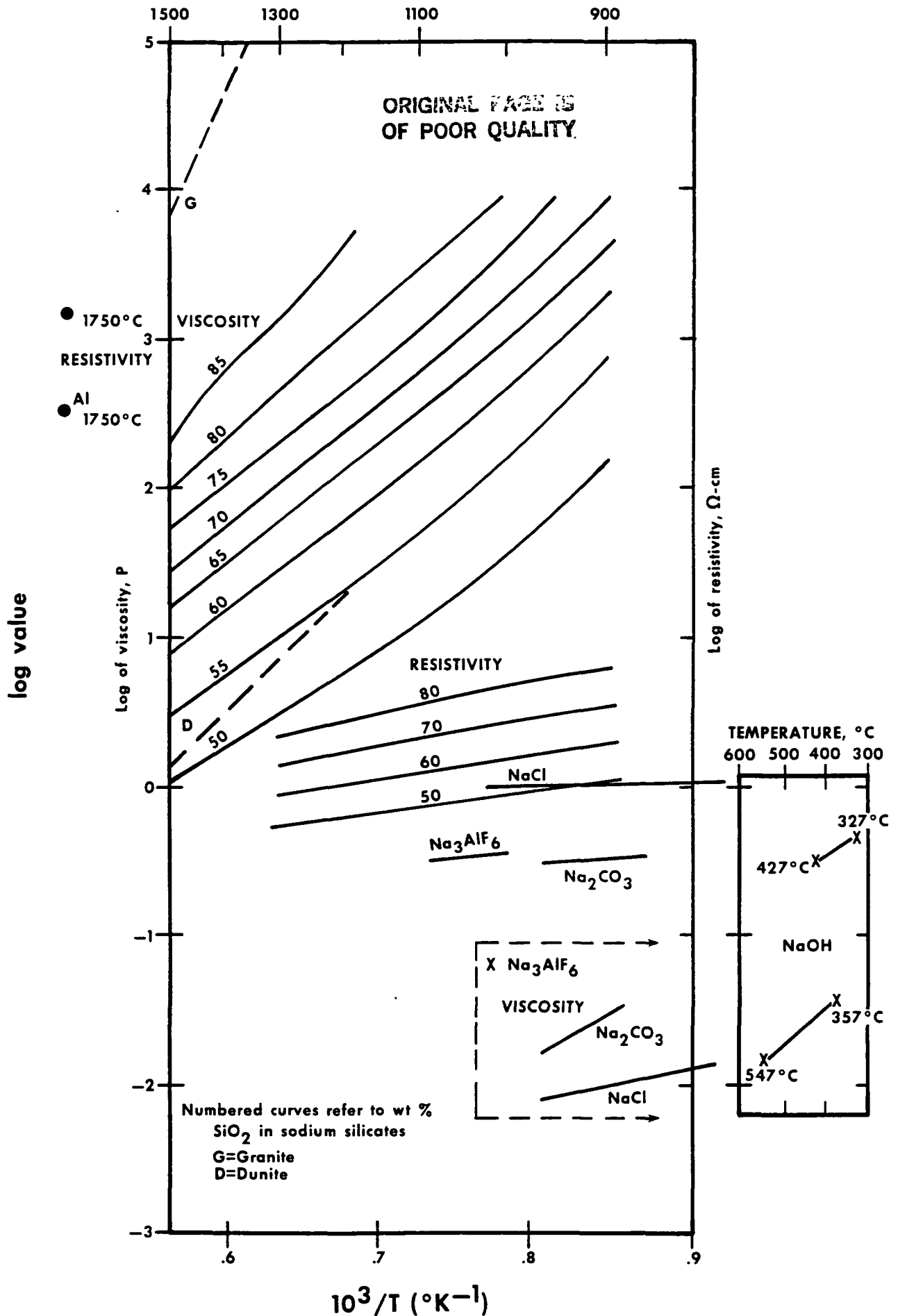


Figure 12

Chapter IV

THE HF ACID LEACH PROCESS

Detailed Analysis and Revisions

The HF acid leach process was described in considerable detail in R1, pp. II-44 to 47 and Appendix I (pp. II-157 to 175). In the previous study a number of process options were presented for various primary reactions and recycle or regeneration steps. Subsequent work has led to a narrowing of practical options; steps which are both technically feasible and with high specific output. More detailed considerations of reagent attrition have led to alternative systems which can substantially reduce the amount of reagent which must be resupplied from earth. This is primarily due to reduction in fluoride loss in oxide mass streams exiting the process by conversion to sulfoxy compounds -- the latter being pyrolyzed to oxides. Although this may be expected to lead to residual sulfur in the oxides, this can be supplied from lunar sources and thus reduce requirements for earth reagent supply.

Generalized Mass Flow Analysis

The mass flow and balance of any quasicontinuous process for conversion of lunar soil fractions can be represented by a chart of the form shown in Fig. IV-1. In this treatment, mass flows of an intermittent nature including periodic removal of scale, sludges, corrosion products and even equipment replacement are represented by equivalent continuous mass flow rates. While the primary mass flow due to the input material(s) proceeds from left to right, the mass flows associated with reagents and solvents are quasicyclic and proceed in both left-right and return directions. If all chemical reactions, including reagent regeneration and phase separations, are depicted in left-right flow, the

return flows are limited to materials handling or transport steps. This has the important consequence that the mass inventory associated with reverse flow is negligible in comparison with the forward flow, since transport times are much lower than reaction and separation times.

A flow chart directly applicable to the HF acid leach process is shown in Fig. 2. The principal chemical compounds involved in the mass flows are shown for the respective stages. In terms of total mass flow, the transport of water dominates the overall process. The process options may be viewed as alternative routes to convert specific initial or intermediate compounds to other intermediate or final products with various reagent (input) and byproduct (output) flows as necessary. These will be discussed in some detail in following sections.

Using the revised table of time-mass ratio factors (Table I), one may construct a graph depicting the mass flow rate and process time for the respective process steps. This is shown in Fig. 3, where the ordinate represents mass flow rate, and the abscissa process step time. In this representation, the areas of specific process steps are proportional to the mass inventories (or TR products) for the respective steps. In this figure, the process times for reverse flow cannot be directly depicted, but are assumed so short that the masses can be neglected and these flows are accordingly represented by lines instead of areas. It may be seen that the process mass is dominated by three steps -- the acid leach step, silica hydrolysis, and electrolysis of NaOH. (Note the time scale for electrolysis is folded seven times to fit on the same time scale.) Some reduction in mass inventory for the first two steps is possible using the process options discussed below. Mass reductions in the electrolysis step may be possible if narrower electrode spacings and/or higher current densities can be achieved.

Discussion of Process Steps

(Acid Leach)

The acid leach (dissolve) step (Table III, Eqn. 1) step was discussed in considerable detail in R1. The process time for this step (one-half hour) was estimated from laboratory experience with terrestrial samples. Wszolek and others (1,2,3) used an acid dissolution step with 20 - 40% DF reagent for one to two hours for detection of deuterocarbons and other hydrolysis products released from actual lunar soil fractions. In one experiment, lunar soil 14,240 with more than 50 wt.% consisting of particle sizes greater than 420μ is more than 90% dissolved in 30% DF in one hour under "gentle warming" (2). It would appear that one-half hour would be a conservative figure for dissolution of minus 100 micron soil fractions. Dissolution experiments with mixed DF-DC1 leachants were also successfully conducted. Mixed acids, and in particular HF-H₂SO₃, constitute useful options for the dissolution step.

Solubility data for fluorosilicates are shown in Fig. 4. The solubilities for compounds which form insoluble fluorides (Ca and Mg) are pH dependent and the curves refer to solutions with limited excess H₂SiF₆. Precise data for Al is not available, but a rough estimate of 15 wt.% has been reported (4).

Options

Mixed Acid Leaching

A desirable option to minimize reagent F attrition occurring in a later stage is to convert MF₂ or MSiF₆ to MSO₃ which may be subject to dry pyrolysis to obtain metal oxides (MO). This will be discussed in greater detail in a later section. This conversion may be achieved following the dissolution step, or alternatively by leaching with mixed hydrofluoric and sulfurous acids (Eqn. 2). The leach solution may be defluoridized by passing a stream of SO₂ through the system and trapping fluorine compounds (HF, SiF₄, etc.) in the

exit flow. The solubilities of polyvalent bisulfites with excess SO_2 are uniformly high, as shown in Fig. 5, but they may be effectively precipitated from the solutions by depressurizing and flushing the SO_2 out of the solution(s). Solubilities of normal sulfites and bisulfites are also listed in Table II. Aluminum may be effectively removed under high partial pressures of SO_2 in the form of basic salts at elevated temperatures. These may be further converted to hydrated aluminum oxide by additional flash heating (6) (Eqn. 19c). The other major elements may be separated by a variety of conventional methods (fractional precipitation, ion exchange, etc.). It should be pointed out that by leaching in a mixed acid mode it is not necessary to efficiently isolate the acid fluoro compounds, since they will be recycled to leaching as a mixture.

B. Ammonium Salt Fusion

In R1, the possibility of replacing the aqueous acid leach with fused NH_4FHF was described (Eqn. 3). Further studies have indicated the potential utility of this and other reagents in reducing the process mass associated with the acid leach and silica hydrolysis steps. These advantages are obtained at the cost of introducing another element, N, to the earth reagent requirements. This also requires consideration of nitrogen fixation steps, since small amounts of NH_3 may be expected to dissociate and/or oxidize in processing to yield elemental N_2 . This must then be reconverted to NH_3 by one or more routes.

The principal advantages in using NH_4FHF as leaching agents are minimization of solvent water in the leaching step, and the conversion efficiency of hydrolysis of SiF_4 approaching 100% per pass when neutralization with NH_3 is possible (Eqn. 7) instead of 20% for acid hydrolysis.

In addition to NH_4FHF , it is possible to use $(\text{NH}_4)_2\text{SiF}_6$ (Eqn. 4) and/or $(\text{NH}_4)_2\text{TiF}_6$ (Eqn. 5) as fused salt leachants. The pyrolytic behavior of these

salts are not as thoroughly studied (7,8) as for the $\text{NH}_4\text{F}-\text{NH}_4\text{FHF}$ system, but they undoubtedly dissociate at elevated temperatures to NH_3 , HF and SiF_4 or TiF_4 . $(\text{NH}_4)_2\text{TiF}_6$ may be a particularly effective leachant for treating lunar ilmenite ores (FeTiO_3).

Ammonium salt fusion leaching may be conducted with excess fused salt for total conversion to fluorides, or alternatively with excess silicate primarily to remove silica from the input material. In the latter case, the residue could then be leached with HCl or H_2SO_3 for later treatment.

(Silicon Oxide Production and Acid Recovery)

Silica by Acid Hydrolysis

The hydrolysis of SiF_4 was examined for both vapor phase and liquid phase reactions under acid conditions in R1. The prior work indicated that liquid phase hydrolysis was more efficient from both capital mass and process energy considerations. Even so, it is necessary to introduce 66 moles of vapor (SiF_4 and H_2O) per mole of SiO_2 produced (Ch. II, Appendix I, Table A, R1). This results in a sizeable heat transfer requirement to vaporize and condense the intermediates. This can be substantially reduced by going to process options involving neutral hydrolysis.

Neutral Hydrolysis

This option involves formation of silica in a first stage, followed by acid recovery in a second step, and is naturally adapted from the use of fused ammonium bifluoride as a leach option. Ammonium bifluoride is readily obtainable by the pyrolysis of NH_4F (Eqn. 3b). The thermochemical requirement for this step is given in Table IV. This step can probably be combined with the acid leach step if desired, but in any event, the NH_3 vapors released are absorbed in the same solution which hydrolyzes the SiF_4 . Using a slight excess of NH_3 , the pH can be raised to 8 or 9 and the SiF_4 will be quantitatively

hydrolyzed, according to Eqn. 7 (9). The hydrolysis can be carried out in a nearly saturated solution of NH_4F from which the solid salt may be recovered by differential cooling. Thus, by cooling a saturated solution of NH_4F at 80°C in 400 g of H_2O to 20°C , one may separate approximately 4 moles of solid NH_4F . This requires removal of about 34 Kcal from the solution. Pyrolysis of the 8 NH_4F for acid recovery will require about 75 Kcal of thermal energy. Hydrolysis of the SiF_4 according to Eqn. 7, will release 94 Kcal of thermal energy (136 Kcal if H_2O is introduced as vapor). This energy is more than sufficient to reheat the solution. The total thermal requirements appear to be well below that of the acid hydrolysis route.

Metal Oxide Production and Acid Recovery

(Hydrolysis of Metal Fluorides)

In R1 we used direct steam hydrolysis of metal fluorides to obtain the output metal oxides where reduced products were not desired. To hydrolyze the NaF produced in the reduction operations, an indirect hydrolysis was proposed involving the formation of cryolite (Na_3AlF_6) which was then hydrolyzed and the NaAlO_2 formed was then separated into NaOH and $\text{Al}(\text{OH})_3$ by solution methods. As previously mentioned, the hydrolysis of CaF_2 and to a lesser extent, MgF_2 , require high temperatures, and substantial mass flows of steam and are thus energy intensive.

Figure 6 shows the equilibrium constants for the water vapor hydrolysis of a number of fluorides. Also shown is the percent conversion per pass (@1 atm) if the inlet stream is pure steam. It is seen that the direct hydrolysis of CaF_2 @ 1200°C results in only 1% conversion of steam to HF @ 1 atm pressure. Hydrolysis of the remaining fluorides appears to be effective enough for practical operation. It may be more desirable to convert to sulfite or sulfate salts which can be converted to oxides by dry pyrolysis, rather than hydrolysis,

in order to minimize loss of fluoride reagent (and possibly hydrogen) as previously stated.

The impracticality of direct hydrolysis of NaF (Eqn. 10) is also clearly illustrated in Fig. 6. Although the practicality of hydrolysis of cryolite is clearly established, there may be other more effective ways of regenerating NaOH and HF from NaF and H₂O or alternatively, Na, O₂ and HF. These are discussed in a later section.

Hydrolysis of TiF₄ was not discussed in detail in R1. The hydrolytic behavior of TiF₆⁼ differs from SiF₆⁼ in two principal details: titanium forms partially hydrolyzed species such as TiOF₄⁼ of greater stability and sparingly soluble salts as one progressively neutralizes H₂TiF₆(pH>2)(Eqn. 11a, 12a)(10), and TiF₄ is essentially nonvolatile even in strongly acid solution in contradistinction to SiF₄. This circumstance may be used effectively to purify SiF₄ prior to production of semiconductor grade Si by scrubbing the gas stream with silica saturated concentrated H₂SiF₆ to trap trace quantities of TiF₄.

Process Options

(Sulfuric Acid Conversion of CaF₂)

An indirect process which uses two steps to recover CaO and HF from CaF₂-H₂O and which is particularly efficient if anhydrous or high strength HF is needed, involves use of sulfuric acid and sulfur as intermediate reagents. The CaF₂ is initially reacted with sulfuric acid to yield substantially dry HF, according to Eqn. 13. The CaSO₄ formed is then pyrolyzed preferably under reducing conditions to form CaO and SO₂ (Eqn. 14,15), followed by reconversion of SO₂ to S and SO₃. Application can undoubtedly be extended to MgF₂ if desired. Figure 7 shows the decomposition pressures vs temperature for Ca, Mg and Al sulfates and also sulfide-sulfate systems. The pyrolysis of sulfates has been well studied and has a history of commercial development (11).

Decomposition of Sulfites

As discussed under mixed acid leaching option, it is possible to obtain or convert metal fluorides or fluorosilicates to bisulfites by initial leaching or post-leach conversion. The bisulfites may in turn be converted to normal sulfites by depressurization of solutions or pyrolysis of salts.

The normal sulfites may be decomposed to oxides and SO_2 by pyrolysis at elevated temperatures (Eqn. 16). The chemistry is somewhat complicated by a competing solid state disproportionation of a sulfite salt to a mixture of sulfide and sulfate (Eqn. 17). The relative rates of decomposition of true sulfites and equivalent sulfide-sulfate mixtures have not been thoroughly explored, but the latter reaction must inevitably be slower. Flash heating of the sulfite under reduced pressure may be expected to favor direct dissociation. Further complicating the matter is the possibility of pyrolysis under more strongly reducing conditions whereby a mixture of SO_2 and elemental sulfur (S_2) would be formed (Eqn. 18b). The relations for the Ca system are shown in Fig. 8.

The equilibrium pressures of SO_2 over solid MS and MSO_4 phases as a function of temperature for the major elements of interest are shown in Fig. 7. The metastable equilibrium pressures over normal sulfite salts, MSO_3 are equal to or greater than the pressure curves shown. The figure indicates that decomposition of CaS-CaSO_4 is the most difficult, as expected. However, the required temperatures are below those needed in direct hydrolysis of CaF_2 , and since no phase separation requiring fractional distillation is required, the total process thermal requirements are lower.

It is difficult to estimate the probable residual S content following pyrolysis. Residual S present after pyrolysis of sulfates at atmospheric pressures have been determined in a number of cases in experiments conducted

activity of MgF_2 in the melt will be nearly unity, while the activity of NaF will be substantially less than 1. Thus, the equilibrium constant times sodium pressure will represent the lower limit of $\text{Mg}:\text{Na}$ ratio in the vapor phase: that is,

$$\frac{P_{\text{Mg}}}{P_{\text{Na}}} \geq K_{\text{eq}} \cdot P_{\text{Na}}$$

Substitution of saturation pressures at 1400°K leads to a predicted minimal 20% conversion per pass.

Reagent Makeup Requirements

In R1, upper limits of reagent replacement mass requirements of .112% (H) and .15% (F) based on throughput mass were estimated. A more detailed analysis, including Na and N with a breakdown of assumed exit stream concentrations, is shown in Table V. The estimated total reagent replacement mass requirement is 2,969 ppm based on throughput mass or .297%.

It may be noted that the Na requirement is substantially less than the Na input content for typical Lunar Feldspar sources. The N requirement is optional and would arise only if ammonium salt fusion options are adopted. In the absence of a specific earth supplied requirement for Na and N, the estimated replacement mass requirement would drop to 1,744 ppm.

Further reductions are possible if sulfoxy replacement of fluoride is adopted. One may anticipate that F replacement requirements would drop to 10% or less of the baseline value (i.e., to about 137 ppm) while S replacement requirements may be comparable with original F levels (~1400 ppm). However, the S requirement can, in all probability, be met entirely from lunar source input.

With these options one may predict upper limits of net reagent requirements of 514 ppm in (H + F) systems and 1,047 ppm in (H + F + N) systems.

over a span of many years (12,13). In favorable cases, the residual S has been reduced to a few tenths of a percent. It is felt that by finishing the procedure under vacuum and with close attention to particle size and heating cycle, that the residual S content could probably be held below 0.1% by weight. At this level, the loss of sulfur reagent could be compensated completely by the content of the input material for almost all lunar soils.

Pyrolysis of CaSO_4 (under slightly reducing conditions) is practiced commercially for recovery of lime for cement production and sulfuric acid. The reaction kinetics tend to be diffusion limited through the solid phases (CaSO_4 , CaS and CaO) present. Using a sulfite as a starting material should minimize crystallite sizes of the stable solid phases and thus speed the reaction. Decomposition according to Eqn. 18a ($M = \text{Ca}$) is reported as quantitative in one hour @1100°C (11).

The SO_2 formed may be easily recycled to form bisulfites and any S_2 or SO_3 formed as reduction or oxidation products may be easily removed by cold trapping the SO_2 stream.

NaOH Production

(Conversion NaF to $\text{NaOH} + \text{HF}$)

This process requirement arises from the NaF formed in reduction steps and may represent a major materials conversion requirement, since 50% or more of the input equivalents may be reduced, depending on plant output requirements. Since direct hydrolysis is impractical, it is a multistep subset of the total plant operations, but it is best treated as a group, since selection of a given first step option may well impose unique requirements on later step(s). We shall analyze the process options by first classifying the overall methods into groups with certain common features primarily related to the method of HF recovery. These are:

1. HF via CaF_2 using nonvolatile acid (H_2SO_4)
(In this process, NaF is reacted with Ca(OH)_2 to form CaF_2 and NaOH according to Eqn. 20. These are separated by solubility and the CaF_2 is treated with sulfuric acid to yield HF and CaSO_4 according to Eqn. 13. The latter is then pyrolyzed to regenerate the lime and sulfuric acid.)

2. HF via volatile fluorides (TiF_4 or SiF_4)
(In this process NaF is reacted with amphoteric oxides to form a mixture of complex oxides and fluorides (Eqn. 21,22). The fluorosilicates or fluorotitanates are pyrolyzed to transport SiF_4 or TiF_4 to an aqueous hydrolysis reactor. The residual complex oxides are leached to recover NaOH and the amphoteric oxides (or complex oxides of lower alkali content) (Eqn. 23).

3. HF via pyrohydrolysis of complex fluorides
(In this process NaF is reacted with amphoteric oxides as in 2. The mixture in this case is directly hydrolyzed with steam to form HF and complex oxides (Eqn. 9). The latter are differently leached as in 2.)

Equations covering the reactions of these methods are given in Table III. Although SiF_4 was listed as possible intermediate in class 2, the difficulties of separating the alkali from silica in sodium silicates in aqueous media may preclude successful application. However, the separation of alkali from titanium, iron or aluminum appears to be straightforward. Figure 9 shows the solubility of these metals as a function of NaOH concentration. As noted, the solubility of Al(OH)_3 is higher than the other hydrous oxides, but alumina-containing NaOH solutions can be essentially purified by evaporative concentration of initial leachant and the residual aluminum content can be

nearly completely removed in the form of NaAlO_2 .

The thermodynamic properties of many of the complex fluorides and oxides are poorly known, but estimated or reported values are shown in Table IV.

Based on incomplete thermodynamic data, it is difficult to select an optimum process route for this subset of the overall process. While the information and documentation for the aluminum complex compounds is most complete and we can definitely be assured that such an option would function properly, the author feels that the corresponding titanium and/or iron compounds will probably function more efficiently.

It is worth noting that the high temperature fused salt reaction and pyrolysis or pyrohydrolysis of the mixture need not be quantitative in their displacement of fluoride from the system, and similarly the extraction of sodium from the complex oxides need not be quantitative, since even large residual contents of Na and F values can be recycled to the initial step. This greatly simplifies the NaF conversion task.

Reduction with Sodium

(Aluminum, Silicon, Titanium, Magnesium)

In R1, chemical reduction of fluorides with sodium was proposed for production of aluminum and silicon, but a secondary process was proposed for magnesium (reduction of MgO with silicon) since the free energy change for the fluoride reduction would not be sufficient to obtain quantitative yields. Reconsideration of the reaction and the phase diagram of the liquid Na-Mg system has led to the conclusion that the reaction could be used effectively for magnesium reduction as well. This will be discussed in greater detail below.

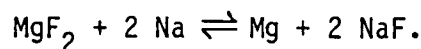
An independent investigation of sodium reduction of SiF_4 has and is being pursued at SRI International as a route for production of solar cell or semiconductor grade silicon. The results to date appear promising, and

extension of the work to recovery and reduction of titanium, zirconium and other elements may be undertaken. Very high specific outputs appear possible from the reduction cells, since the reaction is quite exothermic. Process modifications using Na_2SiF_6 or Na_2TiF_6 are possible in a "thermite" type reactor with essentially instantaneous reaction times.

Production of aluminum by reduction of AlF_3 or Na_3AlF_6 was disclosed in patents filed in the 19th Century (15,16). A modern study of this route may be advisable, since total process efficiency for aluminum production may be improved over current commercial methods if anticipated improvements in sodium production processes can be realized.

(Magnesium Reduction)

The reduction of MgF_2 with sodium may be described by the equation:



At sufficiently high temperatures and moderate pressures, the metallic phases may exist entirely in the vapor phase limited by the condensation curves shown in Chapter III, Fig. 8. Under these conditions and with co-existing solid phases of $\text{NaF} \cdot \text{MgF}_2$ and MgF_2 or NaF , we obtain an equilibrium constant:

	1000°K	1200°K	1400°K
$K_{\text{eq}} = \frac{P_{\text{Mg}} \cdot a_{\text{NaF}}^2}{P_{\text{Na}}^2 \cdot a_{\text{MgF}_2}}$	$\Delta G_r = -3.29$	-7.97	-10.82
	$\log K_{\text{eq}} = - .719$	-1.45	$- 1.69$

The metallic vapors may be condensed at temperatures just above the melting point of Mg (650°C) at which point two liquid metal layers separate of approximate compositions 7.5 w/o Mg and 98 w/o Mg. The sodium rich layer may be recycled to the reactor, while the magnesium rich layer may be further purified by fractional distillation or crystallization.

By operating at or near the eutectic between MgF_2 and $\text{NaF} \cdot \text{MgF}_2$ the

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Table I

EQUIPMENT AND REAGENT MASSES — PROCESS AND EQUIVALENT TIMES

Eqn.	Step	t Process Time(hr)	R_m	r_m	R'_m	$h_1=tR_m$	$h_2=tr_m$	$h_3=tR'_m$
			<u>Contents</u> Equiv. input	<u>Mass Ratios</u> <u>Container</u> Equiv. input	<u>Net Contents(LDE)</u> Equiv. input	<u>Equivalent</u> <u>Container</u>	<u>Times* (hr)</u> <u>Contents</u>	<u>Net(LDE)</u> <u>Contents</u>
1	Acid Leach	.5	22.2	.48	7.95	11.1	.24	3.97
	Sedim. centrifuge/ Distill	.0167	22.2	28.8	7.95	.371	.48	.133
6	Hydrolyze	.5	44.9	.96	14.7	22.5	.48	7.36
	Sedim. centrifuge	.0167	44.9	42.6	14.7	.75	.71	.207
	Distill/ Condense	.00278	7.06	86.4	2.14	.0196	.24	.006
	Distill (1/2)	.00278	22.5	86.4	7.36	.0625	.24	.020
8,9	Hydrolyze/dry	3.0	3.0	.55	.728	9.0	1.66	2.18
	Distill	.00278	7.63	86.4	1.36	.021	.24	.004
24	Electrolysis	27.5	1.45	.173	.036	40.05	4.75	1.0
25,26	Metals reduction	3.0	1.76	.48	.7	5.28	1.43	2.1
20,23	Regeneration (est.)	.5	5.0	.48	.7	2.5	.24	.35
	Miscellaneous	.5	1.0	.4	1.0	.5	.2	.5
Subtotal		35.54				92.15	10.91	17.83

Eqn.	Step	t Process Time(hr)	R_m Contents Equiv. input	r_m Mass Ratios Container Equiv. input	R'_m Net Contents(LDE) Equiv. input	$h_1 = tR_m$ Equivalent Container	$h_2 tr_m$ Times* (hr) Contents	$h_3 = tR'_m$ Net(LDE) Contents
OPTIONS								
2	Mixed-Acid Leach	.5	4.04	.48	1.76	2.02	.24	.88
3	Ammonium Salt Fusion	.5	6.48	.4	6.48	3.24	.2	3.24
3b	Ammon. Bifluoride Regeneration	.5	2.52	.4	2.52	1.26	.2	1.26
11	Neutral Hydrolysis	.5	1.99	.3	.66	1	.15	.33
16	Bisulfite-sulfite Pyrolysis	3	2.65	1.5	.03	7.95	4.5	.09
23	Basic Leach Separation	1	.64	.3	.07	.64	.3	.07

EXTRA MASS	(metric tons @ 4.21 ton/hr input)	Equiv. time (hr)
Reagent Inventory	20	4.7
Compressors	10	2.4
Heat Exchangers	10	2.4
Pipes, Valves	5	1.2
Electrical	6	1.4
Structural and miscellaneous	25	5.94
Radiators (20 MW)	24	5.7
Electric Power (30 MW)	<u>120</u>	<u>28.5</u>
Subtotal	220	52.24

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Table II
 SOLUBILITIES OF SULFITES/BISULFITES
 (wt. percent @ 25°C except where noted)

CATION	SOLUTE		
	MSO_3 $P_{SO_2} < 10^{-3}$ atm	$M(HSO_3)_2$ $P_{SO_2} \sim 1$ atm	$M(HSO_3)_2$ $P_{SO_2} \rightarrow VP SO_2$ $\left\{ \begin{array}{l} 2.72 \text{ atm @ } 15^\circ\text{C} \\ 3.94 \text{ atm @ } 25^\circ\text{C} \end{array} \right.$
Ca	.047	13.6	(>20 est)
Mg	.94 [†]	43.3	(>50 est)
2/3 Al	~.41*	>24%	(>40 est)
Fe(15°C)	<< 4.5	~21.6%	~30.4%

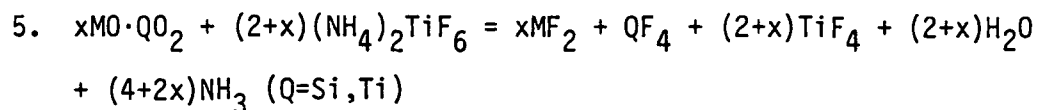
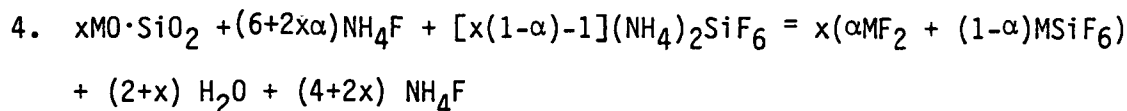
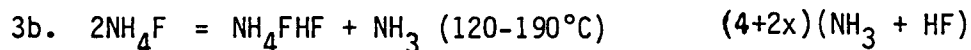
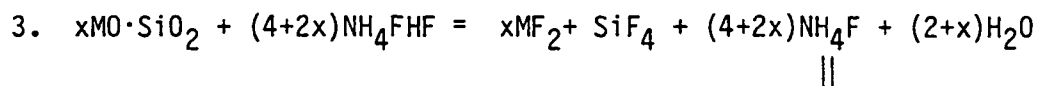
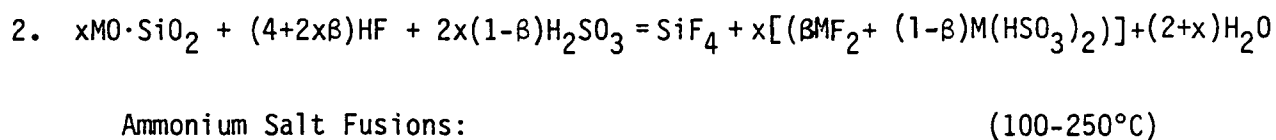
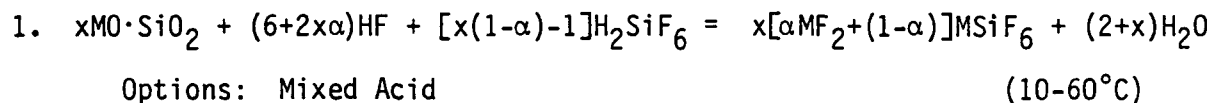
[†] Soly. Max. @ 42°C

* Equil. phases basic aluminum sulfites and/or $Al(OH)_3$

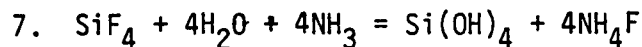
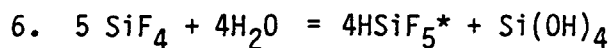
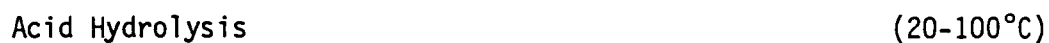
Table III

HF ACID LEACH PROCESS EQUATIONS

Acid Leach



Silica Hydrolysis

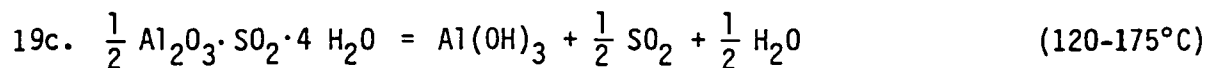
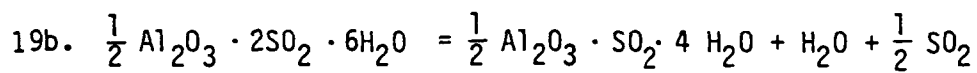


Metal Oxide Production and Acid Recovery

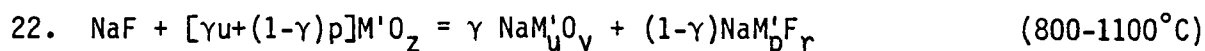
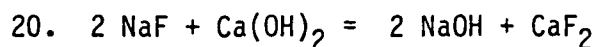
Hydrolysis Metal Fluorides



8. $MF_2 + H_2O = MO + 2 HF$
 Complex Fluorides (500-1100°C)
9. $NaM'_pF_r + (\frac{r}{2})H_2O = NaM'_uO_v + rHF$ (Note: excess Na_2O or $M'O_z$ if $u > r$ or $u < r$)
 NaF (Hypothetical)
10. $NaF + H_2O = NaOH + HF$ (very high temperature; equilibrium unfavorable)
 Titanium Fluorides (20-100°C)
- 11a. $TiF_4 + H_2O = H_2TiOF_4$ (pH 2-3)
- 11b. $TiF_4 + 4 H_2O = Ti(OH)_4 + 4HF$ (pH >3)
- 12a. $TiF_6^{=2-} + H_2O = TiOF_4^{=2-} + 2 HF$ (pH 2-3)
- 12b. $TiF_6^{=2-} + 4H_2O = Ti(OH)_4 + 4 HF + 2 F^-$ (pH >3)
 Sulfuric Acid Conversion CaF_2
13. $CaF_2 + H_2SO_4 = CaSO_4 + 2 HF$ (200-300°C)
 Decomposition Sulfitess and Sulfates (400-1200°C)
14. $MSO_4 = MO + SO_2 + \frac{1}{2} O_2$
15. $MSO_4 + \frac{1}{4} S_2 = MO + \frac{3}{2} SO_2$
16. $MSO_3 = MO + SO_2$ (200-1100°C)
17. $4 MSO_3 = MS + 3 MSO_4$ Variable T
- 18a. $MS + 3 MSO_4 = 4 MO + 4 SO_2$ (400-1200°C)
- 18b. $MS + MSO_4 = 2 MO + SO_2 + \frac{1}{2} S_2$ (400-1100°C)
- 19a. $Al(HSO_3)_3 + \frac{3}{2} H_2O = \frac{1}{2} Al_2O_3 \cdot 2SO_2 \cdot 6H_2O + 2 SO_2$ (65-85°C)



NaOH Production (20-100°C)



Leach Separation



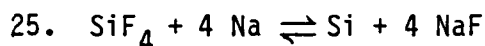
(for M' = Ti, Si, u = $\frac{1}{2}$, v = $\frac{3}{2}$, z = 2; for M' = Al, Fe, u = 1, v = 2, z = $\frac{3}{2}$)

Redox Reactions

Na Production



Si Production



Metals Production

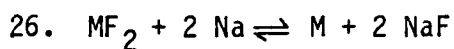


Table IV
THERMOCHEMICAL PROPERTIES OF COMPOUNDS

Compound	ΔH_f°	ΔG_f°	ΔS°	C_p	ΔH_d^*	Notes
	Kcal/mole		cal/mole	OK	Kcal/mole	
Oxides and Hydroxides						
Al_2O_3	-400.4	-378.1	12.17	18.89		
$Al(OH)_3$	-306.3	-273.4	16.76	22.25	23.4	15.6 per mole steam
CaO	-151.8	-144.25	9.13	10.07		
$Ca(OH)_2$	-235.7	-214.75	19.93	20.91	26.1	
FeO	-65.	-60.1	14.52	11.93		
Fe_2O_3	-197	-177.4	20.89	24.82		
$Fe(OH)_3$	-196.7	-166.5	25.5	24.3	11.5	7.67 per mole steam
MgO	-143.8	-136.0	6.44	8.88		
$Mg(OH)_2$	-221.0	-199.3	15.1	18.44	19.4	
Na_2O	-99.4	-90.	17.4	16.52		
NaOH	-101.99	-90.6	15.40	14.23	23.4	46.8 per mole steam
SiO_2	-217.72	-204.75	10.00	10.62		
$Si(OH)_4$	-354	-318.6	46		20.7	10.35 per mole steam
TiO_2	-225.8	-212.6	12.03	13.15		
$Ti(OH)_4$	-344.1				7.3	3.65 per mole steam
H_2O (l)	-68.32	-56.69	16.71	18.00		
H_2O (v)	-57.80	-54.63	45.10	8.03		

Complex

Oxides

FeTiO ₃	-295.6	-277.05	25.3	23.78	4.8	
NaAlO ₂	-270.8	-255.6	16.83	17.61	20.9	41.8 per mole Na ₂ O
NaFeO ₂	-166.9	-153	21.1		18.7	37.4 per mole Na ₂ O
Na ₂ TiO ₃	-380.5	-357.8	29.1		55.3	
MgAl ₂ O ₄	-552.8	-523.5	21.2	27.71	8.6	

Silicates

A ₃ S ₂	-1627.7	-1537.1	65.7	77.83	-8.9	Thermodynamically stable but endothermic
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CS	-390.76	-370.39	19.58	20.38	21.3	
C ₂ S	-554	-526.1	28.87	30.27	32.7	
C ₃ S	-700.1	-665.4	40.3	41.08	27	
F ₂ S	-353.7	-329.6	34.7	31.76	6	
MS	-370.22	-349.46	16.2	19.45	8.7	
M ₂ S	-519.6	-491.2	22.74	28.37	14.3	
NS	-373.2	-350.7	27.21	26.74	56.1	

Fluorides

AlF ₃	-361.0	-342.0	15.89	17.96		
CaF ₂	-291.5	-279.	16.46	16.02		
FeF ₂	-168	-158	20.79	16.28		
FeF ₃	-249	-232	23.5	21.75		
MgF ₂	-268.7	-256.0	13.68	14.72		
NaF	-137.5	-130.3	12.24	11.20		
KF	-135.9	-128.8	15.91	11.71		

SiF ₄ (v)	-385.98	-375.88	67.49	17.60		
TiF ₄ (s)	-394.2	-372.7	32.02	27.31		
TiF ₄ (v)	-370.8	-362.2	75.2	20.36		
HF (v)	-64.8	-65.3	41.51	6.96		
HF (aq)	-78.66	-66.08	48.44	-2.3		
NH ₄ F	-110.9	-83.4	17.2	15.60	{ 35.1	To NH ₃ + HF (v)
					{ 9.4	To $\frac{1}{2}$ (NH ₃ + NH ₄ FHF)
NH ₄ FHF	-191.9	-155.6	27.61	25.50	{ 51.3	To NH ₃ + 2 HF (v)
					{ 16.2	To NH ₄ F + HF (hypothetical)
Complex Fluorides						
Na ₃ AlF ₆	-791	-751	57	51.56	17.5	
Na ₂ SiF ₆ (s)	-697.4	-660.1	49.49	44.71	36.4	
Na ₂ SiF ₆ (aq)	-687					
K ₂ SiF ₆	-708.8	-671.7	56.3		51	
Na ₂ TiF ₆ (s)	-700.1	(-664.5)	(58)		54.3	
Na ₂ TiF ₆ (aq)	-688.1					
K ₂ TiF ₆	-710.9	(-675.5)	(65)	68.3		
(NH ₄) ₂ SiF ₆	-640.96	-565.38	66.98	54.52	{ 33.1	To 2 NH ₄ F + SiF ₄
					{ 103.3	To 2 NH ₃ + 2 HF + SiF ₄
					{ 52	To NH ₃ + NH ₄ FHF + SiF ₄
Na ₂ SiF ₆ (aq)	-687					
H ₂ SiF ₆ (aq)	-575.4					
H ₂ TiF ₆ (aq)	-573.7					
Sulfur Compounds						
Al ₂ S ₃	-173	(-169)	(23)			(Estimated value)
CaS	-113.5	-112.3	13.5	11.34		

FeS	-24.13	-24.22	14.42			
MgS	-82.7	-81.7	12.03	10.90		
Na ₂ S	-89.2	-86	23.4	18.99		
H ₂ S (v)	-4.82	-7.90	49.18	8.17		
Al ₂ (SO ₄) ₃	-821.0	-838.1	57.2	62.00	136.9	45.6 per mole SO ₃
CaSO ₄	-342.76	-315.93	25.5	23.82	96.4	
FeSO ₄	-221.9	-197.2	28.9	24.04	62.3	
Fe ₂ (SO ₄) ₃	-617.0	-540.9	73.5	63.27	136.3	45.4 per mole SO ₃
MgSO ₄	-307.1	-279.8	21.9	23.06	68.7	
Na ₂ SO ₄	-330.9	-302.78	35.73	31.79	136.9	
H ₂ SO ₄ (l)	-194.55	-164.93	37.50	33.20		
(NH ₄) ₂ SO ₄	-282.23	-215.56	52.6	44.81		
NH ₄ HSO ₄	-243.75	-199.66	58.6	-.9		
SO ₃ (s)	-108.63	-88.19	12.5			
SO ₃ (v)	-94.58	-88.69	61.34	12.11		
CaSO ₃	(-282.3)		24.23	12.92	(59.6)	(Estimated)
CaSO ₃ · 2H ₂ O	-418.9	-371.7	44	42.7		
MgSO ₃	-241			26.3		
Na ₂ SO ₃	-260.6	-239.5	34.9		90.3	
NaHSO ₃ (aq)	-206.6					
H ₂ SO ₃ (aq)	-149.67	-126.15	33.4			
SO ₂ (v)	-70.94	-71.75	59.30	9.53		
(NH ₄) ₂ SO ₃	-211.6					
(aq)	-215.2	-154.2	47.2			
NH ₄ HSO ₃	-183.7					
(aq)	-181.34	-145.12	60.5			

Miscellaneous

$\text{NH}_3(\text{v})$	-11.02	-3.94	45.97	8.38
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* ΔH_d is the enthalpy of dissociation to constituent simple oxides or fluorides. H_2O , HF , SO_3 , SO_2 , SiF_4 , TiF_4 and NH_3 are assumed to be formed in vapor (v) state.

Table V

REAGENT MAKEUP REQUIREMENTS

1. Hydrogen		Net Water Content
Nonmetallic Solids		
5,000 ppm		(.05%) Dry
100		Metals, Silicon
100		Oxygen
<u>3,367</u>		<u>Average H₂O</u>
377 ppm		Average H
2. Fluorine		
Net Content		
1,000 ppm		Silica
3,000		Balance Nonmetallic Solids
100		Metals
<u>100</u>		<u>Oxygen</u>
1,367 ppm		Average F
3. Sodium		
1,000 ppm		Dry Nonmetallid Solids
100		Metals
<u>0</u>		<u>Oxygen</u>
692 ppm		Average Na
4. Nitrogen		(Option)
800 ppm		Dry Nonmetallic Solids
<u>0</u>		<u>Balance</u>
533 ppm		Average N
TOTAL		
REPLACEMENT	2,969 ppm	Average (H + F + Na + N)
	1,744 ppm	(H + F) only

*Based on assumed residual contents and Output Mass Distribution $\frac{1}{3}$ SiO₂,
 $\frac{1}{3}$ Other Nonmetallic Solids, $\frac{1}{6}$ Metals + Silicon, $\frac{1}{6}$ Oxygen.

FIGURE TITLES

- Fig. 1 Generalized Flow Chart for Lunar Materials Processing
- Fig. 2 Flow Chart HF Acid Leach Process
- Fig. 3 Mass Flow
- Fig. 4 Solubility vs Temperature: Aqueous Fluorosilicates
- Fig. 5 Solubility vs SO Content: Aqueous Sulfites/Bisulfites
- Fig. 6 Equilibrium Constant for Hydrolysis of Fluorides
- Fig. 7 Equilibrium Decomposition Pressures of Sulfates and Sulfide/Sulfate Systems
- Fig. 8 Phase Diagram $\text{CaO-CaS-CaSO}_4\text{-SO}_2\text{-S}_2\text{-O}_2$

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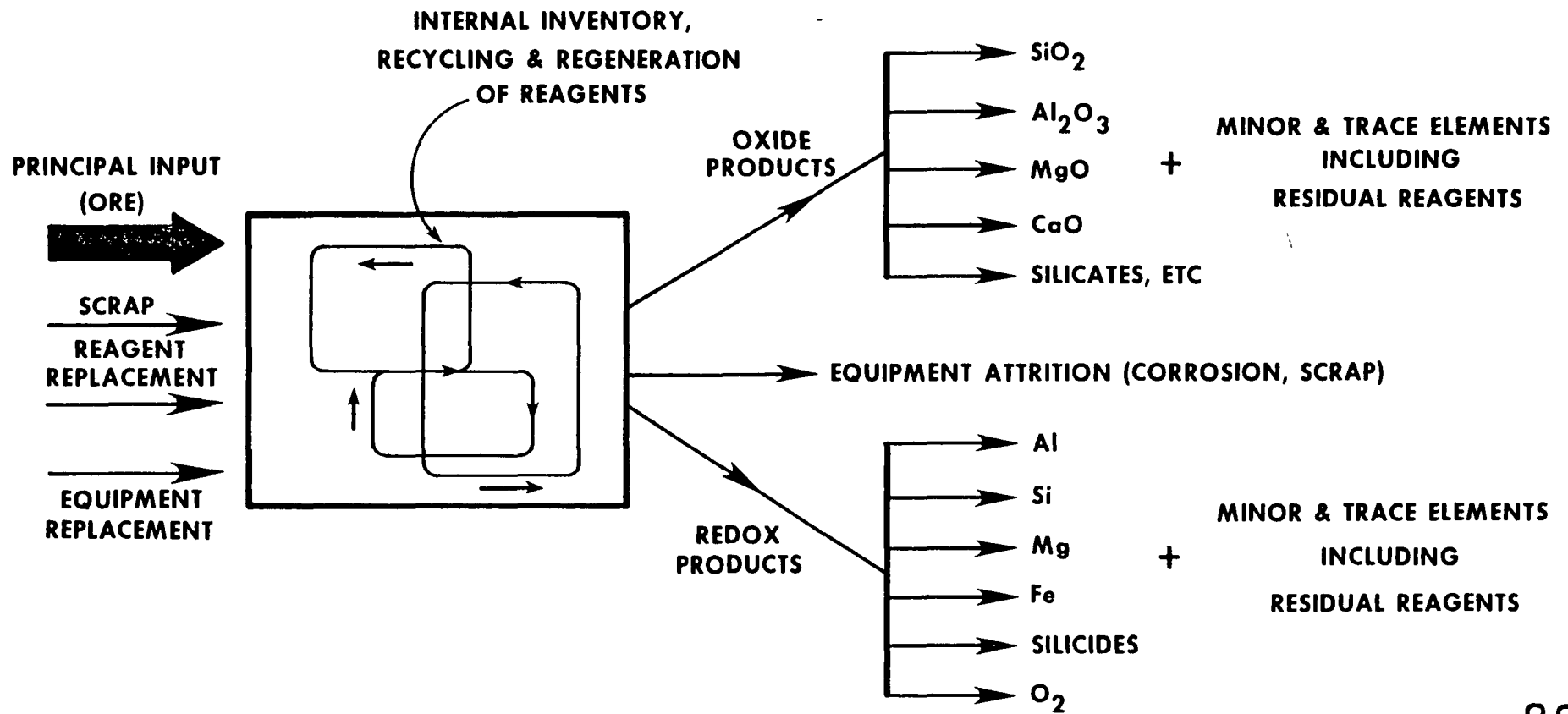


Figure 1

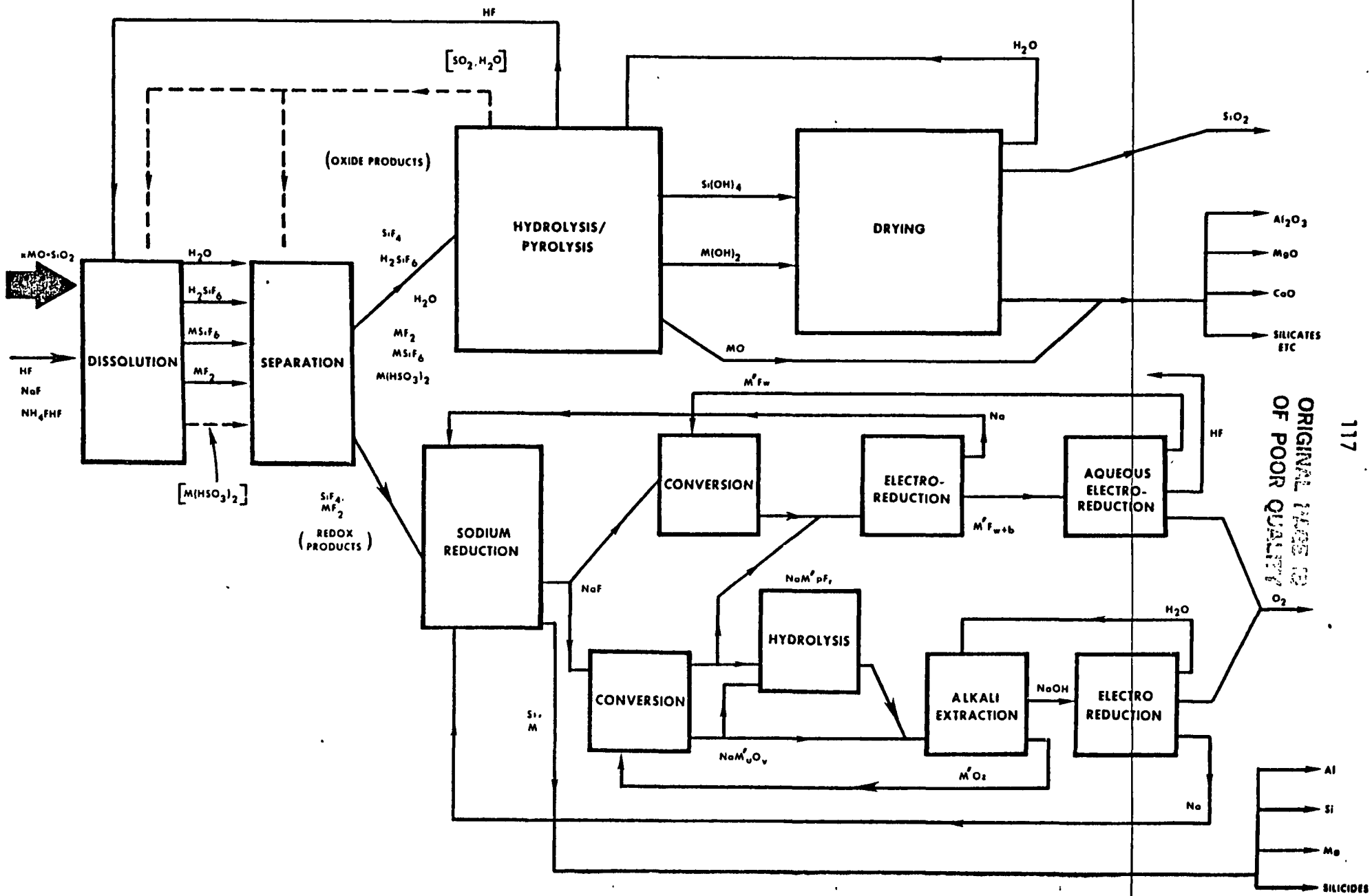


Figure 2

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MOLAL SOLUBILITY OF VARIOUS HEXAFLUOROSILICATES

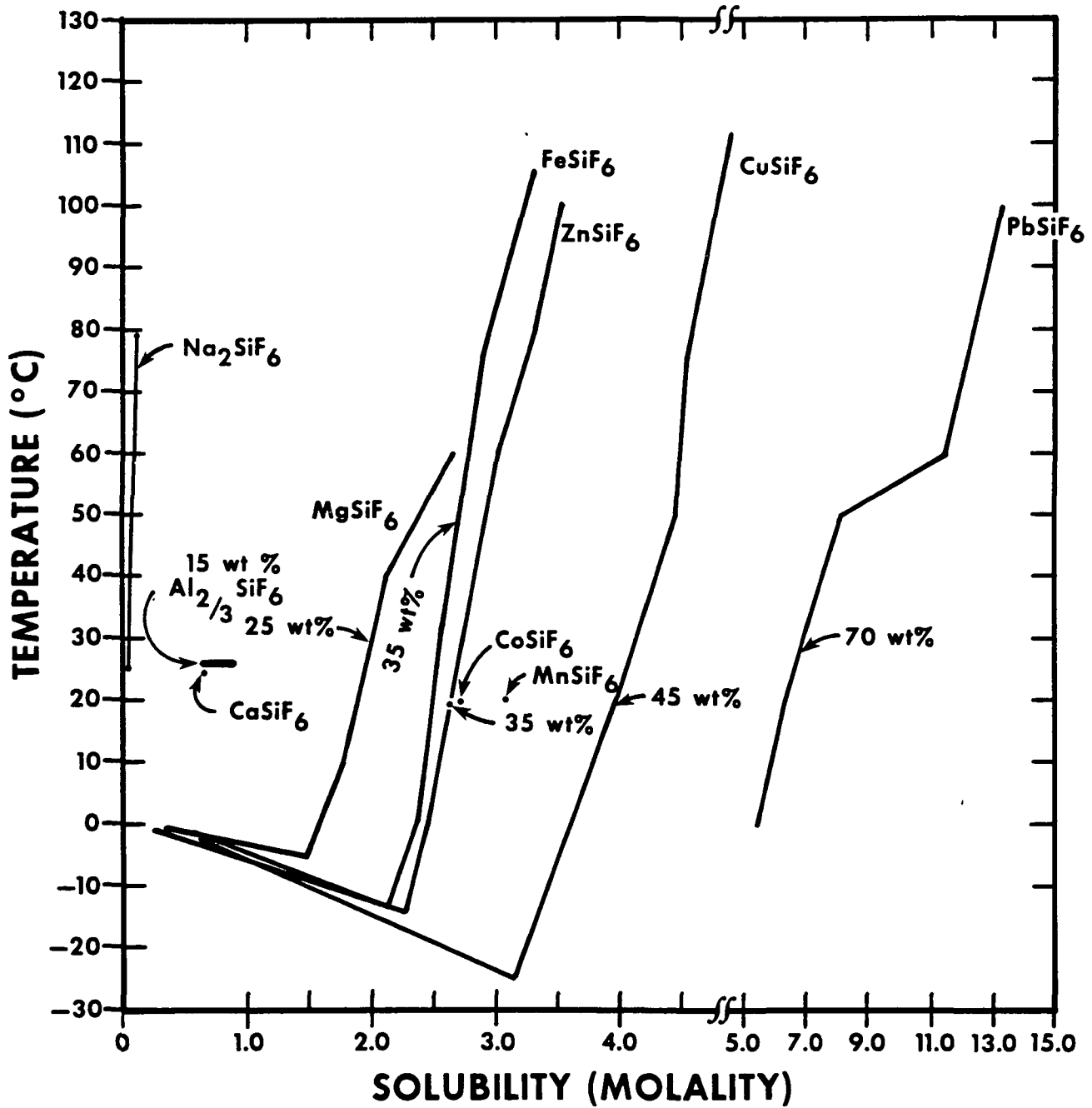


Figure 4

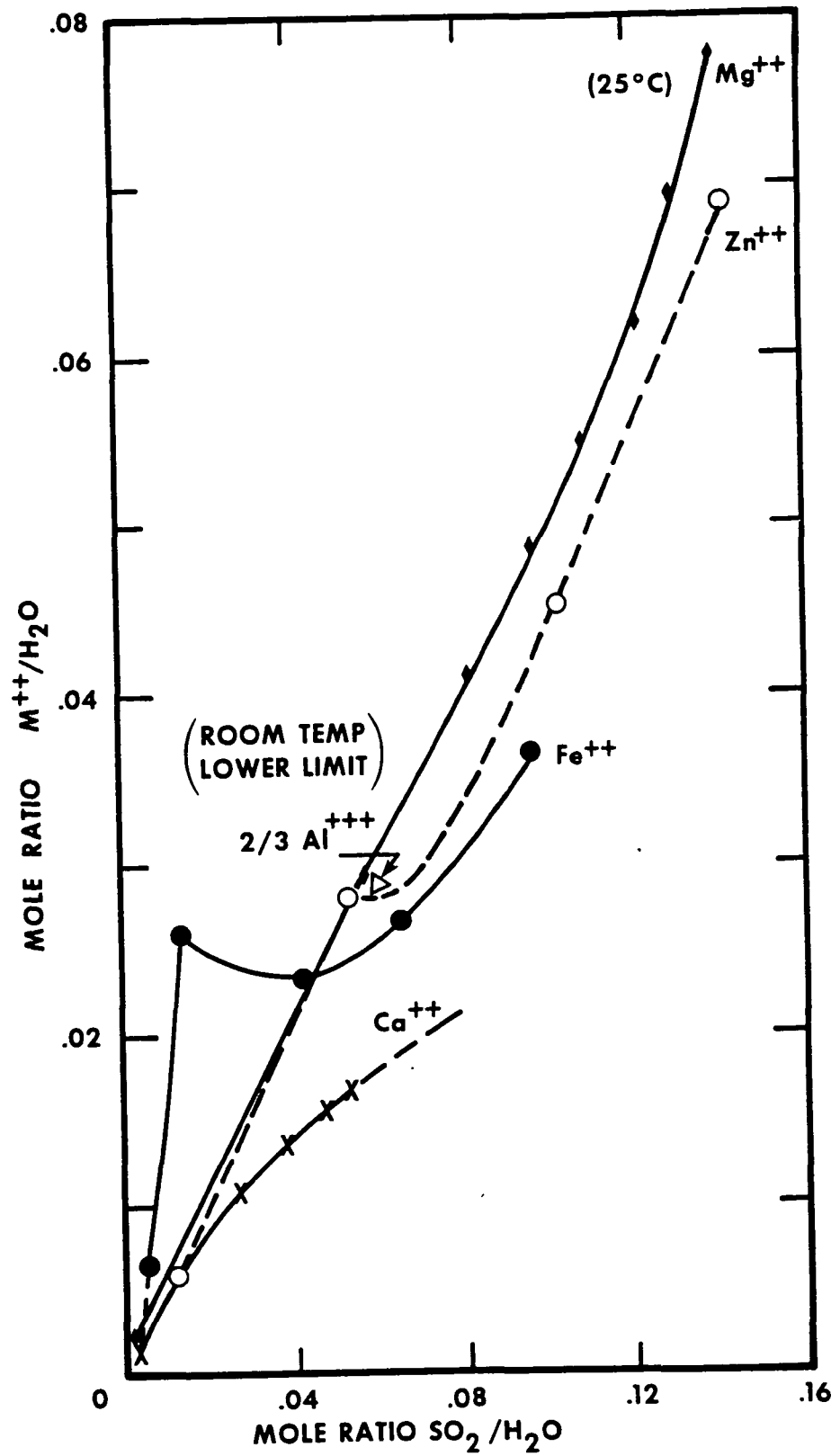
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Figure 5

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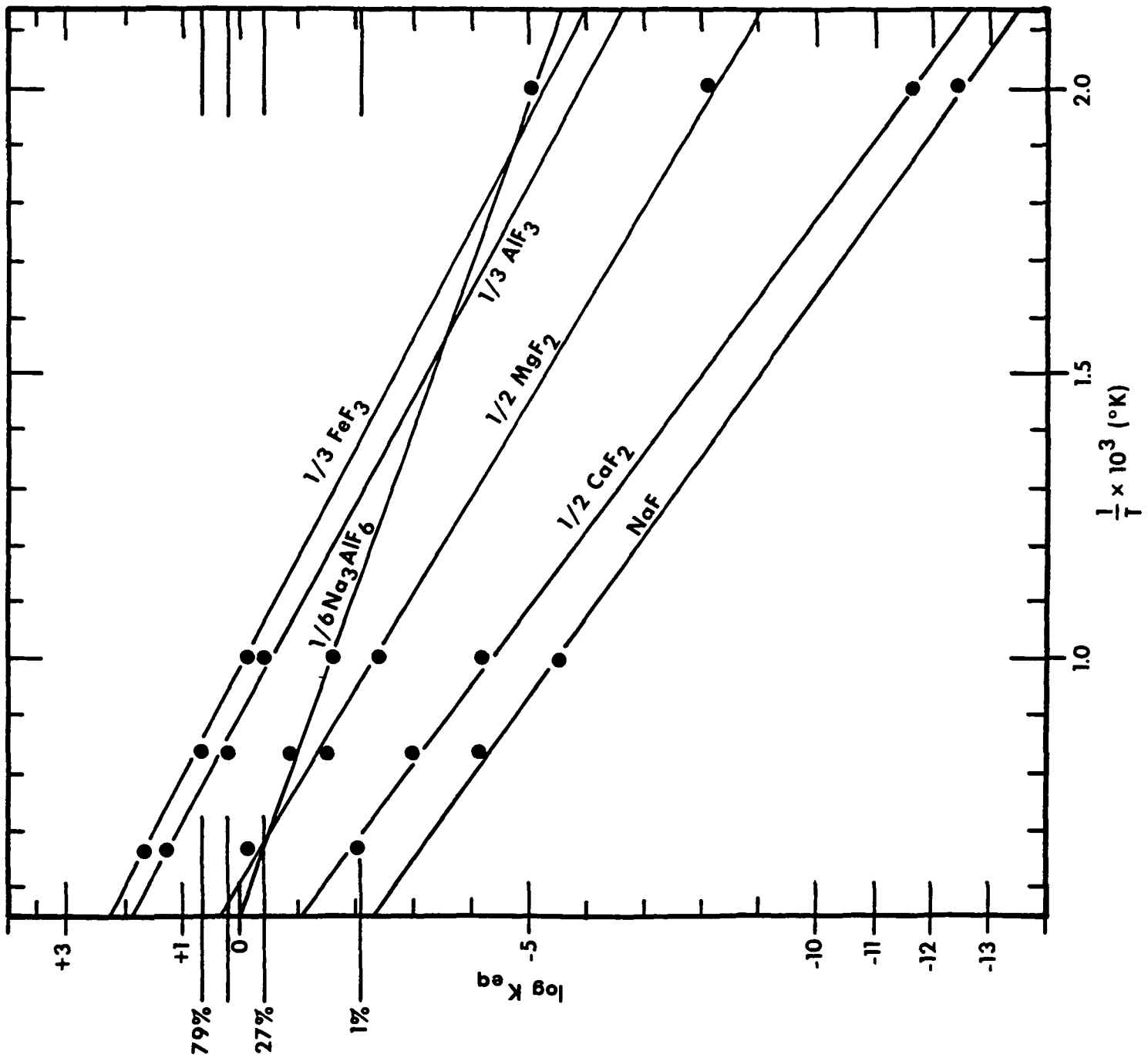


Figure 6

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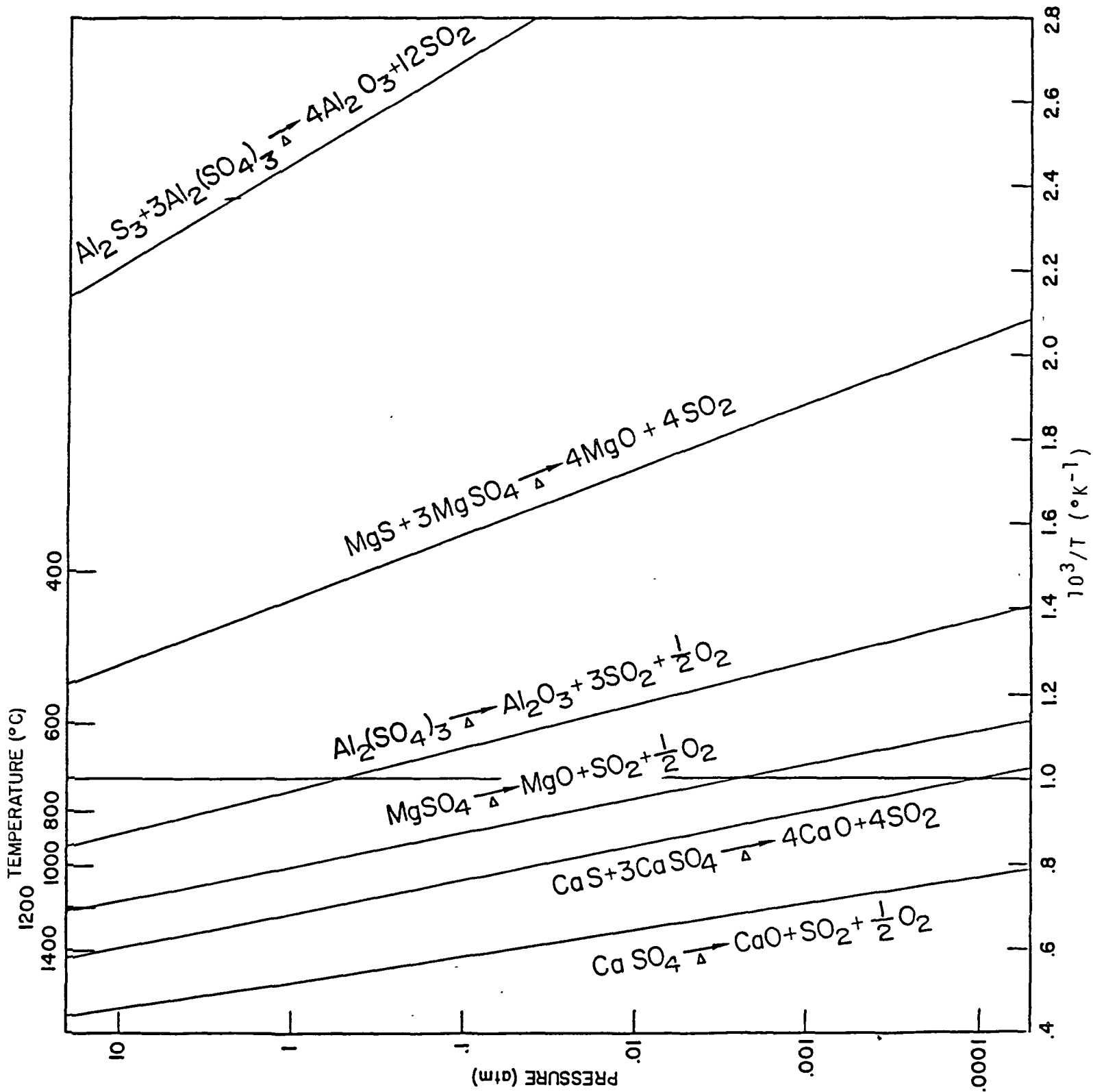
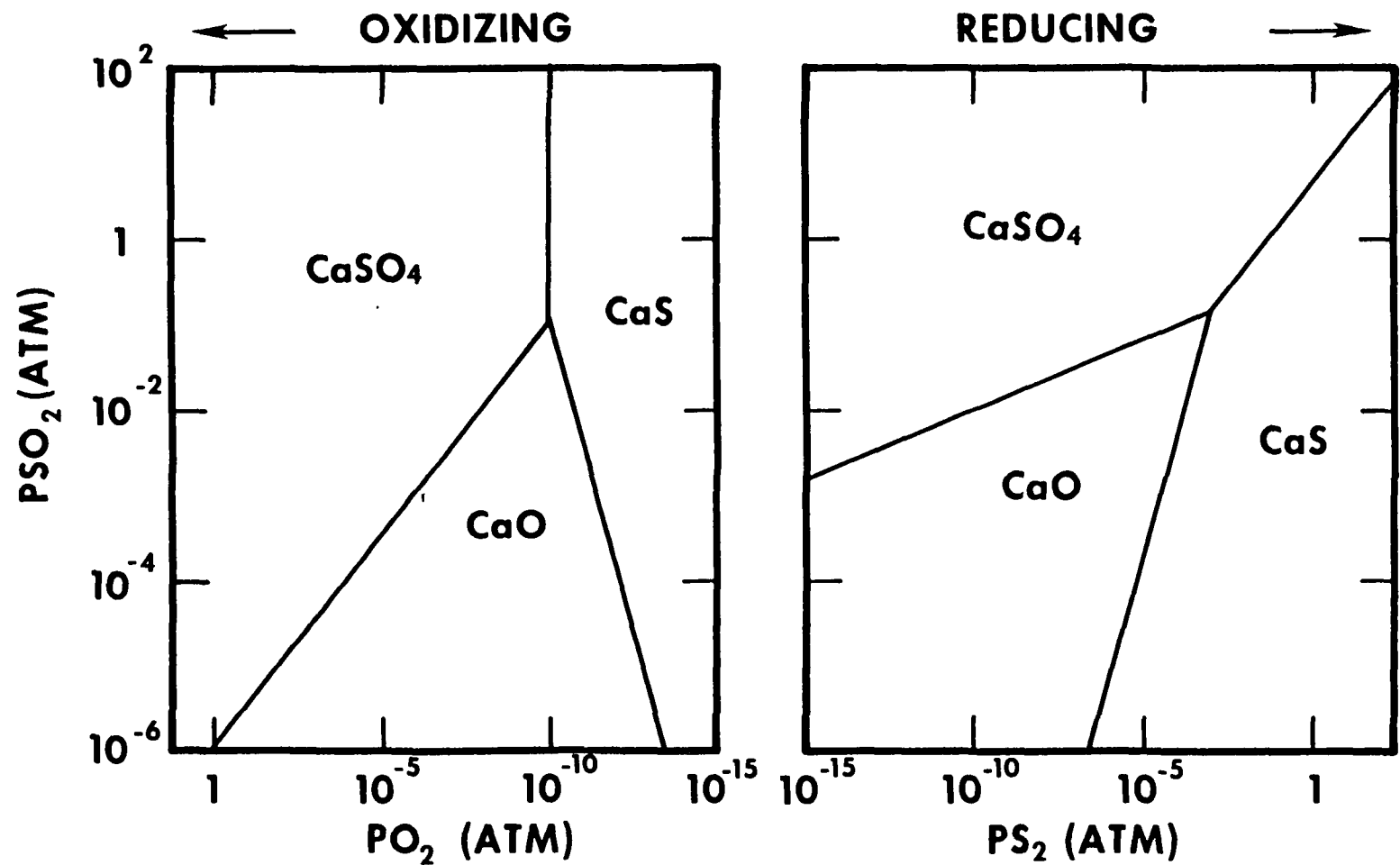


Figure 7

EQUILIBRIUM DECOMPOSITION PRESSURES
OF SULFATES AND SULFIDE/SULFATE SYSTEMS

Figure 8



PHASE DIAGRAM @ 1300°K

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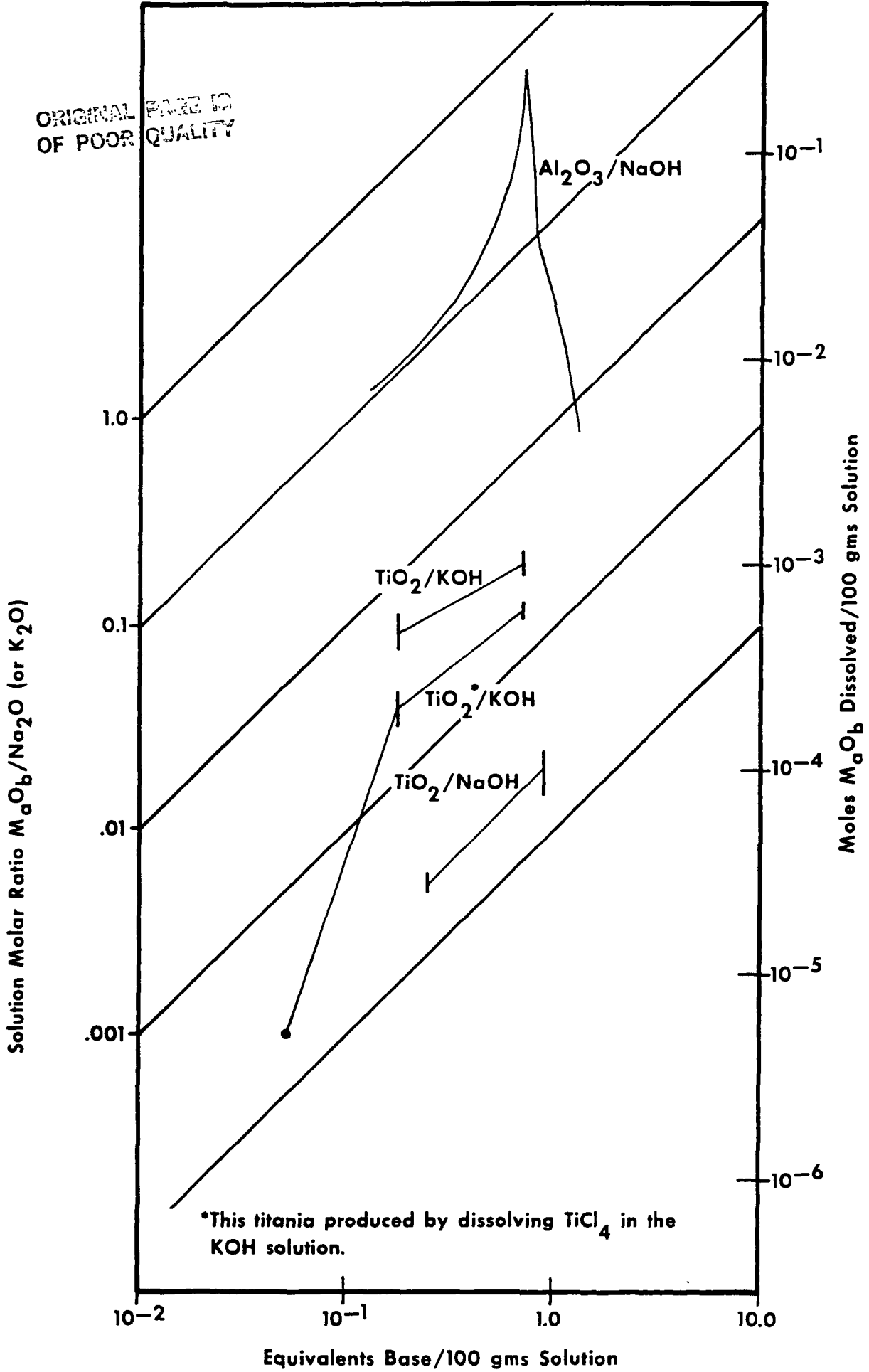


Fig. 9

Chapter V

ELECTROREFINING PROCESS FOR LUNAR FREE METAL AND
METAL DERIVED FROM CHEMICAL PROCESSING OF LUNAR SOILS

Lunar soils contain a small fraction of metallic particles or grains, either free-standing or welded to glassy to crystalline material, which are predominantly iron but contain minor amounts of nickel and cobalt and trace amounts of other elements. Metal contents of typical soils may range from less than 0.1% by weight to more than 1%. Impure metal (again mostly iron) may also become available as a result of chemical beneficiation or processing of lunar soils, primarily as a result of electrowinning operations in aqueous or fused magmatic liquids. The principal impurities for these metals will likely be manganese, chromium and traces of more noble metals such as copper, lead, etc.

For metal products intended primarily for mechanical properties applications, it may be unimportant to purify or refine the alloys derived from these sources save for reduction of sulfur and/or phosphorus levels through slagging operations during initial melting of lunar metal grains. For electrical conductor or magnetic applications, however, it may become important to be able to reduce impurity levels in iron. Figure 1 shows the effect of various alloying elements on the resistivity of iron -- note that the resistivity nearly doubles for 5 to 6% Ni content, a range typically present in lunar free metal. Thus purification could probably reduce the mass requirement for conductor wire approximately 50% over that needed with impure metal.

Electrorefining would also be advantageous in offering a source of nickel and cobalt which would be virtually inaccessible from other lunar sources.

We have studied possible means of separating and purifying ferrous based metals of this type and have designed a water based electrorefining process of

the two compartment cell types in which the anode and cathode are separated by a membrane and the impure anode solution (anolyte) produced by dissolution of the impure cast anodes is withdrawn and the metal values transferred to the purified cathode solution (catholyte) by the use of ion exchange techniques. In the process a third solution loop (purification loop) is used to aid separation and transfer. In addition, a certain amount of water must be transferred from loop to loop to maintain water balance.

A schematic flow chart for the process is shown in Fig. 2. The separations of metals is based on the differential distribution of iron, cobalt, nickel and other elements between anion exchange resin and solution in the presence of chloride ion. Published data are available on distribution constants as a function of HCl concentration for transition metal ions, and limited information on the distribution in neutral chloride and self equilibration has been reported (1,2,3).

In hydrochloric acid solution, the distribution coefficients between resin and solution for the transition metal ions decreases in the order Fe^{+++} , Co^{++} , Fe^{++} , and Ni^{++} at fixed chloride ion concentration, and increases with $[\text{Cl}^-]$ up to at least 9 molar (except for Ni^{++} which is essentially non-absorbed) (Fig. 3). Unfortunately, information at other than room temperature and under proposed solution compositions is not available, but one may estimate the behavior from the existing data. Small changes in the values will require minor adjustments to the resin, flow, and elution volumes, but will not invalidate the procedures proposed. Thus, elution of chloride complexes from HCl and LiCl solutions differ markedly at $[\text{Cl}^-] > 6\text{N}$ (normal) but are substantially equivalent under higher dilutions. Thus, we may expect Cl^- furnished by Fe^{++} , Ni^{++} , Co^{++} and other chloride salts to behave similarly.

Detailed Process Analysis

A brief summary of ion exchange theory is given in the Appendix. Terms used in the following discussion are defined in that section.

The process will be analyzed for a presumed input composition of cast anodes of 94% Fe, 5.5% Ni and 0.5% Co (atomic). The weight percent values are almost identical (93.71 Fe, 5.76 Ni, and .53 Co). Refining of electrowon metal would be substantially altered, but primary transfer is expected to be nearly the same.

The process is based on transfer of iron and impurities from the anolyte loop to a primary ion exchange bed or column by batch equilibration. The primary column is then rinsed or eluted under conditions that substantially all of the Ni, Co and other impurities are removed from the resin to the purification loop for further separation, but substantially all of the iron (present in Fe^{+++} state) remains in the resin. The resin is then eluted into the catholyte loop from which the iron is deposited on the cathode.

A secondary ion exchange column in the purification loop then incompletely separates the solution into nickel, cobalt, ferrous iron, and mixed salt fractions -- with the first two going to deposition cells for recovery and the remaining being used for elution or transferred back to the anolyte loop. A mass flow analysis is given in Table I.

Engineering Analysis

The mass and power requirements for the process may be derived by the methods indicated in R1. It is apparent from a consideration of process times that the major mass requirements will be due to the mass of electrolyte in the anolyte and catholyte sections and these, in turn, depend on current or deposit 1 gram equivalent at 100% current efficiency. Since the mean density and electrode separation. Thus, 16.802 Amp/hr are required to dissolve or deposit 1 gram equivalent at 100% current efficiency. Since the mean atomic weight of the reference composition is 56.02 and there are 2.94 equivalents per gram atom (based on Fe^{++}), the equivalent weight is 19.05 and there are 52,481 equivalents per metric ton. Thus, for a throughput of 1 metric ton/hr, a total current of 1.4066×10^6 amperes will be required.

The minimum solution volume required will depend on the electrode area (which will depend on allowable current density) and electrode separation. Table II gives the electrode areas and solution volumes required as a function of current density, i , and electrode separation, d , for a 1 metric ton/hr facility. It is seen, that for a fairly conservative system with $i = 10^3 \text{ Amp/m}^2$ and $d = .05 \text{ m}$, a solution volume of 70.33 m^3 of electrolyte would be needed which would have a mass of 84.4 metric tons at an assumed specific gravity of 1.2. About 19% or 16 tons represent lunar deficient elements (H and Cl).

The mass associated with the ion exchange and purification system is almost negligible in comparison with the electrolyte mass in the cells. Based on the input solution composition to the anolyte cell and the assumed current density, a 1 metric ton/hr facility would process $20.588 \text{ m}^3/\text{hr}$ of anolyte solution and, a time of 1.71 hr would be required to reach the output composition needed for transfer, if half the total electrolyte volume is in the anolyte loop. Since

the primary transfer is by batch equilibration, it is virtually instantaneous, and the process time for the anolyte solution in the resin bed will be determined by solution entry and removal times.

Process Options

The process would also be generally applicable to iron alloy recovered by electroreduction of lunar silicate, titanate, or spinel sources but with substantial modification of elution procedures. One may anticipate that Cr and Mn would be the principal impurities from aqueous electrodeposition from dissolved nonmetallic lunar ores. Both elements are easily separable from ferric iron by anion exchange of chloro complexes, and separation of Cr from Mn would be qualitatively similar to separation of Ni from Fe(+2). Recovery of other trace elements, including precious metals, also appears feasible by cementation or ion exchange methods.

Appendix

ION EXCHANGE THEORY

The equilibrium ratio between the concentrations of an ionic species A^- in a resin and in the contacting solution is expressed by the distribution constant $D = (A^-)/[A^-]$, where (A^-) is the concentration in the resin phase and $[A^-]$ is the concentration in solution. The concentrations may be specified in several units: moles per liter, or moles per kg dry resin or solvent while the resin volume may be expressed as apparent bulk (bed) volume or true volume of the resin beads. We shall find it convenient to express (A^-) as moles per liter of column bed and $[A^-]$ as moles per liter of true solution.

The distribution constant is approximately constant for low concentrations or fractional loading of the resin L , where $L = (A^-)/(S)$ and (S) is the concentration of resin exchange sites. D is, however, a function of L , temperature, and $[Cl^-]$ (for chloride complexes).

The dependence on L may be derived from the law of mass action. If we denote by (S_u) the concentration of unoccupied resin sites (by A^-) we have the equilibrium: $S_u + A^-_{soln} \rightleftharpoons A^-_{resin}$ with equilibrium constant $K_{eq} = (A^-)/(S_u)[A^-]$. But $(S_u) = (S)(1-L)$ so $(A^-)/[A^-] = D = K_{eq}(S_u) = K_{eq}(S)(1-L) = D_0(1-L)$ where $D_0 = K_{eq}(S)$ is the limiting distribution coefficient at low concentrations as ordinarily reported in the literature.

The elution constant $E = (D + \alpha)^{-1}$ represents the ratio of the rate of movement of a band or zone of species A^- during elution to the rate of progression of solution through an empty column of equal dimensions. α represents the void fraction of the column accessible to solution and is usually taken as 0.4. Thus if $D = 0$, $E = 2.5$ which represents the maximum speed of elution for nonabsorbing species which is roughly equivalent to passage of

solution down a column filled with glass beads.

Under conditions of high solution concentration, it is found that even species which do not form anion complexes enter the resin phase as charge neutralizing species for their corresponding simple anions (such as Cl^-). This is apparently the case for Ni^{++} which has an elution constant ~ 2.5 independent of $[\text{Cl}^-]$ for low nickel concentrations. No data is available for higher nickel concentrations, but from available data for BaCl_2 we may estimate $D \sim 0.1$ for $[\text{Ni}^{++}] > 1$ mole/liter.

We may depict the estimated resin loading curves derived from published data in Fig. 4. For Fe^{+++} and Co^{++} in Cl^- buffered solution, the lower curves given fractional resin loading vs solution concentration. Fe^{++} curves would be parallel to and above the Co^{++} curves for the same Cl^- , while we have assumed that the Ni^{++} curve falls on the $D = .1$ line.

For elution equilibria, the non Cl^- buffered case, or self-elution curve, becomes important. The self-elution curve for CoCl_2 is shown on the figure, while the estimated self-elution curve for FeCl_3 is also given. (The lower limit of the self-elution curve is derivable from the buffered case by assuming no complex formation which would yield a free chloride ion concentration equal to the total chloride ion concentration.)

Table I

Process Point	MASS BALANCE				ELECTROREFINING PROCESS					Notes
	Solution or Resin Concentration (Moles/liter)				Volume (ml)	Millimoles: Contained (Transferred)				
	I	F	N	C		I	F	N	C	
1	.225		1.052	.053	1000	225	1567.5 -x-y	1052.3	53.06	
2							(x)			Influx through diaphragm or membrane
2'							(y)			
AD	(Anodic dissolution)					(815)*		(47.7)	(4.34)	*Combined iron
3	1.04	1.5675	1.1	.0574	1000	1040	1567.5	1100	57.4	Volume additions neglected
4	.02097	1.5	1	.0466	1000	20.97	1500	1000	46.6	
PIXB	1.1325	.2175	.1	.0108	1000	1132.5 (1019.5)	217.5 (67.5)	100 (100)	10.8 (10.8)	Primary ion exchange bed
5	Variable				93.5	5.24	145	52.3	6.45	From 14c, d, f, and 16
9			1		4.8			4.8		From 14b
10		1.5	1		136		204	136		From 14c
11		2.25			15		33.8			From 14d
12	DW (Distilled Water)				94.2					Partially from 14a
13a	.021	{ 1.5 2.25	{ 1 0	.0432	250	5.24	382.8	240.8	10.8	Figures in brackets: Top: 240-1 ml Bottom: 9-10ml
SC	(Short Column)				5	(5.24)	(1)	(.5)	(.05)	Also content
13b	0	1.5	1	.0431	250	0	381.8	240.3	10.75	
13c	DW (Distilled Water)				74.52					
14a	DW (Distilled Water)				35					To 12
14b			1		52.5			{ 47.7 4.8		To N recovery, 47.7 ml To 9, 4.8 ml

Process Point	MASS BALANCE				ELECTROREFINING PROCESS					Notes
	Solution or Resin Concentration (Moles/liter)				Volume (ml)	Millimoles: Contained (Transferred)				
	I	F	N	C		I	F	N	C	
14c		1.5	1		188.5	{ 204 78.8	{ 136 51.8			To 10, 136 ml To 5, 52.5ml
14d		2.25			23.1	{ 33.8 18.2				To 11, 15 ml To 5, 8.1ml
14e		2.25		.1385	20.9	47		2.90		To 5
14f				1.74	4.52			{ 4.34 3.51		To C recovery 2.5 ml To 5, 2.02ml
15	DW (Distilled Water)				10					
16	Variable				10	(5.24)	(1)	(.5)	(.05)	To 5
PIXB						1127.3 (-5.24)	72.5 (-145)	0 (-100)	0 (10.8)	After 13a To 13a
20		.508			1800	914				
21						(471.2)				Neutral iron addition for reduction
22	.04	1.25			1800	72		2250		
2								(-x)		
2'								(-y)		
CD	(Cathodic Deposition)					(815 + 471.2)				Net transfer plus iron redissolved @21. (Excluding N&C)
23	0	.508			1800			914		Same as 20
PIXB	.113	.15			1000	113 (-72) (-942.3)	150 (+77)	0	0	After 22 To solution 22 Appears as F in 22 From 20
							(+77.5)			

ELECTROREFINING PROCESS

Millimoles: Contained
(Transferred)

Process Point	Volume (ml)	I	F	N	C	Notes
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SOLUTION LOOP INPUT/OUTPUT BALANCE

ml · Millimoles

Anolyte Loop	Volume (H ₂ O)	I	F	N	C	Notes
IN						
AD		(815)		47.7	4.34	Total iron
2,2'	x'+y'		121.8			
5	93.5	5.24	145	52.3	6.45	
SUM	x'+y' 93.5	(1087.04)		100	10.79	Total iron
OUT						
PIXB		-1019.5	-67.5	-100	-10.8	Total iron
Water Removal	-93.5-x'-y'					
SUM		(-1087)				Total iron

PURIFICATION LOOP

IN						
PIXB		5.24	145	100	10.8	
Water Input	(From Anolyte Loop)	93.5				
OUT						
16		-5.24	-1	-5	-0.05	
14c,d,e,f		-93.5	-144*	-51.8	-6.41	-78.8(c)-18.2(d) -2.9(e)-3.51(f)
N Recovery				-47.7		Water to N,C
C Recovery					-4.34	recovery distilled and returned to loop
SUM		-93.5	-5.24	-145	-100	-10.79

ELECTROREFINING PROCESS

Millimoles: Contained
(Transferred)

Process Point	Volume (H ₂ O)	I	F	N	C	Notes
SOLUTION LOOP INPUT/OUTPUT BALANCE						
	ml	Millimoles				
Catholyte Loop						
IN						
PIXB	1014.3					
21			(471.2)			Neutral iron converted to Fe ⁺²
	Internal Reduction by 21		942.3			
	Electro Reduction		72			
	SUM	1014.3	1485.5			
OUT						
PIXB			-77.5			
2,2'			-121.8			
	Internal Reduction by 21	-942.3				
	Electro Reduction	-72				
CD	(Cathodic Deposition)		(-1286.2)			Neutral iron removed from Fe ⁺²
	SUM	-1014.3	-1485.5			
	NET TRANSFER	1286.2	-471.2	(021) = 815		(AD)

FIGURE TITLES

- Fig. 1 Electrical Resistivity of Binary Iron Alloys
- Fig. 2 Pictorial Flow Diagram for Lunar Metal Electrorefining Process
- A. Consumable Anode Section
 - B. Inert Anode (Oxidation) Section
- PIXB Primary Ion Exchange Bed
- IXC Ion Exchange Column(s)
- Fig. 3 Elution and Distribution Constants for Divalent Transition Metal and Ferric Chloride Complexes on Anion Exchange Columns (Dowex 1)
- Fig. 4 Calculated Distribution Properties of Transition Metal Chloride Complexes vs Fractional Loading on Anion Resins (Dowex 1)

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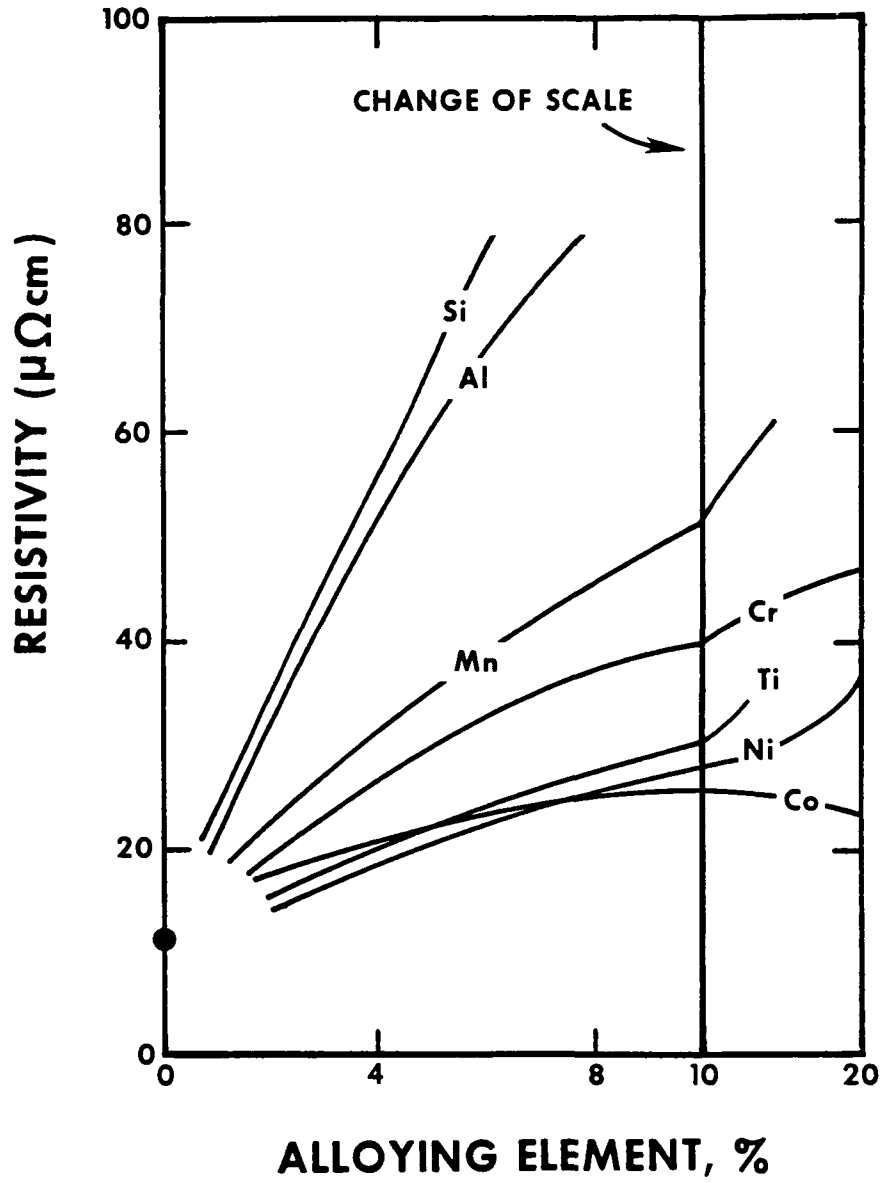


Figure 1

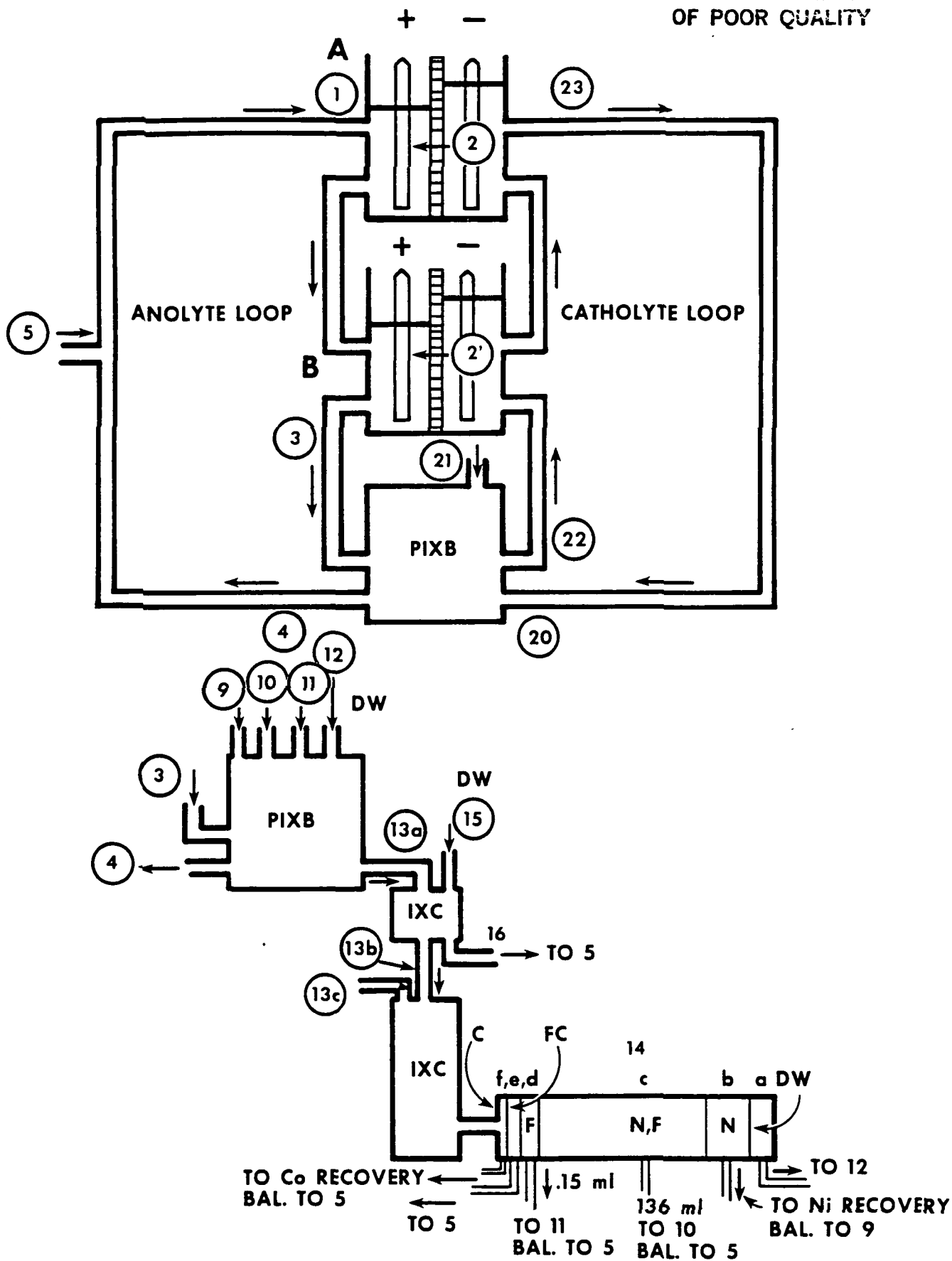


Figure 2

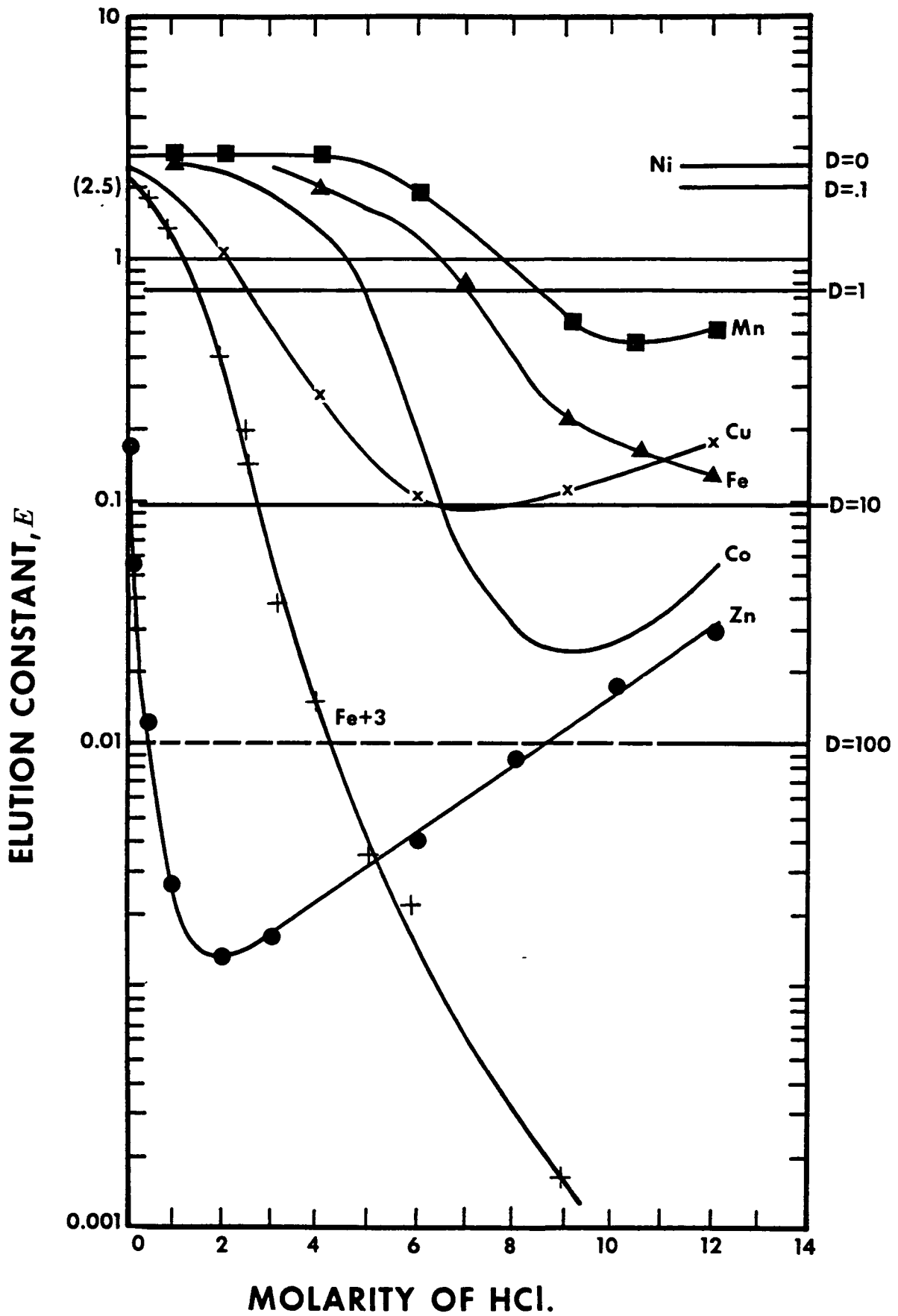


Figure 3

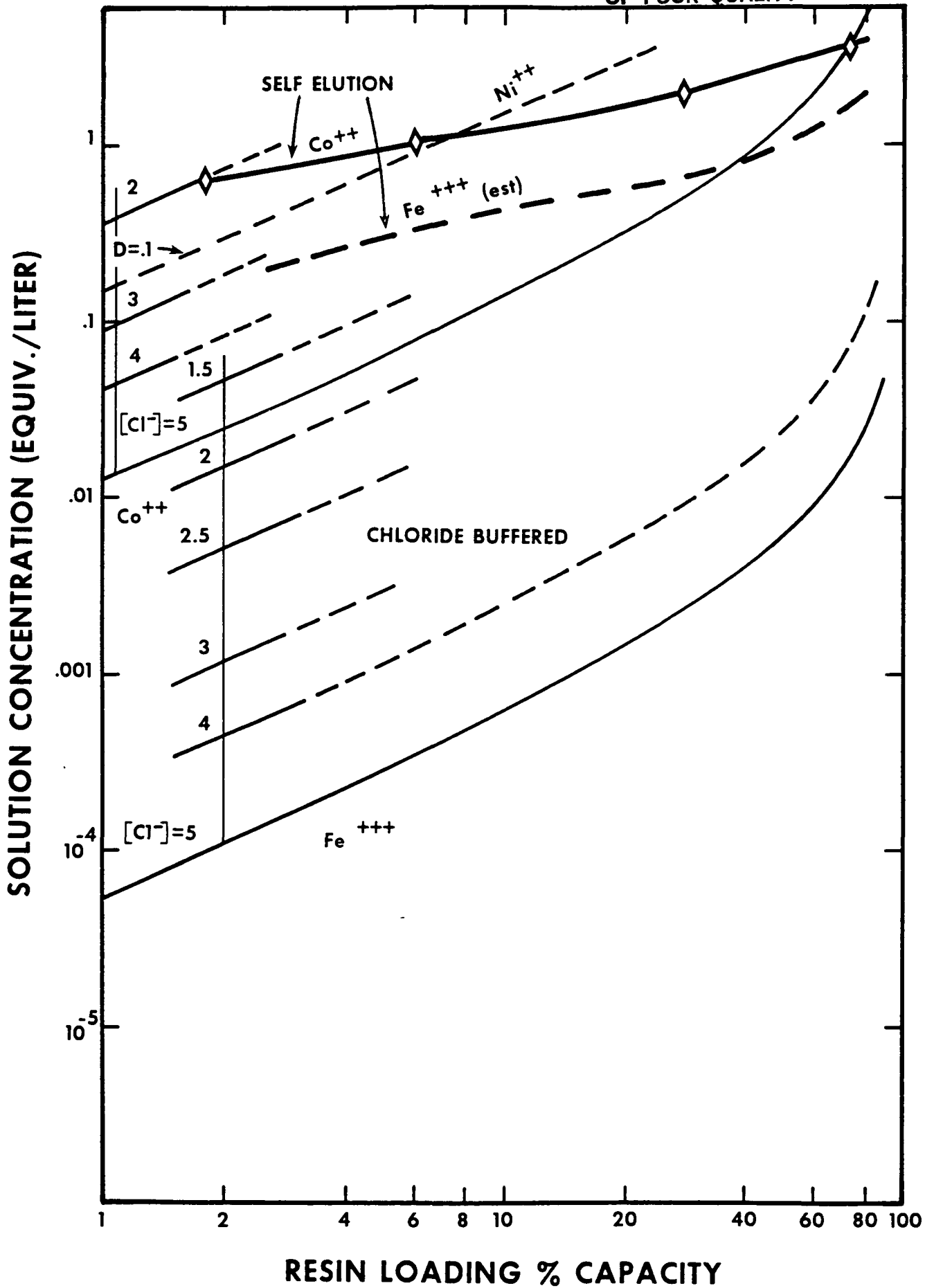


Figure 4

Chapter VI

PRODUCTION AND USES OF SILANES

Silanes are the silicon equivalents of hydrocarbons in which silicon atoms replace carbon atoms. (The name is sometimes loosely used to denote halo or polyhalosilanes as well.) Silanes may exist in gaseous, liquid or solid form ranging in molecular weight from 32 in gaseous monosilane, SiH_4 (b.p. -112°C), the silicon equivalent of methane, to high polymers with MW's of 10,000 or more. Silanes generally have higher heats of combustion than the corresponding hydrocarbons. Because of the plentiful availability of silicon from the moon they may provide a useful source of propellants with a minimal earth mass requirement (hydrogen).

Properties

The properties of low molecular weight silanes are shown in Table I. Silane polymers of approximate compositions $(\text{SiH}_2)_n$ corresponding to polyethylene (1) and $(\text{SiH})_n$ analogous to polyacetylene (2) have been described. The polymeric compositions may be useful in solid propellant formulations. The low molecular weight silanes are less stable than the corresponding hydrocarbons and are subject to slow thermal disproportionation to silicon and smaller molecules even at room temperature. Storability of the first three members of the series, SiH_4 , Si_2H_6 , and Si_3H_8 , appears to be adequate for operational purposes, however.

The lower silanes are spontaneously flammable in contact with air and are hence, hazardous to handle where potential leaks to an oxygen containing atmosphere may occur. This property does not appear to constitute a serious constraint against use of the fuel in lunar and earth orbit operations, because of the lack of uncontained oxidant.

The critical temperatures of the silanes are sufficiently high (see Table I) that it would be relatively easy to store them in liquid form. Thus, Si_2H_6 has a vapor pressure of about 3.61 atm @ 300°K, while SiH_4 could be stored at about 10 atm @ -61°C.

Synthesis

There are four general methods of preparing silanes. These are:

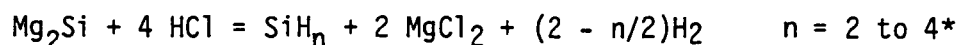
- (1) reaction of silicides with acids,
- (2) reduction of chlorosilanes with hydrides,
- (3) reactions of silicon monoxide with acids, and
- (4) reactions of silicon difluoride with acids.

As with other extraterrestrial processes, it is necessary to develop overall process routes starting with lunar soil fractions (i.e., silicates), synthesize the starting materials and recycle and regenerate all chemical intermediates. The yields obtainable from the acid reaction routes 1, 3, and 4 will be substantially below 100% and usually below 40% if conducted in aqueous media. Much higher yields appear possible with different solvents such as liquid ammonia or fused salts. The impact of yield and starting material requirements will be discussed below.

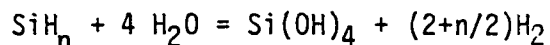
Detailed Discussion of Process Routes

Method 1: Reaction of Silicides with Acids

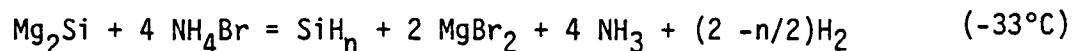
This is the historical method first used to prepare silanes (3). Stock (4) produced and identified a series of silanes by acid hydrolysis of Mg Si. The reactions may be written:



The yields are reduced in contact with water by hydrolysis of the silanes:

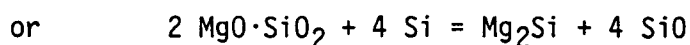
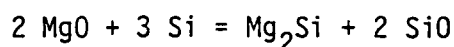


Improved yields (70 - 80%) are possible using liquid ammonia for the solvent (5). Thus:



It may be possible to use chlorides or fluorides efficiently in this step.

The Mg_2Si may be made by direct combination of the elements or in a single step according to the equation(s):

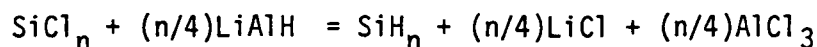


The magnesium halides may be steam hydrolyzed to yield MgO and HCl or HBr . The MgO is then reduced to reform Mg Si .

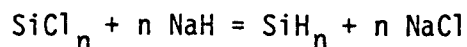
*In this and the following equations, a mixture of silane(s) may be characterized by n , the average atomic ratio of $\text{H}:\text{Si}$, and higher silanes such as $\frac{1}{2} \text{Si}_2\text{H}_6$ and $\frac{1}{3} \text{Si}_3\text{H}_8$ are written as SiH_3 , $\text{SiH}_{8/3}$, etc. SiH_3 may, however, also designate $\frac{1}{4} (\text{SiH}_4 + \text{Si}_3\text{H}_8)$.

Method 2: Reduction of Chlorosilanes with Hydrides

Chlorosilanes may be reduced with LiAlH_4 in ether solution by the reaction:

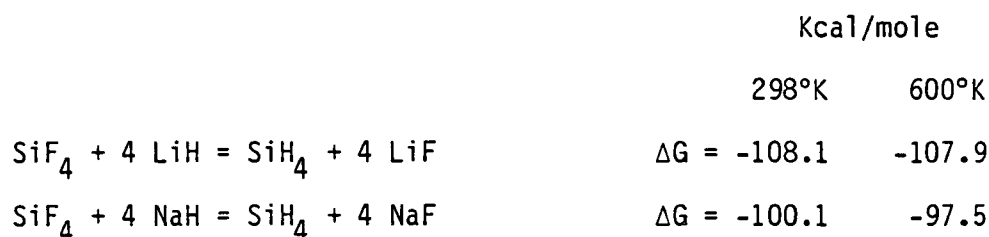


A similar reaction may be carried out in fused salt (chloride) media as:



Yields are reported to be high (5).

The halosilanes may be synthesized from silicon and Cl_2 or HCl , or by interchange of halogen with SiF_4 . However, since SiF_4 is expected to be directly available as a general chemical intermediate in lunar soil processing, it would be preferable to react it with hydrides directly according to the equations:



The free energies of reaction for these equations are shown and indicate the reaction should occur readily. Fused salts may be possible solvents for these reactions.

Sodium and lithium hydrides are prepared in excellent yield by direct combination of the elements (7).

Method 3: Reaction of SiO with Acids

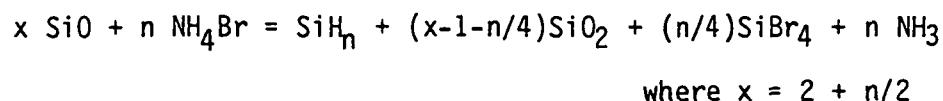
SiO in contact with aqueous HF is reported to form silanes (8) according to the following equation:



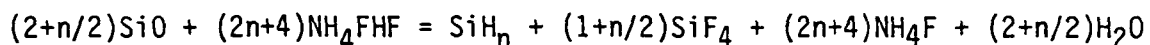
$$\text{where } x \geq 2 + n/2$$

Yields of up to 7.8% have been reported (9). In contrast to the silicide reaction, yields of silanes based on SiO cannot approach 100%, but are limited to fractional values below $1/x$ due to the oxygen bonded to silicon atoms, unless some other strong reductant is used to combine with the oxygen. One may expect yield improvement, however, by going to nonaqueous media such as liquid ammonia.

Thus:



Reactions may also be possible in fused NH_4FHF according to:



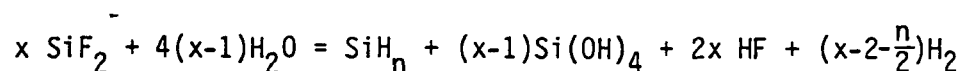
SiO may be synthesized according to the equation:



The reaction product is metastable at temperatures below 1180°C so the reaction mixture must be quenched to avoid disproportionation. The silane yield upon acid dissolution is sensitive to the method of formation of SiO with best results reported for SiO subject to vapor transport at low pressures and condensed on a cold trap. The vapor pressure of SiO is 1 torr @ 1325°C .

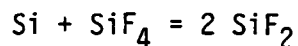
Method 4: Reaction of Silicon Difluoride with Acids

SiF_2 reacts with 20% aqueous HF to produce silanes and hydrogen according to the reaction:



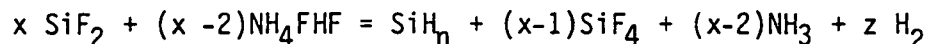
Yields of up to 10.4% have been reported (10).

The SiF_2 may be prepared by reacting Si with SiF_4 .



The product is a vapor which is condensible at low temperatures and may polymerize to a rubbery solid. Improved yields may be possible with nonaqueous solvents such as liquid ammonia or fused NH_4FHF . In the latter medium, we may

anticipate a reaction:



$$\text{where } x = 2 + z + n/2$$

The SiF_4 may be recycled with Si to yield more SiF_2 .

In comparing yields of the various processes, it is worth noting that the energy required to synthesize a mole of silane (SiH_n) depends not only on process yield, but on the number of reduction equivalents to synthesize the silicon containing starting material. Thus, if silanes are made from Mg_2Si which we make take as formed from Mg_2SiO_4 (forsterite), it requires 8 equivalents (40 atoms) removal to form the starting material, or $8/Y$ equivalents if Y is the fractional yield. On the other hand, SiO requires only 2 equivalents per mole, so a fractional yield $Y' =$ only 25% of Y would require the same number of actual reduction equivalents per output mole of SiH_n .

Engineering Analysis of Chemical Propellants Partially Derived from Lunar Materials

It is possible to operate chemical rockets in space transportation systems using propellants partially or completely derived from lunar materials. Silanes may be considered to be a member of the partially lunar-derived class, since the amount of lunar hydrogen may be insufficient to support moderate traffic levels in earth-lunar transportation.

It would be desirable to establish a propellant figure-of-merit for such systems, since the ordinary specific impulse parameter is not well suited to rate comparative systems. In the following analysis, we shall derive expressions for the mass or weight ratios of payload to propellant fraction which must be supplied from earth. We consider this ratio a useful figure of

merit, since the cost of delivering a given mass of earth material will greatly exceed that of locally producing many times the given mass from lunar sources. This figure of merit, of course, is not applicable to propellants solely derived from lunar materials.

Figure of Merit

Let m_i = mass of i th portion of rocket: $i = o$, initial, $f =$ final, $p =$ propellant(total), $pf =$ propellant portion requiring earth supplied material, $t =$ tankage, $e =$ engine system, and $pl =$ payload. $R =$ rocket parameter = $\exp(\Delta V/I_{sp}g)$, where $\Delta V =$ equivalent velocity increment, $I_{sp} =$ specific impulse and $g =$ (earth) acceleration of gravity. The ratios $m_t/m_p = \beta$, $T/m_o = (1 + \alpha)g_L$ where $T =$ initial thrust and $g_L =$ (lunar) acceleration of gravity; also $T/m_e = \gamma g_L$ define auxiliary parameters α , β , and γ .

From the rocket equation

$$\ln R = \Delta V/I_{sp}g = \ln(m_o/m_f).$$

But $m_o = m_p + m_t + m_e + m_{pl}$ or $m_{pl} = m_o - (1+\beta)m_p - m_e$

and Figure of Merit (FOM) = $m_{pl}/m_{pf} = (m_o - (1+\beta)m_p - m_e)/m_{pf}$

By substituting $m_o = (m_o/m_f)m_f = R \cdot m_f = R \cdot (m_o - m_p)$

we obtain: $FOM = R (m_o - m_p)/m_{pf} - (1+\beta)(m_p/m_{pf}) - m_e/m_{pf}$.

We may eliminate m_o and m_e by noting

$$m_e = (m_e/m_o)m_o = (1+\beta)m_o/\alpha$$

and $m_o = R m_p/(R-1) = m_p(1 + 1/(R-1))$

and derive: $FOM = \left[\frac{R}{R-1} - (1+\beta) - \frac{R}{R-1} \cdot \frac{(1+\alpha)}{\gamma} \right] (m_p/m_{pf})$
 $= \left[\frac{1}{R-1} - \beta - \frac{(1+\alpha)}{\gamma} \cdot \frac{R}{R-1} \right] m_p/m_{pf}$

The ratio m_p/m_{pf} is determined by chemistry and fuel/oxidizer ratio -- thus for silanes expressed as SiH_n in stoichiometric combustion, we have $SiH_n + [1 + (n/4)]O_2 = SiO_2 + (n/2)H_2O$, we have $m_p/m_{pf} = (60 + 9n)/n = 9 + 60/n$

with values of 24 and 29 for $n = 4$ or 3 , respectively. For stoichiometric H_2/O_2 with earth H_2 and lunar O_2 , $m_p/m_{pf} = 18/2 = 9$.

One may compare partial lunar derived propellant systems with earth propellants with the above formulae by setting $m_p/m_{pf} = 1$ for the latter. While H_2/O_2 has a higher specific impulse and thus lower R , it would be more than offset by its lower value of m_p/m_{pf} , especially for the lower ΔV 's required for cis-lunar operations. The tankage factor β is also greater for hydrogen propellant systems due to lower densities.

Estimates of specific impulse of SiH_4/O_2 in mixture ratio 1:2 by approximate methods give values of $I_{sp} = 309-349$ sec and $I_{sp}(vac) = 328 - 378$ sec.

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Table I
 PROPERTIES OF THE NORMAL SILANES

	SiH ₄	Si ₂ H ₆	Si ₃ H ₈	n-Si ₄ H ₁₀
Melting point, °C	-185	-132.5	-117.4	-84.3
ΔH fusion, cal/mole	159.5			
Boiling point, °C	-111.9	-14.5	52.9	107.4
ΔH vaporization, cal/mole	2982	5069	6783	8500
Vapor pressure equation liquid	$\log p = \frac{740.0}{T}$ +1.75 log T -0.0079701T +4.87448	$\log p = \frac{1380}{T}$ +1.75 log T -0.0069309T +5.78216	$\log p = \frac{2247.3}{T}$ +1.75 log T -0.00576T +6.4472	
Vapor pressure at 0°C, mm			95	9.1
-118°C, mm	530	1		
Critical temperature, °C	-3.5	109	189	249
Critical pressure, atm	47.8			
Heat of formation, ΔH _f ^o , Kcal/mole	+7.8	15.1		
Entropy ΔS, std.	48.7			
Density liq. at m.p.	0.68	0.69	0.725	0.79
Surface tension at b.p., dynes	15.11			

Chapter VII

PRODUCTION AND USE OF SPECTRALLY SELECTIVE MATERIALS

Because of the absence of external fluid heat transfer mechanisms for lunar surface and orbital heat transport, and the inferior dissipative performance of internal convection with reduced gravity, it is important for both industrial and biological heat management to take advantage of favorable radiation properties to minimize or eliminate specific heat transfer load requirements. Radiation may also offer a higher level of reliability than mechanical heat pumps.

The surface temperatures reached on lunar surface or orbital structures will depend on the attitude or orientation of solar exposure, solar concentration ratio, shading if present, radiant exchange with other surfaces facing the given surface, heat flux to or from the interior and the coefficients of absorption, α , and emission, ϵ , which may in turn be temperature dependent. In practice, it will usually be desirable to have two types of spectrally selective materials: "cool" surfaces with minimum α/ϵ , and "warm" surfaces with maximum α/ϵ ratios.

Typical cool materials include white, clear or transparent stable inorganic crystals of oxides, silicates, etc., which will scatter or transmit most solar radiation with little absorption, but which are effective absorbers (emitters) at longer wavelengths. A second class of cool surface may be constructed by using an efficient optical mirror with silver, aluminum, calcium or sodium with a thin overlay coating of glass, quartz or other transparent oxide. The overlay coating is an effective emitter, while the mirror reflects most of the solar radiation.

Reported values of α/ϵ for several materials are shown in Table I. Cool

surfaces have been prone to degradation in some cases due to long term exposure to ultraviolet radiation, vacuum and ionizing radiation. Considerable research has been done to provide stable thermal control surfaces for spacecraft temperature control.

Warm surfaces include copper and some alloys, normally reflective metals such as aluminum or silver with extremely thin dark anodized or other glossy dielectric film overlays and some specialty materials such as silicon. Typical values are shown in Table I.

Cool Materials

Many materials derivable from lunar soils would be satisfactory materials for cool surfaces. Calcium, magnesium or aluminum oxides or silicates plus silica itself could be readily produced in powdered, foamed or other form suitable for engineering application. Simply spreading a thin layer of such material over the lunar surface would be adequate to maintain subsurface temperatures well below ambient levels even at local noon illumination conditions. Figure 1 shows the equilibrium temperature vs α/ϵ for normal solar illumination and zero backside heat transfer as a function of concentration ratio-duty cycle product.

Very high performance cool material may be especially useful in reducing refrigeration requirements for oxygen and other cryogenic storage applications.

Warm Materials

The most generally useful warm surface materials will probably be aluminum or iron with a dark anodized or sputtered film containing transition metal oxides such as FeO , Fe_3O_4 , Cr_2O_3 , NiO or CoO or their complex compounds with Al_2O_3 . Some typical values are given in Table I.

As noted from Fig. 1, it is possible to reach fairly high temperatures, even with unconcentrated solar radiation, and further increases are possible

with solar concentrating devices. Under many conditions, the physical properties of the substrate and/or surface films may become limiting; for example diffusion, vaporization and creep processes may become important. The limiting values for both cool and warm surface materials are determined the lowest values for coefficients α_{lim} and ϵ_{lim} , respectively, assuming reasonably high levels of emission and absorption can be achieved by appropriate geometrical or compositional means. The minimum and maximum temperatures that can be achieved thus depend on the highest levels of reflectance (or lowest levels of absorptance or emittance) for short (solar) or longer wavelength (self radiance) radiation. The emissivity for several metals is shown in Fig. 1, and the crossing points of these curves with the α/ϵ curves indicate the lowest or highest temperatures achievable with these substrates. It may be noted that molybdenum may be the best substrate for concentrating "hot" surfaces while SiO_2 or MgO may offer the best opportunities for cryogenic cool surfaces.

Applications

Several applications are expected to assume importance for lunar base activity. Among these are:

1. Space heating and cooling.
2. Passive refrigeration for maintenance of cryogenic fluids.
3. Development of high capacity hot and cold thermal storage for lunar night time operations including power generation.
4. Development of improved surfaces for solar absorptive and space radiator systems for industrial heat exchangers.

Categories 2 and 3 may involve primarily stationary systems, but the first and last groups could also include moveable structures to either track or avoid the sun or to transfer thermal inertia from interactive to insulated zones, etc. Purely stationary spectrally

selective surfaces may also be combined with controllable thermal valves or "diodes" such as gravitationally directed (non-wicking) heat pipes to maximize heat retention or rejection for specific applications.

Table I

SOLAR ABSORPTANCE AND THERMAL EMITTANCE FOR SELECTED SURFACES

Material	α	Notes	$\epsilon(\text{RT})$	$\epsilon(\text{T}^\circ\text{C})$	α/ϵ
Cool surfaces					
FEP Teflon	.08	A	(.7)	est	(.11) est
FEP Teflon (Aluminized)		.14		(.6) est	(.23) est
Z-93 Paint ($\text{ZnO-K}_2\text{SiO}_3$)	.17		.90		.189
Fused Quartz					
2nd Surface Silvered	.07	B			
OSR (Optical Solar Reflector) Fused Silica, 2nd Surface Silvered	.05	B	.76		.066
MgO	(.01) est	A	(.5)	est	(.02) est
SiO	(.01) est	A	(.750)	est	(.013) est
Al O	(.01) est	A	.72-.83		~(.013) est
Black Body					
V-Grooves	.98	C	.91		
Warm Surfaces					
CoO	.72		.07		10.3
Gold		D	.01	.07 (830°)	
Evap. Gold on Aluminum	.27		.03		9
Evap. Gold on Aluminum	.2	D	.04	.06 (360°)	5 Evap.
Aluminum					

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Evap. Aluminum on St. Steel	.08	.04	2
Evap. Aluminum on Kapton	.10	E	
Copper		D .02	.15 (liq)(1140°)
Iron		D .05	.25 (830°)
Molybdenum		D .07	.13 (1000°), .24 (2000°)

Notes:

- A. Absorptance dependent on mean optical path length (or thickness) for powdered (or layered) dielectrics.
- B. Most of absorptance due to metallic layer (higher than for first surface mirrors of same metal).
- C. 5 x 8 mil (width-depth 35°◀) in AZ-318 Mg alloy with dichromate conversion coating.
- D. Absorptance can be raised above .5 by roughening, V-grooves or dark coatings with some sacrifice of emittance values.
- E. May be operated as cool surface if backside emittance is possible.

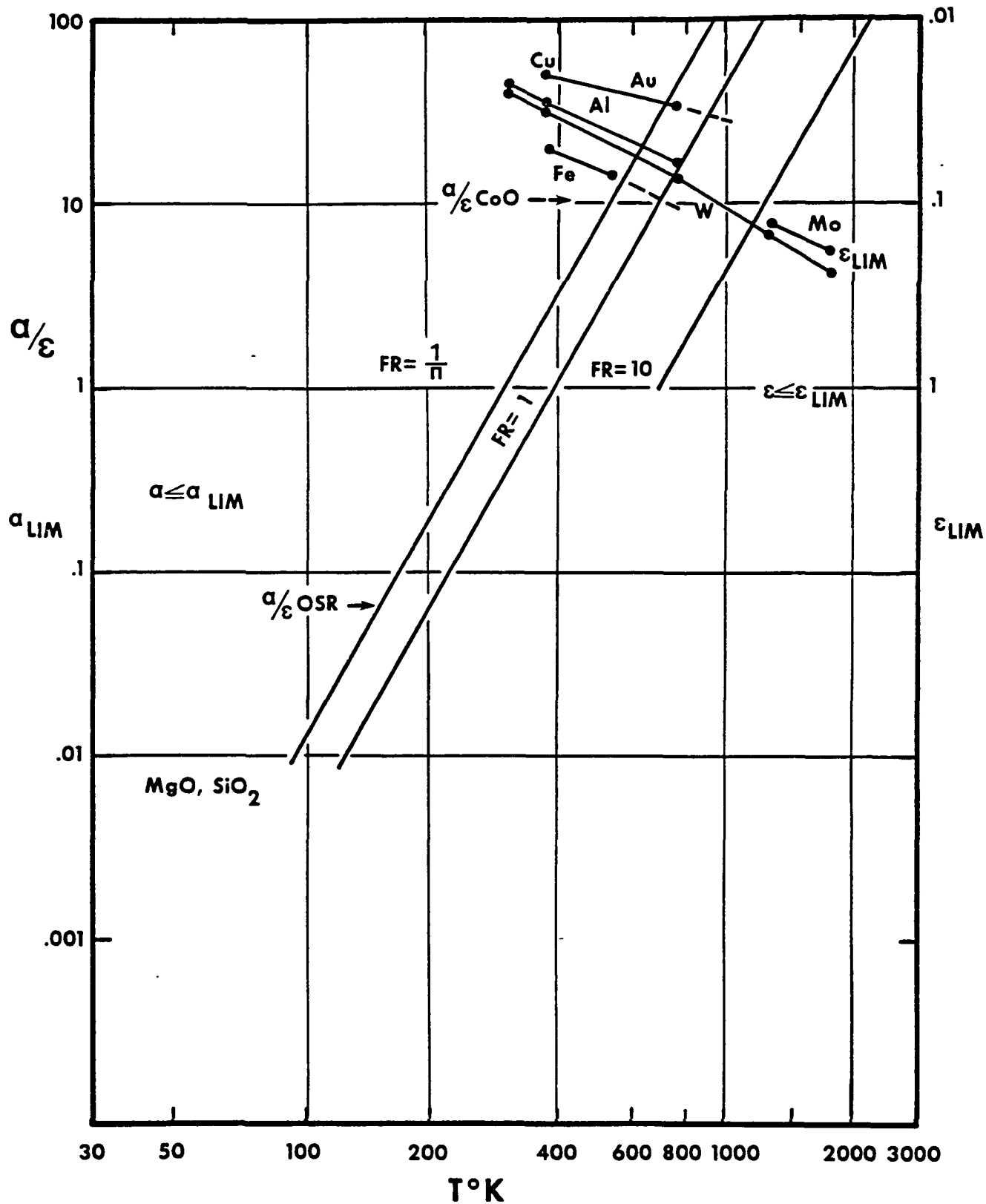


Figure 1

Chapter VIII

WORKSHOPS ON "GLASS AND CERAMICS" AND "ELECTROCHEMISTRY"
AND THE PROCESSING OF LUNAR MATERIALSIntroduction

Considerable research has been conducted on the feasibility of obtaining industrial feedstocks on the moon and in space from lunar materials (1,2,3). Extensive engineering design (4) and system studies (5) have been conducted on the feasibility of constructing major fractions of a satellite solar power station from components derived from lunar material following the original suggestions for using lunar materials industrially (6,7). These studies indicate that 90 to 95% of a spacepower satellite (SPS) could be derived from lunar materials and that the total program costs and duration might be competitive with SPS launched from earth and assembled in space. General advantages of the approach include: A reduction in the scale of earth-launch operations; opportunities to obtain raw and feedstock materials at significantly lower costs than from earth; less simultaneous or mutual constraints on the various systems design features of the SPS; and the possibility of creating production facilities in large part from the lunar materials. These and other aspects of space manufacturing using lunar materials have been reported in several recent conferences (8,9). A historical review of the prospects and motivations for using extraterrestrial resources is included in preprint form in this report (10,11,14).

More than 10,000 work years of research have been devoted to the analyses of samples returned from the moon and the geophysical data acquired during the Apollo lunar program. Well in excess of 150,000 pages of scientific research has been published in the ten years since the lunar landings began in 1969. Extensive indexing and cross-reference aids are available to access this

material (12,13). Such extensive research, the availability of limited quantities of lunar materials for testing of key processes, and the general healthy growth in the sophistication of materials sciences and industry in the last ten years combine to suggest that it is possible to use lunar materials industrially on our next return to the moon. It has been specifically suggested that we can return to the moon with machines which can process lunar soils. There appears to be adequate knowledge of lunar samples and it seems that sufficient flexibility can be engineered into small production processes to allow this direct approach for most systems.

In order to subject the concepts of lunar materials processing to critical examinations by a range of knowledgeable and critical audiences, it was decided to organize two workshops at the Lunar and Planetary Institute which would bring materials scientists into the discussions. It has been clear for several years that lunar materials would be useful in the production of glass and ceramic products either from the native components or derived fractions such as silicon (Si) and silica (SiO_2) or alumina (Al_2O_3). Therefore, one workshop entitled "Glass and Ceramic Industries in Space Based on Lunar Materials," was organized in cooperation with Prof. J. D. Mackenzie of the Materials Science Department of University of California at Los Angeles. The meeting was held 16-18 April 1979 at the Lunar and Planetary Institute.

Lunar materials can be the source of the major (>1%) elemental constituents of the lunar soil which are O, Si, Al, Fe, Ca, Ti and Mg as well as minor elements (0.1 - 1%) such as Cr, Mn, Na, K, S and P and a few trace elements (H, He, C, N, etc.). Due to the constraints of the lunar environment and space operations in general, it is highly desirable to use chemical processing systems which very effectively conserve and recycle the process or working fluids, especially any that must be supplied from earth. The systems should use either

solar heat or solar electric power as the major consumable in processing. For these reasons there is a strong motivation to consider electrochemical systems. The second workshop entitled "Electrochemistry Applied to the Processing of Lunar Materials," was co-sponsored by the Lunar and Planetary Institute and the Industrial Electrolytics Division of the Electrochemical Society. Prof. J. R. Selman (Department of Chemical Engineering at the Illinois Institute of Technology) was the co-organizer. This meeting was held 12-13 September 1979 at the Institute (Table 2). Approximately sixty individuals attended the two workshops. Of these, twenty had no previous experience with lunar sample research but were involved in research on materials properties or production. Approximately ten of the attendees had worked with lunar samples and had some or extensive experience in applied materials research or development in industrial organizations or academia.

In addition to the technical discussions, one afternoon of the Glass and Ceramics Workshop was devoted to two presentations on the development of legal frameworks relevant to industrial practices in space and on the moon and access to lunar materials and control of lunar based facilities. A very extensive discussion followed.

Tables I and II are the agendas of the two meetings. A set of abstracts submitted prior to the meetings is included. We attempted to balance the meetings between tutorial lectures on lunar materials, presentations on materials processing and discussion periods. Many qualitative recommendations were evolved from these discussions relating to possible products and procedures appropriate to lunar materials, areas of lunar or materials science requiring further investigations and intuitions as to approaches toward the development of lunar and space industries. Many of these qualitative products are summarized in the next section. Following that is a discussion of the bootstrapping of a

lunar glass plant by using lunar materials to make major components of the first plant.

Qualitative Recommendations and Observations Related to Glasses and Ceramics

- Glasses, ceramics and cast basalts can be made out of bulk lunar soils and mineral fractions.
- Properties and production schemes for such products could be established by synthetic terrestrial experiments which could start immediately and would explore a new applications area of glass formation.
- Possible native products could include solar cell backings, tiles, blocks, pipes, electric insulators, thermal insulators, glass fibers, building materials, glass ropes, transparent glass sheets (from anorthosite), containers, foamed glass with reinforcing internal tension members (for low strength beams and girders) mirrors, woven fiber sheets and bulk objects (i.e., hydrocyclones).
- Structures for habitats, launch support facilities, processing and others may be melted directly into the lunar soil using high temperature probes heated by direct solar energy or solar derived electricity.
- It may be possible to manufacture a wide range of products from chemical derivatives of the bulk soil. These include refractories (Al_2O_3 , MgO , TiO_2 , spinels, CaO , etc.); non-oxide refractory or hard materials such as Ti_5Si_3 and chromium silicides; electric and magnetic ceramics such as TiO , Fe_3O_4 or magnetoplumbites; cermets -- especially those with iron-based metallic phases; and heat shields for aerodynamic braking.
- Very clear research needs exist: There should be systematic surveys of

the glass and ceramic forming properties of the lunar minerals and combinations of these minerals with derived oxides and elements in terrestrial experiments; attention must be given to the formation, and production properties of these melts under vacuum and in early shuttle experiments under zero gravity and 1/6th gravity; specific attention must be given to techniques for cooling of the glass products during formation in vacuum and low or zero-gravity.

- Development of sintered materials may be a more difficult challenge than glass, ceramic or casting production and may require the use of pristine lunar materials in the production phases.
- It is a reasonable possibility to make early use of lunar materials on the moon or in space to build a large fraction by mass of the components of a glass manufacturing facility. This approach is referred to as bootstrapping.
- It is likely that many products will require controlled fractions of various raw lunar minerals. The ability to monitor and control the flow of input minerals will be required. Control of the mineral separates will likely require dry processes which can work in a vacuum such as magnetic, electrostatic, sieving or other mechanical techniques. This portion of the processing will benefit from experiments and operations on the moon. However, qualitative and semiquantitative measurements are possible for several separation techniques with lunar samples returned to earth.

Production of Native Iron

- A small fraction of metallic iron can be separated from the lunar soil ~ (0.1% by weight) by low energy and relatively low mass magnetic separation

devices. This iron can provide early general uses in mechanical, electric and magnetic functions.

- Major fractions of magnetic separation systems can be produced primarily from lunar iron, glasses and ceramics.
- For many applications the recovered iron may need to be melted to separate it from small fractions of entrained glass. For some uses the iron may need to be electrorefined or alloyed with terrestrial materials.

Bootstrapping a Glass Factory on the Lunar Surface

In order to force the exploration of the application of glass and ceramic technologies to the production of useful products on the moon, it was decided to qualitatively and semi-quantitatively investigate what would be involved in constructing major portions of a solar power satellite from lunar materials. The 1979 study by General Dynamics (5) offered a take-off point in the selection of possible products. The study pointed out that approximately 90% of a SPS could be produced from native or derived lunar materials by either simple substitution or by functional replacements for components of the terrestrial baseline design. An SPS capable of producing 10 GW of power output on earth and constructed out of lunar materials would have a mass of approximately 112,000 metric tons.

In the report it was estimated that the order of 38,800 tons of components could be produced directly from native materials, that is whole soil or mineral fractions of the various native soils. These components would be produced by melting the lunar materials and processing them into the desired forms. Most of the support structure of the SPS could be made from 27,300 tons of foamed glass beams which would be reinforced by fiberglass threads inside the foam beams. These beams were to replace graphite-epoxy beams formed in space from

terrestrially supplied feedstocks. It was determined at the meeting that the foamed glass structures were in fact worth considering, but that the method of reinforcing the trusses against tension forces would not work because of the brittleness between the foamed glass and the fiberglass stringers. An alternate method of providing tensional strength was proposed. Hollow foamed glass beams would be made. The beams could be fitted with glass plates on each end which would serve to attach one beam to the next. Fiberglass ribbons would be strung down the center of the hollow beam and connected to the glass plates at each end. In this way there would be no brittle connection between the foamed glass trusses and the reinforcing members. The internal ribbons or strings could be tensioned optimally for the maximum expected tensional loads and be reasonably independent of the compressive loads the beam has to bear. In addition to the primary beams which would be tens of meters in length there would be smaller secondary structures or tubes the order of 50 cm long with 1 cm thick walls which would account for 2,100 tons of production.

Hollow wave guides could be a major fraction of the microwave transmission system of an SPS. These can be made by extruding foamed glass into suitable forms. Approximately 8,600 tons of glass would be required. Another 800 tons of glass fibers would be used in various structural functions in the SPS. In the General Dynamics report it was assumed that 300 tons of sodium sulfate and carbon would be used in the glass forming operations and would be supplied from earth for foaming agents in production of foamed glass. It was anticipated that approximately 850 tons of equipment would be required to fabricate the foamed glass structures and fibers just mentioned. As will be discussed presently it was concluded that no qualitatively major problems were apparent which would block the construction on the moon of these items. It was generally agreed that production in space would be more uncertain than on the moon, unless

pseudogravity was provided or an appropriate research and development program begun in Spacelab on zero-gravity production.

Less certainty existed concerning the production of two other components of the SPS photoconversion system -- the extremely thin cover slips ($75 \cdot 10^{-4}$ cm thick) out of silica (SiO_2 - a refined product) and the substrates ($50 \cdot 10^{-4}$ cm thick) out of anorthosite. It was felt that there would be no major challenge in fabricating thicker substrates on the order of ten times the thickness suggested by the General Dynamics study. The challenge was seen to be of a mechanical nature rather than a fundamental problem with a restriction on the glass. The substrates would have a total mass the order of 16,000 tons for the very small thickness recommended in the General Dynamics report. Production of the thin cover slips was considered a considerably more challenging task. Not only are extremely thin coverslips needed, but there is also a problem concerned with adjusting the chemistry of the glass to reduce the creation of color centers due to radiation exposure and thereby darkening of the glass over the life of the SPS. The problem of chemistry was considered manageable. Approximately 24,000 tons of cover slips would be required.

For the above reasons it was decided to size a glass production facility on the moon which could produce the molten products from native materials to satisfy the foamed glass components and the fiberglass production needs, but not address the equipment needed for production of cover slips or substrates for the solar cells of an SPS. General characteristics of a very conservatively designed terrestrial equivalent plant are discussed and then the transition to a lunar installation is explored. Figure 1 illustrates the five major components which would be necessary in a terrestrial plant intended to process a lunar like soil with a fraction of mechanically "free" iron. The melt tank which would be approximately 33 meters long by 7 meters deep and 3 meters wide. A tank of the

suggested size would be capable of processing approximately 100 tons per day of materials or approximately 37,000 tons per year. It would have alumina (Al_2O_3) walls approximately 0.66 meters thick and would have a total mass of 1,800 metric tons exclusive of surrounding insulation. At a shipping rate early in a space manufacturing program of 2,000\$/Kg or 2×10^6 \$/ton. This would imply a shipping cost of 3.6 B\$ ($B=10^9$). Thus, it is worth considering the construction of at least the melt tank out of the native lunar materials. Naturally, if one tank can be built then so can others and other components.

An alternate way exists to estimate the total mass of a glass plant. Mackenzie noted that a large glass plant has a specific cost on the order of 0.2\$/pound or about 0.5\$/kg. Estimates, rather generous, were made of the costs of the major components of a terrestrial plant as shown in Fig. 1: (1) Physical separation units using magnets -- 2 M\$ ($M=10^6$); (2) glass tank for 100 tons/day - 5 M\$; and (4) spinning, weaving and glass rope production - 5 M\$. These total to 32 M\$. Using 0.5\$/kg or 500\$/ton yields a total plant mass the order of 64,000 tons. Thus, the entire plant mass would be at most 30 to 40 times the mass of the melt tank. Transport of 64,000 tons from earth would be prohibitive at a total cost the order of 128 B\$. Even if the plant was not installed until transportation rates had dropped to the order of 100\$/kg or 10^5 \$/ton transport costs would still be approximately 6 to 7 B\$. Naturally, terrestrial plants are not designed for minimum mass. It was considered that the technology necessary to build the glass plant would be far less demanding than required for the space shuttle. Thus, an alternative approach was suggested and explored. The components of the glass plant would be separated into three categories: components that could not be shipped such as the melt tank; components which one need not ship because they could be readily produced on the moon; and components which must be shipped either because they could not be produced on

the moon or because they are sufficiently low mass that it is not worth the trouble of building them on the moon from local materials.

Table III lists the components which must be shipped from earth. The chemical plant is a simplified version of the one described in previous work (1,14) in that the primary product is Al_2O_3 to be used in the manufacturing of the refractory wall for the melt pit. This unit, including a 5 megawatt solar electric power supply, is estimated to have a mass of 50 tons and require at most ten people to operate. It could produce 1000 tons of alumina in one hundred days of operation. Items 2., 3., 4., 6., 7., and 8. are required for the continuous operation of the glass plant in the full production phase and should not require replacement in the first few years of operation. The volatile separator (Item 8.) will produce approximately 300 to 400 tons of volatiles a year and will be a source of oxygen, hydrogen, helium, sulfur, carbon and some volatile metals which are present on the surfaces of lunar soil grains and are released by melting. Solar energy would be used to preheat the soil and provide 90% of the melting energy. Electric heating would be provided in the melt tank for the other 10% of the heat energy, to maintain the molten materials over night and to have precision control of the heating. We note that glass production from lunar soil has also been considered by Ho and Sobon (Chapter V-2, Ref. 3).

Build-up of the facility was not studied in detail. However, it was felt that lunar iron and ceramic products could be used to construct most of the other components of the glass plant. The lunar iron would be extracted from local soil by a 2 ton magnetic separation unit, refined for electrical uses in a subloop of the chemical processing plant, and then provided as bar stock to the machine shop. The machine shop is envisioned as a manned operation in which maximum use is made of numerically controlled machines and presently available

industrial robots. It would be housed in a structure approximately the size of the hydrogen fuel tank of the space shuttle main tank (31 meters long by 8.5 meters in diameter). This shop would produce all possible hardware components of the glass plant from lunar materials. The objective is to fabricate and build the glass plant in one year from touchdown on the moon. Habitats for the crew of forty would require approximately 350 tons, including consumables (3). It should be noted that the glass production facilities can be increased in succeeding years by the import of approximately 100 tons of new supplies and components for every 37,000 tons/year of output capacity. Thus, we are considering an investment in capacity manufacturing rather than simply a fixed output capacity.

It is very difficult to accurately estimate the costs of developing and installing the initial plant. However, if we take the total development costs per ton of the glass related items (150 tons) as being one-third the cost per unit mass for developing the space shuttle (i.e., 20,000 \$/kg or 20 M\$/ton) then development is about 3 B\$. Using shuttle technology and a chemical stage for earth-orbit to moon transportation for a total transportation rate of 2,000 \$/kg or 2 M\$/ton the deployment of the 500 ton base would require 1 B\$. This gives a total investment of 4 B\$ for an installation which would yield approximately 37,000 tons per year of components over a thirty-year life time. Ignoring operating expenses this corresponds to about 4 \$/kg for the costs of the lunar glass products. Parallel plants could be built for considerably smaller costs than the first unit.

Several points are worth discussing concerning the operation and build-up of the plant. Refer to Fig. 1. In full operation the plant is provided with approximately 500 tons/day (23 tons/hour at 90% utilization) of raw lunar soil. This soil is dumped onto a conveyor belt and passes under a second conveyor

which runs just under a large permanent magnet. Iron and glass with significant fractions of embedded iron will be extracted from the non-magnetic glass and attracted to the upper conveyor. This stream of iron and iron enriched glass will constitute 0.1 to 0.5% of the input stream or approximately 0.5 tons/day. The iron rich stream is dumped into a small melting chamber where the chemically free iron gradually sinks to the bottom and is tapped off. This iron migration is aided by the application of a direct current electrical bias from the top to the bottom of the tank. In addition, the melt is very slightly electrolyzed to release oxygen at the positive electrode and increase the FeO content in the melt. Molten slag depleted in free iron but rich in chemically combined iron can be tapped out of the mid-section of the small melt pit. This slag can be used in making fiberglass or other products in which a dark brown or black color is acceptable.

The iron free stream of soil can be further beneficiated or combined with other soil fractions to yield a final feedstock for the large melt tank. Only 1/5 or 100 tons/day of the input stream is finally introduced into the large melt pit. It may well be that the major portion of the beneficiation is done at the excavation site of the soil so as to minimize haulage of the soil from a pit to the processing center. Glass in the large pit can be clear glass, possibly predominantly anorthositic in composition. There are two major output streams. An alternating current is used to electrolyze a small portion of the melt and evolve oxygen off the two electrodes shown. The oxygen evolved on the right hand side of the pit in the extraction pipe functions to produce foamed glass. In this manner there is no need to bring a foaming agent from earth. A considerable savings (0.6 B\$) for SPS is possible by eliminating the costs of providing 300 tons of foaming agents from earth. Glass for fibers and ropes and other uses is extracted from the bottom tap of the large melt pit.

Bootstrapping or the use of local materials to build-up significant portions of a manufacturing unit, can be used at virtually all steps in this approach. For example, the first magnet system used in beneficiation is proposed to have a mass the order of 2 tons. Very conservative estimates are available indicating that such a magnet could process the order of 2 tons/hour of input feedstock or nominally output 0.002 tons/hour of lunar iron. Thus, 1000 hours of operation would be required to acquire the iron to make another magnet. Only 500 hours would then be required for the two systems to obtain the iron for a third system and then 336 hours for the fourth and so on. A total time of 121 days would be required to acquire the iron for 11.5 magnetic separation units which could adequately service the glass plant. We do not include the time to refine the iron and make it into magnet systems. We intend simply to illustrate how the exponential growth can permit an initial small facility to create much larger production over a small period of time. In point of fact the magnetic separation may be much more capital efficient. It may be that a 2 ton magnet can handle 20 tons/hour of lunar materials. Experiments on lunar soils on earth could resolve this order of magnitude efficiency.

Abstracts and Papers of the Glass and Ceramic Workshop

Following are a set of selected abstracts submitted to the Glass and Ceramic Workshop prior to the meeting. Several abstracts relevant to the meeting appear in Lunar Utilization (publication of the Lunar and Planetary Institute, 1975). The draft of one paper (E. Roedder) to be published as a set of papers in the open literature is included for completeness.

The Workshop -- "Electrochemistry Applied to the Processing of Lunar Materials"

Clever use of bulk lunar soils and glass and ceramic products made from the

whole soil and various mineral fractions can provide a wide range of devices and structures to support the construction of industry on the moon and in space. However, it is completely clear that a much wider range of products become possible as the major (O, Si, Al, Ca, Ti, Fe, Mg) elements, oxides and minor and trace elements (especially H, C, N) are made available from the lunar soils and rocks. Members of the Industrial Electolytics Division of the Electrochemical Society (Headquarters - Princeton, NJ) provided considerable assistance in the organization and operation of the workshop (schedule in Section A) which was intended to provide an evaluation by several independent experts in industrial chemistry of the general feasibility of processing lunar materials for the major, minor, trace, and oxide components under the severe economic constraints of processing in the lunar and space environments. In addition, we expected to acquire evaluations of the previous work done at the Lunar and Planetary Institute on chemical processing of lunar ores and to reveal other approaches toward chemical processing. There was no attempt to develop a conceptual outline of a chemical plant on the moon as was done for the Glass and Ceramic Workshop. There are too many specific trade-offs which must be considered in the chemical processing approach that conceptual design of even a general example plant would not be possible in the available time. Thus, the talks were focused on educating the attendees to the lunar source materials and the lunar and space environment and to presentations on a range of operating systems applicable to the lunar conditions.

However, several broad and specific understandings were arrived at during the meeting and in subsequent discussions between members. These are summarized in the following section. Where appropriate, the relevant research needs are sketched. Following this summary are the abstracts prepared before the meeting and three papers which have been submitted for publication as part of a set on

processing of lunar materials.

Broad Points of Consensus

- Chemical processing of lunar materials in the lunar environment is a reasonable challenge within the present state-of-the-art of chemical engineering. Many general and specific options can be identified and research efforts can be started immediately to confirm the relative merits and in some approaches the technical feasibility of the various approaches to lunar processing.
- There is a significant degree of overlap between the technology which must be demonstrated to process the siliceous lunar materials and that which will be required on earth by the turn of the century to process low grade common ores in ways which are energy efficient and generate very little pollution. Thus, development of lunar chemical processing technologies will sharply advance the research base and many development aspects of the processing technologies needed on earth by the turn of the century.
- There is adequate information on the lunar soils and sufficient understanding of the physical bases of chemical engineering techniques that systems can be designed and tested on earth for lunar operations and then can be transported to the moon for immediate use. It may be necessary in some cases to select and process particular fractions of the lunar soils in order to provide uniform feedstock. Processing plants for operation in space would require either pseudogravity or extensive research and development in early Spacelab flights for processing functions sensitive to the lack of gravity.
- It is appropriate at this time to begin preliminary economic and engineering

feasibility studies of various processing systems based on chemical and electrochemical processing approaches. It should be possible to assess the overall cost effectiveness of lunar materials utilization versus the lift of materials from earth.

Technical Points of Consensus

- One proposed approach toward processing of the bulk lunar soils, the HF acid leach process, was not analyzed in detail at the workshop. However, no fundamental or important practical barriers to this route were brought forward. Several new processes were discussed which utilize related approaches. In particular, the HF acid leach process has been demonstrated to lend itself to the production of very high purity silicon which can be used directly in the production of solar cells and of aluminum and titanium by subsequent sodium reduction steps.

- There are three classes of electrochemical approaches which should be considered for lunar processing:
 - A. Direct electrolysis of lunar soil or beneficiated fractions.

 - B. Electrolysis of lunar soil fractions dissolved in fused salt (fluoride, chloride or carbonate) solvents.

 - C. Electrolysis of sodium hydroxide (or chloride) followed by indirect reduction of aluminum, silicon and other desired constituents as in a proposed flow sheet.

- Technical problems requiring additional research and development in the application of these approaches include:
 - A. 1. Solving anode corrosion problem.

2. Operating with higher viscosity melts and successfully recovering oxygen.
 3. Developing secondary refining methods to separate constituents from alloys obtained.
- B.
1. Purification and recycling fused salt solvents.
 2. Developing secondary refining methods for alloys.
 3. Avoiding carbon formation in reduction of carbonate melts.
 4. Development of bipolar cells (if needed).
 5. Attrition of reagents.
- C.
1. Effectiveness of proposed drying cycle for modified Castner cells used in the recovery of sodium in various recycle loops.
 2. Indirect recovery of oxygen with chlorine formed if Downs cell sodium route is chosen.

The total research and development effort (time and money) to develop these methods decreases from A. to C. The relative advantages of these options (if fully developed) will require additional studies.

-- Electrodialysis may be a useful technique in various stages of aqueous processing of lunar materials. Extension to nonaqueous solvents would require additional research and development, especially to higher temperature systems.

Specific Research Topics for Processing of Lunar Materials and Low Grade Terrestrial Ores

- Demonstrate with simulated lunar soils on the bench-scale level the HF acid leach, ammonium salt fusion and mixed acid leaching based on adaptations of well known terrestrial industrial and laboratory procedures for extracting the major oxides and elements (O, Si, Al, Mg, Ti, Ca, Fe) from a wide range of bulk lunar soils. Rates of throughputs, recycle efficiencies, and separability data will be determined in these demonstration experiments. Implications of reagent make-up from native lunar materials will be determined.
- Literature studies should be conducted of methods to recover minor and trace element fractions obtainable from immiscible liquid extraction of magmas (molten fluids) such as would occur in glass production.
- Investigate chemical processing by hydrochemical leaching or dissolution processes based on acid fluoride systems in which recycle recovery of acid and fluoride values approaches or exceeds 90% of input equivalents.

Topics: Comparison of excess fluoride vs. fluoride deficient processes.

Use of mixed acid HF-HCl, HF-H₂SO₃, and HF-H₂SiF₆ systems. Use of NH₄FHF salt fusion methods, etc.

- Investigate application of acid fluoride dissolution processes to sodium reduction or electrochemical reduction of silicon, aluminum, titanium and other metal fluorides.
- Investigate electrochemical processing by direct high temperature electrolysis of silicates or other semirefractory source materials, either as molten systems or dissolved in high temperature fused salt systems such

as fluorides or carbonates.

Topics: A. Science -- Solubility and immiscibility limits in specific systems. Distribution coefficients between magmatic and fused salt phases where liquid immiscibility exists. Potentiometric studies of specific elements in molten, fluoride and carbonate systems.

B. Engineering -- Preliminary economic and engineering feasibility studies. Cell materials compatibility studies for magmatic, fluoride and carbonate systems, including container and anode materials.

- Investigate the limits of chemical recycling in the alternative methods of salt splitting or recycling acid and fluoride values.

Topics: Pyrolysis of NH_4F . Conversion of meal fluorides to compounds more readily pyrolyzed -- sulfites, formates, oxalates, etc. Conversion to hydroxides with NH_3 . Conversion of NaF (from sodium reduction) to Na , HF and O_2 via NaOH and Castner cell, or from fused fluorides using consumable anodes.

- Survey the large scale low grade-terrestrial mineral sources to identify candidates for general technology areas covered by processing and probable price/profitability parameters. Establishment of kg scale electrochemical feasibility tests for molten silicate and fused salt (fluoride and carbonate) systems.

-- Carefully survey the lunar literature for data on the sources of minor and trace elements as to concentrations in various grain sizes and mineralogical and vitreous fractions, possible surface and subsurface source regions and

experiments by which concentrations or enhancements of these elements could be located from lunar orbit in a general survey of the moon.

Abstracts and Preliminary Reports of the Electrochemistry Workshop

The abstracts prepared prior to the Electrochemistry Workshop are presented in this chapter. Papers prepared for publication as a set in a suitable open journal constitute the last portion of Chapter VIII. We anticipate that selected papers from the Glass and Ceramic Workshop and the Electrochemistry Workshop will be published as a group with introductory articles which relate lunar processing to the broader goals of creating a materials industry in space and to the collection of solar power in space for retransmission to earth users.

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9. Grey J. (editor) "Space Manufacturing Facilities -- Space Colonies," American Institute of Aeronautics and Astronautics, New York, 1977.

10. Criswell D. R. and Waldron, R. D., "Chemical Processing of Lunar Materials," Paper No. 79-116, XXXth Congress of the International Aeronautical Federation, 16-22 September 1979, Munich, Germany, 1980.
11. Criswell D. R. and Waldron, R. D. (see preprint section), 1980.
12. Proceedings of the Annual Lunar and Planetary Science Conferences, Set 1 (1970) through Set 10 (1979), Pergamon Press.
13. Lunar and Planetary Institute, Computer Bibliography Aid for Access the Lunar and Planetary Literature by Subject, Key Words and Authors. Contact the library of the LPI.
14. Criswell D. R. (Principal Investigator) Extraterrestrial Materials Processing and Construction, Lunar and Planetary Institute, NSR 09-051-001, Mod. No. 24, 1978.
15. Refer to the abstracts in this section.

LUNAR GLASS AND CERAMIC WORKSHOP SCHEDULE 16 - 19 April 1979

Monday (16th)	Tuesday (17th)	Wednesday (18th)	Thursday (19th)
<p>9:00 AM WELCOME TO LPI (Berkner Room) D. R. Criswell (LPI)</p> <p>9:05 Workshop Objectives and Organization J. D. Mackenzie (UCLA)</p> <p>9:30 Space Industrialization Based on Lunar Materials D. R. Criswell (LPI)</p> <p>10:00 Lunar Melt Glasses R. Schaal (Lockheed/JSC)</p> <p>10:15 Electrolytically Altered Melt Compositions D. Lindstrom (Washington Univ.)</p> <p>10:45 Coffee Break</p> <p>11:00 Magnetic Beneficiation D. Kelland (MIT)</p> <p>11:20 Semirefined Feedstocks and Products R. D. Waldron (LPI)</p> <p>11:40 Discussion</p>	<p>8:35 AM Lunar Source Materials D. S. McKay (JSC)</p> <p>9:05 Workshop Session</p>	<p>8:30 AM Workshop Sessions</p>	<p>8:30 AM Reports and Final Inputs</p>
12:00 - 2:00 PM LUNCH	12:00 - 2:00 LUNCH	12:00 - 2:00 LUNCH	11:00 - 1:00 PM LUNCH
<p>2:00 PM Lunar Scientist's Thoughts on Possible Products E. Roedder (USGS-Reston)</p> <p>2:20 Sol-Gel Process S. P. Mukherjee (Battelle-Columbus)</p> <p>2:40 Lunar Sintering C. H. Simonds (Northrop Corporation)</p> <p>3:00 Melted Soil Structures J. W. Neudecker (Los Alamos Scientific Laboratory)</p> <p>3:40 Coffee Break</p> <p>4:10 Workshop Teams Sessions</p>	<p>2:00 PM Workshop Teams Sessions</p> <p>* Contributed Papers Welcome</p> <p>3:30 Space Shuttle Era Dr. Don Lind Astronaut (JSC)</p>	<p>LEGAL SESSION</p> <p>2:00 PM Space Law and Private Enterprise A. Dula</p> <p>2:30 International Aspects L. Berlin</p> <p>3:00</p> <p>4:00 Workshop Session</p>	<p>1:00 - 3:30 PM Special Tour of the Johnson Space Center</p>
6:00 - 7:30 PM Social at the Lunar and Planetary Institute	6:00 PM Open Evening	6:00 PM Open Evening	

Table Ia

Table Ib

SPEAKERS* AND ATTENDEES

- F. L. Baiamonte (space power generation)
Johnson Space Center (JSC)
Houston, TX
- * L. Berlin (space law)
Los Angeles, CA
- D. P. Blanchard (lunar sample research)
JSC
- N. J. de Vries (artist)
UH/CLC
Houston, TX
- † * D. R. Criswell (space industries)
Lunar and Planetary Institute (LPI)
Houston, TX
- M. B. Duke (lunar sample research) JSC
- * A. M. Dula (patent and space law)
Butler, Binion, Rice, Cook and Knapp
Houston, TX
- T. E. Erstfeld (chemical engineering)
Lockheed Co. (LH)
Houston, TX
- R. B. Ferguson (space power generation) JSC
- R. A. Happe (glass research/skylab)
Rockwell, Inc.
Downey, CA
- * D. Kelland (magnetic separations)
Massachusetts Inst. of Technology (MIT)
Cambridge, MA
- D. Lind (physicist/astronaut) (JSC)
- G. Lofgren (lunar sample research) JSC
- * D. S. McKay (lunar sample research) JSC
- † * J. D. Mackenzie (glass and ceramics research)
UCLA
- M. F. Matthews (patent counsel) JSC
- * S. P. Mukherjee (glass production
in space)
Battelle
Columbus, OH
- * J. C. Rowley (rock glass production)
Los Alamos Scientific Laboratory (LASL)
Los Alamos, NM
- R. Windland (civil engineer)
Houston, TX
- * E. Roedder (lunar sample research) USGS
- * R. Schaal (lunar sample research) LH
- * C. H. Simonds (lunar sample research)
Northrup Corporation
Houston, TX
- K. Sono (glass production)
Nippon Sheet Glass Co.
Clark, NJ
- * R. D. Waldron (chemical engineering) LPI
- J. Wildenthal (attorney)
Houston
- R. J. Williams (lunar sample research) JSC
- T. Williams (production automation)
Department of Engineering
Purdue University
Lafayette, IN
- *D. Lindstrom (lunar sample research)
Washington University
- R. Junker (controls and automation)
PPG
Pittsburg, PA
- M. Sakamoto (science writer)
Ashai Shimbun
Tokyo, Japan

* Speaker

† Co-organizer

ELECTROCHEMISTRY APPLIED TO THE PROCESSING OF LUNAR MATERIALS

12 - 13 September 1979
(14th Optional)

Lunar and Planetary Institute
3303 NASA Road 1
Houston, Texas 77058

SPONSORS	LUNAR & PLANETARY INSTITUTE	THE ELECTROCHEMICAL SOCIETY, INC.	JOHNSON SPACE CENTER
	Drs. David R. Criswell and R. D. Waldron 713-488-5200	Dr. J. R. Selman Illinois Institute of Technology Department of Chemical Engineering Chicago, Illinois 60616 312-567-3037	Dr. R. J. Williams Planetary & Earth Science Division Houston, Texas 77058

12 SEPTEMBER 1979 (WEDNESDAY)

- 9:00 a.m. WELCOME TO THE INSTITUTE
OVERVIEW OF SPACE INDUSTRIALIZATION & ROLE OF CHEMICAL ENGINEERING - *D. R. CRISWELL - LPI*
- 9:30 LUNAR SOURCE MATERIALS - *R. J. WILLIAMS - JOHNSON SPACE CENTER*
- 10:00 NASA RESEARCH AND DEVELOPMENT ON FLUID DYNAMICS PHENOMENA IN LOW AND ZERO GRAVITY
- ENGINEERING SIGNIFICANCE - *R. K. ALLGEIER - JOHNSON SPACE CENTER*
- 10:30 COFFEE BREAK
- 10:45 ELECTROCHEMISTRY EXPERIMENTS ON SYNTHETIC LUNAR SOILS - *D. LINDSTROM AND L. HASKIN - WASHINGTON UNIVERSITY*
- 11:10 GENERAL CONSIDERATIONS OF LUNAR AND SPACE PROCESSING - *R. D. WALDRON - LPI*
- 11:40 SPACE PROCESSING AND ELECTROCHEMISTRY - *J. R. SELMAN - ILLINOIS INSTITUTE OF TECHNOLOGY*
- 12:00 noon LUNCH
- 1:30 p.m. ELECTROCHEMICAL ENGINEERING AND SCALE UP OF EXTRATERRESTRIAL INDUSTRIAL PROCESSES -
T. R. BECK - ELECTROCHEMICAL TECHNOLOGY CORPORATION
- 2:00 FUSED SALT PROCESSING - *W. H. SMYRL - SANDIA LABORATORIES*
- 2:30 PREPARATION OF CELL FEED MATERIALS FOR ALUMINUM AND MAGNESIUM PRODUCTION -
J. A. BARCLAY - U. S. BUREAU OF MINES
- 3:00 COFFEE BREAK
- 3:15 ELECTROWINNING OF ORES - *S. K. DAS - ALCOA LABORATORIES*
- 4:15 MAGNESIUM REDUCTION AND FLUORIDE-BASED EXTRACTION PROCESSES - *L. VAALER - BATTELLE COLUMBUS LABORATORIES*
- 5:15 DISCUSSIONS AND ORGANIZATION OF WORKING GROUPS
- 6:00-7:00 SOCIAL AT LUNAR AND PLANETARY INSTITUTE

13 SEPTEMBER 1979 (THURSDAY)

- 8:00 a.m. COFFEE AND DONUTS
- 9:00 PRODUCTION OF SOLAR GRADE Si BY Na REDUCTIONS OF SILICON FLUORIDE COMPOUNDS - *A. SANJURJO SRI INTERNATIONAL*
- 9:30 CARBONATE BASED OXYGEN PRODUCTION - *J. R. SELMAN - ITT*
- 10:00 COFFEE BREAK
- 10:15 ELECTRODIALYSIS - *F. LEITZ - U. S. BUREAU OF RECLAMATION*
- 10:45 GROUP DISCUSSIONS
- 12:00 noon LUNCH
- 1:30 p.m. GROUP OBJECTIVES - SUMMARIES BY GROUP LEADERS
- 2:30 WORKING GROUPS
- 5:00 CONCLUSION

14 SEPTEMBER 1979 (FRIDAY)

- 8:30 a.m. WORKSHOP GROUP MEETING — FOR ANY PARTICIPANTS WHO CAN REMAIN IN THE AREA
- 12:00 noon LUNCH
- 1:30 p.m. TOUR OF SPACE SHUTTLE SIMULATORS AND FACILITIES AT THE JOHNSON SPACE CENTER

Table III
 COMPONENTS AND PEOPLE
 BROUGHT FROM EARTH TO MOON
 TO CONSTRUCT PLANT IN ONE YEAR

Item	Tonnage (Tons)	Personnel (Two Shifts)
1. Chemical Plant (Primarily Al_2O_3 Plant, Power Supply, and Fluids	50	10
2. Refractory Forming Equipment	10	} 20
3. Forming Equipment for Pipes, Blocks, etc.	5	
4. Forming Equipment for Glass Ropes	5	
5. Machine Shop	50	
6. Heating Equipment and Molybdenum Electrodes	24	8 (Materials handling and maintenance)
7. Control Equipment	2	
8. Volatile Separator	2	
9. Magnetic Separator		2
Direct Equipment	150	
10. Habitats	<u>350</u>	<u>2</u> (Supervisors)
TOTAL MASS	500	40 People

BUILD-UP OF 30,000 TONS/YR
PLANT FOR GLASS PRODUCTION

PRODUCTS — FOAMED GLASS, GLASS FIBERS, GLASS ROPE (COATED),
SUBSTRATE OR PLATE GLASS, OXYGEN AND IRON

PLANT SCHEMATIC

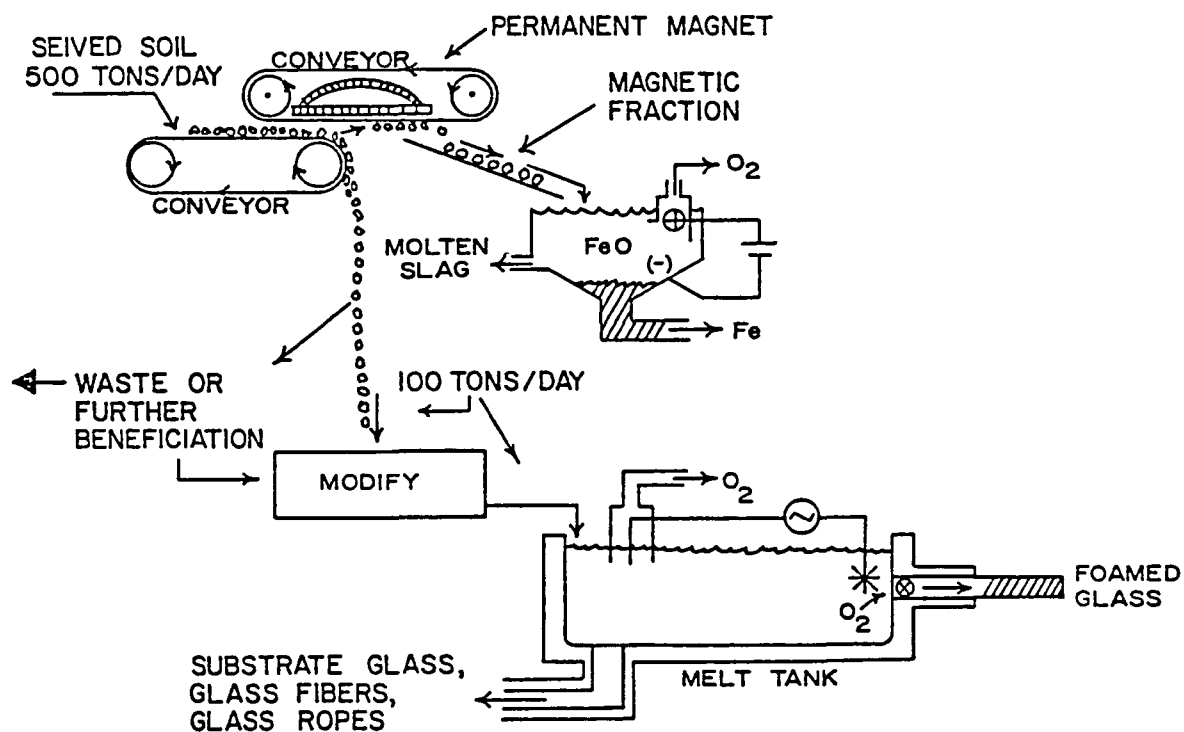


Figure 1. Schematic of a glass processing plant to be constructed on the lunar surface primarily from lunar materials. Major products of the plant would be foamed glass structures for a solar power satellite, glass plates and fibers. By-products of the operation of the plant would include iron and gases recovered during the first melting of the input lunar soil. Refer to the text for details.

GLASS AND CERAMICS WORKSHOP

Abstracts

PHYSICAL PHENOMENA IN CONTAINERLESS GLASS PROCESSING
(Experiment No. MPS77F010)

R. S. Subramanian and Robert Cole, Clarkson College,
Potsdam, NY 13676.

The purpose of this experiment is two-fold: (1) to develop novel techniques for mixing and fining glasses in a weightless environment and (2) to improve our understanding of the science of formation of hollow spherical shells with uniform wall thickness used in inertial confinement fusion.

The experiments using molten glasses and model fluids will be carried out in a special furnace which uses a three-axis acoustic positioning device to manipulate the samples and to prevent them from contacting the furnace walls. A spot-heater will be used to introduce a thermal gradient to investigate thermocapillary mixing and thermal migration of bubbles. The centering of a bubble in the sample will be investigated by various mechanisms such as successive rotation about the three axes.

Containerless processing of glasses in a weightless environment is a promising technological endeavor because problems of chemical reaction and nucleation at the container wall can be avoided. Also, without gravitational effects, a more detailed examination of bubble-centering mechanisms may be made than is possible on earth. The absence of gravitational forces may, on the other hand, adversely affect both the homogenization and fining (removal of gas bubbles) of the melt; therefore, it is necessary to consider alternate methods for accomplishing these operations in zero-g.

The types of glasses that may eventually be produced in space range from lanthanum and other rare earth oxide glasses with unique optical properties to high efficiency laser host glasses for high power lasers. Glass shell fuel containers with diameters in the range 1-5 mm and uniform wall thickness will eventually be needed for the inertial confinement program to develop fusion as a virtually inexhaustible energy source. Present earth-based technology has not succeeded in producing satisfactory shells in this size range, and the zero-g experiments are expected to help in improving the earth-based technology. It is anticipated that this project will provide fundamental information of potential value to glass processing in space and/or on earth.

REPORT ON INTERNATIONAL LAW FOR LUNAR MATERIALS
PROCESSING, OR WHO'S IN CHARGE OUT THERE?

Laurence M. Berlin,
Member Int'l Inst. of Space Law
Law Offices of Bruce J. Brothers
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Manhattan Beach, CA 90266
(213) 379-2489

Up to now, man's adventure in outer space has been preceded by international law comprehensive enough to encompass current technology. Nevertheless, rapidly increasing technological ability and the shift in emphasis from exploration to industrialization/utilization¹ threatens to put our activities in space beyond the scope of existing international law. Problems such as those caused by nuclear technology's development prior to applicable law, make the prospect of growing into the "space age" with insufficient legal guidance very frightening.

International cooperation in outer space activities began with the International Geophysical Year near the time the Soviets launched the first Sputnik. Although a sovereign state owns the air-space or atmosphere within its extended boundaries, no objections were made to Sputnik's orbit over sovereign territory. Thus, international "customs and usage" gave rise to the concept that states on earth have no sovereignty in outer space. In 1967 the United Nations General Assembly approved the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, the Moon and Other Celestial Bodies² (hereinafter the "Outer Space Treaty").

Over seventy nations have ratified the Outer Space Treaty. It serves as a constitution mandating the international community to conduct space activities in cooperation and harmony for the benefit of all countries.³ It is the most decisive step towards the establishment of a global legal regime for outer space and provides the principles upon which all other international space law is based. Other major instruments emanating from the United Nations included the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space;⁴ the Convention on International Liability for Damages Caused by Space Objects;⁵ and the Convention on Registration of Objects Launched into Outer Space.⁶

The international legal framework founded upon the Outer Space Treaty has been instrumental in realizing the full potential of the applications of space research and technology in the fields of meteorology, communications, remote sensing and navigation. Specialized organizations and international cooperative efforts, like the European Space Agency of the United Nations, INTELSAT, INTERSPUTNIK, INTERCOSMOS, AND INMARSAT, influence many such activities, but there is no such framework for international

REPORT ON INT'L LAW FOR LUNAR MATERIALS
PROCESSING, OR WHO'S IN CHARGE OUT THERE?
Berlin, L.M.

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cooperation in processing lunar materials.

Some of the relevant provisions of the treaties are described below:

The preambles of each recognize the "common interest of all mankind" and the belief that "the exploration and use of outer space should be carried on for the benefit of all peoples irrespective of the degree of their economic or scientific development."

The Outer Space Treaty:

Article II - "Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claims of sovereignty, by means of use or occupation, or by any other means."

Article VI - "Government agencies and nongovernmental entities carrying on space activities will be the responsibility of States Parties to the Treaty and will require their approval and continuing supervision."

Article IX - "Exploration of the moon and other celestial bodies shall be conducted so as to avoid harmful contamination in space and adverse changes in the environment on earth." This provision may call for reports akin to those required by the United States Environmental Protection Agency.

Article XI - "Those conducting activities in outer space have a duty to communicate to the international community the nature, conduct, location and results of such activity."

The Return and Rescue Treaty stresses that astronauts are "envoys of mankind" and are to be treated accordingly.

The Liability Treaty makes the launching states or entities absolutely liable for all damages caused by space objects on the surface of the earth or to aircraft in flight and liable according to fault for damages caused elsewhere. Thus, liability for damages caused between lunar operations will be determined according to fault.

The registration treaty provides for a centralized registry (with the United Nations Secretary General) for all objects (and significant components thereof) launched into orbit. It should also be applicable to operations established or built on the moon.⁷

The Draft Treaty Relating to the Moon,⁸ not yet in force, repeats the principle that space activities should be for the benefit and in the interest of all countries and adds that due regard must be paid to the interests of future generations and to promote better economic and social conditions globally.⁹ Samples of the lunar surface may be collected and removed for scientific purposes and in quantities appropriate for support of lunar missions.¹⁰ Additionally, State parties establishing a station may use only that area required for the needs of the station.¹¹

Thus, use of lunar materials to build the station would arguably be legal.

Perhaps the most provocative provisions of the Draft Moon Treaty appear in Article X:

"The natural resources of the moon [and other celestial bodies] shall be the common heritage of all mankind."¹²

No one may claim the surface or subsurface of the moon as their property.¹³ Lunar materials are not subject to "grant, exchange, transfer, sale or purchase, lease, hire, gift or any other arrangement or transaction with or without compensation ..."¹⁴ Finally, a meeting of all States parties is to be convened to negotiate arrangements for international sharing of the benefits at such time as "utilization" of the resources of the moon becomes feasible.¹⁵

It has been suggested that this language be intended to create an equal right in all nations to exploit the natural resources of the moon without discrimination. It is not clear whether this means equal access for all or mandatory sharing of benefits extracted.¹⁶ Furthermore, it has been suggested that the meeting to negotiate sharing of benefits should result in the establishment of a legal regime governing lunar activities.¹⁷

Obviously, it is essential that open lines of communication be maintained between the scientific/technological and legal communities. Lawyers cannot create workable frameworks for continued international cooperation in space unless they are up to date on the technological possibilities and probabilities. Important considerations include what activities are projected; what the likely results/benefits will be; projected costs; and suggestions regarding technological aspects of international sharing. Space lawyers would also be better able to serve if they are kept current on specific legal, social and political issues which scientists and technologists experience and foresee in the pursuit of lunar materials processing.

Footnotes:

- 1 President Carter's official press release re: his administration's current space policy.
- 2 United Nations General Assembly (U.N.G.A.) Res. 2222(XXI).
- 3 Outer Space Treaty, Article I.
- 4 U.N.G.A. Res. 2345 (XXII).
- 5 U.N.G.A. Res. 2777(XXIX).
- 6 U.N.G.A. Res. 3235 (XXIX).
- 7 Draft Moon Treaty, Article IV, ¶3.
- 8 1973 Report on the United Nations Committee on the Peaceful Uses of Outer Space, Appendix A.
- 9 Draft Moon Treaty, Article IV, ¶1.
- 10 Draft Moon Treaty, Article IV, ¶2.
- 11 Draft Moon Treaty, Article VIII, ¶1.
- 12 Draft Moon Treaty, Article X, ¶1.

REPORT ON INT'L LAW FOR LUNAR MATERIALS
PROCESSING, OR WHO'S IN CHARGE OUT THERE?
Berlin, L.M.

Footnotes cont.

- 13 Draft Moon Treaty, Article X, ¶2.
- 14 Draft Moon Treaty, Article X, ¶3.
- 15 Draft Moon Treaty, Article X, ¶4
- 16 1973 United Nations COPUOS, Legal sub-committee report.
- 17 1973 United Nations COPUOS, Legal sub-committee report.

THE LAW OF LUNAR RESOURCES AND DOING BUSINESS WITH NASA

Art Dula, Butler, Binion, Rice, Cook & Knapp
1100 Esperson Building, Houston, Texas 77002

- I. BRIEF HISTORY OF SPACE LAW
 - A. Defacto Space Law (1958 to 1967)
 - B. Treaty Law
 - 1. Treaty of Principles (1967)
 - 2. Rescue and Return Treaty (1968)
 - 3. International Liability Convention (1972)
 - 4. Registration Treaty (1976)
 - C. Future Trends (1979 to 2000)

- II. THE DRAFT LUNAR TREATY
 - A. History (1971 to date)
 - B. Ownership and Use of Lunar Resources
 - C. Other Provisions
 - D. How Can the Moon Treaty be Interpreted

- III. DOING BUSINESS WITH NASA
 - A. The National Aeronautics and Space Act of 1958
 - B. NASA's Treaty Obligations
 - C. NASA Regulations
 - D. Practical Business Problems
 - 1. Patent and Data Rights
 - 2. Indemnification of Shuttle Users
 - 3. The Draft "Shared Shuttle" Launch Agreement, A Brief Analysis
 - E. Some Suggestions for Business Planners

SIGNIFICANCE AND APPLICATIONS OF SOL-GEL PROCESSES IN GLASS
AND CERAMIC INDUSTRIES IN SPACE - SHYAMA P. MUKHERJEE

A processing route for the production of homogeneous glasses and glass-ceramics in space has been outlined. The concept is developed by combining Sol-Gel Process with High Temperature Solar Technology. An embryo of this concept exist in the work of Mukherjee et.al.,⁽¹⁾. On earth, they prepared highly homogeneous glasses by the fusion of multi-component gels in a solar furnace⁽¹⁾.

The significance and applications of Sol-Gel Processes in Glass and Ceramic Processing in space are discussed in terms of zero or microgravity phenomena such as:

- Absence of gravity induced convection
- Suppression of segregation due to density difference
- Weightlessness

The presence of gravity has a marked effect on many processes that involve the use of fluids. Buoyancy and thermal convection processes cause a physical redistribution of the components to be processed which can be either useful or harmful. A suspended mass, in absence of gravity, stays where it is put in a fluid medium. Consequently, in space inhomogeneities in liquids can take a long time to disappear under the influence of diffusion alone. Similarly, the initial uniformity of composition can be retained in absence of convective stirring.

The manufacture of homogeneous silicate glasses in space can not be achieved simply by applying the standard glass-melting technique using conventional raw materials. There exist two problems:

- Homogenization
- Refining

Homogenization is normally done on earth either by convective stirring (applied in industry) or by mechanical stirring which is applicable in laboratory scale. Since under microgravity or in absence of gravity, no buoyancy exists for gas bubbles developing during the melting process, refining is another problem.

Homogeneity of glasses or glass-ceramics is a very important requirement for their applications in many fields. Hence, the production of homogeneous glasses in space or at lunar surface is as important as it is on earth. Multicomponent, non-crystalline gel can be prepared by the sol-gel process, and this appears to be a promising starting material for melting glasses in the space environment.

The essential features of sol-gel processes for preparing multicomponent ceramic oxides and glasses have been described. Two methods of the preparation of glasses via gel route have been described^(1,2,3). Method I which is based on the gelation of colloidal silica/silicates containing other metal salt solutions has been suggested as a route for the processing of lunar materials. This method could be modified or developed on the basic principles of the colloid chemistry of concentrated silicate sols and hydrolysis of metal salts. Hence, it is suggested that suitable thermochemical treatment of lunar soils or materials could produce a homogeneous glass batch in "sol" state. Subsequently, sol can be converted to solid "gel" which on fusion or on sintering could be transformed into homogeneous glasses or glass-ceramics in space.

The high temperature solar furnace in the ceramic field has been used mostly in fundamental studies in the temperature range beyond 2000°C.

S. P. Mukherjee

However, the French work⁽⁴⁾ on the fusion of single component refractory oxides indicates that the solar furnace could be utilized for the fusion of ceramic oxides in kg. scale. The work of Mukherjee et.al.,⁽¹⁾ on the fusion of gels in $\text{SiO}_2 - \text{La}_2\text{O}_3$ system in a laboratory solar furnace indicates the suitability and advantages associated with the solar fusion of gels for glass or glass-ceramics preparation. The potential advantages of using solar furnace for materials processing in space are discussed.

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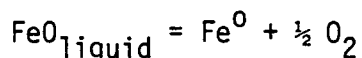
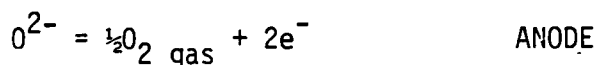
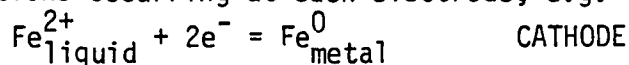
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DIRECT ELECTROLYSIS AS A MEANS OF ALTERING LUNAR MELT COMPOSITIONS

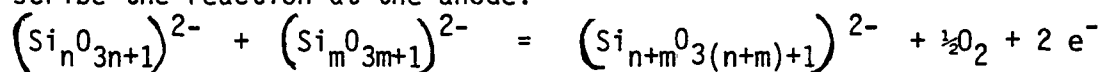
David J. Lindstrom and Larry A. Haskin, Dept. of Earth & Planetary Sciences and McDonnell Center for Space Sciences, Washington University, St. Louis, Missouri 63130.

Compositions of glasses and ceramics produced on Moon will be limited by the compositions of lunar soils and rocks available as raw materials and by the processes available for altering these compositions. Any process requiring industrial chemicals not readily available on Moon must be ruled out. Direct electrolysis is a particularly attractive process for altering compositions since it requires only heat and electricity, both of which are readily available from sunlight. We have initiated an exploratory study of electrolysis of silicate melts(1). The primary aim has been to see which metals can be obtained by this process.

The overall reaction can be thought of in terms of the sum of the half-reactions occurring at each electrode, e.g.



Since the species undergoing oxidation at the anode is unknown but yields oxygen gas, we have written it as simple oxide ion. It is unlikely to be free oxide ion, however, since O^{2-} is present in very small amounts in natural melts which approximate MSiO_3 stoichiometry and thus are highly polymerized(2). A general silicate polymerization reaction may better describe the reaction at the anode:



By analogy with aqueous and molten salt electrochemistry, an electrochemical series can in principle be constructed. Such a series can be thought of as the minimum electrical potential that must be applied in order to force a given reaction to occur under standard conditions. In theory, more readily reducible ions can be selectively plated out without affecting those ions requiring higher potentials.

Experiments were done using a small drop of silicate liquid supported on a platinum wire loop which serves as the anode (Fig.1). Potentials applied were of the order of 1-2 volts and currents ranged from 1-500 milliamperes. Preliminary experiments used a diopside composition (table 1) which had been previously shown (3-5) to be electrochemically well-behaved. Aliquants of this composition were separately doped with up to 5 wt. % Al_2O_3 , TiO_2 , FeO , Na_2O , and NiO and electrolyzed at 1425°C under varying furnace atmospheres. Materials formed by the electrolysis were analyzed by electron microprobe. No reduction of Na^+ or Al^{3+} was observed; in these charges, and when undoped diopside was electrolyzed, Si(IV) was reduced and a minimum-melting metallic liquid was formed. This liquid contained approximately 3.6 wt. % Si (about 21 mole % Si), the remainder being platinum. According to Berezhnoi (6) this minimum in the Pt-Si system occurs at 4.1 wt. % Si and 830°C . Formation of this liquid destroys the cathode and ends the experiment, so other cathode materials are being investigated. This reaction might be useful as a means of separating Si from other components, since oxidation of the Pt-Si alloy will result in SiO_2 and pure Pt.

DIRECT ELECTROLYSIS

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Electrolysis of Ni-doped diopside compositions led to quantitative removal of the Ni from the melt resulting in Pt-Ni alloys which electron microprobe analyses showed to contain up to 27 wt. % Ni. Pure Ni may have formed initially and later diffused into the Pt cathode, judging from the gradient of Pt concentration toward the center of the electrode.

Ti(IV) was reduced to Ti(III), as evidenced by the appearance of a purple color in the glass near the cathode. In reducing atmospheres, the platinum cathode was corroded and both the Si-Pt alloy described above and a Pt-Ti metal phase containing up to 5.5 wt. % Ti formed. This composition approximates Pt_4Ti .

The electrochemical behavior of iron is somewhat more complex owing to the presence of all three oxidation states, Fe^{3+} , Fe^{2+} , and Fe^0 . Iron-doped diopside melts are greenish brown when fused in air since under these conditions about 60% of the iron is present as Fe^{3+} (7), and light bluish green when melted near the iron/wustite buffer curve, under which conditions iron is dominantly Fe^{2+} . When electrolyzed in air, the liquid near the cathode becomes lighter in color, apparently due both to reduction of ferric to ferrous iron and to local depletion in total iron due to plating out of Fe metal on the electrode.

Electrolysis experiments were also done on synthetic analogs of several important lunar rock types (Table 1). A composition similar to average Apollo 15 olivine basalt(8), but omitting minor elements, was prepared from oxide reagents, fused, and electrolyzed under varying conditions. In all cases, metallic iron was produced in the form of fine dendrites which grew from the cathode directly toward the anode, eventually shorting out the system. Near these dendrites, the glass was much more transparent than elsewhere in the charge, in spite of the fact that microprobe analyses showed a higher Fe content in this glass. This effect is presumably due to essentially all of the iron being Fe^{2+} , reflecting the locally reducing conditions. Near the anode, the glass was nearly opaque owing to high concentrations of Fe^{3+} , even in those experiments run under rather reducing conditions near the iron/wustite buffer curve.

When similar experiments were done in air, even more complex behavior is observed. An iron-titanium oxide phase precipitated near the anode. Although microprobe analyses do not allow determination of Fe oxidation states, it is clear from the analysis totals that this phase is largely oxidized, a member of the ilmenite-hematite solid solution series. In addition, the fact that the phase is not stable under reducing conditions at the same temperature implies that substantial amounts of Fe(III) must be present. Microprobe analyses were also done on a phase containing about 69% SiO_2 , 20% total iron as FeO , about 2% each TiO_2 and Al_2O_3 , and about 1% each MgO and CaO . Microscopic examination of these regions showed them to contain extremely small iron oxide grains. The remainder of the material in those areas must be a very high SiO_2 glass. Pending further study, we suggest that this iron- and silica-rich phase formed as an immiscible liquid that later crystallized iron oxides. Such expansion of 2-liquid fields with oxidation has been observed by Naslund(9). Formation of immiscible liquids by electrolytic oxidation may prove to be an important step in preparing useful glasses and ceramics from lunar compositions.

Electrolysis experiments were also done on a composition corresponding to an average anorthositic gabbro(10) taken as a representative lunar highlands composition. Metallic iron also formed at the cathode during electrolysis, although dendritic growth did not occur. Perhaps the slower

Lindstrom, D. & Haskin L.A.

electrolysis rate brought about by the higher electrical resistance of this composition is responsible for the more regular growth texture. A brownish tint to the glass near the anode suggests some formation of Fe^{3+} .

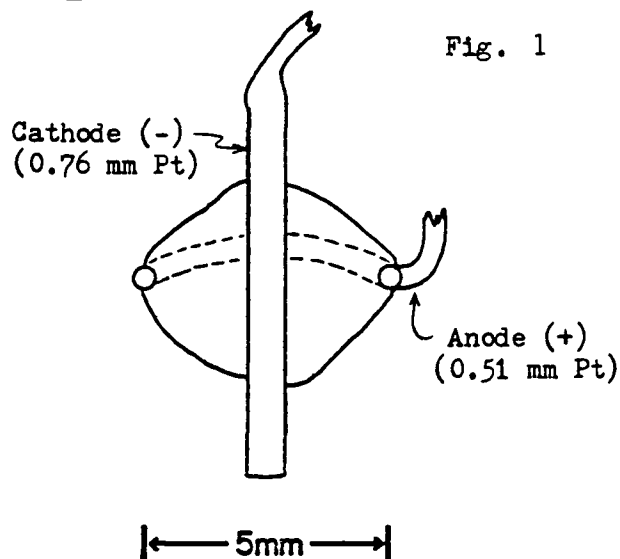
Finally, an anorthositic composition was prepared by mixing one part anorthositic gabbro composition with two parts oxide mix of anorthite composition. Although this composition contained only about 1% iron, iron metal plated out on the cathode. In fact, iron was quantitatively removed from the melt adjacent to the cathode. This may be a feasible way of producing clear glass from lunar raw materials.

Acknowledgements: We thank Roy Brown for his assistance with the microprobe analysis, R.J. Williams for helpful discussion, and NASA for partial support of this work under Grants NSG-9073 and NSG-7372.

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Table 1

	Apollo 15 Olivine Basalt	Anorthositic Gabbro	Anorthosite	Diopside
SiO	45.64	44.62	43.67	55.49
TiO ₂	2.48	0.39	0.13	---
Al ₂ O ₃	9.04	26.01	33.10	---
FeO	22.75	5.75	1.92	---
MgO	9.90	8.08	2.69	18.61
CaO	10.18	14.90	18.41	25.90
Na ₂ O	---	0.25	0.08	---



MELTED IN-PLACE LUNAR SOIL FOR CONSTRUCTION OF PRIMARY LUNAR* SURFACE STRUCTURES. J. C. Rowley and J. W. Neudecker, Los Alamos Scientific Laboratory, Los Alamos, NM, 87545.

The Los Alamos Scientific Laboratory (LASL) conducted an excavation and drilling technology research project based on rock and soil melting from 1962 to 1976 (1,2,3). The demonstrated technical advantages of a practical field system based upon the results of this research were: a method (melting) of hole formation relatively independent of rock or soil type, creation of formed in-place rock-glass structural linings ("casings"), and production of unique forms (glass pellets or wools) of debris or "spoils" suitable for application of improved materials handling techniques. The general results (4) of this research project established that soil melting technology may be employed to construct primary lunar structures. With this prospect in mind the facts and data established by the LASL project are reviewed. The wide variety of melted rock and soil properties (5,6); the design, analysis, and fabrication of several rock melting systems (7,8); the properties of rock and soil glasses (9); and the field demonstration (10) of a simple, prototype structure are described. These results strongly suggest that a technology based upon electrically heated soil melting penetrators could be developed to form in-place in the lunar regolith primary structural elements for construction of several types of lunar surface facilities. This proposed approach has the potential advantage of not requiring refinement or processing of the lunar soil.

In the course of the research project many different terrestrial soil samples were used to assess the performance of various electrically heated melting penetrator designs in both laboratory tests and field operations. Tables 1 through 3 record some of these rock types and sketch the composition of two of the basalts that were used in "boring" experiments. The compositions in Table 3 are rather similar to those cited (11) as the "average" for the lunar regolith. Indeed, holes were melted in a wide variety of wet and dry samples of clays, sands, shales, gravels, tuffs (Fig. 1), and even "perma frost" and in all cases competent glass walls were formed. It seems very likely that similar results will be obtained in melting lunar soils.

The new hardware to be developed for melting lunar soils would be direct extensions of the designs established previously. Two basic types of rock melting penetrators could be developed. These consolidating (7) and extruding (8) penetrator systems fabricated from tungsten and molybdenum could be easily adapted to lunar surface conditions. Both types of penetrators form glass lined holes and therefore can be used to construct the primary structure visualized. A consolidating penetrator was used to melt a tunnel or room into an earth embankment. Figure 2 shows this prototype "tunnel" produced in-situ by melting the soil. The roof and side walls were formed melting a series of 50 mm diameter horizontal holes approximately 2 m deep into the mound of soil using a consolidation penetrator. The holes were placed sufficiently close together for adjacent glass linings to fuse and thus produce a double walled lining reinforced by webs between the individual holes. After the holes were melted to form the roof and sides of the tunnel the interior volume was excavated to expose the glass lining and form the useful volume of the structure. This small test tunnel demonstrated the concept of supporting the overburden of a tunnel or room with a glass lining formed in-situ by such a kerf melting system. Such structures would then form the primary meteorite protection and could be used directly as vacuum space for

MELTED IN-PLACE LUNAR SOIL FOR CONSTRUCTION OF PRIMARY STRUCTURES

J. Rowley and J. Neudecker

such applications as warehousing, heavy equipment housing, surface transportation equipment garages, etc. Alternately, a vacuum tight inner structure could be constructed within the space provided by the in-situ formed primary construction.

Different melting penetrators, but of basically the same forms could be devised to make utility conduits (12) and foundation pilings in loosely consolidated lunar materials. Three types of lunar structures that are particularly suitable for construction using soil melting techniques are illustrated in the sketch in Figure 3.

The rock glass properties obtained during recent melting penetrator experiments show that materials having in-situ porosities of 40% have 7% porosities after being consolidated. The structural compressive strengths of these glassy structures are similar to portland cement structures (9). Additional investigations are required to adapt and verify the melting soil techniques in lunar soils and under the lunar environmental conditions. Relatively straight-forward laboratory tests of melting dry samples of soils similar to lunar soils under vacuum conditions will resolve these questions. Some design modifications to provide thermal optimization of penetrators for lunar use can be anticipated.

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*Work performed under the auspices of the U.S. Department of Energy.

MELTED IN-PLACE LUNAR SOIL FOR CONSTRUCTION OF PRIMARY STRUCTURES

J. Rowley and J. Neudecker

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TABLE 1

MELTING BEHAVIOR DATA

Material	Melting Temperatures, K		Remarks
	Start	Complete	
Bandelier tuff	---	1750	Melt viscosity increased as quartz crystals were consumed.
Jemez basalt-1 ^a	---	1570	Melts uniformly with some gas evolution.
Jemez basalt-2 ^b	---	1510	
Dresser basalt	---	1570	
Charcoal granite ^c	---	1670	Dark phase melted first and then proceeded to consume the matrix.
Westerly granite	---	1760	
Sioux quartzite	---	1760	
Tennessee ping marble	---	--	Heated to 2270 K without melting; some decomposition
Shale, Santa Fe County, New Mexico	1470	1560	Discrete phase melting accompanied by gas evolution. Viscosity increased as more material melted
Caliche, Santa Fe County, New Mexico	1570	1850	
Green River Shale, Cuba, New Mexico	1550	1600	
Concrete	1620	1700	Localized melting. Less gas evolution than from shales or caliche.
Coal, Madrid, New Mexico	---	--	Heated to 2120 K without signs of melting.

^aStarted with rock fragments ~ 1 to 3 mm.^bStarted with powder \leq 1 mm.^cAlso called St. Cloud gray granodiorite.

TABLE 2

CRUSH STRENGTH OF ROCKS AND ROCK-GLASSES

Material	Crush Strength, MPa	Number of Specimens
Jemez basalt	44 + 46 - 26	10
Jemez basalt-glass ^a	108 + 101 - 72	4
Bandelier tuff	2.8 + 0.3 - 0.5	3
Bandelier tuff-glass from 51-mm-diam-hole wall		
Axial	55 + 58 - 23	5
Tangential	36 + 3 - 3	2
Bandelier tuff-glass from 114-mm-diam-hole wall		
Axial (2.3 Mg/m ³)	126 + 37 - 23	4
Axial (2.2 Mg/m ³)	110 + 8 - 12	3
Radial (2.3 Mg/m ³)	115 + 14 - 16	3
Tangential (2.3 Mg/m ³)	132 + 27 - 42	3

^a Uniform glass prepared by Corning Glass Works.

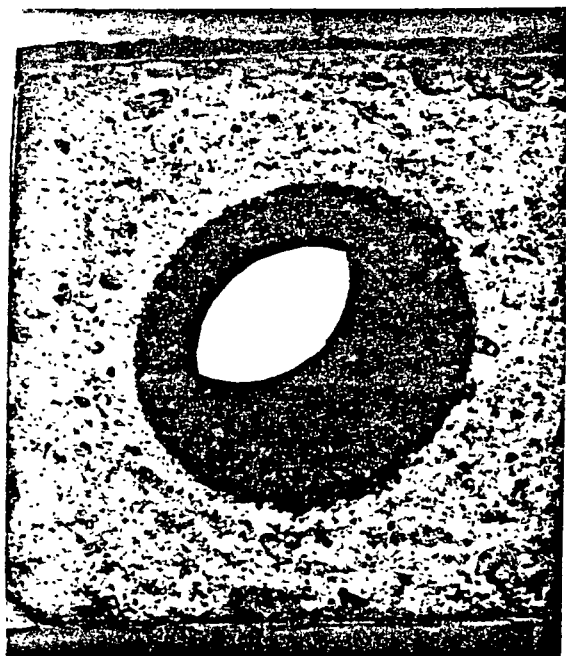
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MELTED IN-PLACE LUNAR SOIL FOR CONSTRUCTION OF PRIMARY STRUCTURES

J. Rowley and J. Neudecker

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CHEMICAL COMPOSITION OF ROCKS AND ROCK-GLASS

Constituents	Composition, wt%			
	Dresser Basalt	Dresser Basalt-Glass	Jemez Basalt	Jemez Basalt-Glass
SiO ₂	48.2	49.52	50.01	50.09
Al ₂ O ₃	16.13	15.54	16.82	16.81
Fe ₂ O ₃	7.65	8.19	2.83	4.38
FeO	5.41	4.68	7.60	6.53
MgO	6.25	6.50	6.70	6.69
CaO	8.69	10.05	9.62	9.68
Na ₂ O	2.54	2.47	3.94	3.40
K ₂ O	0.96	0.97	0.97	0.94
H ₂ O	0.38	0.004	0.14	0.003
TiO ₂	1.45	1.66	1.38	1.46
P ₂ O ₅	0.16	--	--	--
CO ₂	0.048	0.003	0.02	0.003
B ₂ O ₃	--	--	--	--
MnO	--	0.18	0.15	0.15

Fig. 1 Section of Glass Lined Hole
Melted in Tuff RockFig. 2. Prototype Melted In-Place
Structure - Dimension 2m
x 1m Opening, 2m Depth -
Interior Partially Excavated

MELTED IN-PLACE LUNAR SOIL FOR CONSTRUCTION OF PRIMARY STRUCTURES

J. Rowley and J. Neudecker

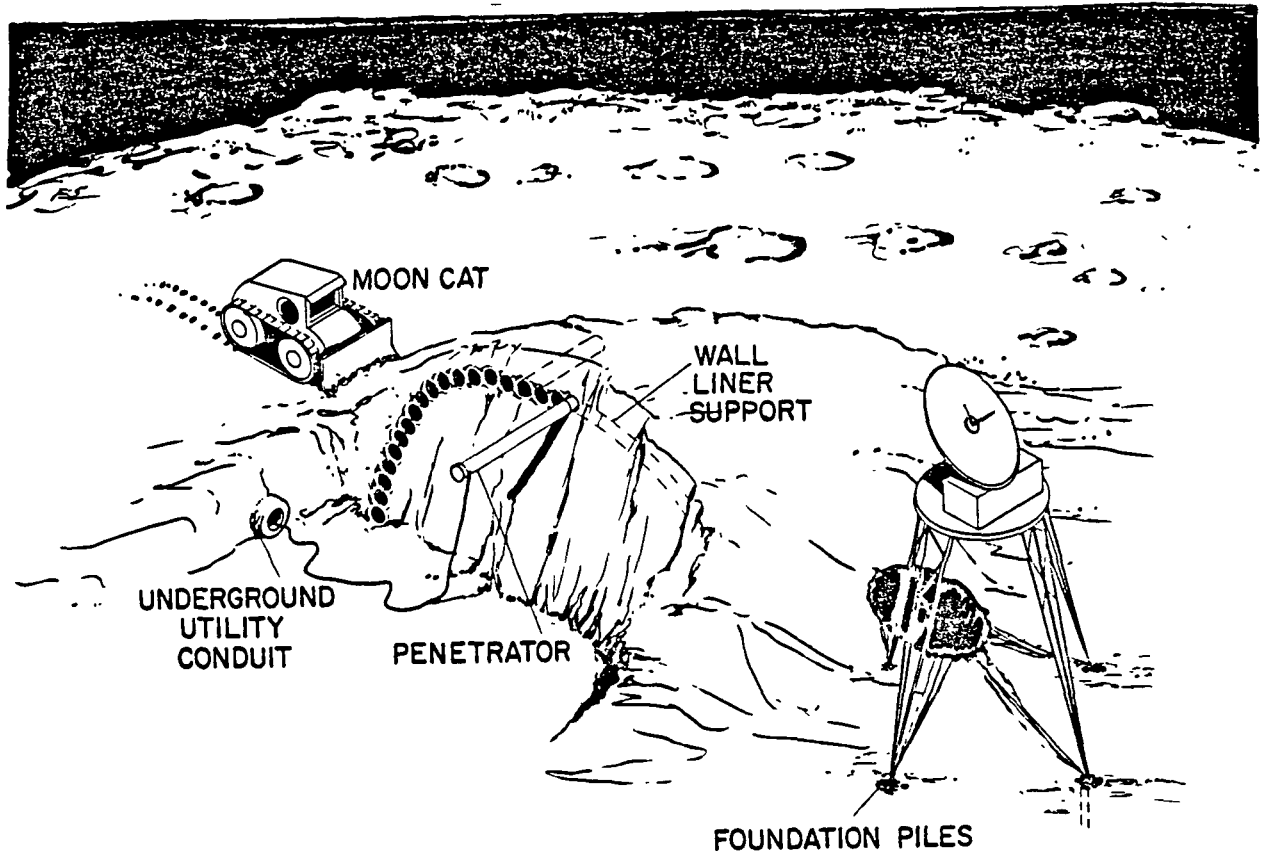


Fig. 3. Conceptual Sketch of Melted In-Place Primary Lunar Structures

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EXPERIMENTAL SHOCK SINTERING OF GRANULATED LUNAR BASALT 75035

Rand Schaal, Lockheed Electronics Co., Inc., Houston, TX 77058

INTRODUCTION: From a geological standpoint investigations of the effects of hypervelocity impact on lunar materials and analogues permit us to interpret the cratering history on the lunar surface on both megascopic and microscopic scales. In the ballistic shock wave facility at the Johnson Space Center shock experiments have been performed during the past four years on massive crystalline rock samples and on porous, particulate samples, both lunar and terrestrial, in order to determine the role of porosity and grain size on the production of shock melt. From an industrial standpoint laboratory investigations of shock melting provide data for estimating what peak shock pressures are necessary to create shock glasses artificially and for predicting both the relative volume and composition of glass that will be produced at specified pressures. Petrographic details of intergranular melting gained from these studies give a better understanding of shock lithification and shock sintering proposed earlier as effective rock-forming processes (1,2).

EXPERIMENTS: Shock experiments are performed by launching a flat-faced metal projectile from a 20 mm gun barrel and allowing it to impact a rock sample encapsulated in a metal target mounted in a vacuum chamber. Sample masses are restricted to only 20 mg in order to ensure that the sample will attain the same peak shock pressure as the target metal. The purpose for this metal-on-metal impact is twofold. First, it allows us to accurately control the peak shock pressure produced in the sample. Because shock properties of metals are well known, it is possible to calculate peak pressure using only the shock impedance of both target and projectile and the measured projectile velocity. Second, this procedure allows us to recover as much sample as possible after shock loading for petrographic, crystallographic and chemical analyses. Projectile velocities of 1 to 2 kilometers per second are sufficient to generate pressures between 10 and 100 GPa (100 and 1000 kilobars) using different target and projectile metals. Velocities are controlled simply by changing the amount of gun powder used to launch the projectile.

We have performed experiments on both crystalline and porous samples to compare the resulting metamorphic effects and relative percentages and compositions of shock-induced melts (3,4). Our lunar regolith analogue is a granulated lunar basalt obtained by pulverizing and sieving lunar basalt 75035. I will limit the description of shock glasses to those produced only in the 100 to 150 micrometer grain size fraction of this sample. Initial sample porosities are approximately 40%.

SHOCK GLASS ABUNDANCE: Detailed petrographic descriptions have been made in thin sections of seventeen samples recovered from experiments ranging in pressure from 6 to 74 GPa (4). A significant finding is that intergranular melting is present in granulated basalt samples shocked to pressures as low as 20 GPa (5). Figure 1 compares the relative amounts of shock glass created in particulate samples of different grain sizes and in nonporous basalt. Generally, with increasing pressure the amount of intergranular melt increases. In porous samples, flow becomes prominent at about 40 GPa, with the production of larger glass volumes and vesicles. Over half of the sample volume is melt at pressures greater than 65 GPa. The difference in melt volumes between porous samples of different grain size is less significant than between porous and nonporous samples (5). For example, if both porous and nonporous samples are shocked at 60 GPa the porous sample will generate nearly 40% melt whereas the nonporous sample will generate less than 10% melt.

SHOCK SINTERING

Schaal, Rand

SHOCK GLASS COMPOSITION: Numerous chemical analyses of shock glasses with the electron microprobe indicate that the glass is very heterogeneous and that the average glass composition changes with pressure (3). Chemical heterogeneity in the basaltic shock glasses is represented by the broad scatter of compositional data in Figures 2 and 3. Each analytical spot in the thin section was selected at random. Figure 4 shows the average glass composition from eight basalt samples and illustrates the chemical variation of the average glass chemistry with increasing pressure. At low pressure (33.2 and 38.8 GPa) the glasses are enriched in plagioclase components and with increasing pressure become more enriched in pyroxene and ilmenite components. At pressures over 60 GPa the average composition of the glass is nearly the same as the whole rock composition, indicating that shock melting is total at high pressure. Fluid mixing tends to homogenize the melt.

CONCLUSIONS: These experiments demonstrate three important points dealing with shock melting: 1) The onset of melting occurs at lower peak shock pressures in porous, particulate samples than in nonporous, massive samples. 2) It is possible to generate sufficient intergranular melt to lithify or sinter a porous basaltic or feldspathic sample at pressures as low as 20 GPa. Samples containing predominantly pyroxene or ilmenite require higher pressures (30-35 GPa) to create significant intergranular melts of their respective compositions. 3) Especially at low pressures (less than 15 GPa), shock induced compaction and intergranular melting in shocked samples occur nearly uniformly throughout the sample and cause effective lithification throughout the entire sample. Many lunar breccias, particularly from the highlands, are natural products of this lithification process.

APPLICATIONS: This shock sintering and lithification may be useful in converting particulate lunar material into a more useful form for transport, storage, or even construction. For example, unrefined ore, beneficiated feedstock, or other particulate material may be more easily transported on or off the lunar surface, loaded into mass-driver buckets, or stored in stockpiles if they are coherent. Construction materials, like "bricks", may be produced by shock lithification. If nonmetallic construction members are desired in space they most probably must be fabricated on the lunar surface. Shock compaction and sintering might be accomplished by using one of the following methods to accelerate a flat metal "lid" into a refillable container: 1) light gas gun; 2) gun powder; 3) military grade plastic explosives (C-4 or Detasheet) (7); and, probably the most practical, 4) electromagnetic accelerator (8).

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SHOCK SINTERING

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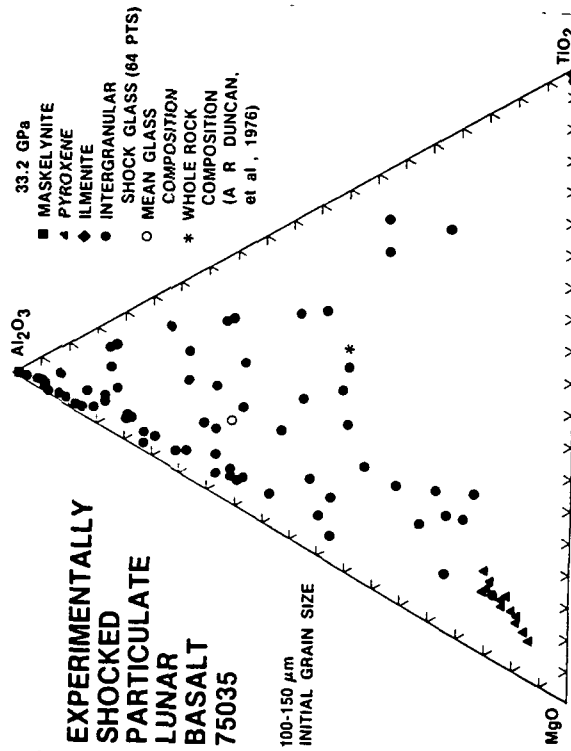


Fig. 2

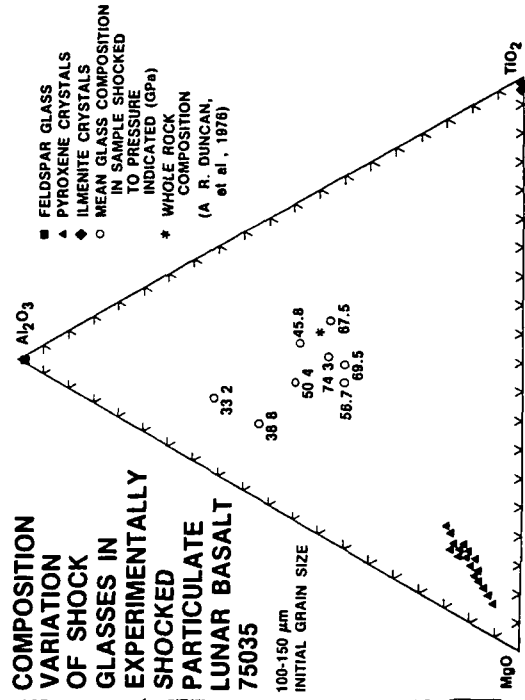


Fig. 4

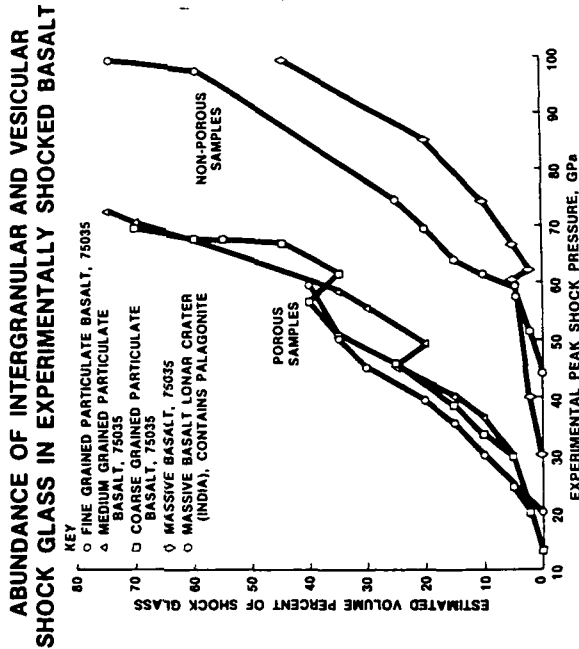


Fig. 1

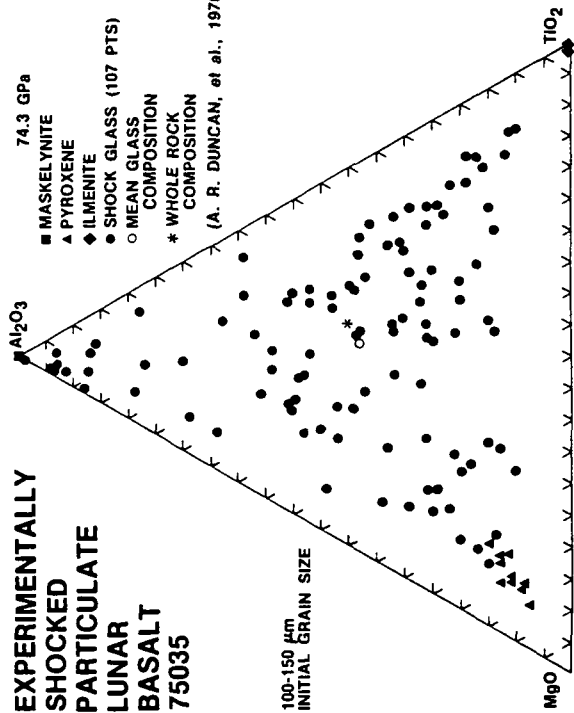


Fig. 3

- Fig. 1 Relative amounts of intergranular and vesicular shock glass in massive (nonporous) and granulated (porous) basaltic samples. Volumes estimated in thin section.
- Fig. 2 Ternary diagram showing relative compositions of minerals and glasses in particulate basalt shocked to 33.2 GPa. Note relative locations of mean glass and whole rock composition (6).
- Fig. 3 Same as Fig. 2 in sample shocked to 74.3 GPa.
- Fig. 4 Ternary diagram plotting mean glass compositions from eight samples shocked to pressures between 33.2 and 74.3 GPa. Note variation from Al₂O₃-rich composition toward the whole-rock composition with increasing pressure.

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DISTRIBUTION OF MINERAL FRAGMENTS IN THE LUNAR SOIL. D. T. Vaniman, J. J. Papike, and T. C. Labotka, Dept. of Earth and Space Sciences, State Univ. of New York, Stony Brook, N. Y. 11794

Criswell *et al.* (1) have pointed out the importance of obtaining pure mineral separates through a preliminary beneficiation of the lunar surface, prior to the ejection of regolith "ore" for processing in space. Electrostatic processing is the mineral-separation technique which appears to be most promising for operation on the lunar surface (1). However, Criswell *et al.* have noted that little is known about the grain-size distribution of mineral fragments in the regolith; with such knowledge it may be possible to select an optimal soil size fraction for electrostatic beneficiation.

The data we discuss are our modal point counts of soils from Apollo 17 (size ranges 0.2-2 mm, 0.02-0.2 mm, and 0.01-0.02 mm) and Apollo 16 (size ranges 0.2-2 mm, 0.02-0.2 mm) (2,3,4). Note that the point counts, which are produced from epoxy-impregnated thin sections over-represent the < 0.02 mm size fraction by ~ 140% due to the dilution of soil by epoxy in the production of thin sections. This was determined by comparing sieved and point-counted size fractions of the same soils (see references 2 and 5). The effects of epoxy dilution have been accounted for where they apply to the discussion below (i.e., Table 2). The point-count data represent volume percentages and are, therefore, discussed in terms of volume content. For conversion of the data to weight percentage, note that the ratios of specific gravities for (anorthite):(pyroxene/olivine):(ilmenite) are approximately (1):(1.24):(1.72).

Criswell *et al.* (1) emphasize the importance of obtaining clean mineral separations. It is quite likely that small lithic fragments and glasses of similar composition will accompany the mineral phase being concentrated through the separation process. Therefore, it is important to know which soil fractions are "cleanest" (i.e., have the highest ratio of minerals to other components).

Table 1 shows the volume percentage of mineral fragments in three mare and two highland soils. The mare soils represent three levels in the Apollo 17 drill core: a coarse-grained immature soil rich in mare basalt fragments (~ 26 cm depth, 70008); a finer-grained, more mature soil with a greater content of highland material (~ 147 cm depth, 70005); and a very fine-grained mature soil (~ 241 cm depth, 70003). The highland soils represent two levels on the Apollo 16 double drive tube 60009/60010: a coarse, immature anorthite-rich soil (~ 55 cm depth, 60009) and a more mature upper layer of more mafic composition (0-27 cm depth, 60010). Volume percentages of mineral fragments are listed for three size fractions in the mare soils, but at this time we only have data for the two coarser size fractions in 60009/60010. One immediate observation from this table is that the relative abundance of mineral fragments increases with decreasing grain size. Since a high concentration of mineral fragments is desirable prior to electrostatic separation, some advantage may be gained from a preliminary size separation. The value of such a separation will depend in part on the distribution of mineral types by size.

Figure 1 shows the size distributions of ilmenite, plagioclase, and pyroxene/olivine mineral types; the bar height in each histogram represents the volume percent of each mineral for the indicated soil size fraction.

Size-Fraction Mineral Distribution in Mare-Dominated Heterogeneous Soil (Mixed High-Ti Mare Plus Highland)

In the mare-dominated soils we note two effects of size distribution on mineral composition: first, that ilmenite is virtually absent in size fractions greater than 0.2 mm and second, that the mineral distribution becomes quite uniform in the finest size fraction (< 0.02 mm) even though the coarser soils reflect the extreme heterogeneity of the Apollo 17 drill core. Evi-

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dently, the net monomineralic ilmenite content of soil "ore" can be increased in all of these samples by discarding the coarser than 0.2 mm soil fraction; this enrichment is on the order of 16-41% by volume (Table 2). Further enrichment might be obtained by finer separations, but note that this is not true for all soils: the immature mare-rich soil of 70008 actually decreases in relative ilmenite content, if the size fraction above 0.02 mm is discarded. The homogenization of an otherwise heterogeneous soil in the finest size fraction suggests that very fine size separation (< 0.02 mm) would not be beneficial in cases where the lunar miner wishes to capitalize on a local heterogeneity (e.g., mining of a 70008-type soil for ilmenite).

Size-Fraction Mineral Distribution in Highland Soils

Figure 1 and Table 2 indicate that the volume of monomineralic plagioclase in highland soils may be increased by 20-26% through a preliminary separation of the > 0.2 mm size fraction. This beneficiation is effective in both mature and immature soils, though it is evident that immature anorthositic soils (e.g., the 55 cm layer in 60009) are a better anorthite source than more mature highland soils. Ilmenite, as in the Apollo 17 drill core, is virtually absent from soils coarser than 0.2 mm though the Fe-Ti oxide concentration in any size range of the Apollo 16 soil is negligible.

Conclusions

The Apollo 17 drill core and the Apollo 16 double drive tube 60009/60010 provide evidence that monomineralic feldspar and/or ilmenite concentrations might be enhanced by size separation of coarser soils prior to further beneficiation (e.g., electrostatic separation). The size cutoff for rejection of "coarser" soils is 0.2 mm in this study, though further fine-tuning of this cutoff could place it anywhere between 0.1-1 mm. A mechanical size separator with adjustable grid spacing in this size range may be a useful design to obtain optimal size separation while operating on site. Size separation on a finer scale may be useful in some cases but detrimental in others (e.g., for ilmenite concentration in 70008). Moreover, problems of particle-particle adhesion and clogging between sieve bars could make sieving operations finer than 0.1 mm impractical.

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Table 1. Volume percentages of mineral fragments* in soil size fractions.

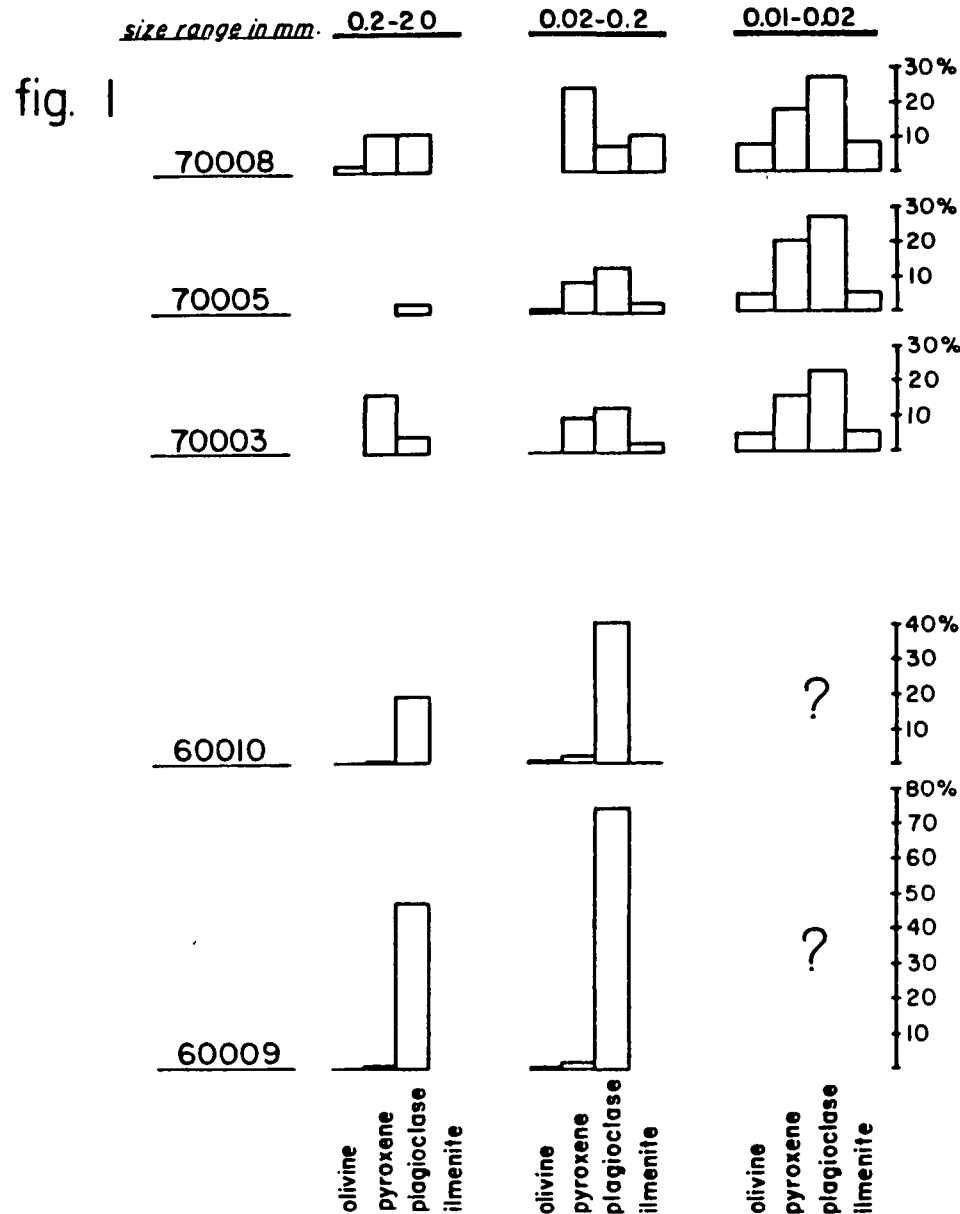
Core segment	Depth	0.2-2 mm	0.02-0.2 mm	0.01-0.02 mm
70008	26 cm	24.7%	44.3%	63.0%
70005	147 cm	2.8%	24.8%	58.0%
70003	241 cm	21.8%	25.7%	50.1%
60010	0-27 cm averaged	19.5%	44.1%	---
60009	55 cm	49.3%	78.7%	---

* Total individual fragments of pyroxene, olivine, feldspar and ilmenite.

Table 2. If sieving and removal of larger particles is practiced, what concentration and enrichment in mineral fragments may be expected? Note that because of present data constraints, we have assumed that the 0.01-0.02 mm size fraction represents all soil less than 0.02 mm in size.

	(I) all soil 0-2 mm	(II) 0.2-2 mm fraction discarded	(III) 0.02-2 mm fraction discarded
<u>Ilmenite</u>			
70008	6.6%	9.3%(41%)	8.1%(23%)
70005	2.9%	3.4%(17%)	5.2%(79%)
70003	3.2%	3.7%(16%)	5.1%(59%)
<u>Feldspar</u>			
70008	16.6%	18.9%(14%)	27.7%(67%)
70005	15.5%	17.9%(15%)	27.5%(77%)
70003	15.8%	17.7%(12%)	23.0%(46%)
60010	32.2%	40.6%(26%)	?
60009 immature	62.2%	74.8%(20%)	?

Percentages of the indicated mineral fragment type by volume; values in parentheses are percent enrichment over column I (total soil of 0-2 mm size range).



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MINERAL FRAGMENTS IN THE LUNAR SOIL

ORIGINAL PART OF
OF POOR QUALITY

GLASS AND CERAMICS WORKSHOP

Technical Paper

(For publication as one of a group of papers stemming from a Workshop on Glass and Ceramic Industries in Space, NASA, April 1979)

USE OF LUNAR MATERIALS IN SPACE CONSTRUCTION, Edwin Roedder, National Center, Stop 959, U. S. Geological Survey, Reston, VA 22092

INTRODUCTION

Large construction projects in Earth-Moon space, such as solar power satellites (SPS) will certainly be undertaken in the future; the only question is when? Such projects will consist of hundreds of thousands of tons of a variety of materials. What materials will be needed, where will we get them, and how and where will they be processed into the desired form? At a workshop on Glass and Ceramic Industries in Space held at NASA-Houston in April 1979, people from a very wide range of disciplines and interests were brought together to explore some of the many options and constraints. Of the three possible sources for such materials, Earth, Moon, and Earth-orbit-crossing asteroids, only the first two are of immediate concern, although the last may eventually become the optimum source. The choice between a source on Earth and one on the Moon, for a material available from both, is easy. Several studies (e.g., Criswell and Waldron, 1978) have proven that for two reasons, the Moon presents a tremendous physical and, hence, financial advantage over the Earth as a source for materials available from both. The "gravity well" we live in on Earth requires a huge expenditure of energy to overcome. Although the Moon's gravity is one-sixth that of the Earth, the energy needed for a given mass to escape from the Moon is only 5% of that needed for it to escape from the Earth; the resistance of the Earth's atmosphere increases this difference. This lunar

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advantage is multiplied, however, by still another major factor. To take a payload off the Earth by currently available technology (e.g., chemical rocket) requires a vehicle whose payload normally consists of 1.5% of the original lift-off mass. On the Moon, however, as a result of the lack of an atmosphere, essentially pure payloads, without a vehicle, could be accelerated to escape velocity on the surface, by using solar-derived electrical energy in a linear electric motor or "mass driver" (O'Neill, 1974).

Thus, the energy requirements alone make it obvious that for any given space application, lunar materials should be used if at all possible. Certainly not all materials needed for space construction can be obtained most economically from the moon, and much additional research and development is needed to optimize the system. The possible ramifications of such a new and developing technology are so numerous that input from individuals having widely differing experiences and backgrounds might well be useful. The following comments, adapted from those I presented at the workshop, are made in that context.

PHYSICAL SEPARATION OF LUNAR SOIL

Much has been written on physical separation of lunar soil (e.g., Criswell, 1978; Billingham et al., 1979; Williams, 1978), and answers are still needed to many questions; however, the properties of the major components of lunar soils are sufficiently different that at least partial separation seems very likely. Other papers in this series cover certain separation procedures in detail. Physical separations of granular materials are now being made commercially, with large throughputs, on the basis of seemingly trivial differences in the nature and behavior of the several constituents under a wide range of special conditions. The materials involved include seeds, grains, and other foods, small manufactured objects, and of course, minerals.

A striking example of how effective small differences between mineral grains can be is provided by a novelty item put out by a chemical company; the item consists of a glass bottle containing subspherical grains of essentially pure, precipitated Al_2O_3 that are all identical except for a small range in grain size. The various grain sizes were separated, each size range was dyed a different color and then recombined. It is almost impossible to mix the contents to a uniform color without streaks representing partial size separation by flowage. The lunar soils contain minerals varying in size, shape, density, surface electrostatic properties, magnetic properties, electrical conductivity, etc., and any one of these differences may be exploited for separations. Color differences may even be used for separation. For example, if mixed grains of glasses that are similar except in color were all given an electrostatic charge and then were heated by visible light during passage through an intense beam of sunlight from a solar mirror, even different intensities of coloration of the same color glass would probably be heated differently; thus, they would lose different amounts of their static charge, as the electrical conductivity of glass is extremely sensitive to temperature. The differences in charge could then be used to effect a separation. In view of the wide range of both the wave lengths in sunlight and the absorption bands in various glasses, filters might be necessary to make a separation based on color.

Good reasons exist for delving into the separation of lunar soil in some detail. Others have discussed the concentration (or perhaps better "purification") of bulk constituents such as plagioclase, and the concentration of lesser constituents such as ilmenite, and such separations might well be made early in the development of a lunar minerals industry. Obviously, a lunar metallic iron concentrate could be separated relatively easily during any bulk handling of the lunar soil and would be very useful. Separation of other

constituents in the lunar soil will probably merit consideration in the future, particularly if the soil is handled for other reasons anyway. Included here are the high-chromium spinels, and even several zirconium phases. High-potassium glass and silica, in particular, seem far more important than their relatively low concentrations in the lunar soil would seem to indicate, and they do not seem to have been considered in the literature on lunar resources.

High-potassium glass

One of the two late-stage residual melts in practically all mare basalts is a high-silica, high-potassium melt (now a glass) which formed as a result of silicate liquid immiscibility (Roedder, 1978). Because the original basalts contain only 0.3% K_2O maximum, and many have only 0.5%, and this late melt contains 6-8% K_2O , not much of it can be present (1). The other liquid of the immiscible pair, called high-iron melt, contains considerable phosphorus (1.5 - 3% P_2O_5), and crystals of apatite or whitlockite (calcium phosphates) from its crystallization are commonly found around the edges of the masses of high-potassium glass. If even an impure concentrate of this high-potassium, high-phosphorous material could be made, as a byproduct of material handling for other products, it might be valuable to an SPS program in several ways. (However, no evidence now indicates that it can be separated.)

First, any permanent lunar base will presumably grow food hydroponically. The early results on Apollo 11 soils showed that plants grew better if lunar soil was added to the water. I suggest that this improved growth was probably a result of the added potassium (and phosphorous?), which should dissolve more readily from the potassium-rich glass than might be expected from the overall low concentrations present. Even if all biological wastes at such a base are recycled, use of potassium and phosphorous hydroponic "fertilizer" from lunar soil would mean that much less material to be transported from Earth.

Second, this high-potassium glass could be an important additive in several types of ceramic mixtures. Most ceramics consist of crystals of various phases, bonded together by glass. The properties of both are important in controlling the properties of the ceramic, but the one most important property of the glass is its viscosity at a given temperature. Potassium aluminum silicate melts such as this melt have extremely high viscosities and, hence, such material should be useful for increasing the viscosity of various glasses, whether they are to be used with crystals in ceramics or for pure glass products. They would also be useful in lowering the melting temperatures of non-refractory ceramics.

Figure 1 shows the relationship between viscosity and temperature for various silicate melts. The high-potassium lunar glasses would presumably have viscosities in the general range of curve 2, for anhydrous obsidian. Note that the viscosity of obsidian at 1100°C is about 9 orders of magnitude higher than that of some basaltic lunar rocks. The actual viscosity of the potassium glass will probably be less than the viscosities shown for obsidian, because the viscosities of alkali-aluminosilicate melts show a sharp maximum at a 1:1 mole ratio of alkalis to alumina, as in many obsidians (Schairer and Bowen, 1947), but the lunar glasses are deficient in alkali.

Silica

Another phase present in lunar soils derived from mare basalt that might be useful in ceramic products is silica. A relatively pure silica phase, either tridymite or cristobalite, is present in many mare basalts in amounts as great as 6%. Anyone who has ever tried to transfer carefully weighed aliquots of powdered cristobalite knows that it is positively devilish in the way in which it takes on a static charge on even minor handling. After extensive handling under low humidity conditions (e.g., on pouring the powder after screening) lumps of the powder commonly levitate from the paper and plaster themselves on

the outside on the container into which it is being poured. Electrostatic processes have considerable potential for the separation of plagioclase and ilmenite from lunar soils (Criswell, 1978), hence a silica separate might also be obtained as a byproduct of these processes. Such a concentrate would be of considerable value for the manufacture of silica glass or fibers (Ho and Sobon, 1979), and even large shapes (Vasilos, 1960), and additions of silica will generally increase the viscosity of most silicate glasses.

CHEMICAL SEPARATION OF LUNAR SOIL

Extraction of Water

In all discussion of lunar resources, one of the recurring questions is the availability of water. If adequate supplies of water can be obtained locally and need not be brought from Earth, many of the problems in mineral beneficiation and chemical processing would be minimized. Even more important, perhaps, the logistics of maintaining a lunar base would be greatly simplified. Supplies of water, along with carbon dioxide, would permit the production of food and oxygen (2). The lunar soils contain 100 ppm hydrogen, implanted into the surfaces of the grains from the solar wind (Billingham et al., 1979). The amount held varies with the nature of the substrate, and an ilmenite concentrate may yield much more hydrogen (or water) on heating than other constituents of the soil (Williams et al., 1979). Considerable attention has been given to the problems of obtaining an ilmenite concentrate for this purpose. If an ilmenite concentrate (or any other fraction) is made and subsequently heated, certainly the evolved gases should be saved. But for large-scale production of water, it would seem more reasonable to use raw, untreated soil. The heating of large volumes of a fine, powdery material in vacuum poses severe heat-transfer problems, but if a heat-exchange fluid could be used, these problems would be eliminated. Apollo; the proposal has since been largely ignored. Wechsler et

al., proposed Such a process was proposed by Wechsler et al. (1965), in a paper published before the use of pumped circulation of the evolved volatile materials themselves as a heat-exchange fluid (with an external heater), to both heat and pump the soil in a continuous countercurrent process. Heat loss via the effluent spent soil would be minimized by its transfer to new feed in a countercurrent fluidized-bed heat exchanger. Because lunar soils evolve not only hydrogen and water on heating but also CO and CO₂ (e.g., Epstein and Taylor, 1975), both hydrogen and carbon could be recovered in such a process.

Parallels with terrestrial pyrometallurgical practice

Various nonaqueous chemical processing procedures have been proposed to obtain specific materials from the lunar soils (e.g., Waldron et al., 1979, Criswell, 1978). Many of the flow sheets for these processes are based on theoretical considerations or adaptations of existing extractive pyrometallurgical practice, and quite obviously these will undergo considerable further changes when tried in a terrestrial pilot plant on simulated lunar materials. The literature on such practice is extensive and scattered, and information useful to lunar processing may be available but unrecognized in the literature on seemingly irrelevant processes. For example, the Torco "copper segregation process," successfully used in Africa and elsewhere on a fairly large scale on oxidized copper ores, has some parallels, both in chemistry and technology, with some of the processes suggested for lunar "ores." It involves a simultaneous chloridization, volatilization, transport and reduction of the copper (Martinez, 1967).

A considerable body of seemingly irrelevant terrestrial metallurgical technology may still be pertinent and should be drawn on for help in anticipating and, therefore, avoiding otherwise unexpected and potentially serious problems. Most important, some of these problems may not appear in

laboratory or small pilot plant operations. A good example from the steel industry is found in the study of blast furnace refractories. The iron blast furnace is a continuous process, in which ore, coke, and flux are charged in at the top and molten metal and slag are tapped out the bottom. The important parallel with some of the proposed lunar processes comes about because the fresh cold charge is heated (and in part reduced) by the effluent gases. This countercurrent flow is a common heat-saving feature of many pyrometallurgical processes. However, at the temperature of the hottest zone of the blast furnace, 1659°C, many seemingly nonvolatile constituents in the charge have significant vapor pressures and volatilize, at least in part. Zinc and alkalis are such substances. As a result of the countercurrent flow, are, however, the vaporized zinc and alkalis condense on the colder charge and hence recycled. Even though very little alkali and even less zinc may be in the ore, this rather efficient "winnowing" concentrates alkalis and zinc or zinc oxide in specific zones of the furnace, where they may decrease the permeability of the charge and cause serious reactions and deterioration of the blast furnace refractories. Similar problems may not arise in the lunar ore processing, but they should be carefully considered and avoided by appropriate design or operation.

LUNAR EXPLORATION FOR SUITABLE MINING SITES

In order to obtain several different materials from one mining site on the Moon, it has been suggested that this site be near the contact between the highlands and the mare. This suggestion is appropriate, but in reviewing some of the literature on potential lunar mining, I believe that too much reliance has been placed on a simple bimodal composition for lunar surface materials -- anorthositic in the highlands and basaltic in the mare. The picture is actually more complex than that. For example, the mare basalts range from 1 to 13 wt.% TiO_2 and from 6 to 16% MgO (Papike et al., 1976), and lunar soils formed on

these can be expected to vary similarly. However, this is the variation among basalts sampled by Apollo 11, 12, 15, and 17 only, and these compositions are highly unlikely to be the extremes. In fact, the basalts from the Soviet Luna 24 site differed considerably from all of the above. Similarly the anorthositic breccias of the highlands range widely in their ratio of plagioclase to mafic minerals such as olivine and pyroxene, as well as in the content of minor but important elements such as potassium, both within a given site and globally, as is evident from the various orbital lunar analyses.

The variations mentioned above are essentially areal variations. However, a lunar mining operation would probably take a vertical section of one or more meters of soil, so knowledge of the variation of composition with depth is essential. The surface composition is not always a good predictor of composition at depth, and core samples, perhaps made by a remotely operated drill, will be essential. Such three-dimensional control is even more important if the center of the mining operation is to be set up on the border between highlands and mare, as this is exactly where vertical changes are most likely. The problem of the exploration strategy to use in the search for a good site is not as trivial as it is sometimes portrayed to be. Arnold and Duke (1978) evaluated many of these ramifications and proposed some specific steps.

General Nature of Needed Materials; Use in Tension vs Compression Demandite

Criswell and Waldron (1978) and Waldron et al. (1979) have applied the concept of the imaginary molecule of demandite, corresponding to the gross composition of the nonrenewable resources humans use in a given economy (Goeller and Weinberg, 1976), to the problem of the availability of materials in space for an SPS. They find that because the lunar soils are composed of 85-90% of the nonfuel, nonrecoverable elements used by United States industry, and because these materials can be obtained from the Moon at a smaller unit cost (\$/kg) than

equivalent materials can be supplied from the Earth, the Moon is presumably the best source for the bulk of the materials needed. Although I agree with the conclusion, I want to point out that comparison between terrestrial demandite and lunar soil composition is not a good basis for consideration of the availability of the needed materials on the Moon, because demandite for a space economy will differ drastically from demandite for a terrestrial economy. Even for construction of a given purpose, such as a solar power unit, we can expect that a major difference will exist between the two, because the design of construction in space will be based on little or no gravity. The effects of this difference are so fundamental that the demandite composition for terrestrial construction will bear little relation to that for space. On Earth, almost 90% of nonfuel demandite makes up materials such as brick, concrete, and tile that are used in compressive loading -- columns, walls, foundations, roads, etc. Criswell (1978) has emphasized the huge reduction (>99.8%) in the mass of material needed for a given function in space from the mass needed for the same function on Earth by comparing, for example, the Grand Coulee dam (or a terrestrial solar power unit) and an SPS having equivalent energy output. However, the major part of the mass of either of the terrestrial installation is concrete in compressive loading due to gravity, whereas, the bulk of the space construction will have no such gravitational stresses and, hence, will not require much material having a high compressive strength. Thus, much of the discussion that has gone on of the possible technology of melting and casting blocks of fused lunar materials may have relatively little pertinence for most applications in a SPS, though such blocks may well be valuable for constructing radiation and micrometeorite shielding around lunar base buildings.

Fused basalt

The currently available technology of melting and casting of silicates can

provide a wide range of useful products, in addition to simple structural block, but very little attention has been paid to it in the discussions of materials for space. Thus, fused mullite ($3 \text{ Al}_2\text{O}_3 \cdot 2 \text{ SiO}_2$) is an excellent refractory for some special duty installations involving high temperatures and abrasive or corrosive environments. However, far more important, perhaps, are the possibilities of manufacture of many more mundane products from simple fused lunar soil. Fused and cast basalt is relatively simple to produce, and has many desirable properties such as a very high resistance to abrasion and corrosion, and a surprising mechanical strength, even when hot. Many different commercial products are currently being made from cast slag and basalts of various compositions in many countries in Europe. The technology of cast basalt has been explored in detail in Czechoslovakia. Thus, Kopecky and Voldan (1959) reported on extensive studies of the viscosity, liquidus temperatures, melting range, and phase assemblages obtained for various basalts and additives, and the grain size and texture obtained at various cooling rates, as these features are important in controlling the properties of the products. They found that spherulitic crystallization of pyroxene yields products have maximum abrasion resistance. Extensive studies of silicate crystal morphology under various conditions of crystallization (e.g., Lofgren, 1974), reveal that control of such morphology no longer need be empirical.

Commercial companies in Europe currently market fused basalt (1) tiles and slabs in a variety of size and shapes for lining chutes, bins and hoppers, (2) straight and curved pipes, (3) reducers, (4) complex T's and Y's, and (5) centrifugal slurry pumps; they even market a fused basalt cyclone separator (Fig. 2). The piping is of particular interest for lunar mineral operations as it has a high abrasion resistance and, hence, is useful for pumping of granular materials or slurries. Many of the applications of cast basalt could also be

filled by the use of metals, which have the added advantage of flexibility under the expected severe thermal stress, but metals would require more extensive lunar processing and, hence, may not constitute a valid option, particularly in the early stages.

Foamed Silicate Melts

For many construction applications, both on the Moon and in space, considerable advantage would accrue from causing the fused silicate melt to foam before solidifying. This provides much more volume of product per unit of material processed (and per unit of energy expended), and it also provides a lower density product. Fused silicate melt to be used in an SPS would probably be foamed in space and not on the Moon. Various possible foaming agents have been considered, including sodium sulfate plus carbon and even oxygen (evolved on electrolysis of the melt during reduction of iron). Possibly only carbon need be used; it would form CO bubbles. If the extraction of water from lunar soils becomes operational, steel industry technology can provide a simpler foaming method. Blast furnace slag as produced is thoroughly anhydrous. Water injected into the molten slag will dissolve rapidly, however, as appreciable water must dissolve before the partial pressure of water reaches 1 atm. On subsequent cooling, anhydrous silicate phases form, increasing the concentration of water in the residual melt, until finally this vapor pressure exceeds 1 atm and the material foams.

Much space construction will involve the use of very large, low-mass units, but rigidity will certainly be a common prerequisite, to maintain alignment of various parts. The most logical material for rigid construction in space, i.e., that which requires a minimum investment in materials transport costs, from Earth or Moon, would appear to be a foamed silicate glass made of lunar soil. Considerable discussion at the workshop centered on the seemingly difficult

problem of how blocks of such foam could be combined to form long rigid columns on which large two- or three-dimensional structures might be based. Numerous procedures, including even "welding" of the blocks together by various exotic sources of heat has been suggested, but the shrinkage of such foams on surface melting prior to "welding" would present serious difficulties.

I believe that at least one rather simple solution to this problem exists. Rigidity in a structure is normally achieved through a combination of elements, some in compressive loading and others in tensile loading. From the literature and the workshop, it appears that glass fibers (Ho and Sobon, 1979) might provide an effective basis for most elements in tension, and foamed glass for elements in compression. I suggest that thin glass fiber elements be run through holes in a stack of foam blocks, with tension adjusted to hold the blocks together, in analogy to the use of steel cables in prestressed concrete beams. Such a combination beam would be limited probably by the compressive strength of the foam, which could be controlled, in turn, by the size and amount of bubbles. Silicate melts, both in metallurgy and geology, commonly show a nonuniform bubble size and distribution near to a quenching surface. A normally low-density foam may have only a few small bubbles at its contacts with a heat sink, such as a slag pot or a cold rock. Thus, it should be possible, by adjusting the heat flow during nucleation and growth of the bubbles in the lunar foam blocks, to obtain a block that has a dense, strong rind and a light-weight core and that hence is considerably improved rigidity per unit weight. Nature evolved that optimum structure in the bones of animals millions of years ago, and we need only reproduce it.

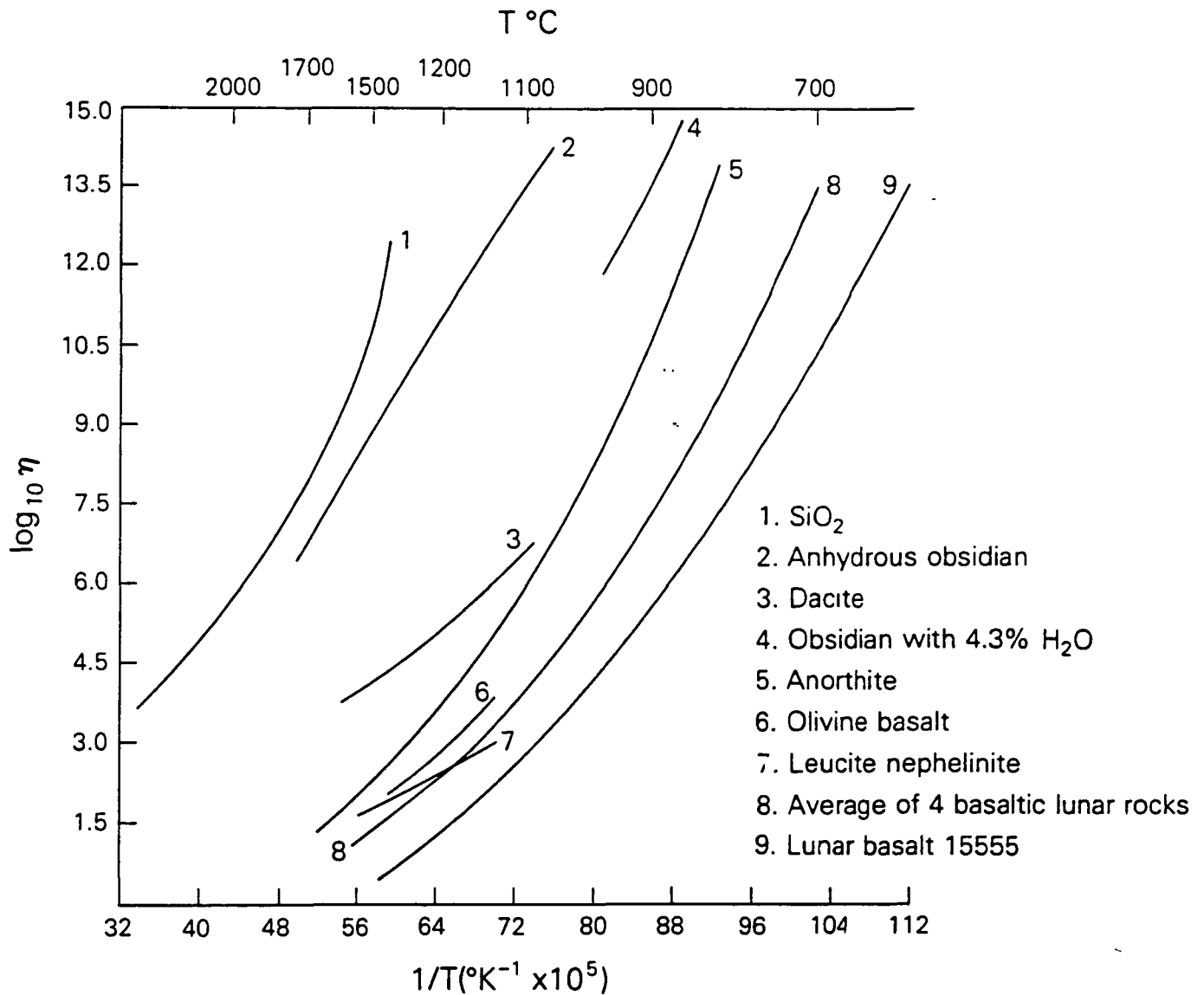
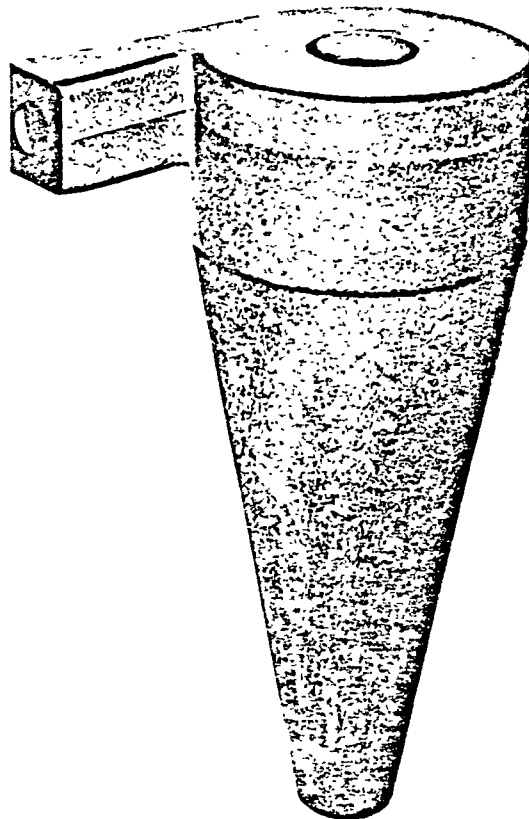


Figure 1. Plot of viscosity vs temperature for various silicate melts. The original data (from numerous sources, and only in part graphical) have been replotted on a single set of coordinates for easier comparison.

Figure 2. A hydrocyclone made of cast basalt. From Kopecky and Voldan (1965).

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ELECTROCHEMISTRY WORKSHOP

ABSTRACTS OF PRESENTATIONS

OVERVIEW OF SPACE INDUSTRIALIZATION AND THE ROLE OF THE CHEMICAL ENGINEER, David R. Criswell, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, TX 77058.

It is expensive to ship raw or finished materials from the surface of the earth into space through the dense atmosphere of the earth. In order for space flight and industrial operations in space to become significantly less expensive and more extensive, the resources of space must be utilized. Known materials of the lunar surface can provide most of the functionally necessary refined elements with which to produce a wide range of products for use in space. Space power stations would capture sunlight, convert the energy to microwaves and beam the energy to earth for terrestrial uses. Approximately 90% of the mass of such a satellite could be made from lunar materials. One can be certain that many other products can be derived from lunar materials. One key to making such products possible and economically attractive is the demonstration of proto-type industrial processes in which lunar materials surfaces are separated into the constituent elements and oxides. A major objective will be to produce reliable systems for the completion of these separation processes in which the primary expendable is energy. Inputs of process chemicals from earth must be minimized. Separation systems should be designed so that subsequent units can be made primarily of lunar derived materials. The electrochemical approach is of direct interest because of the relative mechanical simplicity of such systems, the possibility of high reliability and low manpower. Both near and far term process options should be delineated. Experiments using lunar and analog samples on early missions and in Spacelab should be suggested that could lead to the early use of lunar materials in space and on the moon.

LOW GRAVITY FLUID ORIENTATION, Robert K. Allgeier, NASA Johnson Space Center, Houston, TX 77058

Much has been learned of low and zero gravity fluid behavior in the last two decades or so. Much more must be done in the decade to come if the ideas set forth in this workshop are to become a reality. In the past, delivery of a liquid from a storage vessel has usually been accomplished by settling the liquid consumable using auxiliary acceleration devices.

When a vapor has been required aboard the vehicle, the fluid may have been stored as a supercritical fluid or Joule-Thompson expansion may have been employed. Either method does not rely upon fluid orientation and the problem was neatly solved, but bypassed.

Dielectrophoresis, bladder expulsion, and piston expulsion can theoretically be designed to expel liquids and/or vapors, but much development remains in either technique, materials, or understanding. Thus, recent efforts have concentrated on using capillary phenomena. Feasibility demonstrations have been carried out using acquisition screens of both fabric and metal with a high degree of success when the medium is an ambient temperature fluid. Cryogenic acquisition devices are still in development and will be relatively heavy.

Farther downstream, the processes to be discussed here dictate a requirement to acquire and orient highly corrosive fluids, sometimes at elevated temperatures. Success in this venture will, in years to come, prove to be a most significant challenge.

ELECTROCHEMICAL EXPERIMENTS ON MOLTEN SILICATES OF LUNAR COMPOSITION, David J. Lindstrom, and Larry A. Haskin, Dept. of Earth and Planetary Sciences, and McDonnell Center for Space Sciences, Washington University, St. Louis, MO 63130.

Electrolysis experiments have been done on melts of diopside ($\text{CaMgSi}_2\text{O}_6$)

composition doped with several percent NiO, FeO, TiO₂, Al₂O₃, or Na₂O. To date, Ni and Fe metals have been obtained in nearly pure form, while Si and Ti have been obtained as alloys with the platinum cathodes used. Oxygen gas is given off at the anode. A simplified composition approximating lunar anorthositic gabbro produced when electrolyzed Fe, Si/Pt, and nearly Fe-free, colorless glass. Electrolysis of a mare basalt analogue produced Fe metal at the cathode, and oxide minerals and an immiscible liquid rich in silica and iron near the anode.

These preliminary experiments (1,2) show that useful materials can be obtained by electrolysis of melts having compositions similar to ordinary lunar rocks. Further work will be done to investigate other electrode materials and other compositions (especially mineral concentrates), and to obtain necessary data for scaling up the process.

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- (2) R. Rizzo, Electrochemical Studies in Calcium Magnesium Silicate Liquids, Ph.D. Thesis, University of Wisconsin-Madison (1976).

GENERAL CONSIDERATIONS OF LUNAR AND SPACE PROCESSING, R. D. Waldron, Lunar and Planetary Institute, Houston, TX 77058.

A general discussion of the criteria of importance in the selection and evaluation of processing options for the production and refinement of industrial feedstocks from lunar raw materials will be given. These criteria will be weighted differently according to the mass, nature, and location of end use products or systems generated from the respective materials plants.

A method for the general classification of materials processing systems

based on phase states of input, reactant and output streams, and the nature of specific operations (physical, semi-physical, chemical or electrochemical steps) will be presented. A discussion of the engineering limitations of specific classes, especially with regard to specific throughput and reliability or durability of equipment will be given.

Methods used for the rough sizing estimates for size and mass of specific steps of the HF acid leach and other proposed processes will be discussed. The possible trade offs between current density, energy efficiency, product quality and equipment life and maintenance for various electrochemical operations will be examined.

The importance of efficient recycling of reagents containing elements not readily extractable from lunar sources will be discussed. The implications of this requirement on the compositions, purification and handling of fused salts, slags, alloys or other intermediates or final products will be noted.

SPACE PROCESSING AND ELECTROCHEMISTRY, J. R. Selman, Department of Chemical Engineering, Illinois Institute of Technology, Chicago, IL.

A brief introduction to the industrial-electrochemical presentations will be given. The proposed utilization of electrochemical processing in the lunar or extra-terrestrial environment is first and foremost a consequence of the abundance of solar energy. However, other factors such as low gravity and the absence of space limitations (compared to the terrestrial situation) also work in its favor, since electrochemical processes are characterized by low volume-reaction rates.

ELECTROCHEMICAL ENGINEERING AND SCALEUP OF EXTRATERRESTRIAL INDUSTRIAL PROCESSES, T. R. Beck, Electrochemical Technology Corporation, 3935 Leary Way,

N.W., Seattle, WA 98107.

A procedure of design of electrochemical plants outlined by MacMullin can be used for design of extraterrestrial processes taking into consideration the differences in environmental conditions. These differences include: zero of 1/6 earth gravity, high vacuum, solar electrical and heat source, space radiation heat sink, long days and nights on the Moon, and different availability and economics of materials, energy, and labor. On earth, gravity plays a role in electrolytic cell design and operation in several ways: natural convection stirring as in copper refining cells, gravity gas disengagement as for Cl_2 and H_2 in chlor-alkali cells and establishment of horizontal cathode-electrolyte interfaces in molten salt electrowinning cells. In zero-g environment, forced convection by pumping can replace natural convection and capillary forces in porous electrodes or centrifugal forces can replace gravity separations. Such techniques were already worked out for hydrogen-oxygen fuel cell systems used in the U. S. lunar landing program. Design and operation of closed aqueous electrolytic processes for extraterrestrial conditions appears to be within the state of the art. Finding or developing compatible materials for construction and operation of fused-salt metal winning cells will present a real engineering challenge.

PREPARATION OF CELL FEED MATERIALS FOR ALUMINUM AND MAGNESIUM PRODUCTION, by James A. Barclay, Bureau of Mines, U. S. Department of the Interior, Washington, DC 20241.

Magnesium chloride for electrolysis to magnesium in a fused-salt bath is made by reacting seawater with milk of lime to precipitate magnesium hydroxide, separating the latter from the barren seawater, dissolving it in hydrochloric acid, and crystallizing and drying the compound $\text{MgCl}_2 \cdot 1.5 \text{H}_2\text{O}$. Solar

evaporation of Great Salt Lake brine, followed by spray drying, also is practiced. Dolomite may be calcined and ground to a fine powder to be mixed with ferrosilicon for reduction to magnesium in vacuum retorts by a nonelectrolytic process.

Alumina for smelting to aluminum in Hall-Heroult cells is prepared from bauxite by pressure digestion with strong NaOH solution, thickening and filtration to separate a waste "red mud," and crystallization of $\text{Al}_2\text{O}_3 \cdot 3 \text{H}_2\text{O}$ in the presence of seed crystals. The $\text{Al}_2\text{O}_3 \cdot 3 \text{H}_2\text{O}$ then is calcined to Al_2O_3 .

Bureau of Mines and other research on the recovery of alumina from nonbauxitic aluminous materials will be discussed, and possible application of acid leaching, alkaline sinter-caustic leaching, and carbochlorination processes to lunar materials will be briefly evaluated.

ELECTROWINNING OF ORES, N. Jarrett, S. K. Das, W. E. Haupin, Alcoa Laboratories, Alcoa Technical Center, Alcoa Center, PA 15068

The history of extractive metallurgy of aluminum is reviewed. The modern Bayer-Hall process for making aluminum from Bauxite is described. A flow diagram is presented summarizing most of the alternate processes for making aluminum that have been either proposed or are being developed to replace the Bayer-Hall process.

Consideration of the lunar environment suggests modification of the Bayer-Hall approach leading to a conceptual process for extracting aluminum and oxygen from lunar soil. The process consists of electrowinning Al-Si-Fe-Ti alloy and oxygen from unrefined lunar soil in a bipolar fluoride type cell with inert anodes. Aluminum and other elements are recovered from the alloy by vacuum fractional distillation.

PRODUCTION OF SOLAR GRADE Si BY THE Na REDUCTION OF SILICON FLUORIDE COMPOUNDS,
A. Sanjurjo, L. Nanis, K. Sancier, R. Bartlett, SRI Internatinal, 333 Ravenswood
Ave., Menlo Park, CA 94025

New methods have been developed at SRI that produce Si at low cost and with low energy requirements. The starting materials, solid Na and Na_2SiF_6 powder, react to produce Si and NaF when heated together to 500°C . In an alternative method, the Na_2SiF_6 can be first thermally decomposed to produce SiF_4 gas which is then reduced by Na to Si. In both cases, Si and NaF are produced by a highly exothermic reaction.

Extraction of Si from the reaction products is accomplished by heating the granular Si-NaF mixture above the melting point of Si. At this temperature, the Si deposits in a pool at the bottom and NaF floats on top. The melt can be carried out in graphite crucibles since the NaF prevents the Si from contacting the crucible. Since the SiF_4 -Na reaction has an adiabatic temperature of 2200°K , the reaction itself can produce the heat needed for melt separation.

The purity obtained by either method is better than 99.999% Si, providing an excellent feedstock for solar cell fabrication.

CARBONATE-SILICATE-BASED OXYGEN PRODUCTION, J. R. Selman, Illinois Institute of Technology, Chicago, IL 60616

Although carbonates are not present on the Moon, molten alkali-carbonate mixtures have solvent properties and corrosion characteristics which make them very attractive as a base material in silicate processing for oxygen production and metal deposition. The electrochemistry of carbonate melts will be discussed with emphasis on oxygen production, CO_2 concentration, and carbonate reduction to carbon. Expected chemical and electrochemical behavior of carbonate-silicate melts will be used to formulate a carbonate recycling scheme.

REFINING AND RECYCLE OF MATERIALS IN SPACE, J. Paul Pemsler, Castle Technology Corporation, P. O. Box 403, Lexington, MA 02173

The advent of materials processing in space will bring with it the challenge of efficient utilization of materials and energy that exists today on earth. The space scenario will even further emphasize the interdependence of materials and energy. Efficient use of materials has come to include provisions for recycle in order to conserve both the materials themselves and also the energy required to extract them from their ores.

Recycle technology in space will be governed by some of the same considerations that govern primary extraction and processing such as avoiding storage and reuse of gases and not using carbonaceous reductants.

In this paper we consider recycle technology, largely electrorefining, for the metals aluminum, magnesium, titanium and solar grade silicon. The discussion will be general in nature and discuss the various options available.

ELECTRODIALYSIS, F. B. Leitz, U. S. Bureau of Reclamation, Denver, CO 80225

Basically, electrodialysis is a separation process. In its simplest aspect, ions of a particular charge pass from one flowing stream to another through a membrane under the influence of an electrical potential gradient. It is widely used as a salt removal process in water desalination and in deashing of cheese whey. It is also used as a salt concentration process in preparation of table salt from another by electro-dialysis has not yet been proven practical.

The purpose of this paper is to review electrodialysis as a process to determine if there are applications in processing of lunar materials.

Electrodialysis is presently used solely with aqueous solutions. While there is no reason that some other ionizing solvent could not be used, this area

is almost completely unexplored. Solute concentrations used range from a few parts per million to near saturation.

The useable temperature range for existing membranes is generally 0° to 45°C, although higher temperatures may be used. Design current densities are higher and power consumption is lower at the higher temperatures. A typical pressure range is between 100 and 400 kPa, the lower limit being that required to prevent boiling of the solvent.

Certain materials are hostile to electro dialysis membranes. These include suspended solids, tri- and tetravalent ions, certain types of organic ions and strong oxidants like chlorine.

Possible applications are:

- Separation of ionized salts from un-ionized material like soluble silica.
- Concentration of salts to near saturation.
- Stripping out of salts from waste streams.

Some modifications of present-day commercial equipment would be required to make the process suitable for cis-lunar applications.

ELECTROCHEMISTRY WORKSHOP

Technical Papers

PREPARATION OF CELL FEED MATERIALS FOR
ALUMINUM AND MAGNESIUM PRODUCTION

by

James A. Barclay¹

ABSTRACT

Magnesium chloride for electrolysis to magnesium in a fused-salt bath is made by reacting seawater with milk of lime to precipitate magnesium hydroxide, separating the latter from the barren seawater, dissolving the hydroxide in hydrochloric acid, and crystallizing and drying the compound $MgCl_2 \cdot 1.5H_2O$. Solar evaporation of Great Salt Lake brine, followed by spray drying, also is practiced. Dolomite may be calcined and ground to a fine powder to be mixed with ferrosilicon for reduction to magnesium in vacuum retorts by a nonelectrolytic process.

Alumina for smelting to aluminum in Hall-Heroult cells is prepared from bauxite by pressure digestion with strong NaOH solution, thickening and filtration to separate a waste "red mud," and crystallization of $Al_2O_3 \cdot 3H_2O$ in the presence of seed crystals. The $Al_2O_3 \cdot 3H_2O$ then is calcined to Al_2O_3 .

Bureau of Mines and other research on the recovery of alumina from nonbauxitic aluminous materials will be discussed, and possible application of acid leaching, alkaline sinter-caustic leaching, and carbochlorination processes to lunar materials will be briefly evaluated.

¹Staff Chemical Engineer, Division of Mineral Resources Technology, Bureau of Mines, U.S. Department of the Interior, Washington, D.C. 20241

CELL FEEDS FOR MAGNESIUM PRODUCTION

Magnesium is produced in the United States mainly by the fused-salt electrolysis of magnesium chloride obtained from seawater or brines, although some also is made by metallothermic reduction of magnesium oxide obtained from dolomite. A block flowsheet for the latter process is shown in figure 1. Cell feed preparation in this case involves nothing more than calcining the dolomite and pulverizing it to a fine powder.

Magnesium chloride for the electrolytic process may be obtained from seawater or from lake or well brines. For all practical purposes, the sea is an inexhaustible source. If 100 million tons of magnesium per year was extracted from the sea for 1 million years, the concentration of magnesium in seawater would only drop from 0.13% to 0.12%.

The Dow process for economic recovery of magnesium chloride from a solution as dilute as seawater is an excellent example of chemical engineering ingenuity, as shown in figure 2. The Freeport, Texas, plant of Dow Chemical Company originally used oyster shells dredged from Galveston Bay as the source of lime, as shown by the solid lines at upper left in the figure. An alternative processing route is shown by the dashed line, where dolomite is calcined to furnish the lime. This technique has the advantage of recovering the MgO content of the dolomite along with that precipitated from the seawater.

NL Industries, Inc., at its Rowley, Utah, plant, uses solar evaporation to concentrate magnesium chloride from the brine from Great Salt Lake, followed by spray drying to recover solid salt, as shown in figure 3. Three solar evaporation ponds cover about 40,000 acres, and 5,000,000 tons per

year of waste mixed salts are flushed back into Great Salt Lake. Excess chlorine over that required in the chlorinator shown in the flowsheet is sold as a byproduct.

CELL FEED FOR ALUMINUM PRODUCTION

Bauxite is the almost universally used raw material for aluminum production. It is a product of the weathering of aluminum silicate minerals, and principal deposits are found in a globe-circling belt near the equator, as shown in figure 4.

Bauxites vary widely in composition and appearance, but the principal constituents are alumina monohydrate, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, and alumina trihydrate, $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$. The main impurities are oxides of silicon, iron, and titanium. There are usually many trace impurities as well.

In order to prepare feed for aluminum electrolytic cells, the crude bauxite must be refined to pure alumina by the Bayer process. The conditions under which leaching of the ore is carried out differ considerable for bauxites that are mainly alumina monohydrate and those that are mainly trihydrate, as shown in table 1. In either case, however, pure alumina trihydrate is precipitated from the leach solutions, and is then calcined to anhydrous alumina as the final product. Figure 5 shows a flowsheet for the Bayer process. The product is extremely pure, as is shown in table 2.

BUREAU OF MINES ALUMINA RESEARCH

Although the United States produces about 30% of the world's primary aluminum, it must import more than 90% of the raw materials needed. This high dependence upon imports prompted the Bureau of Mines in 1973 to begin an extensive R&D project to test, improve, and evaluate several processes

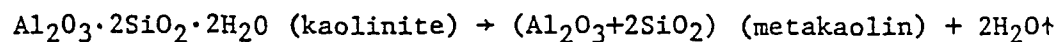
for recovering alumina from domestic nonbauxitic raw materials. Two of the processes were based on alunite $[K_2SO_4 \cdot Al_2(SO_4)_3 \cdot 4Al(OH)_3]$, and dawsonite $[NaAl(OH)_2CO_3]$, minerals that are unlikely to be found on the moon, so they will not be discussed here.

If discussion is restricted to the aluminosilicate minerals, which have been shown to be typical constituents of moon rocks and soils, there are three approaches for recovering alumina--

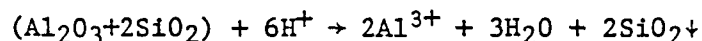
- acid (hydrochloric, nitric, sulfuric, or sulfurous) leaching-thermal decomposition
- alkaline sintering-caustic leaching
- carbochlorination

Key reactions in acid leaching processes for clay are--

Calcination ($\sim 750^\circ C$)



Leaching



Thermal Decomposition ($\sim 950^\circ C$)

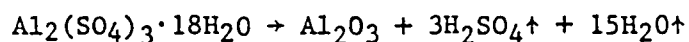
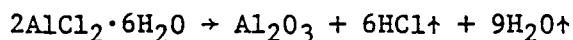
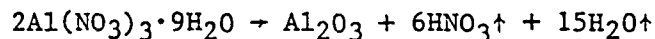
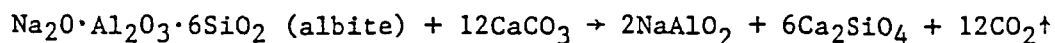
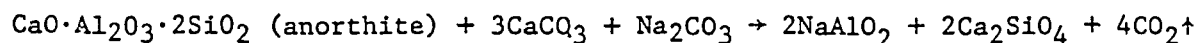


Figure 6 shows a block flowsheet for the clay-hydrochloric acid process. A double precipitation with HCl gas has been found necessary in order to obtain an alumina product meeting the specifications for P_2O_5 and MgO. A two-step thermal decomposition is planned in order to minimize materials of construction problems, simplify HCl recovery, and to

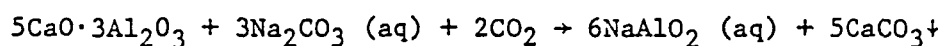
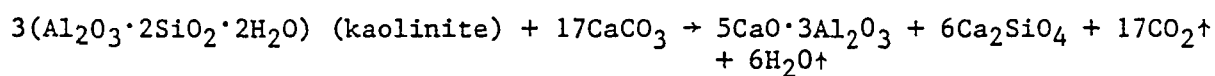
enable the maximum use of coal as the source of the energy needed for the decomposition.

The key reactions for the alkaline sinter processes are--

Anorthosite



Clay



Precipitation

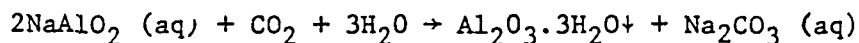
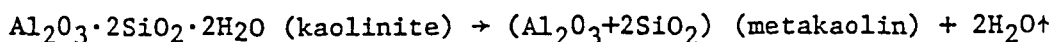


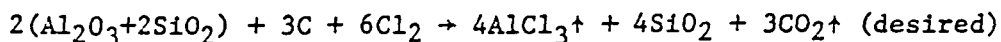
Figure 7 shows a block flowsheet for the anorthosite-alkaline sinter process. This process is energy intensive, partly because of the need to grind the anorthosite to a very fine powder before pelletizing and sintering, and partly because of the high ($\sim 1,330^\circ \text{C}$) required for sintering. The soaking and "dusting" step avoids the need to grind the sinter product before leaching. By holding the sintered pellets at about 700°C for $\frac{1}{2}$ hour, a phase change from β -dicalcium silicate to γ -dicalcium silicate takes place, and the sinter falls to a powder on cooling.

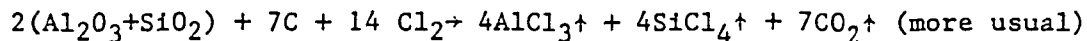
Key reactions for the carbochlorination process are--

Calcination

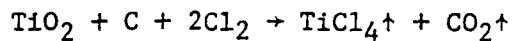
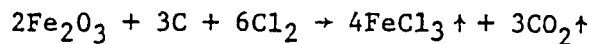


Chlorination





Impurity Reactions



Oxidation

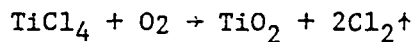
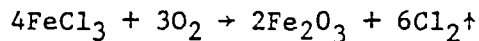
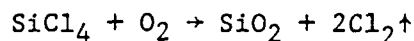
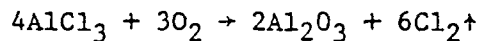


Figure 8 shows a block flowsheet for the carbochlorination of clay. It should be noted that this is a completely dry reaction, and that the chlorine, except for losses, is recycled.

Bureau of Mines research, coupled with a feasibility study contracted to Kaiser Engineers, led to the conclusion that in the United States, the clay-hydrochloric acid process using HCl gas sparging crystallization to separate aluminum chloride hexahydrate, is the most likely to be commercially competitive with the Bayer-bauxite process. Alkaline sinter processes are more costly both to build and to operate and are energy intensive. Carbochlorination holds promise, but there are a number of important technical problems for which there are insufficient large-scale test results to make good decisions.

As far as processing on the moon is concerned, there are major problems with all three techniques. Presumably, there has not been on the moon the kind of weathering of aluminum silicate rocks that has occurred on earth. Thus acid leaching processes are less favorable than alkaline sinter processes. The Bureau of Mines is working on a fluoride-catalyzed acid leach

of clay or anorthosite which is promising, but at present the fluoride consumption is high and there are unsolved problems related to recovering and recycling acid values from alkali and alkaline earth constituents of the raw materials.

On the other hand, to use the alkaline sinter process would require a large supply of limestone--twice the weight of the anorthosite processed. The waste product, dicalcium silicate, cannot be recycled, although it is a useful raw material for making portland cement.

In either of the two above cases, large volumes of aqueous solutions are involved, and settling and thickening to separate solids from liquids is practiced. In the low-gravity lunar environment, these operations would be difficult to carry out.

As mentioned, carbochlorination is a dry process, but both chlorine (the initial charge plus makeup) and carbon (all consumed) would have to be transported to the moon. Processing problems still requiring large-scale testing are--

- catalysts to speed up the chlorination reactions (NaCl , KAlCl_4 , and BCl_3 are mentioned in patents)
- modifiers to inhibit chlorination of the silica content of the material being chlorinated (oxyanions of alkali metals, such as Na_2CO_3 have been patented)
- separation of the various chlorinated species (there are large differences in boiling points, but vapor complexes are known)
- oxidation of the purified AlCl_3 to Al_2O_3 (the technology would be similar to that used to make TiO_2 pigment, but has not been tested)

- materials of construction (possibly not a major problem, but requires investigation)
- materials handling (need for a closed system; transporting hot, corrosive gases and solids)

Rather than oxidize the AlCl_3 primary product to Al_2O_3 for smelting in a conventional Hall-Heroult cell, it may be desirable to electrolyze the AlCl_3 to metal directly in a fused-salt bath, as in the Alcoa process. In either case, Cl_2 is recovered for recycling. As 30% less electrical energy is apparently required for smelting the chloride to metal than is required in the best oxide smelting cells, the preparation of metal by fused-salt electrolysis seem to be most attractive, provided the lunar aluminum silicate minerals can be chlorinated effectively.

Table 1. - Comparison of Bayer process leaching conditions ($\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ ratio = 1.6-1.8).

Bauxite type	Caustic conc., g/l		Temp., ° C	Time, hr
	Total Na_2O	Free Na_2O		
Trihydrate	140	90	140	1
Monohydrate	300-350	270-315	170-180	2-8

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TABLE 2. - Specifications for cell-grade alumina (May 1979).

<u>Impurity</u>	<u>Allowable conc.,%</u>	<u>Impurity</u>	<u>Allowable conc.,%</u>
SiO_2	0.025 (0.015)	NiO	0.005
Fe_2O_3	.030	MnO	.002
Na_2O	.40	MgO	.002
CaO	.06 (.04)	V_2O_5	.002
Ga_2O_3	.02	Cr_2O_3	.002
ZnO	.02 (.01)	B_2O_3	.001
CuO	.01	P_2O_5	.001
K_2O	.005	Cl	.1 (.05)
TiO_2	.005 (.002)		

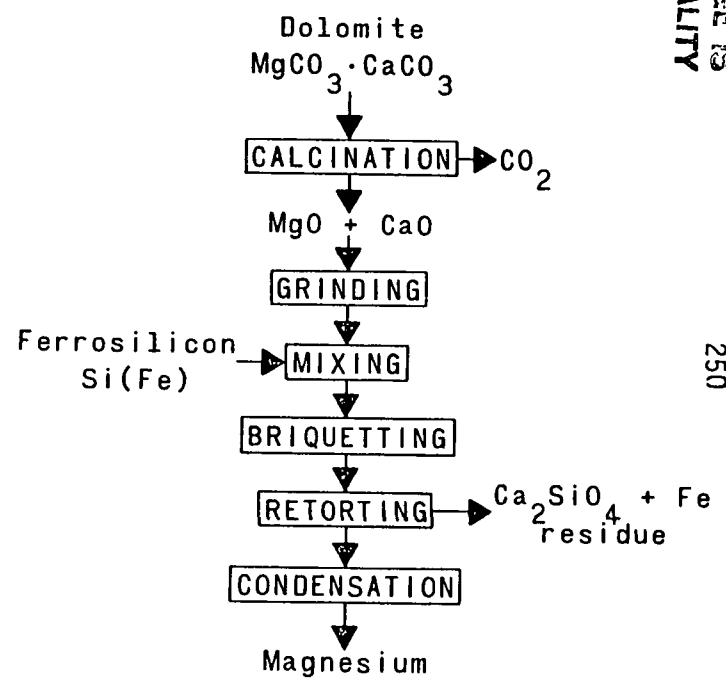
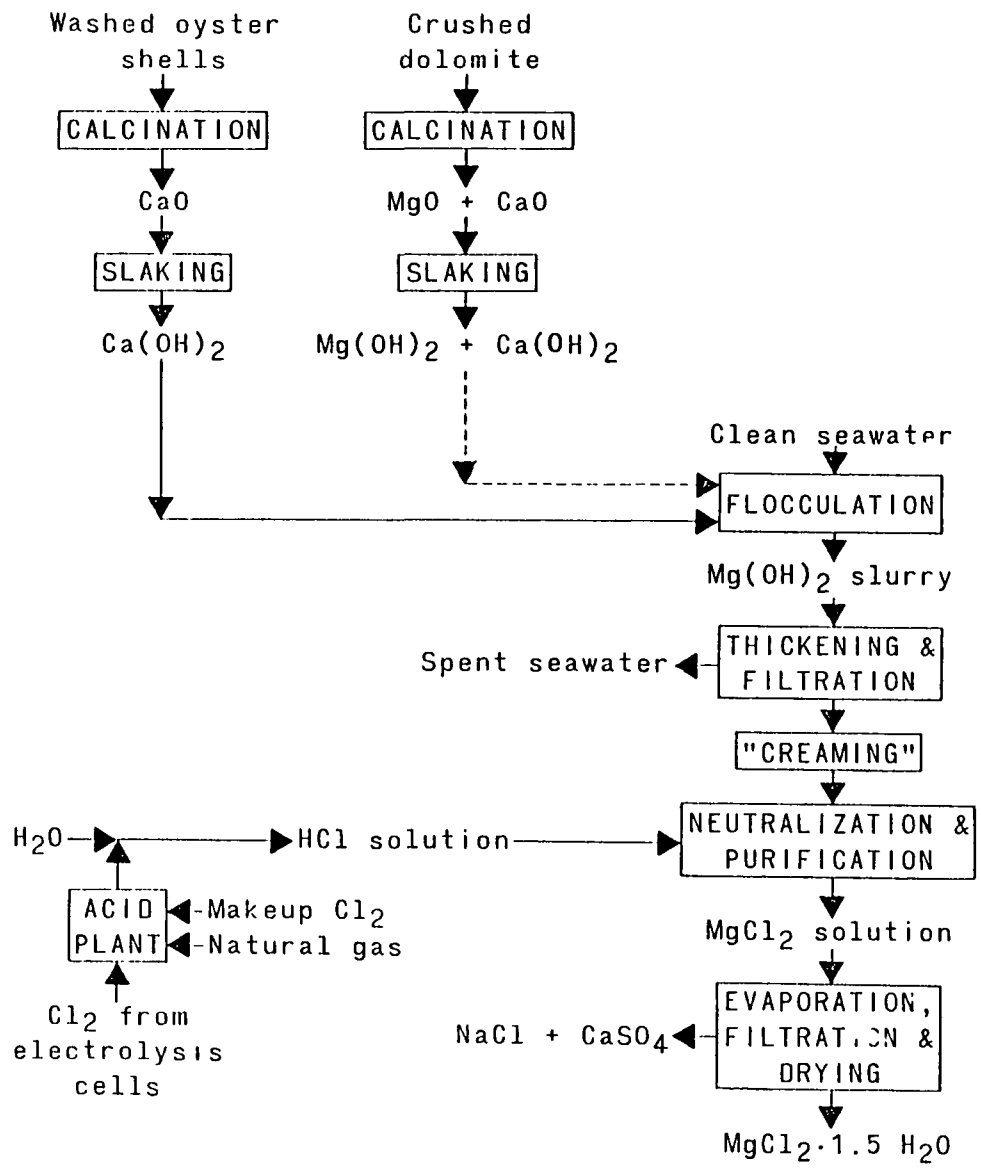
Particle size (dry screening)
 Plus 100-mesh 10% maximum (5%)
 Minus 325-mesh 10% maximum

Surface area 45 m^2/g minimum

Alpha-alumina content 10%-25%

Values in parentheses are target values.

FIGURE 2. - Block flowsheet for Dow process for magnesium chloride from seawater.



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FIGURE 1. - Block flowsheet for ferrosilicon reduction process for magnesium.

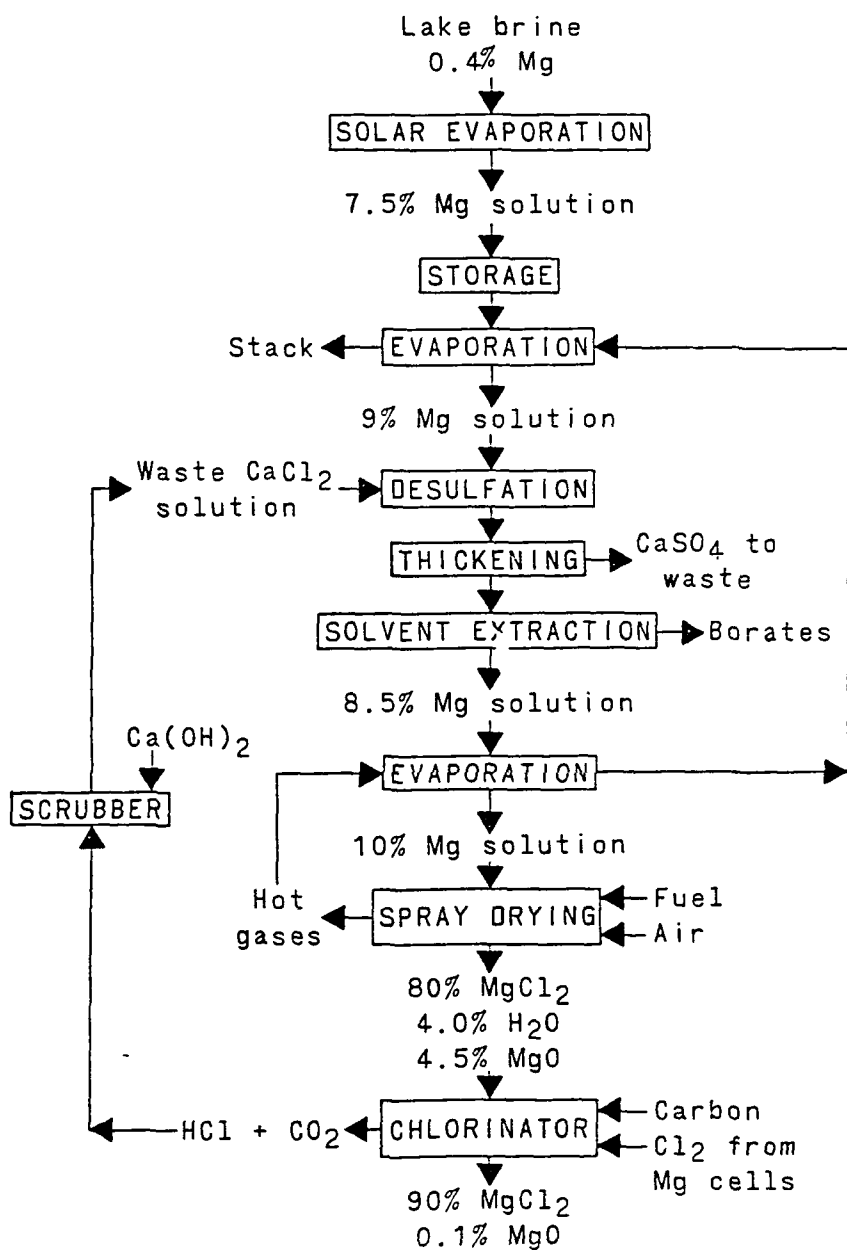
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FIGURE 3. - Block flowsheet for NL Industries process for magnesium chloride from the Great Salt Lake.

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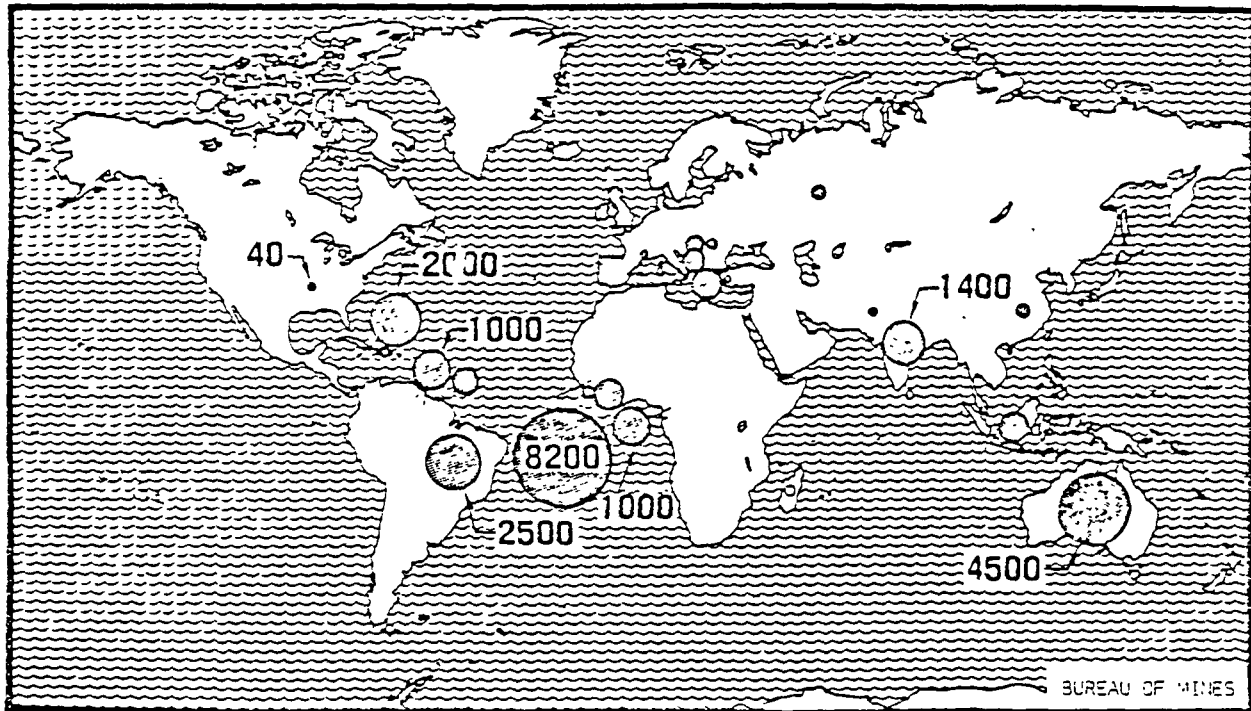


FIGURE 4. - World bauxite reserves (millions of long tons).

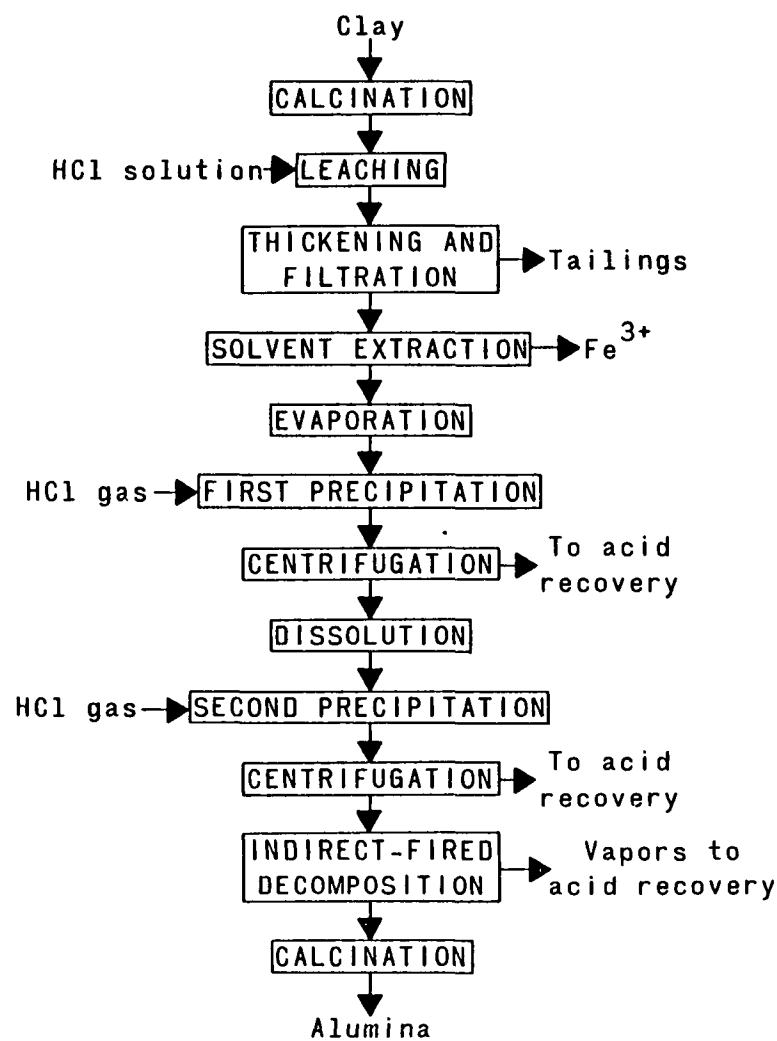


FIGURE 6. - Block flowsheet for clay-HCl, HCl gas sparging process.

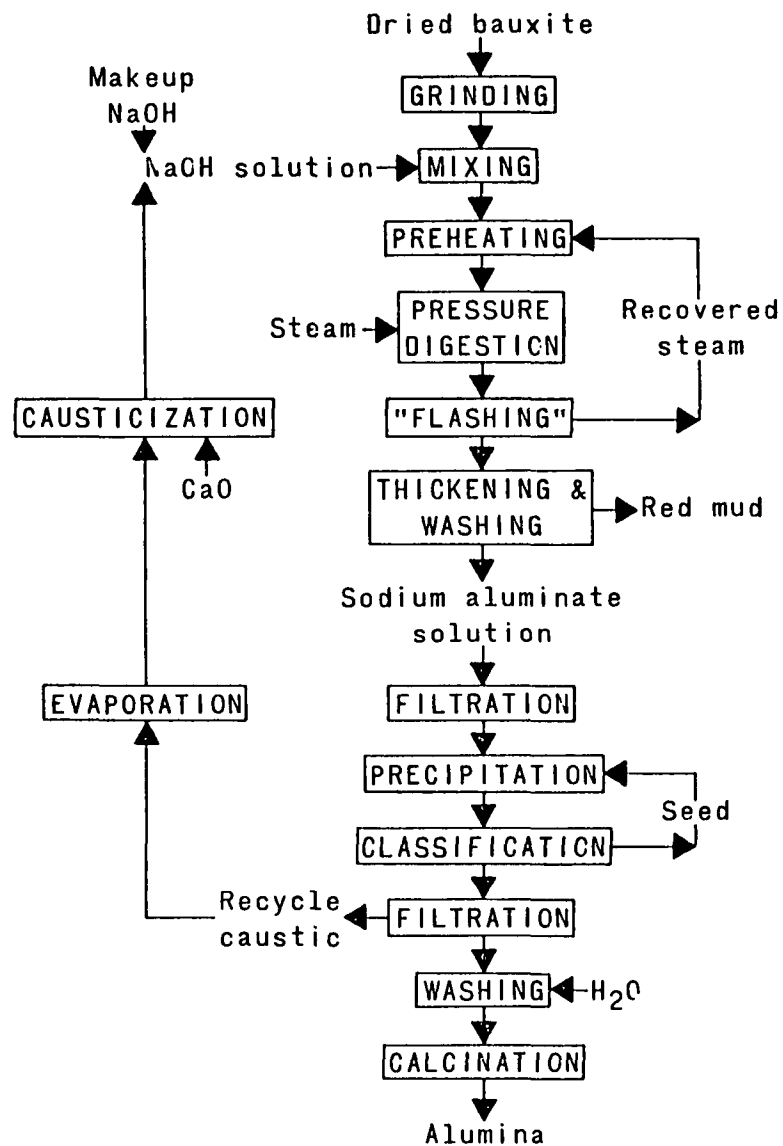


FIGURE 5. - Block flowsheet for Bayer-bauxite process

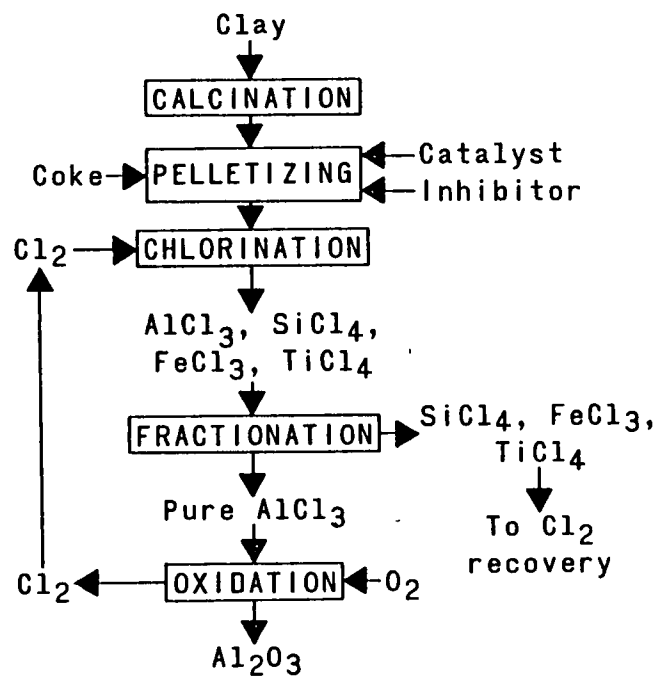


FIGURE 8. - Block flowsheet for clay carbochlorination process.

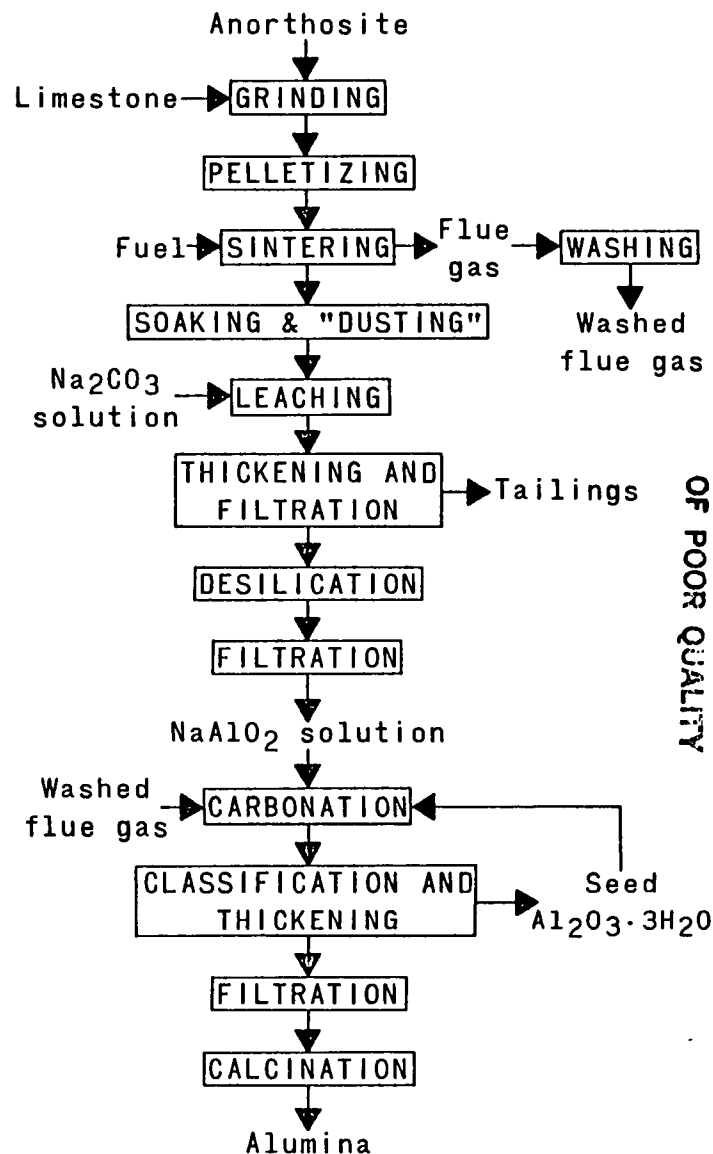


FIGURE 7. - Block flowsheet for anorthosite-alkaline sinter process.

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EXTRACTION OF OXYGEN AND METALS
FROM LUNAR ORES

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I. Abstract

Consideration of the lunar environment suggests modifications of the Bayer-Hall approach leading to a conceptual process for extracting aluminum and oxygen from lunar soil. The process consists of electrowinning aluminum-silicon-iron-titanium alloy and oxygen from unrefined soil in a bipolar fluoride type cell with inert electrodes. Aluminum and other elements would be recovered from the alloy by vacuum fractional distillation. The silicon produced would be used to produce solar cells for additional electrical power.

II. Introduction

Energy is the major factor that encourages us to consider space industrialization. Terrestrial energy needs have increased to such huge levels that serious consideration is being given to constructing large solar power stations (SPS) in space to convert solar energy into microwave power and then beam microwaves to the earth for reconversion to terrestrial electricity. Solar energy is clearly available continuously to do work in space and space industrialization is technically feasible. However, the development of a space materials economy or space industrialization is strongly inhibited by the extremely high cost of transporting matter from earth with which to work in space.

The moon is a primary source of raw material for large scale use in space. The motivations for use of lunar materials are:

1. The moon is the largest source of matter near the earth. We possess considerable general knowledge of the entire moon and extremely precise knowledge of the specific areas of the moon.
2. Terrestrial technology can be transferred to the gathering of lunar materials and the processing of raw lunar materials into industrial feedstock. Devices and tools have been identified that can allow us to obtain materials from the moon for large scale use in space at considerably lower cost than will ever be possible by transporting materials into space from the earth.

Because the lunar escape energy is 5% of that of the earth, the cost of lunar ejections (by means of electromagnetic launchers) could be in the order of a few cents per kilogram. In addition, the moon has no atmosphere to cause drag and frictional heating.

3. The moon offers a large supply of the elements with which industry has experience in working and producing the broad range of goods that sustain our present style of life. About 92% of chemical elements used on the earth, exclusive of fossil fuels, can be obtained from lunar soil. The economically significant elements, like oxygen, silicon, calcium, iron, aluminum, magnesium and titanium, can be extracted from the lunar soil. Space power stations could be constructed of approximately 90% lunar derived material.

III. Lunar Environment

The principal distinguishing requirement for a successful lunar operation is that all materials unavailable from lunar sources must be shipped from earth and recycled with minimal loss.

The following constraints apply to processing lunar ore:

1. Lack of virtually inexhaustible supplies of air and water.
2. Lack of fossil fuels.
3. Lack of inexhaustible oxidizing and reducing agents.

Carbon is very scarce on the lunar surface.

4. Lack of expendable halogens, acids and bases.
5. Lack of air and water makes the management of process waste heat especially important. Rejected heat will ultimately have to be transferred to space through radiation.
6. Processing conditions must be adjusted for the lower lunar gravity.

IV. Lunar Ore

The major lunar raw materials are ilmenite, plagioclase and anorthite. Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) contains 19.4% aluminum, 20.2% silicon, 14.4% calcium, and 46% oxygen. A typical composition of lunar rock from Maria section would be silica 42%, titanium dioxide (TiO_2) 7.5%, alumina 13.9%, iron oxide (FeO) 15.7%, magnesium oxide (MgO) 7.9%, calcium oxide (CaO) 12.1%. The composition of lunar rock from the highland area would be silica 45.4%, TiO_2 0.5%, alumina 23.4%, FeO 7.4%, MgO 9.2%, CaO 13.4%, and traces of potassium oxide, sodium oxide, manganese oxide, phosphorus oxide, and chromium oxide. (1)

The majority of lunar soil is completely anhydrous and has an average grain size of 30-70 microns. Eighty-five percent to 95 wt.% of the lunar powder is less than 1 mm in diameter.

V. Review of Lunar Extraction Processes

Since carbon is very scarce on lunar surface, Rao and co-workers⁽²⁾ decided quite early that carbothermic reduction of lunar soil would probably be impractical for space processing. They chose carbo-chlorination of lunar anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and lunar ilmenite (FeTiO_3). A major advantage of carbo-chlorination is that it would require little water. However, the recycling of chlorine and carbon would require facilities much larger than the basic processing plant.

Of the nonelectrolytic processes studied to date, the hydrofluoric acid leach method appears to require the minimum operating mass to be transported to the moon. Waldron, et al,⁽¹⁾ have described a low temperature hydrometallurgical step to remove the silicon from the other metallic oxides by conversion to fluorides and fluosilicates. This is followed by vaporization of the silica as SiF_4 , and separation of the calcium and the structural metals (aluminum, iron, magnesium, titanium) by a variety of solution, precipitation, ion exchange or electrolyte steps. However, this process requires water or at least hydrogen to make water. This must be transported from earth.

Electrolytic systems to process lunar materials have a strong appeal because of their potential simplicity and low use of water and other reagents.

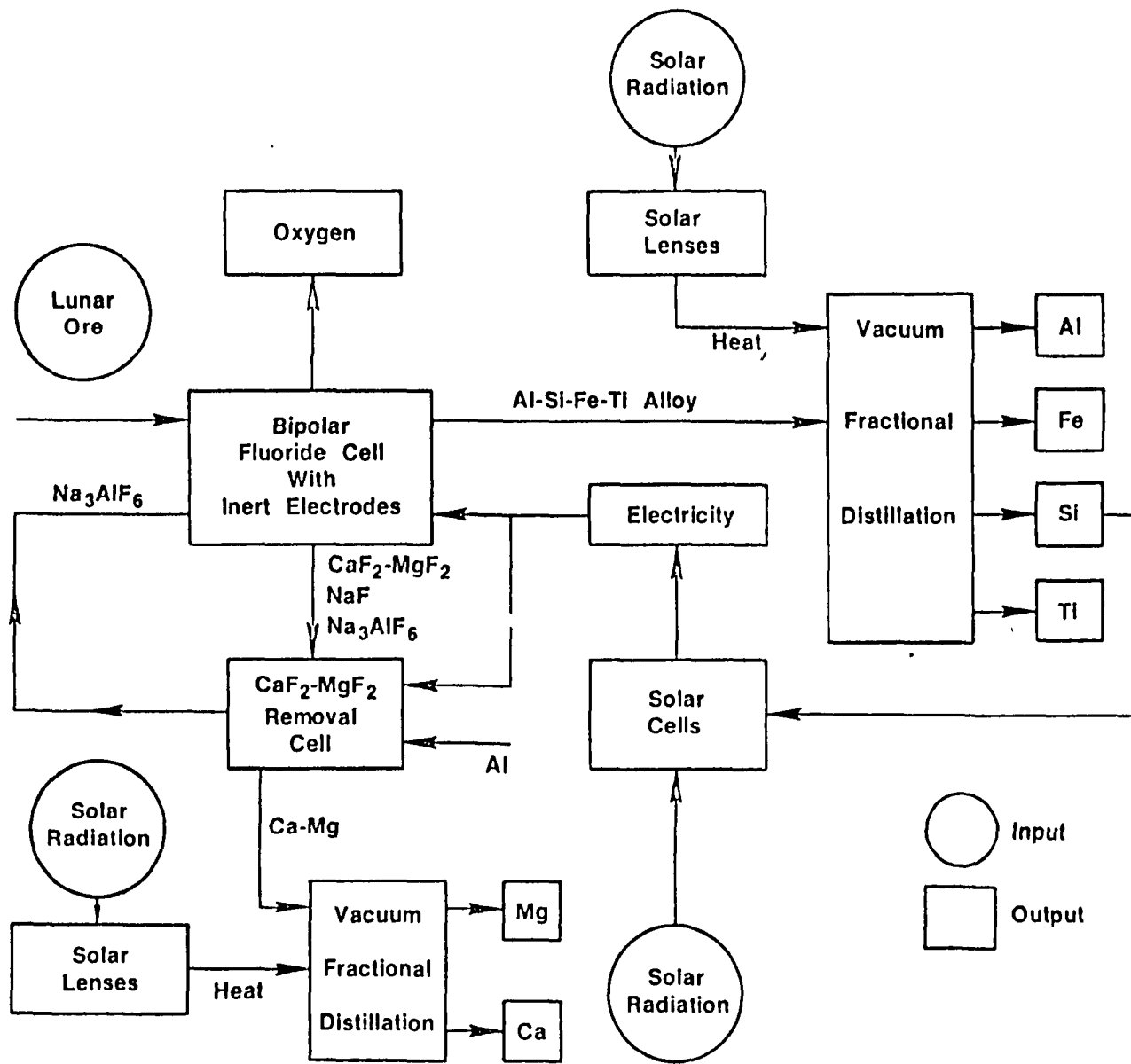
Limited investigation of direct electrolysis of molten silicates of compositions similar to lunar soils have been performed.^(3,4) The high melting point and the viscosity of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the reagentless advantage of the direct electrolysis route and requires consideration of extraction and recycling of fluxing reagents. The chief objections are corrosion or durability of anodes used for oxygen recovery and purification and separation of cathodic reduction products which are likely to consist of iron, iron-silicon-aluminum alloy with minor amounts of additional impurities.

VI. Proposed Process

This paper describes a conceptual process scheme for obtaining oxygen, aluminum, silicon, iron, and titanium from anorthite ore. The lunar environment offers the following opportunities:

1. The abundant solar energy can be converted to electricity to operate electrolytic cells for producing an aluminum alloy and pure oxygen from lunar ores.
2. The complete vacuum (10^{-14} torr) offers a chance to vacuum purify and separate aluminum, iron, silicon, and titanium metals from aluminum-silicon-iron-titanium alloys produced in the electrolytic cell.
3. By using suitable optics, solar energy can generate the high temperatures needed for vacuum fractional distillation.

Figure 1 shows a schematic flow diagram of the proposed process for extracting desirable metals from lunar



Proposed System For Lunar Extraction
Of Oxygen And Metals
Figure 1

ores; it also produces oxygen for life support and for use as propellants.

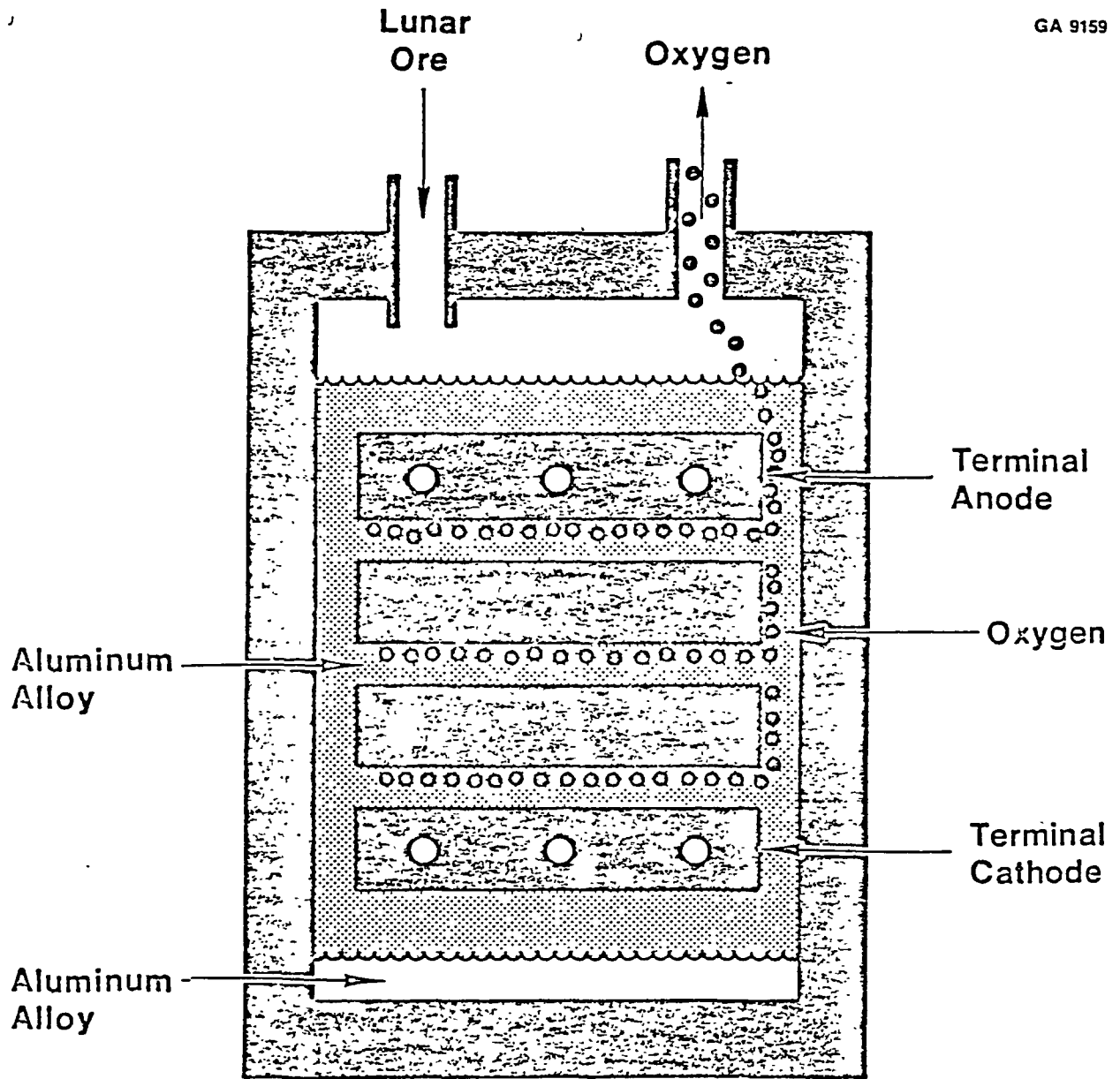
VII. Bipolar Electrolytic Cells

In the proposed system, either unbeneficiated or mechanically beneficiated lunar dust would be used as ore. The fine particle size of the dust makes magnetic and electrostatic separation attractive. No grinding is necessary. All use of water would be avoided. The ore would be fed into a bipolar cell having a cryolite (Na_3AlF_6) base electrolyte. Lunar ore should dissolve easily in molten cryolite. The solubility in cryolite and the decomposition potentials of the various oxides in lunar ores are shown in Table 1.

The proposed bipolar cell would be similar to that used in the Alcoa Smelting Process for electrolysis of aluminum from aluminum chloride in molten chloroaluminate melts (Figure 2). Electric current would enter the cell through a terminal anode, flow through numerous bipolar plates between the terminal electrodes and exit through a terminal cathode. The top surface of each bipolar plate would act as a cathode while the bottom surface would act as an anode. The alumina (Al_2O_3), silica (SiO_2), ferrous oxide (FeO), and titania (TiO_2) content of the ore would be electrolyzed, forming oxygen at each anode and an aluminum, silicon, iron and titanium alloy at each cathode. Oxygen gas would rise from each anode through the electrolyte providing circulation of the electrolyte and leave the cell at the top while the metal alloy would settle to the bottom and be tapped periodically. Calcium and magnesium compounds from the ore would accumulate in the electrolyte and have to be removed. A technique to accomplish this will be discussed in the next section.

TABLE 1

<u>Oxides .,</u>	<u>Solubility in Cryolite at 970°C (%)</u>	<u>Decomposition Potential at 970°C (volts)</u>
Al ₂ O ₃	11	2.2
SiO ₂	8.8	1.8
FeO	6	1.0
TiO ₂	6.9	1.9



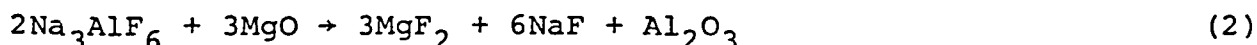
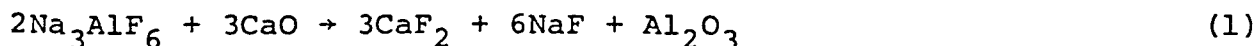
Bipolar Cell

Figure 2

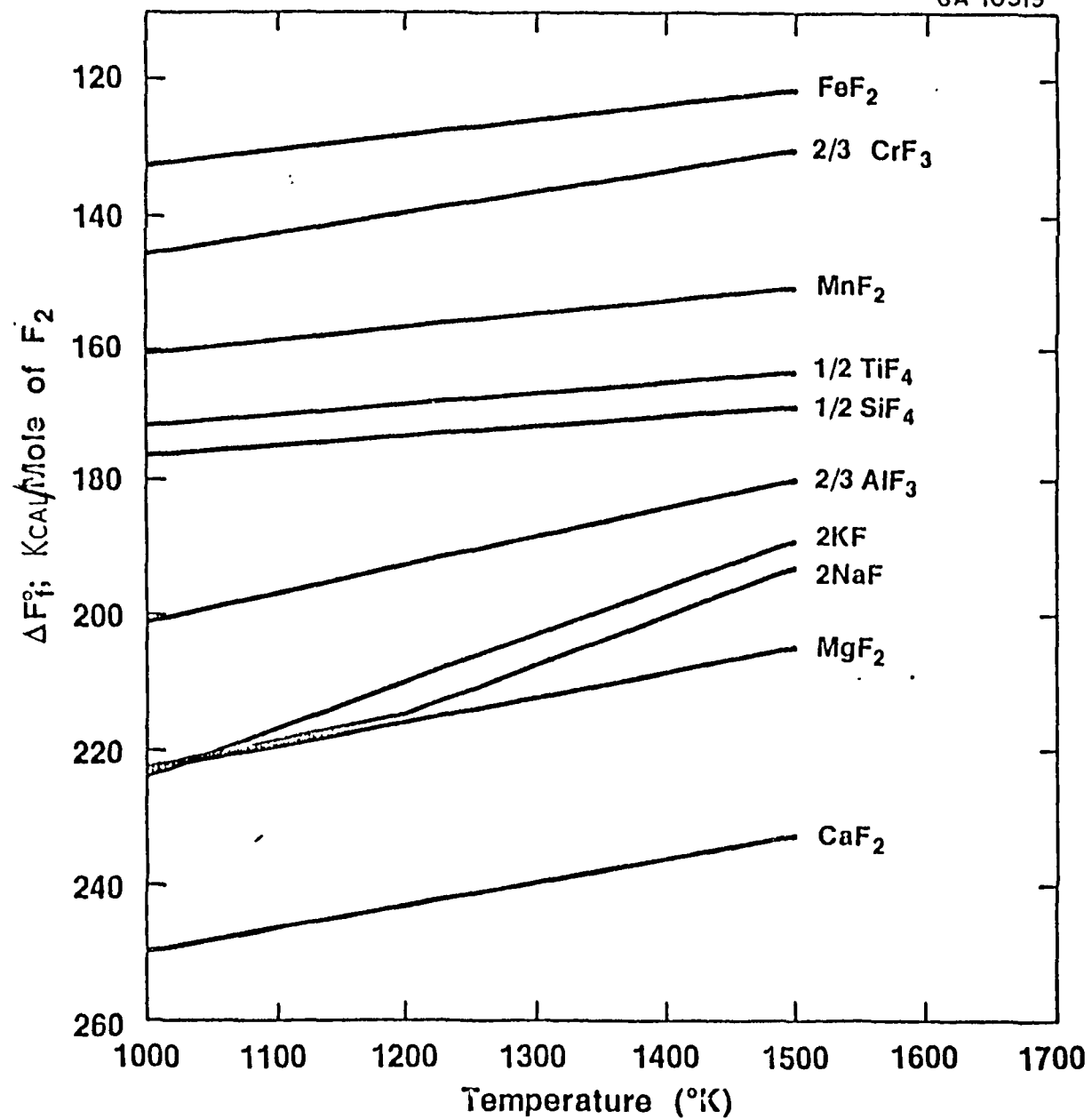
Search for an inert anode material is being pursued actively by various aluminum companies. Not only would inert anodes alleviate the need for frequent replacement of consumable anodes but would also permit collection of essentially pure oxygen. Tin oxide (SnO_2) mixed with various other oxides such as ferric oxide (Fe_2O_3) and nickel oxide (NiO) have been suggested for inert anodes.⁽⁵⁾ Refractory hard metals, titanium diboride (TiB_2) in particular, presumably will make suitable inert cathodes.⁽⁶⁾

VIII. Electrolyte Purification and Recycling System

Since calcium fluoride and magnesium fluoride are thermodynamically more stable than aluminum fluoride (Figure 3), the calcium oxide and magnesium oxide content of the lunar feed material would undergo the following reactions:



Calcium fluoride and magnesium fluoride dissolve in the electrolyte, lowering electrical conductivity, ore solubility and liquidus temperature. Their concentration will be allowed to build up until they pose an operation problem in the electrolytic cell. Once this limit approaches, the electrolyte will be purified. An attractive technique for this purification would be to discontinue feeding ore. When the oxides have been exhausted, the cell will start to electrolyze calcium and magnesium fluorides, at a somewhat higher voltage, producing fluorine instead of oxygen and a Ca-Mg alloy instead of the Al-Si-Ti-Fe alloy (Reaction 3). It might be more convenient to take a side stream of electrolyte off from the main cell

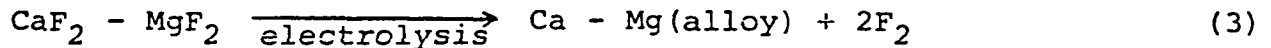


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Free Energy Of Formation Of Selected Fluorides
As A Function Of Temperature

Figure 3

and do this electrolysis in a separate small electrolytic cell:



The fluorine gas produced will be reacted with aluminum to make aluminum fluoride. This will be added back to the aluminum producing cells where it will combine with sodium fluoride to produce cryolite.



Calcium magnesium alloy produced by Reaction 3 can further be separated into its constituent elements calcium and magnesium by vacuum fractional distillation.

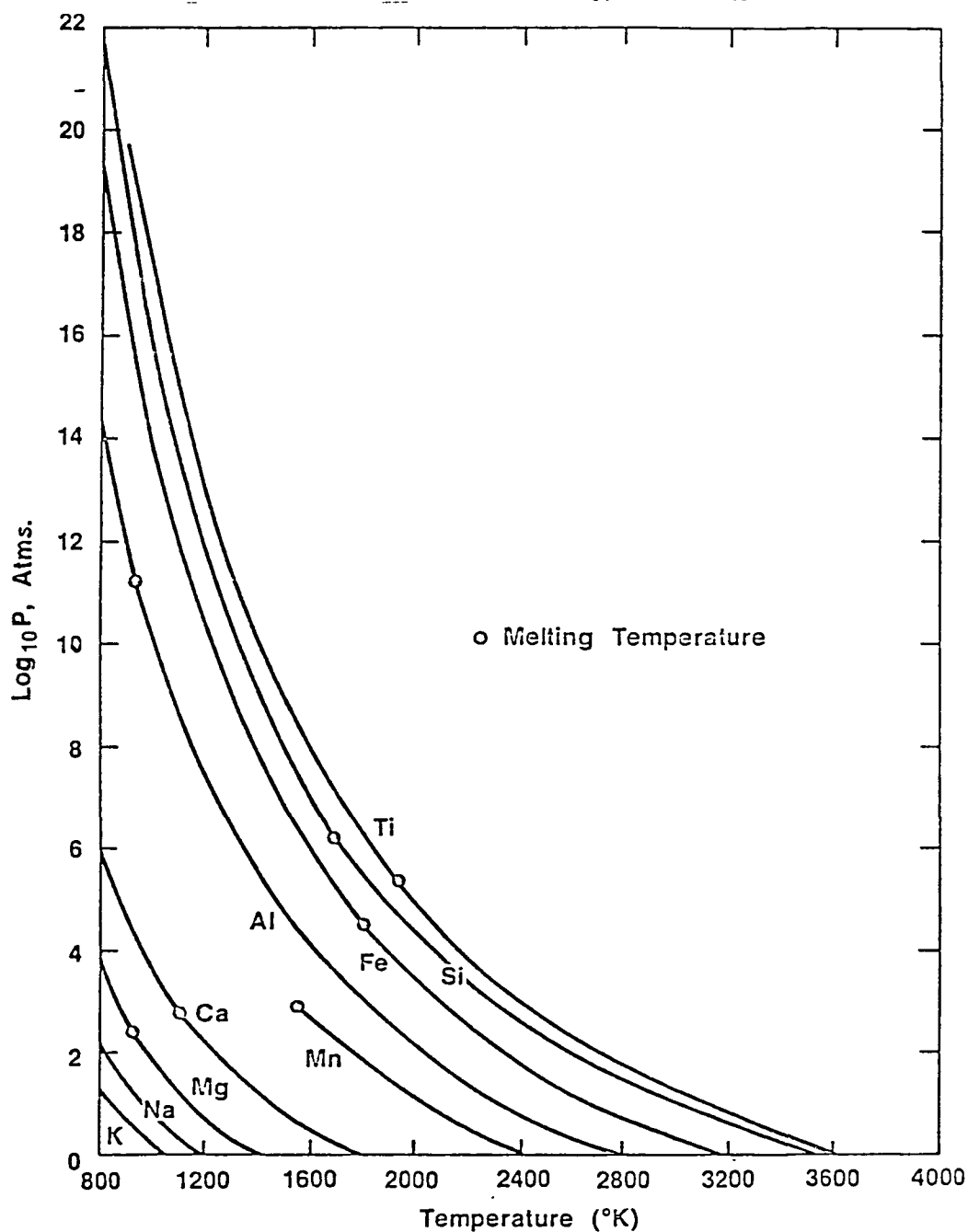
IX. Purification of Aluminum Alloy

The existence of near vacuum (about 10^{-14} torr) on the lunar surface, absence of any oxidizing gas, and wide differences in the vapor pressure of different elements (Figure 4) make the vacuum fractional distillation technically feasible for separating the Al-Si-Fe-Ti alloy into its constituent elements.

X. References

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2. Rao, D.B., et al, NASA SP-428, 1979, U.S. Govt. Printing Office.
3. Kesterke, D., U.S. Dept. of Interior, Bureau of Mines, Report of Investigation RI 7587 (1971).
4. Lindstrom, D.J. and Haskin, L.A., Fourth Princeton/AlAA Conference on Space Manufacturing Facilities, Princeton, N.J., May 14-17, 1979.
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6. U.S. Patent 3,400,061.

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Vapor Pressure Of Selected Elements
As A Function Of Temperature

Figure 4

MAGNESIUM REDUCTION PROCESSES

by

T. E. Leontis and L. E. Vaaler

BATTELLE
Columbus Laboratories
Columbus, OhioINTRODUCTION

The availability and use of magnesium in the scenario that is developing for an extra-terrestrial plant to process lunar materials has been discussed by Dr. Criswell at this conference and in more detail in published papers and in particular in the NASA final report of September 30, 1978. In discussing how electrochemistry (and electrothermics) may find use in such a plant we will not necessarily indicate where the reduction will fit into specific flow sheets. Nevertheless, we will bear in mind some of the more likely compounds of magnesium that will result from the proposed processing steps and some of the materials that will be in short supply or likely to be difficult to recycle, e.g., carbon. We will first discuss the presently employed methods for producing magnesium and indicate how they may or may not be adapted to processing under reduced gravity conditions. Then we will discuss some other methods that have been tried experimentally that could be uniquely adapted to space processing.

COMMERCIAL METHODS

Much of the following information is taken from a report prepared by Battelle's Columbus Laboratories for Argonne National

Laboratory⁽¹⁾, A Survey of Electrochemical Metal Winning Processes.

This latter report was concerned with present and future energy use for metal winning processes.

The principal processes by which primary magnesium can be produced are: (1) fused-salt electrolysis of $MgCl_2$; and (2) silicothermic reduction of MgO ; and (3) carbothermic reduction of MgO .

There are two distinct electrolytic processes in use: (1) the Dow sea-water process using partially dehydrated cell feed, $MgCl_2 \cdot 1.5H_2O$, and (2) the process developed in Germany by I. G. Farben which requires anhydrous $MgCl_2$ as cell feed. The silicothermic process using ferrosilicon as the reductant, was developed in Canada as a commercially viable process by L. M. Pidgeon. It was a batch process using a relatively small externally-heated reactor; two different versions of it are now in use. The Magnetherm process developed in France uses a fluid-slag continuous reactor with a batch-type magnesium condenser. The Amati process, used at Bolzano, Italy, has not been described in the literature but is known to be a batch process using an internally-heated reactor much larger than the Pidgeon reactor. The carbothermic process was developed in Austria by Hansgirg; it is described only in the patent literature and in a Bureau of Mines report. This report presents a detailed analysis of operating variables and costs based on a World War II production plant. This process is no longer used any place in the world. All these processes were used in the USA and various other countries to meet the inordinately large demand for magnesium during World War II. Following the war the demand dropped precipitously and competitive forces completely eliminated the use of thermal reduction processes in the USA for many years.

The Dow Seawater/Electrolytic Process

A schematic flow diagram of the Dow seawater/electrolytic process is shown in Figure 1⁽²⁾. Currently the principal raw materials for this process are seawater, dolomite, salt, and fuels. Seawater is delivered to the plant by 268,000 liter (71,000 gal)/min pumps through suitable screens to remove fish and debris along an earthen flume that runs the width of the plant. Crushed dolomite is calcined at 1000-1100° C (1800 to 2000° F) in 2.9 meter (9.5 ft) diameter, 80.8 meter (265 ft) long horizontal rotary kilns. The white-hot dolime is converted to milk of dolime in a rotary slaker and mixed under vigorous agitation with seawater in a concrete flocculator. The degree of agitation and control of pH are critical factors in this operation in order to produce an easily filterable $Mg(OH)_2$ product and to prevent the co-precipitation of $B(OH)_3$ which would be carried through to the electrolytic cell and drastically reduce its operating efficiency.

The limed seawater then goes to 152 meter (500 ft)-diameter Dorr settling tanks from which a 20 percent $Mg(OH)_2$ slurry is harvested and the spent seawater overflows into peripheral launders for subsequent waste disposal. The magnesium hydroxide slurry is filtered, diluted to 50 percent slurry and neutralized with HCl to produce a 35 percent solution of $MgCl_2$. This is then concentrated to 50 percent by evaporation, spray dried at 171° C (340° F) and finally dried in air on shelf driers from which it emerges at 449° C (840° F) as a free-flowing granular solid. It has the approximate composition $MgCl_2 \cdot 1.5H_2O$ and goes directly to the electrolytic cells.

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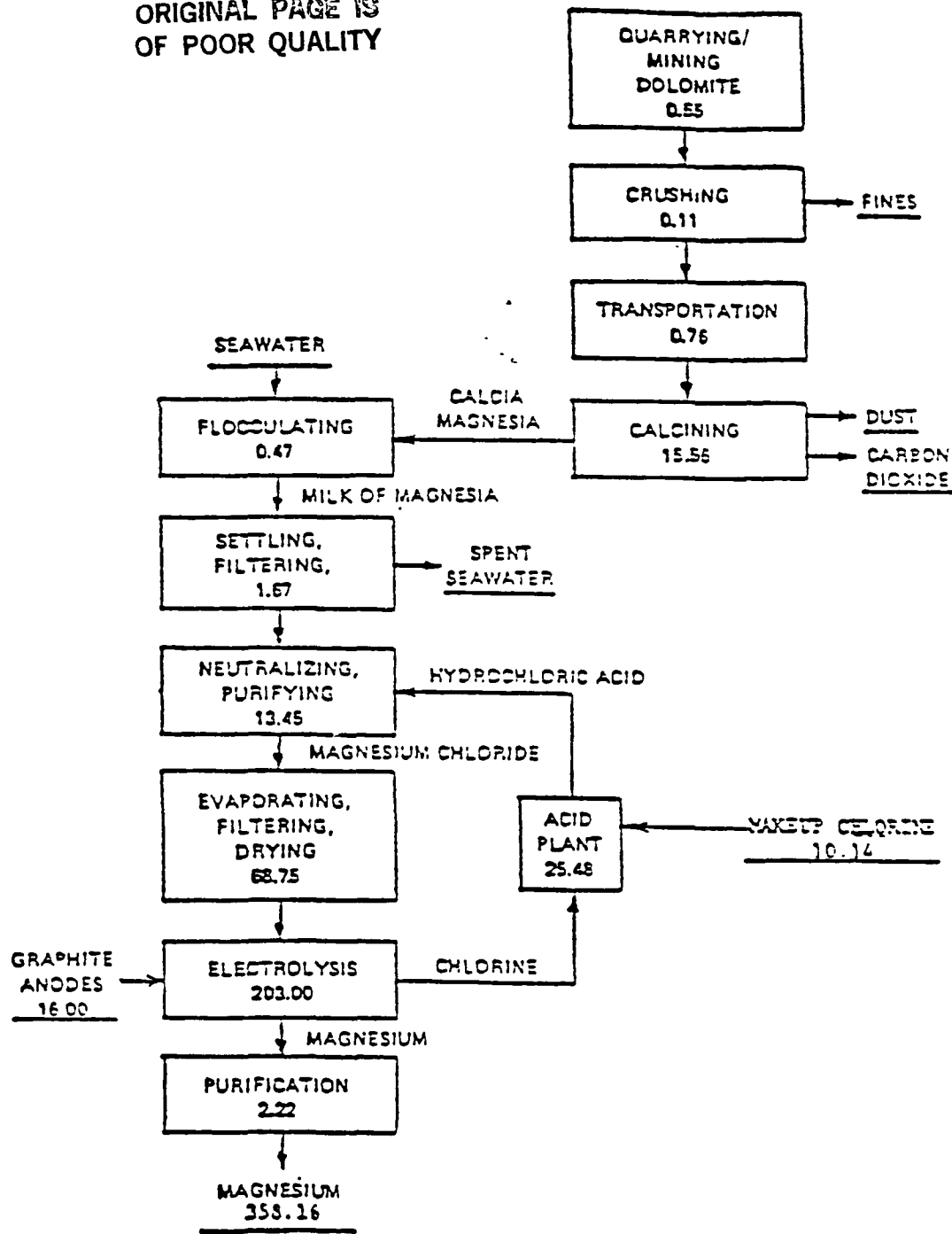


FIGURE 1. PROCESS AND ENERGY FLOWSHEET FOR THE DOW SEAWATER/ELECTROLYTIC PRODUCTION PROCESS
(Units are 10^6 Btu/S ton Mg)

The Dow Cell is a large steel pot about 1.5 meters (5 ft) wide 1.8 meters (6 ft) deep and 4.0 meters (13 ft) long, externally-fired in a refractory-lined setting. Twenty-two graphite anodes 20 cm (8 inches) in diameter by 2.7 meters (9 ft) long are suspended through an arched refractory cover in each cell. The steel pot and the steel baffles around each anode act as the cathode. The granular cell feed is introduced into the top of the cell continuously except during metal removal. The fused-salt electrolyte consists of approximately 20 percent $MgCl_2$, 20 percent $CaCl_2$, and 60 percent $NaCl$ and is operated at a temperature between $700^\circ C$ ($1290^\circ F$) and $720^\circ C$ ($1330^\circ F$) maintained by controlled external gas-firing. Twenty-seven cells are housed in one building and identical buildings are arranged in groups of four each. Thus, a pot line consists of 108 cells of which normally 100 operate in series at any one time. The pot line is serviced by an approximately 100,000 ampere dc circuit with a potential of about 6.3 volts per cell. Cathode current efficiency is about 70 to 80 percent and the dc power requirement is about 18.5 kwh/kg (8.4 kwh per pound) of magnesium produced. During operation molten magnesium is liberated at the cathode, and chlorine gas at the anode. The magnesium rises to the surface of the electrolyte and is directed by inverted troughs to a storage well in front of the cell from which it is pumped into collecting crucibles several times each day, and cast into 9 kg (20 lb) ingots or 18 kg (40 lb) pigs. In addition to chlorine, the effluent gases also contain HCl and water vapor. They are all recycled through the HCl acid plant where an additional 0.5 kg of chlorine per kilogram of Mg produced is added to yield the needed HCl to carry on the process. The chlorine is produced from salt in the Dow diaphragm cells. Thus, the Dow

process is a consumer of chlorine. The water in the cell feed causes the corrosion of the graphite anode which may be of the order of 100 kg/M ton (200 lb/S ton) Mg. Total energy consumed and estimated production costs are discussed in a later section.

Anhydrous $MgCl_2$ Electrolytic Process

With the exception of The Dow Chemical Company all other electrolytic magnesium producers use the I. G. Farben process, or some modification of it. Modifications of both the feed preparation and the cell are in use. The critical step in this process is the dehydration of $MgCl_2 \cdot 6H_2O$. It is relatively easy to proceed to the dihydrate but beyond that special precautions must be taken to prevent the formation of MgO and $MgOCl_2$. I. G. Farben obviated these problems by developing in the mid-twenties a process for direct chlorination of MgO. The flow diagram for this process is shown in Figure 2. The process needs as its principal raw material a caustic-calcined form of magnesium oxide. In the original process, as developed in Germany, this was obtained by calcining magnesite ($MgCO_3$) at an appropriate temperature to produce the reactive form of MgO. Today, as the process is used by Norsk Hydro, $Mg(OH)_2$ is precipitated from seawater with dolime in the same manner as described for the Dow Texas plant. The $Mg(OH)_2$ is calcined to MgO, mixed with powdered coal and binders, and briquetted. Chlorination is carried out in vertical shaft furnaces electrically heated with the temperature at about 1100-1200° C (2010-2190° F). The resulting anhydrous magnesium chloride is tapped from the bottom of the furnace at about 800-850° C (1470-1560° F) and delivered directly to the electrolytic

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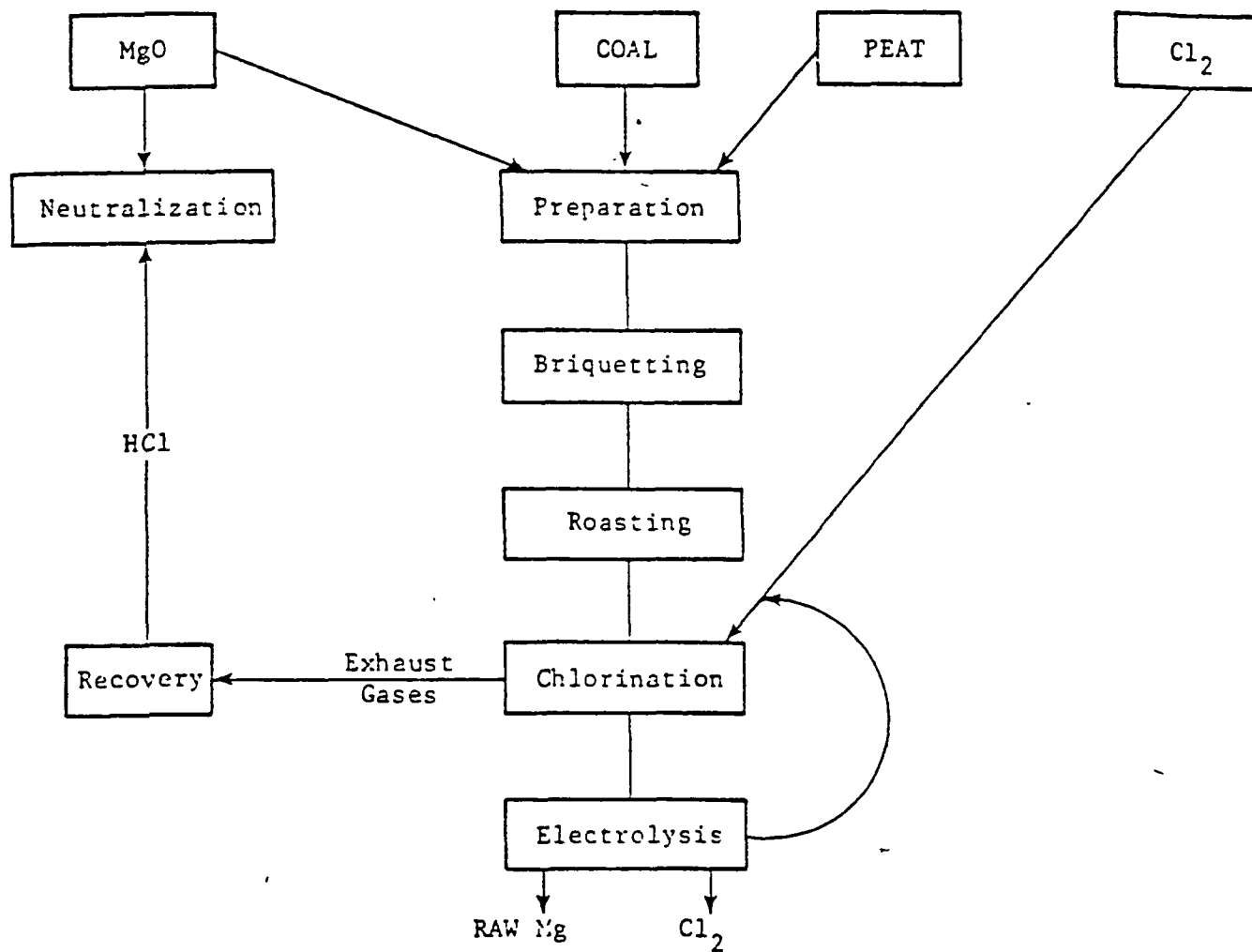


FIGURE 2. I. G. FARBEN ANHYDROUS $MgCl_2$ ELECTROLYTIC
MAGNESIUM FLOW DIAGRAM

cells. As shown in the flow diagram, chlorine gas from the magnesium cells is recirculated in the plant to produce $MgCl_2$ but additional chlorine is needed to the extent of 0.5 kg per kilogram of magnesium produced. Thus, this process is also a chlorine consumer.

In the USA, both NL Industries on the Great Salt Lake in Utah and American Magnesium Company in Snyder, Texas, are using the anhydrous magnesium chloride process, but with the difference that the starting material is already a magnesium chloride brine (bittern). In the case of NL Industries, their raw material source is the Great Salt Lake where natural evaporation has already increased the $MgCl_2$ concentration to about 7 percent in contrast to seawater where it is 0.5 percent. American Magnesium uses an underground brine running between 2.6 and 5.0 percent $MgCl_2$. The flow diagram for producing magnesium from bitterns is shown in Figure 3. The bitterns are concentrated by solar evaporation in large hold ponds almost to saturation (30-36 percent $MgCl_2$). The concentrated brine is reacted with $CaCl_2$ to remove sulfate ion, and then in a series of ion-exchange reactors the small amounts of bromine and boron and the last traces of sulfate ion are removed. The latter step is optional and its use depends on the extent to which these impurities are present and what other means are later provided to counteract their detrimental effects. In a two stage crystallizer, the KCl and NaCl values are recovered separately, and the mother liquor from the second stage is fully saturated in $MgCl_2$ solution (36 percent). This is heated to about 93° C (200° F) and conveyed into large vertical shaft spray driers from which the product is $MgCl_2$ containing about 5 percent H_2O , 5 percent MgO, and about 5 percent KCl + NaCl. This product is fused in the melt-chlorinator

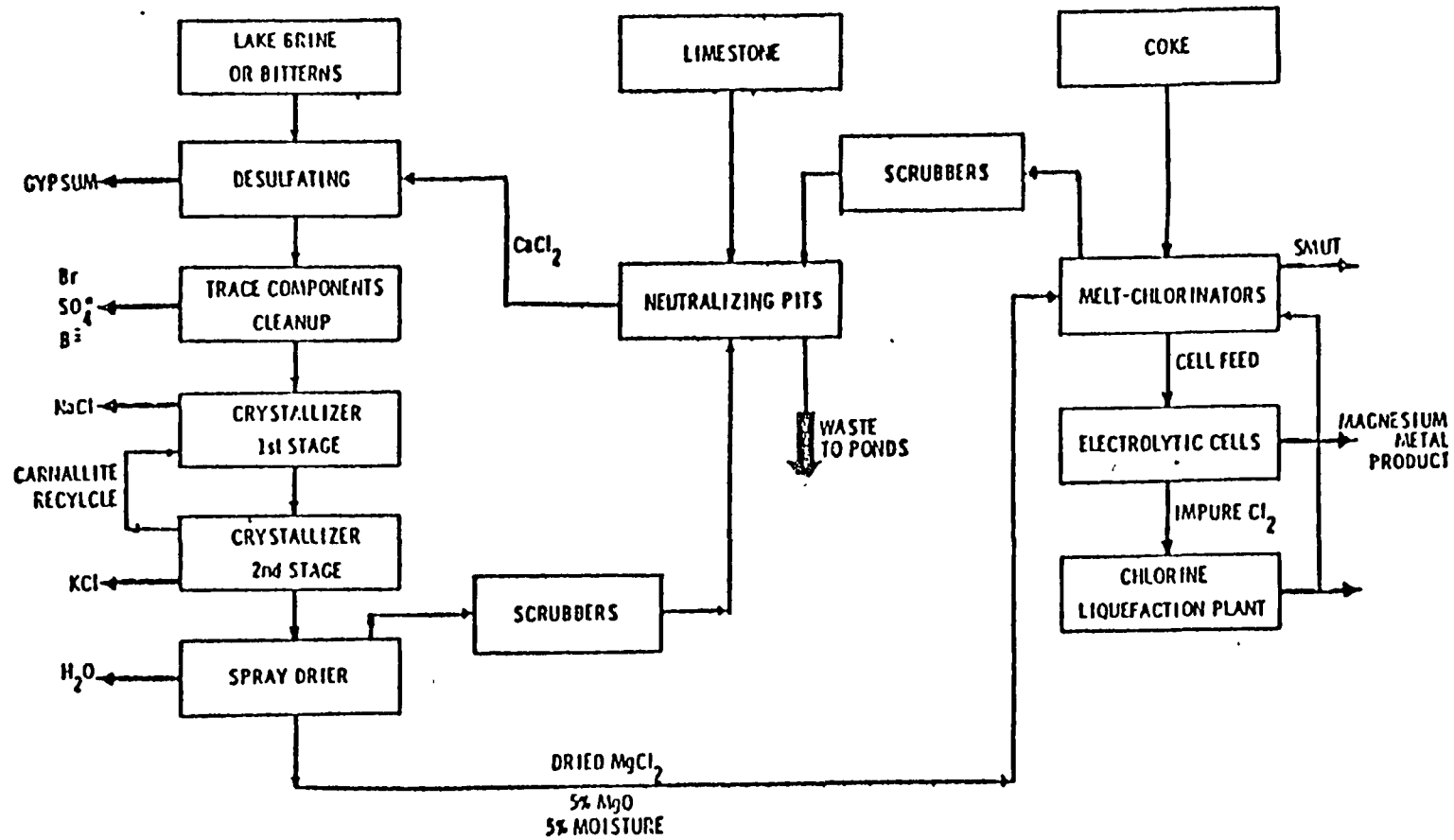


FIGURE 3. FLOW DIAGRAM FOR MAGNESIUM-RICH BRINE ELECTROLYTIC PROCESS

where it is reacted with the chlorine in the presence of carbon to completely remove the H_2O and MgO . The fused, fully anhydrous $MgCl_2$, containing about 5 percent $HCl + NaCl$, goes directly to the electrolytic cells. The off gases from the spray drier and the melt-chlorinator contain HCl gas and are used to react with limestone to produce the $CaCl_2$ needed earlier in the process.

Norsk Hydro has also announced a bitters process with some modification from that described above. Their raw material is bitters imported from Germany and is a by-product of the potash industry. The bitters are concentrated and de-sulfated as described above. Bromine is removed by passing chlorine through the $MgCl_2$ saturated solution, and boron is removed by an undisclosed process. The saturated $MgCl_2$ solution is converted to solid $MgCl_2$ by spray drying as described above. In the final step, however, the residual moisture is removed by drying in an HCl gas atmosphere at an undisclosed temperature. The effluent HCl gas containing moisture is dried and recirculated.

The I. G. Farben electrolytic cell used with anhydrous $MgCl_2$ differs from the Dow cell in that it has been much smaller, it is refractory-lined and it has no provision for external heating. Schematic drawings of this cell are shown in Figures 4 and 5. The original I. G. Farben cell had three graphite anodes and three pairs of steel cathodes as shown in the sketch. To increase production capacity the size was later increased to four graphite anodes; this is the size of the cells currently in use by Norsk Hydro operating at 62,000 amps. Today, cells in Russia (and it is believed the NL Industries cells also) have 5 anodes and operate at 100,000 amps. A very important feature of this cell design

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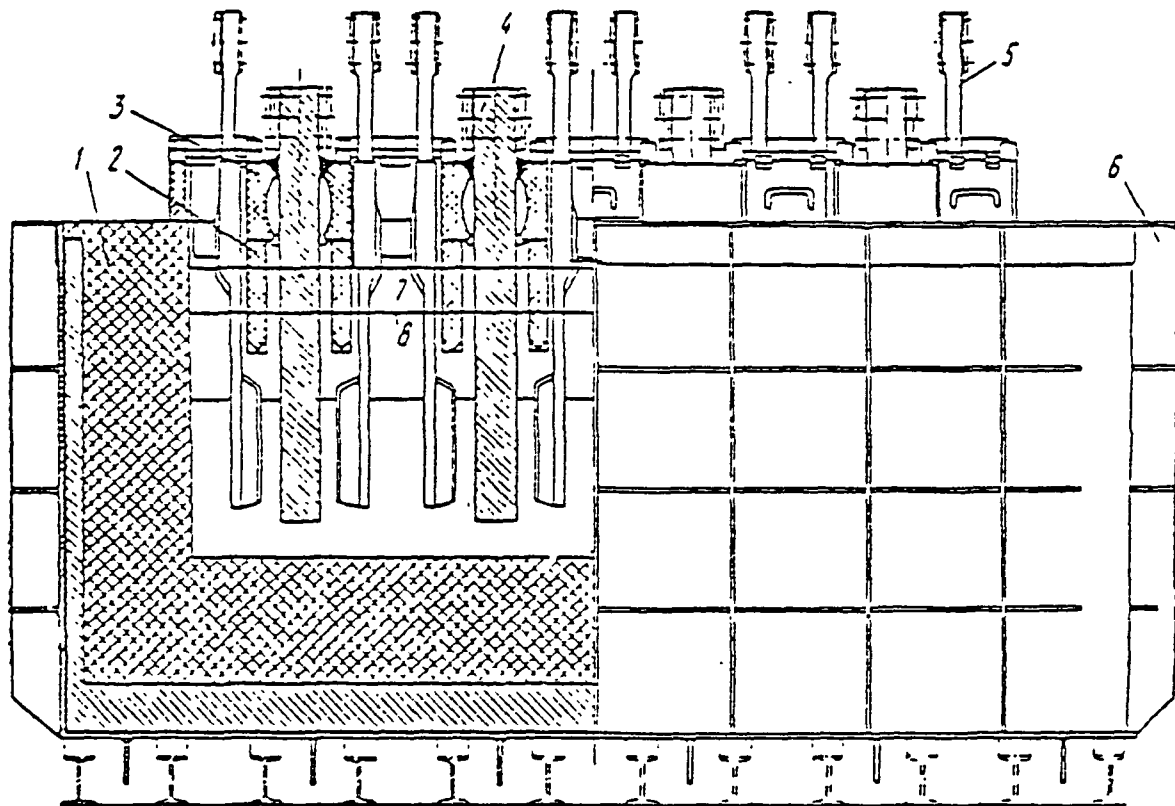


FIGURE 4. FRONT ELEVATION OF I. G. ELECTROLYTIC CELL USED BY NORSK HYDRO

- | | |
|--------------------------|-------------------------------|
| 1. Insulation Lining | 5. Cathode |
| 2. Diaphragm (Semi-Wall) | 6. Outer Shell |
| 3. Anode Box | 7. Upper Level of Electrolyte |
| 4. Anode | 8. Lower Level of Electrolyte |

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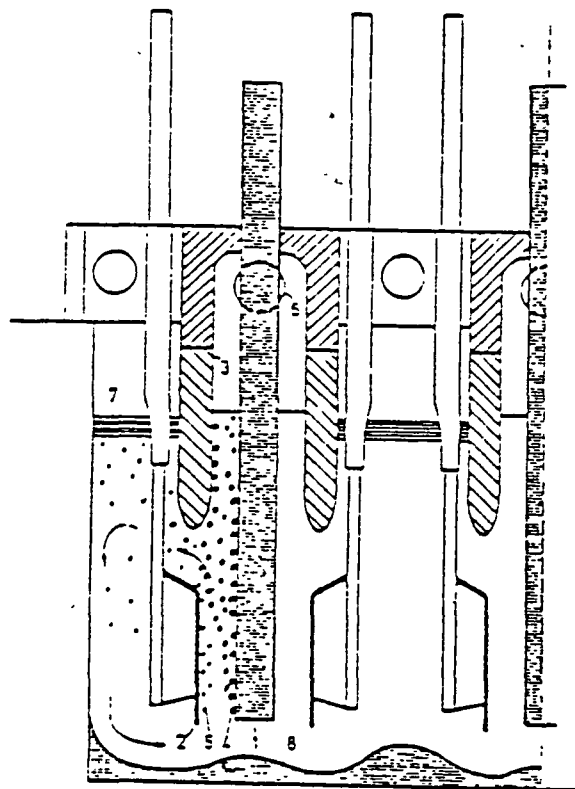


FIGURE 5. SECTION THROUGH I. G. CELL SHOWING ELECTRO-
LYTE CURRENT AND PRODUCTS SEPARATION

- | | |
|---------------------|-----------------------|
| 1. Anode | 5. Magnesium Droplets |
| 2. Cathode | 6. Chlorine Outlet |
| 3. Diaphragm | 7. Magnesium Layer |
| 4. Chlorine Bubbles | 8. Sludge |

is the refractory semi-wall extending from the roof of the cell to a short distance below the surface of the electrolyte and separating the space above the electrolyte into an anode chamber (box) and a cathode chamber. Materials of construction, design, and life of this semi-wall are critical factors in the operating costs of this cell. Operating conditions are critically adjusted so that the chlorine released at the carbon anode collects in the anode box and the magnesium metal collects in the cathode chamber from where it is directed to a collection trough in front of the cell for periodic removal by pumping or suction. The composition of the electrolyte in this cell is 12 percent $MgCl_2$, 40 percent $CaCl_2$, 40 percent $NaCl$, and 8 percent KCl . Impurities should not exceed the following amounts: 0.15 percent C, 0.001 percent B, 0.1 percent H_2O , 0.05 percent SO_3 , 0.02 percent Fe, 0.005 percent Ti, and 0.1 percent $MnCl_2$. The cell is usually operated at about $750^\circ C$ ($1380^\circ F$) and in the present large cells current efficiency ranges between 75 and 85 percent and energy consumption has been reduced to about 15 kwh/kg (7.0 kwh per lb) of magnesium. The freedom from water of the feed also contributes to a low anode consumption, about 0.02 kg per kg of magnesium and to the liberation of chlorine free from the HCl and water vapor.

New Electrolytic Cell at Norsk Hydro

Norsk Hydro has developed a new electrolytic cell which they refer to as their second-generation cell. The cell operates on 250,000 amperes and realizes a current efficiency of at least 90 percent and energy consumption of about 6.0 kwh per pound of magnesium produced. This cell was brought into production operation during December 1978/January 1979.

They now have an additional 11,000 tons of magnesium production capacity operating on this cell. (This is definitely in addition to the 44,000 tons of IG cell capacity.) Graphite anode consumption in this cell is running as low as 0.005 lb of graphite per lb of magnesium produced. No design features of the cell have been divulged. It is suspected from the outward appearance of the cell that it is a diaphragmless cell similar to those described in the Russian literature⁽⁵⁾, an example of which is shown in Figure 6.

An important economic advantage of the bitterns, anhydrous $MgCl_2$ electrolytic process is the production of by-product chlorine for sale. Theoretically, 2.9 kg of chlorine are produced with every kilogram of magnesium. At the NL Industries plant the available chlorine for sale is 1.78 kg per kg of magnesium because of the internal consumption of chlorine in the melt-chlorinator. As much as 2.7 kg of chlorine will be available either for direct sale or for production of chlorinated hydrocarbons in Norsk Hydro from the new 250,000-ampere cell.

Silicothermic Magnesium Process

Current electrolytic processes require a magnesium chloride feed. With the Dow seawater process this requires conversion to chloride of all MgO precipitated out. Even where a chloride salt is the raw material, e.g., bitterns, conversion to feed is more than a matter of simple evaporation. Processes that can use magnesium oxide as a feed material avoid the complexities of preparing chloride feed materials and simplify the process in this regard. They also make possible the direct use of calcined dolomite

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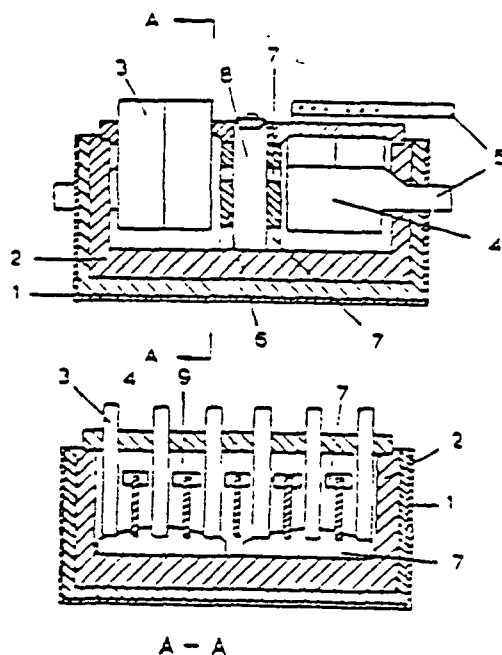
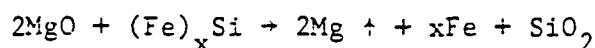


FIGURE 6. FRONT AND SIDE ELEVATION OF
DIAPHRAGMLESS ELECTROLYTIC CELL

- | | |
|----------------------|-------------------------------------|
| 1. Outer Shell | 5. Current Leads |
| 2. Insulation Lining | 6. Semi-Wall |
| 3. Anode | 7. Opening |
| 4. Cathode | 8. Magnesium Collecting Compartment |
| | 9. Cl_2 Collecting Chamber |

(dolime). The silicothermic process and the Magnetherm modification of this process use magnesium oxide feed, but also require ferrosilicon that must be separately manufactured.

The silicothermic process, as developed by Pidgeon, uses dolomite and ferrosilicon as its primary raw materials. It can be considered that ferrosilicon really is the source of energy needed to reduce magnesium oxide according to the equation:



The flow diagram for this process is shown in Figure 7. Dolomite is calcined in a horizontal rotary kiln to produce dolime at 1300-1400° C (2370-2550° F) to a dead-burned condition. The dolime is ground, mixed with pulverized ferrosilicon (Fe-Si, 80-85%) and briquetted.

The success of the Pidgeon process depends very much on the design of the retort in which the reaction takes place. Typically the retort has 25 cm (10 inches) internal diameter, 3.8 cm (1.5 inch) wall thickness, and 3 m (10 feet) of length and is made of either 35Ni-15Cr or 28Ni-12Cr stainless steel. The retorts are set in furnaces with about 50 cm (2 feet) of length extending outside the furnace which forms the cold zone or condenser where the magnesium is collected. A steel liner is placed at the cold end for easy removal of the muff. Dolime/ferrosilicon briquettes are charged, and while they are being heated, vacuum is drawn on the retort reducing the pressure to about 0.1-0.2 mm. The reaction usually takes place at 1150-1175° C (2100-2150° F) and the cycle time is about 9 hours. Each batch produces 20 to 25 kg (44 to 55 lb) of magnesium, which upon removal is remelted and cast into pigs. Efficiency in use of

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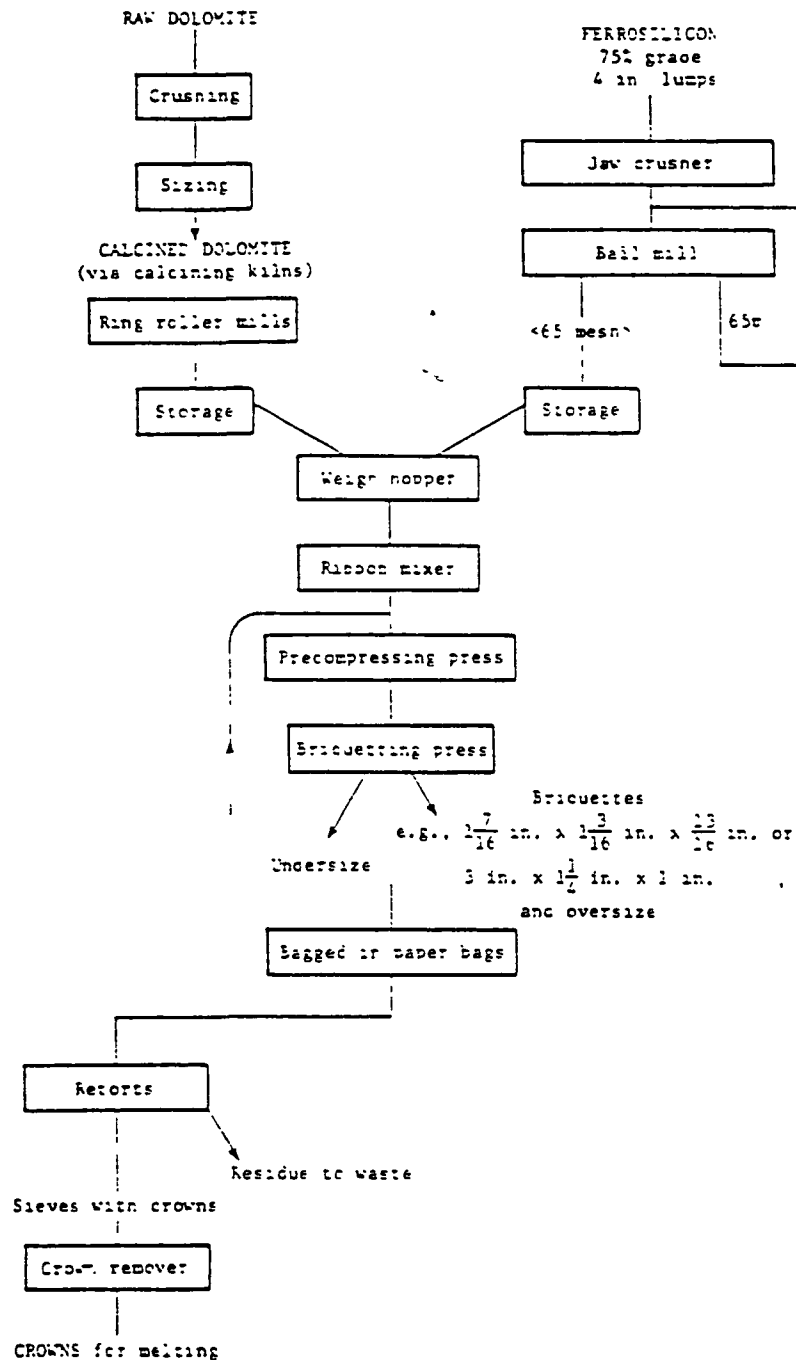


FIGURE 7. PIDGEON SILICOTHERMIC MAGNESIUM
PROCESS FLOW DIAGRAM

silicon has been reported as averaging about 65 percent. The iron does not enter into the reaction. The SiO_2 formed in the reaction combines with the CaO in dolime to form Ca_2SiO_4 . Product purity is equal to or better than the electrolytic grade. The process has been described in detail based on the operation of the wartime government plants⁽³⁾.

The Magnetherm Process

The Magnetherm process is an adaptation of the silicothermic process to provide a reactor that operates semi-continuously. The essential features are shown by the flow diagram in Figure 8 and the sketch of the reaction furnace in Figure 9. As in the Pidgeon process, dolomite and ferrosilicon are the principal raw materials. In addition, an 85 percent grade of alumina is added to reduce the melting point of the CaO/SiO_2 (Ca_2SiO_4) slag resulting from the reaction from about 2130°C to 1500°C (3860 to 2730°F) and thus provide a liquid slag in which the reaction is carried out. About 15 percent alumina in the slag is needed to achieve this. Dolomite is calcined at 1300 - 1400°C (2370 - 2550°F) in horizontal rotary kilns and transferred hot to a storage bin from which it flows directly into the furnace at a temperature no less than 600°C (1100°F). Two other bins directly above the furnace contain the alumina and pulverized ferrosilicon. The original reactors built and operated by Pechiney-Ugine-Kuhlmann in Marignac, France (Figure 7) were 3 m (10 feet) in diameter and 3 m (10 feet) high. The reactors were built in three basic sections: (1) the arched roof; (2) the reactor itself; and (3) the condenser. The reactor and the roof may either be flanged together or preferably welded.

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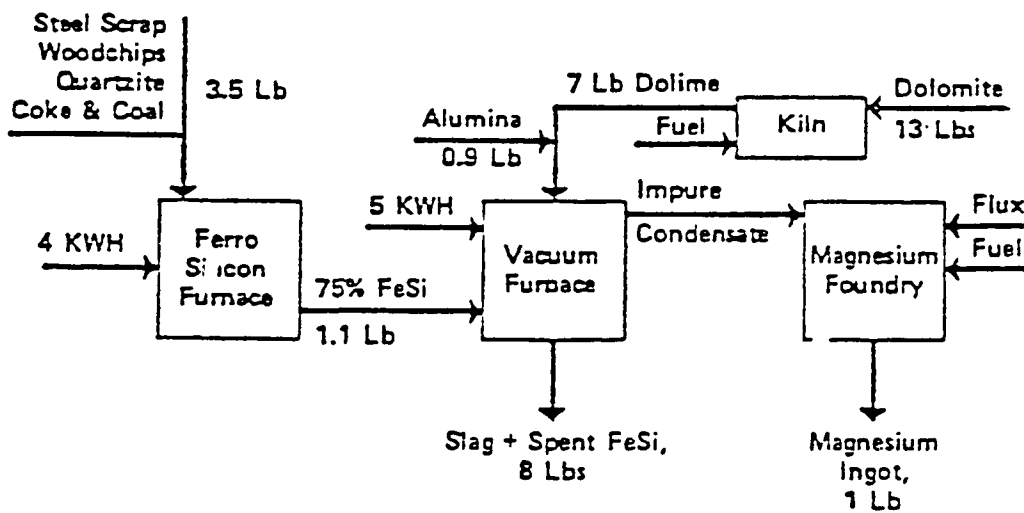


FIGURE 8. MAGNETHERM SILICOTHERMIC MAGNESIUM
PROCESS AND ENERGY FLOW DIAGRAM

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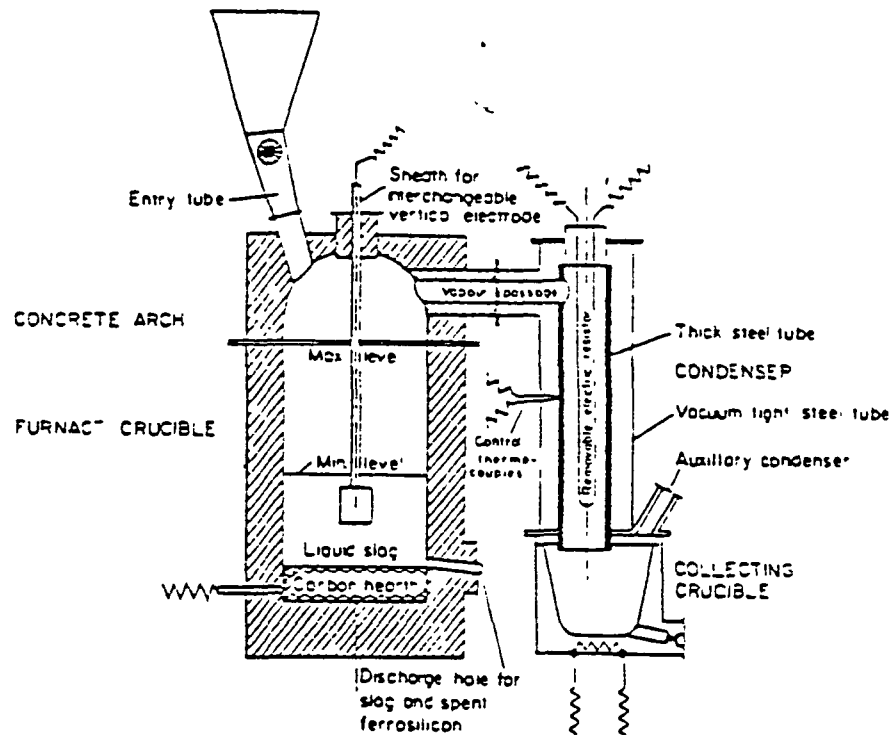


FIGURE 9. MAGNETHERM REACTOR FOR REDUCING DOLIME
WITH FERROSILICON USING A LIQUID SLAG

Dolomite ?

The roof is lined with a high-temperature cement and further insulation. The choice of a lining for the reactor proved to be a difficult problem because of the high temperature involved and the reactivity of the slag. Tightly fitted carbon blocks were finally selected and have been giving excellent performance. A somewhat more porous carbon block forms the bottom of the reaction chamber. The furnace lining acts as one electrode and the other electrode is a water-cooled copper tube with a graphite tip coming in through the roof and submerged in the slag. The furnace is heated by electrical resistance with the current introduced through the carbon hearth passing through the molten slag to the electrode submerged in the slag from the roof. The condenser is operated at a temperature of 650 to 700° C (1200 to 1290° F) so that the magnesium vapors issuing from the exhaust passage in the roof are condensed as a liquid and collect in the crucible attached at the bottom. The metal collected in the crucible is maintained at a temperature just below the melting point in order to conserve its sensible heat but still minimize evaporation. The entire system including the raw material bins is run under a vacuum of 25 mm Hg but is capable of being operated down to 5 mm Hg.

A run starts with the surface of the molten slag at the minimum level shown in the sketch in Figure 9. The ferrosilicon is introduced in a continuous stream, whereas the dolime and bauxite are added intermittently. Variations of this have been reported and other schemes of adding the reactants are possible. The temperature of the slag, and thus the temperature at which the reaction takes place, is maintained at 815° C (1500° F). The alumina content of the slag is critical and is controlled by careful

adjustment of the rate of introduction. About 1.05 kg of ferrosilicon are used for each kilogram of magnesium produced. When the slag reaches the maximum level, the run is stopped, and the furnace brought to atmospheric pressure, and the slag tapped. The slag and residual ferrosilicon, which is also molten at this temperature, differ sufficiently in density so that they may be separated by decantation, as shown. The residual ferrosilicon is recirculated after grinding. The crucible of condensed magnesium is disconnected from the furnace, removed to the cast-house, the metal refined, and cast into pigs. It is reported that energy required for the reaction is about 10.4 kwh/kg (4.7 kwh/lb) of magnesium produced in addition to the energy represented by the ferrosilicon. The size of furnace described here is capable of producing about 910 M tons (1,000 S tons) annually. Furnaces now installed in France produce about 1496 M tons (1,650 S tons) and the furnaces installed in the new Alcoa plant in the USA have an annual capacity of about 2450 M tons (2700 S tons). An important advantage of the Magnetherm process over the Pidgeon process is the semi-continuous operation and the much larger batch sizes which reduce labor cost and improve productivity. A long-term operation of the new Alcoa plant is needed to demonstrate more reliably the competitive position of this process compared to electrolytic processes. It is, however, more suited for installations of capacity less than 27,200 annual M tons (30,000 annual S tons).

ENERGY CONSUMED IN MAGNESIUM PRODUCTION

The standard free energy of formation of MgO is -136.17 kcal/mole (20.1×10^6 Btu/S ton Mg) corresponding to 2.95 volts. Standard

enthalpy of formation is -143.84 kcal/mole (21.3×10^6 Btu/S ton Mg). Thus, the reduction of MgO carried out at the theoretical potential is endothermic and 7.67 kcal/mole of thermal energy must be supplied to maintain a constant temperature.

The standard free energy of formation of MgCl_2 is -143.77 kcal/mole or 5.92×10^6 Kcal/M ton (21.3×10^6 Btu/S ton) Mg corresponding to 3.12 volt. If power conversion losses are 10 percent and the fossil energy requirement for electrical production is 2646 Kcal ($10,500$ Btu)/kwh, the minimum electrical power for reduction at 100 percent current efficiency is 7639 kwh/M ton (6930 kwh/S ton) Mg or 20.21×10^6 Kcal/M ton (72.76×10^6 Btu/S ton) Mg.

The commercial production of primary magnesium by current technology is an energy-intensive operation. Energy uses for the processes discussed are compared in Table 1.

The high energy use for the Dow process is due to the additive effects of (1) the need for external heating of the cells, (2) the high energy needed for dehydrating $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, (3) a deficit rather than a credit for chlorine, and (4) the high consumption of graphite. Dow developed this process and uses it exclusively due to the traditional cheap energy on the Gulf Coast. However, the availability of cheap energy may be at an end or will end shortly. It is probably not feasible to reduce the energy of this process markedly.

The total energy and electrical energy uses are similar for the anhydrous and Magnetherm processes. The choice of one or the other of these systems in the future will depend in part on which can be developed to require the lesser energy. The energy for the Pidgeon process is high probably because it was operated on a much smaller scale

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TABLE 1. COMPARISON OF ENERGY REQUIREMENTS FOR
MAGNESIUM PRODUCTION PROCESSES

Process	Energy/Ton Metal	
	kwh/M ton (kwh/S ton)	10 ⁵ Kcal/M ton (10 ⁵ Btu/S ton)
Dow Electrolytic (USBM)*	23,787 (21,580)	99.50 (358.16)
Dow Electrolytic (ORNL)**	16,589 (15,050)	94.32 (339.52)
Bitterns/Anhydrous Feed Electrolytic	24,157 (21,915)	73.73 (265.40)
Magnetherm Silicothermic	20,977 (19,030)	65.85 (237.04)
Pidgeon Ferrosilicon	-- --	94.03 (338.48)

* U.S. Bureau of Mines

** Oak Ridge National Laboratory

than the Magnetherm process. A retort produced 22.7 kg (50 lb) in an 8-hour run. An obvious way to decrease the energy consumed in the bitters process is to increase the yield of by-product chlorine. If the chlorine yield is increased to the level of 2.7 kg/kg Mg as anticipated by Norsk Hydro, the total energy consumption would be lowered to 68.3×10^6 Kcal/M ton (246×10^6 Btu/S ton) of magnesium. Further reduction can be effected by process improvements in the evaporation step and in the electrolysis. Norsk Hydro has stated that they expect to achieve a level of total energy consumption in their new process of $61-67 \times 10^6$ Kcal/M ton ($220-240 \times 10^6$ Btu/S ton).

The Dow Chemical Company also has been reported to have under development a bitters/electrolytic process which is predicted to lower total energy consumption to 38.9×10^6 Kcal/M ton (140×10^6 Btu/S ton) of magnesium. The nature of the process has not been made known other than that the maximum amount of by-product chlorine will be available for sale or use in other Dow manufacturing processes. However, it can be safely assumed that at least two major technological improvements must be involved: (1) a new and highly efficient method for producing cell feed; and (2) a completely new electrolytic cell with significantly lower resistance and energy requirements. It is known from the patent literature that Dow many years ago developed a bipolar cell for electrolysis of magnesium chloride. Among the many advantages of this cell the following were cited: (1) reduction of operating cell voltage (5.0 versus 6.3 volts); (2) reduction of energy consumption from 18.5 to 13.2 kwh/kg (8.4 to 6.0 kwh per pound) of magnesium; and (3) reduction of graphite anode consumption to

a very low level. Although it has not been divulged by Dow, there is a very high probability that this cell or a modern and improved version of it is being used in this advanced production process. A major-size pilot plant based on this process is scheduled for construction in 1980 and the process should be available for full scale production plants later in the decade of the 1980's.

The figure of 38.9×10^6 Kcal/M ton (140×10^6 Btu/S ton) Mg is drastically lower than for any of the processes discussed and some estimates are useful in determining whether it is in fact possible. A five-volt cell, as described above, operating at 90 percent current efficiency, with 10 percent power conversion loss will require 13,602 kwh/M ton ($12,340$ kwh/S ton) Mg or 36.1×10^6 Kcal/M ton (130×10^6 Btu/S ton) Mg at the power plant. Five volts is still substantially above the theoretical potential of 3.1 volts, leaving room for further improvements. Preparation of an anhydrous feed requires 31.05×10^6 Kcal/M ton (111.77×10^6 Btu/S ton) Mg. However, this might be reduced by dehydration in an HCl atmosphere (Norsk Hydro) to 28×10^6 Kcal/M ton (100×10^6 Btu/S ton) Mg. If 2.9 kg chlorine can be credited/kg Mg the total credit is 16.7×10^6 Kcal/M ton (60×10^6 Btu/S ton Mg). Thus, the total energy consumption can be estimated as:

$$\begin{aligned} (130 + 100 - 60) \times 10^6 \text{ Btu/S ton Mg} &= 170 \times 10^6 \text{ Btu/S ton Mg} \\ (47.2 \times 10^6 \text{ Kcal/M ton Mg}). \end{aligned}$$

A lower overall energy use than this would require further reduction in energy for feed preparation and/or electrolysis.

Plans have been presented on how energy consumption will be reduced in the Magnetherm process. During the next four years the consumption

of all materials is expected to be reduced by no less than 10 percent and the yield of magnesium increased by reducing losses in the condensation stage and in the melting and refining. Beyond that, and over the next 10-12 years, they plan to introduce more energy-efficient ferrosilicon production furnaces, to improve the dolomite and bauxite calcination stage and to build larger and more efficient reduction furnaces. There is no question that the Magnetherm process does hold promise and that the major improvements anticipated by Dow in the bitterns process will need to be made to compete with it in energy consumption.

In summary, it can be stated that the producers of primary magnesium are aggressively seeking improvements in the processes for producing primary magnesium. A major portion of available research funds are committed to lowering the total energy required to produce magnesium. However, the impetus for development has been and will be economic. Energy plays a more dominant role in development now than previously because of its increasing cost.

Cell Design

Traditional electrolytic cells have been designed using electrolytes heavier than the molten magnesium. Thus, both chlorine and magnesium rise concurrently to the top of the cell. In addition, the Dow cell consumes graphite at a sufficient rate to require adjustment or feeding of the electrode into the cell. This requirement has made it difficult or impossible to collect chlorine and perhaps contributed also to lowering cell efficiency through recombination of chlorine and magnesium in the electrolyte. The

anhydrous cell does not have the graphite feeding problem so chlorine is more easily collected. Current efficiency at the outset can be of the order of 90 percent but decreases as the semi-wall deteriorates to a level of 75 to 85 percent.

There is a tradeoff between current efficiency and cell potential. As the cathode-anode spacing is decreased to minimize the voltage, the chlorine and magnesium rising in the cell are brought closer together and recombination is increased, lowering current efficiency. Thus, ignoring semi-wall deterioration for the moment, there is an optimum electrode spacing. Halliday and McIntosh⁽⁴⁾ have been able to demonstrate that the hydrodynamics of the electrolyte and thickness of the gas layer in a 2000-ampere pilot magnesium cell could be simulated by flowing nitrogen through a porous electrode in an aqueous modeling system. This hydrodynamic technique may be extremely useful in simulating cell parameters under conditions of reduced gravity. While their fused salt cell used an LiCl-KCl electrolyte that is lighter than magnesium, the cell and aqueous system should be applicable with some modification to studying heavier electrolytes as well. Optimizing current efficiency with a possible decrease in cell voltage could add up to an effect equivalent to improvement of 10 percent in current efficiency.

It has been shown that clean steel is preferentially wet by magnesium rather than fused salt. This leads to the concept of a porous cathode through which the magnesium deposited on the surface permeates and is collected on the back side. Such a system will allow minimal electrode spacing and could lead to cell potentials as low as 4.0 volts. Obviously

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the gravitational force needed for collecting magnesium through a porous, wettable cathode is much less critical than at a solid cathode from which magnesium must float to the surface.

Halliday and McIntosh⁽⁴⁾ chose to use a low density electrolyte to simplify separation of chlorine and magnesium, since the latter dropped to the bottom of the cell. Electrodes were slightly sloped to enhance the separation as demonstrated in the simulative aqueous system and the fused salt cell. Current efficiencies of over 90 percent were obtained at current densities of 1.5 amp/cm^2 (1400 amp/ft^2), some three times the operating level of the conventional cells. Even at this current density, cell potentials of the order of only 5 volts were obtained. Thus, use of these light electrolytes offers a way of improving cell efficiency with energy savings similar to those cited for a 4 volt cell. Use of light electrolytes, based on a composition containing lithium chloride, has been patented by Dow. However, there appears to be no major effort devoted to use of a lighter-than-magnesium electrolyte at the present time. Aluminum cells operate with lighter-than-metal electrolyte, which is an advantage over conventional magnesium cells.

It is probable that use of an electrolyte with lower density than the metal will facilitate separation of chlorine and magnesium under conditions of reduced gravity since the gas will rise and the metal sink.

SPECIAL CONSIDERATIONS FOR MAGNESIUM PRODUCTION IN SPACE

Feed Materials

Prior discussion has indicated the suitability of MgO as a

feed material. It may either be converted to the chloride, with recycling of chlorine, or used directly for reduction by silicon or ferrosilicon.

Separation of Products

In chloride electrolysis the chlorine gas can be separated under reduced gravity, particularly with the aid of suction if necessary. Separation of molten magnesium is more difficult, especially from electrolytes denser than magnesium. Separation by wetting of a porous cathode and use of lighter electrolytes have been discussed previously as possible methods of improving separation. Another alternative is the deposition of solid magnesium from electrolyte melting at temperatures below that of magnesium. Strelets⁽⁵⁾ provides detailed information of the melting point, viscosity, conductivity, etc., of a variety of compositions, some of which are sufficiently low in melting point. However, solid deposits from fused salts tend to be irregular, which may cause difficulty in removal, interelectrode spacing, etc. Solid deposits may be considered if a feasible method of collecting molten magnesium cannot be developed.

If a rotating module will be the norm for the overall lunar processing system, and approximately 1.0 g is attained, reduced gravitation will cease to be an imposed condition for cell operation.

Anode Materials

Graphite anodes are used in chloride electrolysis and carbon is used in the electric furnace reductions to produce the ferrosilicon for the Magnetherm process. The corrosion of graphite in the I. G. Farben

anhydrous chloride process is small and should be tolerable. Improvements in feed purity, etc., may further minimize corrosion. Recovery of carbon through Fischer-tropsch synthesis by using CO and H₂ and burning to lamp-black will probably not provide a suitable starting material for graphite anodes. Pyrolytic deposition from the Fischer-tropsch products may directly provide a suitable anode.

Other Electrolytic Methods

Magnesium can be electrolyzed from a fused sulfide bath. Magnesium oxide can also be used as feed to a fused cryolite bath⁽⁶⁾ similar to that used for aluminum production. In such a process the carbon anode is extensively oxidized. Insoluble anodes for use in oxide-fed cryolite baths have been considered. Kronenberg⁽⁷⁾ tried depolarizing several anode materials with hydrogen, methane, and carbon monoxide. Water formed by hydrogen, however, caused hydrolysis and other undesirable side reactions.

Silicon, as a reductant for MgO, may also be electrolyzed out of a fused fluoride bath, but the practicality of scaling up this method has not been determined⁽⁸⁾. Investigations are now underway at Battelle to deposit silicon from non-aqueous electrolytes⁽⁹⁾. Thin film deposits for photovoltaic devices are the current objective but electrowinning is a longer range possibility.

CONCLUSIONS

There are several options for direct or indirect electrolytic reduction to obtain magnesium metal from lunar materials. The most

extensively developed process is the chloride process utilizing an anhydrous magnesium chloride feed. This process would probably be most easily adapted into a lunar processing plant if it were compatible with the general chemical system that is chosen for beneficiation and metals separation.

ACKNOWLEDGMENT

This work was supported by the U. S. Department of Energy under Contract No. ANL 31-109-38-4212 for a Survey of Metalwinning Processes, administered by Argonne National Laboratories.

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THE ECONOMICS OF BOOTSTRAPPING SPACE INDUSTRIES --
DEVELOPMENT OF AN ANALYTIC COMPUTER MODEL

Introduction

Three basic strategies for space industrialization have been proposed. The terrestrial approach involves the exclusive use of earth launched materials and equipment for the fabrication of useful products in space. The chief detractor of this scheme is the cost of transporting material into space. Shuttle payloads will initially be delivered into orbit for roughly \$1 million/metric ton, a figure which dwarfs the procurement costs for nearly all conceivable cargoes. Even future shuttle-derived vehicles are expected to decrease this rate by only a factor of 10 (1). As a result, there is a strong incentive to minimize the amount of material brought up from earth.

One way to achieve this goal is by taking advantage of the resources already in space. Like terrestrial inputs, these materials would have to be delivered to some appropriate orbit. However, it has been estimated that launching matter from the moon using currently known techniques will require only 1/20 to perhaps as little as 1/200 the energy needed for even advanced earth-launch systems (1,2). The primary reasons for this difference is that lunar transport does not have to contend with the earth's gravity or atmospheric drag. In addition, lunar cargoes do not necessarily have to be inside a complex and heavy cargo vessel to protect them from the atmospheric heat and pressure, as in terrestrial launches.

Of course, facilities for operating with lunar soil do not currently exist. They would have to be provided from earth. Nevertheless, since most machines are capable of processing many times their own mass each year (3,4), the total

earth-launched mass would still only be a fraction of that required in the terrestrial case. The extensive data base generated by ten years of lunar sample research and availability of lunar samples make it possible to design adequate product machines to convert lunar soils into a wide range of industrial feed stocks prior to return to the moon.

Earth transport requirements could be reduced even further by using lunar soil to manufacture not only the final output, but also the process capital. In this way, only a small seed facility would be required from earth to initiate production. Despite growing interest in this final "bootstrapping" approach (5), no economic model has yet been developed to analyze the potential benefits in detail.

This study begins with the derivation of some basic equations which must apply to all models of space industry, regardless of whether they involve bootstrapping or even utilization of extraterrestrial materials. The difficulties in formulating a general bootstrapping model are then discussed. Finally, attention is focussed on a simplified model and the conclusions which can be derived from it.

General Framework

Two types of inputs that are required for any productive enterprise -- expendables and capital (6). Expendables are materials and services which contribute to productivity only during the period in which they are made or purchased. Included in this group are chemical fuels, food, and reagents lost in process cycles. These items must be supplied regularly for production to occur. According to this usage, even personnel is considered an expendable, because crews must be periodically paid and rotated back to earth.

In contrast, capital goods do not have to be continuously supplied. Indeed, it will be assumed that, once operating, capital remains productive

throughout the life of the project, so that the capital stock never decreases. Even with this assumption, the natural wearout of equipment can be accounted for in two ways. First, replacements for worn parts can be treated as an additional type of expendable. Alternatively, if the wearout rate exceeds the repair rate, resulting in disuse of some equipment, the operating capital stock can be considered constant but with decreasing productivity. Other factors, such as expendable requirements, would also have to be adjusted accordingly.

At the outset, both of these factors of production must be supplied from earth. However, once the process has started, some of the inputs may be made with resources already present in space. The cost of the capital and expendables may then depend greatly on their source.

It will be assumed that the output accumulates in a stock which continuously generates revenue according to its magnitude. Solar power satellites are one example of such an output. As in the case of capital inputs, wear can be accounted for with expendable replacement parts or reduced revenues per unit output. Again, the output and related expendables may be made from either terrestrial or extraterrestrial resources.

A flow diagram is shown in Fig. 1. The capital stock K is supplied in annual increments ΔKE from earth and ΔKS from space. To keep the capital functioning, expendables ΔX must be imported (ΔXE) or produced locally (ΔXS) each year. The space manufacturing Facility (SMF) produces ΔQS , which, together with some material brought up from earth (ΔQE), makes up the final product ΔQ . Finally, for the output to bring in revenue, it must be supplied with some expendables each year (ΔX_Q). The mass flow can always be reduced to this form, no matter how many specific inputs, outputs, or process steps. However, it may sometimes be advantageous to consider some of these factors separately.

The lunar mass flow through this system is limited by the capacity of the

machinery to process it. Assuming full employment of all equipment, this constraint can be expressed mathematically as follows:

$$A \rho K = B \Delta X S + C \Delta K S + D \Delta Q S + E \Delta X_q S \quad (1)$$

where all underlined terms are functions of time and $\rho(t)$ is the productivity of capital in mass output per year/mass of equipment. The scaling functions A, B, C, D, and E are included for generality. They will all be unity provided that the other functions are appropriately defined. However, it is desirable to retain the scaling terms so that waste, overhead, and the like can be treated independently.

If m , n , ℓ , and m_q , are the proportions, respectively, of process expendables, capital, output, and output-related expendables which are produced from extraterrestrial material over time, then

$$A \rho K = B m \Delta X + C n \Delta K + D \ell \Delta Q + E m_q \Delta X_q \quad (2)$$

Defining Z as the mass of expendables required per year/mass of machinery, and Z_q as the corresponding expendable requirement for Q ,

$$A \rho K = B m Z K + C n \Delta K + D \ell \Delta Q + E m_q Z_q Q \quad (3)$$

Rearranging,

$$[A \rho - B m Z] K - [C n] \Delta K = [D \ell] \Delta Q + [E m_q Z_q] Q \quad (4)$$

In this way, then, $Q(t)$ is functionally related to $K(t)$ once the scaling, productivity, expendable requirements, and space-manufacturing proportions are specified (7).

Besides being limited by the productivity of capital in space, extraterrestrial operations may also be constrained by the ability to transport

support material from earth. The mass which must be imported in any given year is

$$UP = B \Delta XE + C \Delta KE + D \Delta QE + E \Delta X_q E \quad (5)$$

Using the definitions introduced above,

$$\begin{aligned} UP &= B(1-m) \Delta X + C(1-n) \Delta K + D(1-l) \Delta Q + E(1-m_q) \Delta X_q \\ &= [B(1-m)Z] K + [C(1-n)] \Delta K + [D(1-l)] \Delta Q + [E(1-m_q)Z_q] Q \end{aligned} \quad (6)$$

Thus, $UP(t)$ is a function of Q and K . Since $Q(t)$ is a function of $K(t)$ in equation (4), the mass which must be supplied from earth depends simply on how the capital stock varies over time.

The value of UP must never exceed the transport capacity, \dot{M} tons/year. The converse, however, does not hold. Indeed, in the long run, even with a fixed launch fleet, UP will decrease as the space industry becomes less dependent on earth. Since UP depends only on $K(t)$, the transport constraint M effectively limits the potential capital growth.

In addition to modeling the physical flows, it is important to describe the cash flows mathematically. The net cash flow CF in any given year is simply the revenue obtained during that year less expenditures. As in national income accounting, costs of goods produced and used within the manufacturing complex are internal transfers which do not contribute to the balance of payments. Consequently, the cash flow can be expressed as follows:

$$CF = PQ - F \Delta XE - G \Delta KE - H \Delta QE - I \Delta X_q E \quad (7)$$

where P is the revenue per year derived from each unit of output, and F , G , H , and I are the costs per mass of process expendable, capital, output, and output-related expendable brought up from earth (8). Simplifying as before,

$$\begin{aligned}
CF &= PQ - F(1-m) \Delta X - G(1-n) \Delta K - H(1-l) \Delta Q - I(1-m_q) \Delta X \\
&= PQ - F(1-m)ZK - G(1-n) \Delta K - H(1-l) \Delta Q - I(1-m_q)Z_q Q \\
&= [P - I(1-m_q)Z_q] Q - [F(1-m)Z] K - [G(1-n)] \Delta K - [H(1-l)] \Delta Q \quad (8)
\end{aligned}$$

Since $Q(t)$ and $K(t)$ are correlated as shown in equation (4), the cash flow, CF like the launch requirement UP , depends only on the capital growth function K .

The most common method for weighing the costs and benefits over the life of a project is by evaluating the present discounted value (PDV) of its net cash flow. When choosing between alternative production paths, the project with the greatest PDV is the preferred one. Mathematically, the goal is to maximize the objective function

$$PDV = \sum_{t=0}^T CF e^{-rt} - RND - INT \quad (9)$$

where r is the discount rate, T is the "time horizon" (which may be infinite), RND is the cost of research and development, and INT is the cost associated with initializing the system.

Within this framework, the three approaches to space industrialization differ only quantitatively, not qualitatively. All can be analyzed with the equations above simply by varying the constituent functions (Fig. 2). In general, increases in the complexity of the forms assumed for these functions and their interrelationships lead to greater uncertainty and mathematical difficulty in evaluating the mass and cash flows.

Obstacles to the Evaluation of Bootstrapping

In order to evaluate bootstrapping, it is important to know the general form of $K(t)$. By definition, the capital stock is non-decreasing. Moreover, since the ability to manufacture equipment in space depends on the amount of

machinery already there, the capital stock will probably increase exponentially at first. Eventually, this growth must slow down so that capacity can be diverted to production of the final output, Q . Indeed, if the project horizon is finite, K will stop growing altogether since production of machinery in the last period yields no benefits.

Taken together, these arguments suggest that $K(t)$ is S-shaped, like a learning curve. There are many mathematical equations which fit this general form, all requiring at least three parameters (9). In general these functions are sufficiently complicated to make numerical analysis a necessity. The computations become especially burdensome since production must be optimized with respect to all three variables for every set of engineering specifications considered. (Additional complications arise from the need to specify the transport capacity function.)

Since the capital stock grows over time, the space-production proportions will not be constant. Instead, just like in underdeveloped countries, the portion of goods which are produced locally will increase as an industrial base is established. Other reasons for augmented ratios include technological improvements and increasing returns to scale, which overtake the impracticality of producing certain items in the small quantities demanded at the beginning of industrialization.

Unfortunately, the growth of the space production ratios cannot be fixed without regard to $K(t)$. Any substantial increase in the number of items produced in space also requires enlargement of the capital stock (10). Consequently, the inflection points of m , n , ℓ , and m_q must occur close to that of K .

This relationship is not the only one that links the functions. Instead, the final space-production ratios depend on how early the inflection point is

reached. These correlation seriously complicate the study of bootstrapping.

The variation of productivity over time poses another major problem. Although ρ tends to increase, like the space-production ratios, due to technological change and returns to scale, there are other considerations which counter this influence. First, the items which are initially produced in space will be those requiring the least capital, so that the mass of output per year/mass of machinery should decrease. In addition, as the output from bootstrapping shifts from K to Q, any equipment which is unique to the production of capital will fall into disuse, decreasing the productivity of the total capital stock. (Of course multi-purpose materials will have the opposite effect.) Finally, there is the effect of equipment wear. Without adequate information to weigh these opposing influences, the net change in productivity is ambiguous. Similar arguments interfere with evaluation of the functions A - E, Z, and Z_q .

Even with these factors constant, one would expect costs to change as the nature of the items brought up from earth changes. Since the first goods to be produced in space will be those which require the least processing, the intrinsic value (cost per ton) of the average import will increase over time. Simultaneously, however, the proportion of imports which are less processed, but which contain lunar deficient elements, will also increase. Only the source of medium cost inputs will change, so the overall effect is again unclear.

Apparently, bootstrapping permits so many degrees of freedom that modeling is extremely difficult. In addition, this strategy necessarily introduces complex interdependencies among the various physical and economic functions. In the absence of any significant experience or information to indicate the nature of the correlations, attempts at formulating a general bootstrapping model seem to have very little chance for success.

Simplified Bootstrapping Model

One way to make the analysis mathematically tractable is to assume that manufacture of the final output is delayed until all of the capital -- whether produced in space or merely transported there -- is operational (11). This restriction has the effect of separating both the mass and cash flows into two simpler equations, corresponding to the two stages of processing.

During the capital production phase, lunar soil is used only to form expendables and machinery. Thus,

$$[A \rho - BZm] \dot{K} = [Cn] \Delta K \quad (4')$$

Since no benefits can be derived until some Q is produced, this initial period will probably be quite short - a few years at the most (12). As a result, the technology, as embodied in the scaling, productivity, expendable requirements, and prices, is nearly constant. Equation (4') then reduces to

$$\Delta K = \phi K \quad (10)$$

where $\phi = (A \rho - BZm)/(Cn)$ is independent of time. Integrating,

$$K = K_0 e^{\phi t} \quad (11)$$

where K_0 is the initial capital supplied from earth. Evidently, separating the production of K and Q requires that the capital stock grow exponentially (13).

The earth launch requirement can be reduced similarly to

$$UP = [BZ(1-m) + C\phi(1-n)] K = K\theta \quad (6')$$

where θ is the annual import mass per unit mass of capital. Assuming a fixed fleet during capital production, UP may never exceed the transport capacity, \dot{M} tons/year.

$$UP = \theta K < \dot{M} \quad (12)$$

Rearranging,

$$K < \dot{M}/\theta \quad (13)$$

Therefore \dot{M}/θ is an upper bound on the capital operating during its formation period. More machinery may be accumulated, but the additional capital cannot function until manufacture of the final product has begun.

The transport fleet also affects the onset of exponential growth. If the vehicles are used to capacity, installation of the initial equipment will take K_0/\dot{M} years. In this way, the entire production path for a given technology can be specified by just two parameters - K_0 and \dot{M} .

These same factors also uniquely determine the cost of developing a given capital mass. The initial capital nominally costs $\$G/\text{ton}$, with the payment schedule fixed by \dot{M} . Once all of this equipment is in place, the cash flows required to finance production of machinery in space is

$$\begin{aligned} CF &= - [F(1-m)Z] K - [G(1-n)] \Delta K \\ &= - [F(1-m)Z] K - [G(1-n)] \phi K = \psi K \end{aligned} \quad (14)$$

where ψ is the annual cost per unit mass of capital. If K is defined as the equipment in actual operation at any given time, equation (8') holds whether the capital grows linearly, as when constrained by fleet size, or exponentially. The costs at all points during SMF formation, (and consequently the PDV costs) are therefore fixed by the same two variables which determine $K(t)$.

The dependence of PDV costs on K_0 and \dot{M} for the base case technology described in Appendix 2 is illustrated in Fig. 3. The lowest isocost contours are at the origin, indicating a preference for the maximum amount of

bootstrapping (smallest K_0) and the smallest transport fleet. The reason for this bias is readily explained. By starting with a minimum of capital from earth, capital costs are deferred to the discounted future. Similarly, a small transport capability forces expenses to be spread out over a long period so that costs are discounted heavily. However, even though this strategy minimizes the cost of establishing an SMF, it also delays receipt of revenues from the final product.

Evaluation of the resulting tradeoff between the time and cost of capital development first requires that the effect of K_0 and \dot{M} on the length of the capital production period be determined. For any given launch fleet, the time required to achieve a certain capital mass is minimized by delaying lunar soil processing until capital can be increased at a faster rate by producing it in space than by transporting it from earth. Mathematically, K_0 must be chosen so that

$$\left. \frac{dK}{dt} \right|_{K = K_0} = \dot{M}$$

Evaluation of the derivative for the exponential portion of K gives

$$\left. \frac{dK}{dt} \right|_{K = K_0} = \phi K \Big|_{K = K_0} = \phi K_0 = \dot{M} \quad (15)$$

Thus, the time can be minimized for every fleet size by starting with a seed facility of \dot{M}/ϕ tons. Indeed, this fact is displayed by the isotime curves of Fig. 4.

The rapid increase in time near the K_0 -axis can be explained in a similar manner. As noted above, it takes K_0/\dot{M} years to transport the initial capital into space. The effect of an incremental change in the transport fleet on the length of this period is

$$\frac{dK}{d\dot{M}} \left(\frac{K_0}{\dot{M}} \right) = \frac{-K_0}{(\dot{M})^2} \quad (16)$$

suggesting that changes in the fleet size have the greatest effect on the time needed to install K_0 when \dot{M} is small. (This influence is accentuated in later periods of lunar soil processing.)

In order to see how detrimental deferral of the revenues can be, it is also important to estimate the magnitude of the benefits. Once production of the final output has started, no more capital is manufactured. Consequently, the lunar mass flow reduces to

$$[A'\rho' - B'm'Z'] K_f = [D\ell] \Delta Q + [Em_q Z_q] Q \quad (4'')$$

where K_f is the total capital mass and the primes serve to distinguish certain functions from their previous values during the capital production phase. Since the equipment does not change, the production method is essentially fixed, thereby freezing the physical and economic parameters (9). It will further be assumed that the amount of output related expendables produced in space ($\Delta X_q S$) is negligible. Therefore, equation (4'') becomes

$$\Delta Q = [A'\rho' - B'm'Z'] K_f / [D\ell] = XK_f \quad (17)$$

which satisfies the condition of steady state production.

This relationship can be incorporated into the cash flow equation as follows:

$$\begin{aligned} CF &= [P - I(1-m_q)Z_q] Q - [F'(1-m')Z'] K - [H(1-\ell)] \Delta Q \\ &= [P - I(1-m_q)Z_q] \Delta Qt - [F'(1-m')Z'] K - [H(1-\ell)] \Delta Q \\ &= [XP - XI(1-m_q)Z_q] K_f t - [F'(1-m')Z' - XH(1-\ell)] K_f \end{aligned} \quad (8'')$$

The PDV can be evaluated by applying the discount factor e^{-rt} , and integrating over the period in question. For a 100,000 T SMF using the base case technology, the PDV of 50 years of net revenues is approximately \$1 trillion, discounted at 10% per year to the time at which production of Q begins.

These benefits are introduced to the total project value at the times specified in Fig. 4. The result of adding the appropriately discounted revenues to the isocost curves of assembling the SMF is shown in Fig. 5. The length of time required to develop the capital obviously exerts the dominant influence. However, the cost of establishing the SMF (Fig. 3) adds a slight bias toward the origin.

Figure 5 still does not tell the whole story. It demonstrates the PDV from the first launch of terrestrial materials, but ignores the costs incurred prior to space operations. Perhaps the most important of these factors is the cost of the transport fleet. Indeed, it is the neglect of this expense which allows the peak PDV to stay at the maximum \dot{M} .

It has been previously suggested that the optimal fleet for bootstrapping would consist of numerous small vehicles (14). In this case, the fleet cost is roughly proportional to the transport capacity and can be viewed on a relief diagram as a plane inclined upwards from the initial-capital axis. When the cost plane for a shuttle derived fleet is subtracted, the PDV contours of Fig. 5 close up (Fig. 6). This effect is simply a graphical representation of the fact that, past a certain point, additional vehicles increase fleet costs without substantially affecting the time or the costs of SMF development.

The other costs that must precede space operations are associated with research and development. In order to analyze the effect of these expenses on the optimal production point, it is important to know just how they vary with

K_0 and \dot{M} . In general, the degree of bootstrapping is related directly to the number of manufacturing processes employed in space. Although most tools and techniques can be used in a variety of processes (3), decreases in K_0 are still expected to raise research costs. At the same time, however, bootstrapping reduces the need for developing optimal equipment at the outset by permitting changes in early project designs. In essence, starting with a small amount of capital enables some of the RND to be integrated with the space operations. The effect of this type of "learning by doing" is diminished by the brevity of the capital growth period.

Since the correlation between RND and K_0 is difficult to assess, it will be assumed negligible. This assumption is reinforced by estimates which show that material processing represents a rather small proportion of the total research costs (15). Development costs should be even more insensitive to changes in \dot{M} , since the transport capacity is enlarged by increasing the number, rather than the size, of the launch vehicles. To the extent that more advanced vehicles might be used at high transport rates, there would be a slight bias in favor of large \dot{M} . (Even though development costs for such a system would be greater, the incremental costs would not be incurred unless some savings could be realized.) Since RND costs are assumed constant over the entire plane, they change only the absolute magnitudes, and not the relative positions, of the contours in Fig. 6.

Conclusions

Although there is great uncertainty in the input parameters for the graphs above, the general behavior of the curves remains the same over a wide range of values. The optimal combination of K_0 and \dot{M} always lies close to a line through the origin with slope ϕ . Since ϕ is dominated by the productivity, the peak PDV must be quite sensitive to ρ .

Just where along the line one should operate is determined by three

considerations. First is the importance of time as indicated by the discount rate and the revenues. Second is the extent to which ϕ enables the utilization of lunar resources to shorten the period prior to steady state operation. Finally, the optimum is influenced by the cost of the transport fleet.

The costs during capital development, in contrast, play only a minor role in determining the optimal production path. They introduce only a slight bias toward the origin. Indeed, Fig. 6 can be approximated quite closely by ignoring these costs altogether (Fig. 7). As transport costs decrease with more advanced launch systems, the difference becomes negligible.

In this way, the model shows that the main reason for producing capital with lunar resources is not that it reduces the cost of transporting materials into space (although it certainly does that), but that it reduces the time needed to assemble a space manufacturing facility using a given fleet. True bootstrapping would be even more attractive than the simplified strategy since it would postpone many of the costs and start delivering benefits much sooner. Furthermore, bootstrapping would decrease research time and risk by transferring more development to the productive phase of operations.

Acknowledgments

This work was performed during a Visiting Undergraduate Intern Appointment to Aaron H. Goldberg at the Lunar and Planetary Institute.

FOOTNOTES

1. Waldron R. D., T. E. Erstfeld and D. R. Criswell, Chemical Engineering February 12, 1979, p. 81.
2. LRU for Space Construction, Contract NAS 9-15560, General Dynamics Final Presentation, pp. 48-49, 1979.
3. Lunar Resources Utilization for Space Construction, Contract NAS 9-15560, General Dynamics Report on "Lunar Materials Processing and Manufacturing."
4. Criswell D. R. ., personal communication, 1979.
5. During the summer of 1979, workshops on bootstrapping were held at the NASA/Ames Research Center and Woods Hole (Telefactors Group).
6. These inputs correspond roughly to the recurring and non-recurring costs discussed in "Extraterrestrial Processing and Manufacturing of Large Space Systems." Contract NAS 8-32925, MIT Space Systems Laboratory Process Report No. 6, Appendix A, 1979.
7. There may, of course, be complicated interdependencies among the bracketed expressions, as well as between them and the functions Q and K.
8. The functions F-I must be adjusted for any deviation of A-E from unity.
9. Two such functions are the logistic and the Gompertz curve.
10. The output of a fixed capital stock could be increased by changing the number or type of inputs. However, any large increase in production would require more machinery.

11. The most detailed analyses of both terrestrial and extraterrestrial SPS production have made this assumption, despite the fact that it prevents true optimization.
12. General Dynamics estimates that the start-up phase for a non-bootstrapping operation would take about three years. See Ref. 2, p. 92.
13. Implicit in the integration is the assumption that the capital stock is infinitely divisible and compounds continuously. This approximation might be approached in practice, since most space equipment is expected to be relatively small.
14. Miller R. H. and D. L. Akin, "Solar Power Satellite Costs as a Function of Material Source and Manufacturing Productivity in Space," in conjunction with Contract NAS 8-32925 (MIT Space Systems Laboratory) 1979.
15. Lunar Resources Utilization for Space Construction. Contract NAS 9-15560, General Dynamics Final Report, Volume II, Section 5, 1979.

Appendix 1. Computer Programs

```

C*****
C
C
C           MODEL.FTN
C
C           THIS PROGRAM COMPUTES THE PRESENT DISCOUNTED VALUE (PDV) AND THE
C           TIME NEEDED TO ESTABLISH THE SMF FOR AN ARRAY OF KO AND M-DOT VALUES.
C           THE SMF PRODUCTION COSTS ARE COMPUTED IN THREE STEPS:
C
C           1) COST OF "EMPLANTING" THE KO SEED FACILITY
C
C           2) COST OF EXPONENTIAL GROWTH (IF ANY OCCURS)
C
C           3) COST OF LINEAR, TRANSPORT-LIMITED GROWTH (IF ANY OCCURS)
C
C           FINALLY REVENUES, FLEET COSTS, AND RESEARCH COSTS ARE ADDED TO GET THE
C           TOTAL PDV. THE POINT WITH THE HIGHEST PDV IS ALSO LOCATED.
C
C           INPUTS
C           FILE 3 : TECHNOLOGICAL PARAMETERS
C
C           OUTPUTS
C           FILE 1 : KO AND M-DOT FOR HIGHEST PDV
C           FILE 2 : PDV AND TIME VALUES FOR THE ENTIRE ARRAY
C
C*****
C           REAL K000, MNM, K, JFL
C           CALL ASSIGN (1, 'DD:')
C           CALL ASSIGN (2, 'DD:')
C
C
C*****INPUT TECHNOLOGICAL PARAMETERS
C
C           READ (3,150) A,B,C,F,G,P1,P2,P3,P4,RATE,RHO,RN,RN,WANT,Z
150  FORMAT (16(6X,F15.5/))
C           R=ALOG(RATE)
C           PEAK=0.
C           TOPK=0.
C           TOPH=0.
C
C
C*****COMPUTES PHI, PSI, AND THETA FOR INPUT TECHNOLOGY
C
C           PHI=(A*RHO-B*RN*Z)/(C*RN)
C           THETA=B*Z*(1.-RN)+C*PHI*(1.-RN)
C           PSI=F*Z*(1.-RN)+G*PHI*(1.-RN)
C
C
C*****CHOOSES POINT IN THE MATRIX
C
C           DO 5678 INT1=1,50
C           K000=1990.*FLOAT(INT1)+500.
C           DO 5678 INT2=1,50
C           MNM=1990.*FLOAT(INT2)+500.
C           VALUE=0.
C           VONE=0.
C           VTWO=0.
C           VTHRE=0.
C
C
C*****COMPUTES COST OF "EMPLANTING" THE SEED FACILITY
C
C           YTTI=K000/MNM
C           VONE=G*MNM*(1.-EXP(-R*YTTI))/R
C           TSTK=K000
C           JFL=YTTI
C           IF (K000.GE.WANT) GO TO 4321
C           STOPK=MNM/THETA
C           STOPK=AMINI (STOPK,WANT)
C           IF (STOPK.LE.K000) GO TO 1111

```

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C
C
C*****COMPUTES COSTS DURING EXPONENTIAL GROWTH
C
C
      TINT=YTTI+ALOG(STOPK/KOOD)/PHI
      VTUO=PSI*KOOD*EXP(-PHI*YTTI)/(PHI-R)
      VTUO=VTUO*(EXP(TINT*(PHI-R))-EXP(YTTI*(PHI-R)))
      TSTK=KOOD*EXP(PHI*(TINT-YTTI))
      JFL=TINT
      IF (TSTK.GE.WANT) GO TO 4321
      GO TO 2222

C
C
C*****COMPUTES COSTS DURING LINEAR, TRANSPORT-LIMITED GROWTH
C      WHEN THERE IS NO EXPONENTIAL GROWTH
C
C
1111  TINT=YTTI
      VTUO=0.
      TFIN=YTTI+(WANT-KOOD)/(PHI*STOPK)
      JFL=TFIN
      VTHRE=PSI*STOPK*(EXP(-R*TINT)-EXP(-R*TFIN))/R
      TSTK=KOOD+PHI*STOPK*(TFIN-TINT)
      GO TO 4321

C
C
C*****COMPUTES COSTS DURING LINEAR, TRANSPORT-LIMITED GROWTH
C      IF THERE WAS PREVIOUS EXPONENTIAL GROWTH
C
C
2222  TFIN=TINT+(WANT-STOPK)/(PHI*STOPK)
      VTHRE=PSI*STOPK*(EXP(-R*TINT)-EXP(-R*TFIN))/R
      JFL=TFIN
      TSTK=STOPK+PHI*STOPK*(TFIN-TINT)

C
C
C*****COST OF ESTABLISHING THE SPACE MANUFACTURING FACILITY
C
C
4321  VALUE=VONE+VTUO+VTHRE

C
C
C*****PRESENT DISCOUNTED VALUE (PDV)
C
C
1999  GRAND=P2*EXP(-R*JFL)-VALUE-P1*MNM-P4-P3*(WANT-KOOD)

C
C
C*****FINDS MAXIMUM PDV FOR INPUT TECHNOLOGY
C
C
      IF (PEAK.GE.GRAND) GO TO 5678
      PEAK=GRAND
      TOPK=KOOD
      TOPM=MNM
5678  WRITE (2,2000) GRAND, JFL
2000  FORMAT (2F25.5)
      WRITE (1,2000) TOPK, TOPM
      STOP
      END

```


C
C
C*****INTERPOLATES IN THE M-DOT DIRECTION
C
C

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DO 2000 IX=1, LIMX
  YY=1.
  CAPTB=YRS(IX,1)-.75
  QT30B=YRS(IX,1)-1.0
  QT50B=YRS(IX,1)-1.25
  QT99B=YRS(IX,1)-1.5
  V050B=PDV(IX,1)-PARM1
  V200B=PDV(IX,1)-PARM2
  V500B=PDV(IX,1)-PARM3
  V999B=PDV(IX,1)-PARM4
  V25TB=PDV(IX,1)-PARM5
  DO 2000 IY=1, LIMY
    CAPTA=YRS(IX,IY)-.75
    QT30A=YRS(IX,IY)-1.0
    QT50A=YRS(IX,IY)-1.25
    QT99A=YRS(IX,IY)-1.5
    V050A=PDV(IX,IY)-PARM1
    V200A=PDV(IX,IY)-PARM2
    V500A=PDV(IX,IY)-PARM3
    V999A=PDV(IX,IY)-PARM4
    V25TA=PDV(IX,IY)-PARM5
1030  X=1990.*FLOAT(IX)+500.
      YC=1990.*FLOAT(IY)+500.
1090  PR1=CAPTA+CAPTB
      IF (PR1.GE.0.) GO TO 1100
      Y=YC-CAPTA*(YC-YY)/(CAPTA-CAPT)
      WRITE (3,9999) X, Y
1100  CAPTB=CAPTA
      PR2=QT30A*QT30B
      IF (PR2.GE.0.) GO TO 1200
      Y=YC-QT30A*(YC-YY)/(QT30A-QT30B)
      WRITE (4,9999) X, Y
1200  QT30B=QT30A
      PR3=QT50A*QT50B
      IF (PR3.GE.0.) GO TO 1300
      Y=YC-QT50A*(YC-YY)/(QT50A-QT50B)
      WRITE (7,9999) X, Y
1300  QT50B=QT50A
      PR4=QT99A*QT99B
      IF (PR4.GE.0.) GO TO 1400
      Y=YC-QT99A*(YC-YY)/(QT99A-QT99B)
      WRITE (8,9999) X, Y
1400  QT99B=QT99A
      PR5=V050A*V050B
      IF (PR5.GE.0.) GO TO 1500
      Y=YC-V050A*(YC-YY)/(V050A-V050B)
      WRITE (9,9999) X, Y
1500  V050B=V050A
      PR6=V200A*V200B
      IF (PR6.GE.0.) GO TO 1600
      Y=YC-V200A*(YC-YY)/(V200A-V200B)
      WRITE (10,9999) X, Y
1600  V200B=V200A
      PR7=V500A*V500B
      IF (PR7.GE.0.) GO TO 1700
      Y=YC-V500A*(YC-YY)/(V500A-V500B)
      WRITE (11,9999) X, Y
1700  V500B=V500A
      PR8=V999A*V999B
      IF (PR8.GE.0.) GO TO 1800
      Y=YC-V999A*(YC-YY)/(V999A-V999B)
      WRITE (12,9999) X, Y
1800  V999B=V999A
      PR9=V25TA*V25TB
      IF (PR9.GE.0.) GO TO 1900
      Y=YC-V25TA*(YC-YY)/(V25TA-V25TB)
      WRITE (13,9999) X, Y
1900  V25TB=V25TA
      YY=YY+1.
2000  CONTINUE

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C
C
C*****INTERPOLATES IN THE XO DIRECTION
C
C
DO 3000 IY=1, LIMY
XX=1.
CAPTB=YRS(1,IY)-.75
QT30B=YRS(1,IY)-1.0
QT50B=YRS(1,IY)-1.25
QT99B=YRS(1,IY)-1.5
V050B=PDV(1,IY)-PARM1
V200B=PDV(1,IY)-PARM2
V500B=PDV(1,IY)-PARM3
V999B=PDV(1,IY)-PARM4
V25TB=PDV(1,IY)-PARM5
DO 3000 IX=1, LIMX
CAPTA=YRS(IX,IY)-.75
QT30A=YRS(IX,IY)-1.0
QT50A=YRS(IX,IY)-1.25
QT99A=YRS(IX,IY)-1.5
V050A=PDV(IX,IY)-PARM1
V200A=PDV(IX,IY)-PARM2
V500A=PDV(IX,IY)-PARM3
V999A=PDV(IX,IY)-PARM4
V25TA=PDV(IX,IY)-PARM5
2030 XC=1990.*FLOAT(IX)+500.
      Y=1990.*FLOAT(IY)+500.
2090 PR1=CAPTA+CAPTB
      IF (PR1.GE.0.) GO TO 2100
      X=XC-CAPTA*(XC-XX)/(CAPTA-CAPTB)
      WRITE (3,9999) X, Y
2100 CAPTB=CAPTA
      PR2=QT30A+QT30B
      IF (PR2.GE.0.) GO TO 2200
      X=XC-QT30A*(XC-XX)/(QT30A-QT30B)
      WRITE (4,9999) X, Y
2200 QT30B=QT30A
      PR3=QT50A+QT50B
      IF (PR3.GE.0.) GO TO 2300
      X=XC-QT50A*(XC-XX)/(QT50A-QT50B)
      WRITE (7,9999) X, Y
2300 QT50B=QT50A
      PR4=QT99A+QT99B
      IF (PR4.GE.0.) GO TO 2400
      X=XC-QT99A*(XC-XX)/(QT99A-QT99B)
      WRITE (8,9999) X, Y
2400 QT99B=QT99A
      PR5=V050A+V050B
      IF (PR5.GE.0.) GO TO 2500
      X=XC-V050A*(XC-XX)/(V050A-V050B)
      WRITE (9,9999) X, Y
2500 V050B=V050A
      PR6=V200A+V200B
      IF (PR6.GE.0.) GO TO 2600
      X=XC-V200A*(XC-XX)/(V200A-V200B)
      WRITE (10,9999) X, Y
2600 V200B=V200A
      PR7=V500A+V500B
      IF (PR7.GE.0.) GO TO 2700
      X=XC-V500A*(XC-XX)/(V500A-V500B)
      WRITE (11,9999) X, Y
2700 V500B=V500A
      PR8=V999A+V999B
      IF (PR8.GE.0.) GO TO 2800
      X=XC-V999A*(XC-XX)/(V999A-V999B)
      WRITE (12,9999) X, Y
2800 V999B=V999A
      PR9=V25TA+V25TB
      IF (PR9.GE.0.) GO TO 2900
      X=XC-V25TA*(XC-XX)/(V25TA-V25TB)
      WRITE (13,9999) X, Y
2900 V25TB=V25TA
      XX=XC
3000 CONTINUE
9999 FORMAT (2F25.5)
      STOP
      END

```

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Additional Engineering Parameters

		Mining	Benefi- ciation	Lunar Launch	Refining	Manufac- turing
Requirements for Process Expendables	$\frac{T/\text{yr}}{T \text{ process capital}}$	8×10^{-4}	8×10^{-4}	1.6	.18	.01
Cost of Process Expendables	$\frac{\$}{T}$	2000	2000	1000	6000	5000
Requirements for Replace- ment Parts	$\frac{T/\text{yr}}{T \text{ process capital}}$	8×10^{-2}	8×10^{-2}	.1	.12	.1
Personnel Requirements	$\frac{\text{men}}{T \text{ process capital}}$	.05	.05	.05	.04	.08
Energy Requirement	$\frac{\text{MW}}{T \text{ process capital}}$	10^{-4}	10^{-4}	.08	.06	.2
Productivity	$\frac{T/\text{yr output}}{T \text{ process capital}}$	8000	8000	160	60	10
Retention	$\frac{T \text{ out}}{T \text{ in}}$	1.0	.2	.9	1.0	.95

DETAILED DESCRIPTION OF BASE CASE TECHNOLOGY

The base case technology is designed to produce solar power satellites. Lunar soil is mined and beneficiated on the moon and then launched into space by a lunar mass driver. Finally, the lunar materials are refined and processed into useful products in earth orbit. The underlying assumptions are as follows:

Capital

Final capital mass -- 100,000 tons
 Space production ratio -- .85
 Process capital -- \$11,000/ton
 Energy production -- 14 tons/MW on the moon
 -- 10 tons/MW in space
 -- \$6,000/ton

Expendables

Space production ratio -- .3
 Replacement parts -- \$11,000/ton
 Personnel support -- .01 tons per man/day
 -- \$3,000/ton
 Personnel -- 100% overhead
 -- 4 shifts/year (2 crews times 2 rotations)
 -- \$100,000/year wage

Output and Related Expendables

Revenue -- \$100,000/year/ton SPS
 Rectenna capital -- \$45,000/ton SPS
 Rectenna expendables -- \$1,350/year/ton SPS
 (only output-related expendable)

Transportation

Cargo -- \$1 million/ton into orbit

Personnel -- \$2 million/ton onto the moon
-- One man = .085 ton

Vehicle -- \$250 million/Shuttle
-- Three-week turn around time
-- 30 tons/flight
-- \$6,000/ton

Discount Rate

-- 10%

Appendix 2. Base Case Technology

INPUT PARAMETERS FOR COMPUTER PROGRAM

A = 1.0

B = 1.0

C = 1.0

F = \$1,421,000/ton expendable

G = \$1,173,000/ton capital

P1 (fleet cost) = \$555,555/ton per year transport capability

P2 (revenues) = \$1,000,000,000,000

P3 (fixed R&D costs) = \$150,000,000,000

P4 (R&D bias) = \$0./ton

Rate = 1.1

RH0 = 2.55 tons output per year/ton capital

RM(m) = .30 tons expendables from lunar soil/ton expendables

RN(n) = .85 tons capital from lunar soil/ton capital

WANT (SMF mass) = 100,000 tons

Z = .1545 tons expendables per year/ton capital

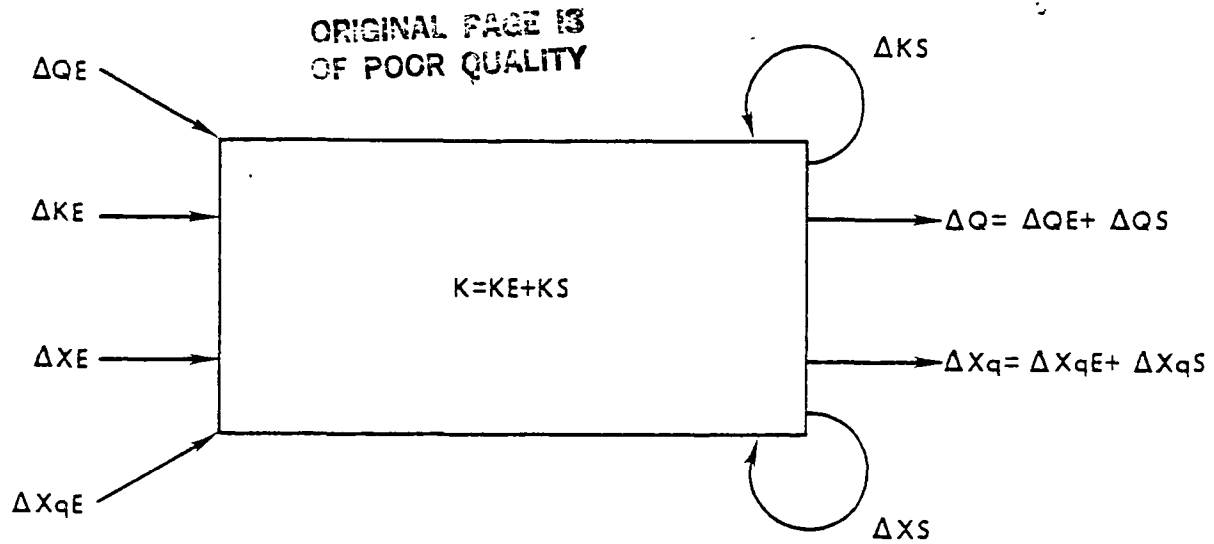


Figure 1. Material flow through the space industrial complex.

Figure 2. Strategies for space industrialization

TERRESTRIAL	LUNAR RAW MATERIALS	BOOTSTRAPPING
$m = 0$ (process expendable)	$m = m(t)$	$m = m(t)$
$n = 0$ (capital)	$n = 0$	$n = n(t)$
$l = 0$ (output)	$l = l(t)$	$l = l(t)$
$m_q = 0$ (output related expendables)	$m_q = m_q(t)$	$m_q = m_q(t)$

Fractions of various mass flows made of extra terrestrial materials

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Figure 3. Isocost curves for establishing an SMF of 100,000 tons (\$ billions)

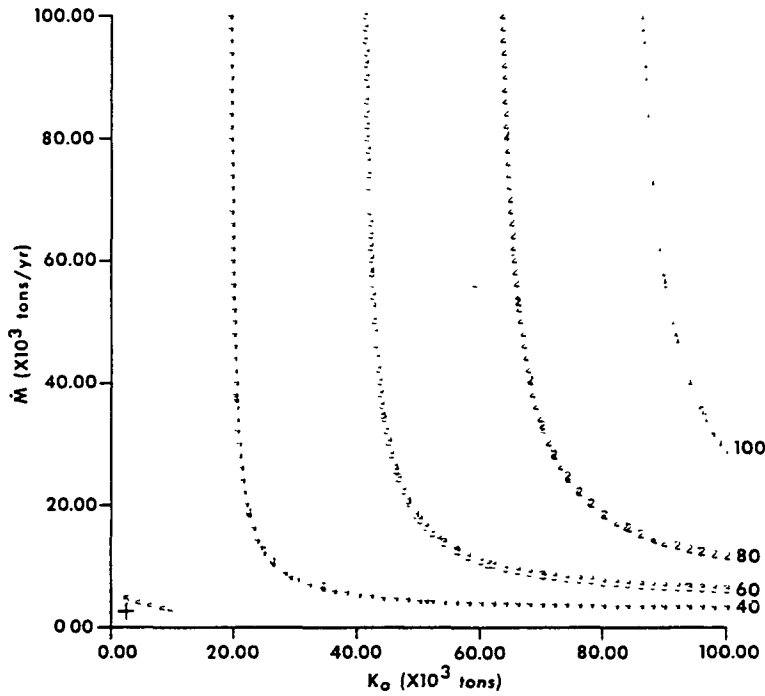


Figure 4. Isotime curves for establishing the SMF

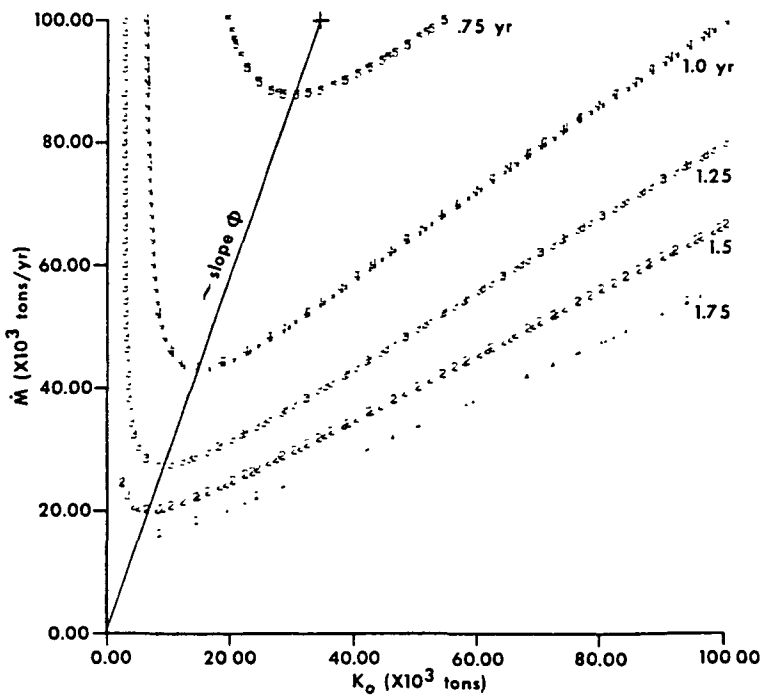


Figure 5. PDV for all space operations (\$ billions)

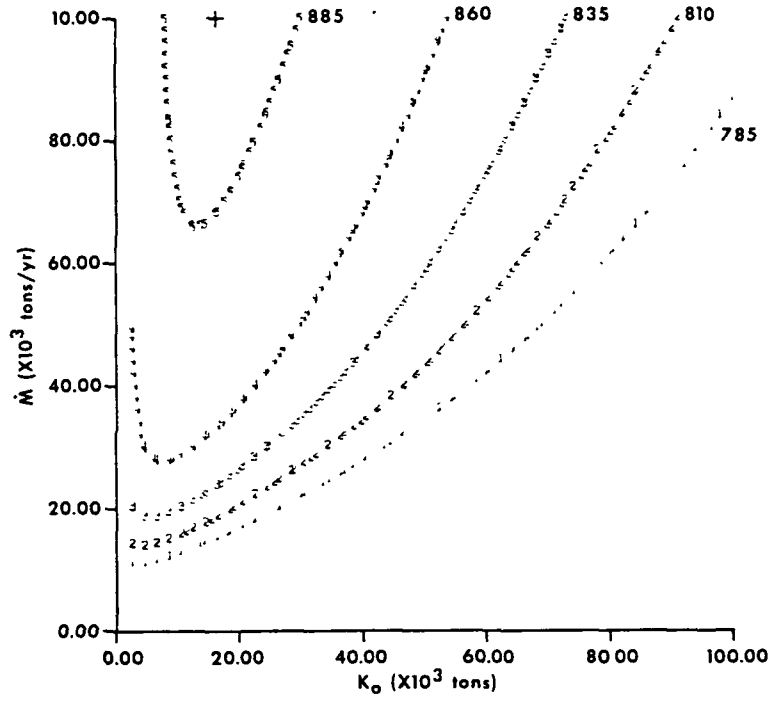
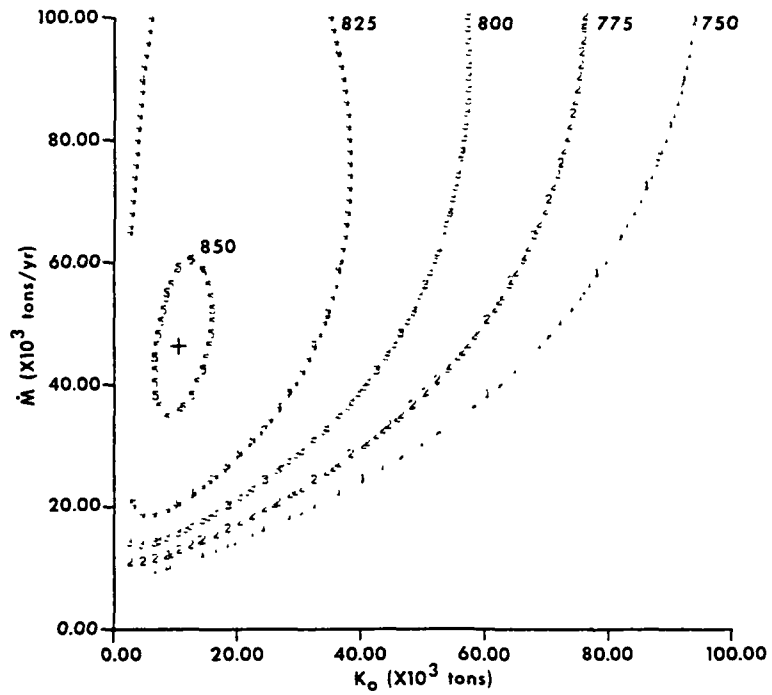
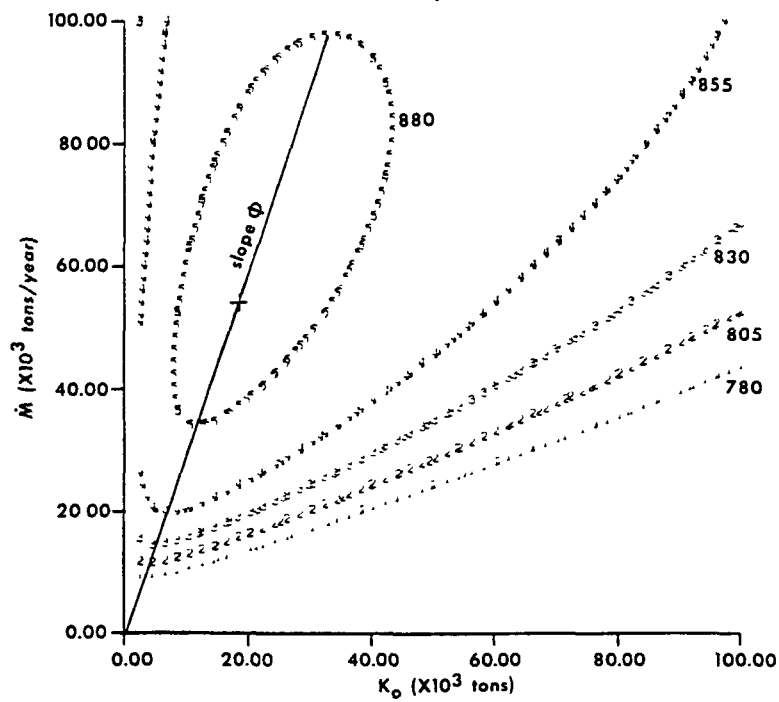


Figure 6. PDV for entire project except R&D (\$ billions) Inclusion of R&D costs changes only the absolute magnitudes, and not the relative positions, of the curves.



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Figure 7. PDV of entire project excluding costs of R&D and establishing the SMF (\$ billions). Inclusion of R&D costs changes only the absolute magnitudes, and not the relative positions, of the curves.



Chapter X

REPRINTS AND PREPRINTS OF 1978 - 1979 TECHNICAL PAPERS

- A. Waldron R. C., Erstfeld T. E. and Criswell D. R. (12 February 1979) The Role of Chemical Engineering in Space Manufacturing, Chemical Engineering, p. 89-94, McGraw-Hill, New York.*
*Reprinted in Chinese in American Industrial Report issue No. 37, September 1979; p. 26-43, American Industrial Report Limited.
- B. Criswell D. R. and Waldron R. D. (1978) Commercial Prospects for Extraterrestrial Materials, J. Contemporary Business 7, No. 3, p. 153-189, Un. Washington Press, Seattle.
- C. Inculet I. I. and Criswell D. R. (1979) Electrostatic Beneficiation of Ores on the Moon Surface, Inst. Physics Conference, Ser. No. XX, Chapter Z, Un. Oxford Press, England.
- D. Ayres R. U., Ayres L. W. and Criswell D. R. (1979) Economic Considerations in Space Industrialization, 4th Princeton/AIAA Conference on Space Manufacturing Facilities (paper 79-1390), pp. 12, American Inst. Aeronautics and Astronautics, New York.
- E. Waldron R. D., Criswell D. R. and Erstfeld T. E. (1979) Overview of Methods for Extraterrestrial Materials Processing (paper 79-1379), pp. 15, *ibid.*
- F. Criswell David R. (1979) Scaling and the Start-up Phase of Space Industrialization (paper 79-1391), pp. 10, *ibid.*
- G. Carrier W. D. (1979) Excavation Costs of Lunar Materials (paper 79-1376), pp. 8, *ibid.*

- H. Mackenzie J. D. and Claridge R. C. (1979) Glass and Ceramics from Lunar Materials (paper 79-1381), pp. 6, *ibid.*
- I. Criswell D. R. and Waldron R. D. (1980) (in press) Chemical Processing of Lunar Materials, Proceedings of the Thirtieth Congress of the International Aeronautical Federation (Munich, Germany) 16-22 September 1979, No. 79-116, pp. 13.
- J. Criswell D., Glaser P. E., Mayur R., O'Leary B. T., O'Neill G. K. and Vajk J. P. (1980) The Role of Space Technology in the Developing Countries, presented at "Non-Governmental Organizations Forum on Science and Technology for Development" (Vienna, Austria) August 19-29, 1979, United Nations, *Space Solar Power Review 1*, 97-107, 1980.
- K. Trotti G. and Criswell D. R. (1978), Lunar Base Habitat Exploration Design Study (AAS 78-143), 25th Anniversary Conference, American Astronautical Society, 30 October - 2 November 1978. Houston, Texas, pp. 26 (micro forms), AAS Publication, San Diego.
- L. Waldron R. D. (1980) Electrorefining Process for Lunar Free Metal: Terrestrial Implications and Applications (Abstract), American Chemical Society (submitted for fall meeting).
- M. Criswell David R. and Waldron Robert D., Lunar Utilization, In Space Industrialization, Brian J. O'Leary, editor, CRC Press, Inc. Boca Raton, Florida.
- N. Waldron Robert D. and Criswell David R., Materials Processing in Space, in Space Industrialization, Brian J. O'Leary, editor, CRC Press, Inc., Boca Raton, Florida.

A reprint from

CHEMICAL ENGINEERING

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The role of chemical engineering in space manufacturing

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The role of chemical engineering in space manufacturing

Robert D. Waldron, Lunar and Planetary Institute,

□ If humans are to exploit the potentials of space, for example by building a solar-power station (pictured at right above), they will likely use lunar ores launched by a mass driver (shown at left, extending to the horizon), and processed in an orbiting plant.

Chemical engineers will play a critical role in identifying and developing the systems that can process these extraterrestrial materials into the feedstocks necessary for industrial developments in space.

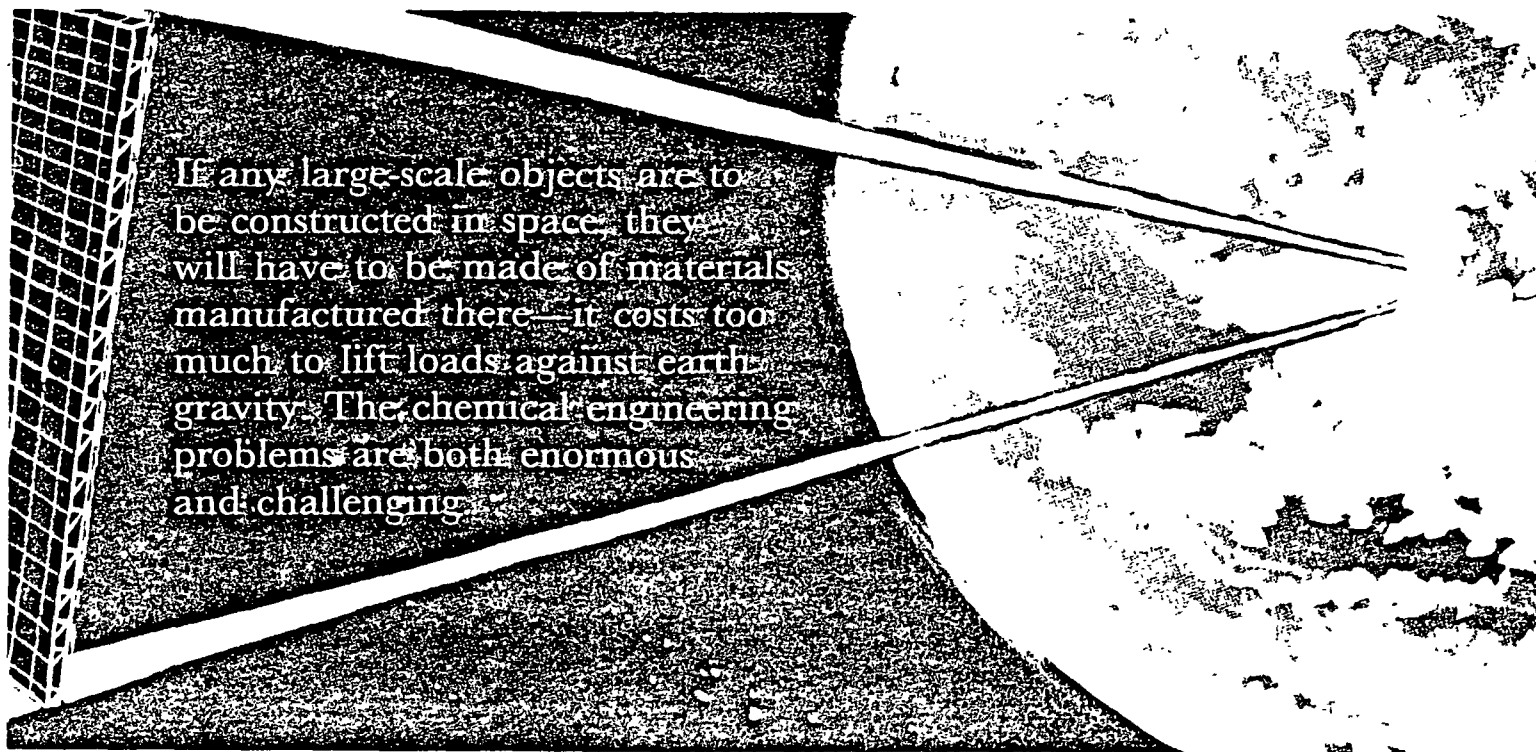
The moon is an extremely likely first source of raw materials. We possess considerable detailed knowledge about it, know how to plan and execute large operations in *cis*-lunar space and have identified the technology to transport materials off the moon at low unit costs. Finally, we know that the moon has a large fraction of the chemical elements needed for a wide range of industrial operations.

Plans for large-scale space operations range from P. E. Glaser's [1a, 1b] concepts of a series of satellite solar power stations (SSPs) [1c, 3], of which NASA is involved in a feasibility study, to G. K. O'Neill's [2] call for space manufacturing using extraterrestrial materials. From these efforts could evolve completely man-created economies and human ecologies in space.

From earth into space

Even if the earth had no atmosphere, its huge mass means that a very high velocity (11.2 km/s) would be required for anything to escape the earth and go into orbit or into deep space. Furthermore, the earth's atmosphere induces drag forces that prevent achieving high velocities at low altitudes. On the other hand, only 2.4 km/s is required to escape from the gravity of the moon, and the moon has no atmosphere.

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If any large-scale objects are to be constructed in space, they will have to be made of materials manufactured there—it costs too much to lift loads against earth gravity. The chemical engineering problems are both enormous and challenging.

Thomas E. Erstfeld, Lockheed Electronics Co. and David R. Criswell, Lunar and Planetary Institute

The total kinetic energy of a moving body is proportional to the square of its velocity. Therefore (even ignoring earth's atmosphere), an object ejected from the surface of the earth must be given $(11.2/2.4)^2 = 22$ times as much energy as a similar object ejected from the moon.

It costs money to produce energy in the proper form to do the job, and more money to provide hardware to use it. However, let us assume that we had a device that could directly use electricity with 100% efficiency to propel payloads from the surface of the earth into deep space. Then (ignoring the earth's atmosphere and assuming a cost of 25 mills/kWh) it would require 17.4 kWh/kg and cost only 44¢/kg to escape the earth. This corresponds to a cost of \$31 to eject a 70-kg person. Ejection energy from the moon would be approximately 5% that from the earth (0.8 kWh/kg) and for the same energy rates would cost 2¢/kg and \$1.40 for ejecting a 70-kg person. (Of course, there is no 25-mill electric power on the moon—yet.)

While the prospect of achieving high-energy-efficiency launches from the earth appears slim, it appears possible for the moon. A device for this purpose, termed a mass driver, was first proposed by G. K. O'Neill [2a]. The mass driver is a two-part electric motor stretched out into a straight line. The moving portion (armature) is a bucket surrounded by superconducting coils that receive accelerating forces from external power lines and levitate the bucket above an aluminum guideway, so that extremely high velocities are possible. Working models have been demonstrated, and the basic theory is very well understood.

Such a device cannot operate on the earth's surface to eject materials directly into space. Passage through the

atmosphere would quickly reduce the velocity, and intense heating of the payload would occur. The cost of launching payloads from the earth is increased greatly because a chemical rocket must be used. Several penalties result: for example, the rocket must be large enough and strong enough to carry not only the payload but also the fuel necessary to lift both the entire rocket and its payload. If one wants to reuse the rocket, additional mass must be included in the form of reentry heat shields, in extra structure both to withstand reentry and to accommodate the overall increased size of the system, and so on. High costs are associated with such reusable systems.

The space shuttle represents advanced technology applied to this problem. The shuttle will carry into orbit approximately 30,000 kg of payload but will have a liftoff weight of 2 million kg, including propellants. The payload represents only 1.5% of the liftoff weight. Payloads will initially be delivered into orbit for \$600/kg. This rate should drop to \$100/kg as advanced shuttle derivatives come into operation.

These are very significant decreases in unit costs compared with the \$2,000 to \$6,000/kg of present expendable launch vehicles. Ultimately, costs to orbit could be expected to drop to \$15 to \$30/kg by the turn of the century if very large single-stage-to-orbit, completely reusable vehicles can be developed and operated [3].

Analyses of more-exotic methods, such as using ground-based lasers to power simple freight rockets into orbit, indicate costs (\$/kg) of this same order. One thing is clear: even with these advanced systems, the unit cost to achieve earth orbit or deep space will be 30 to 100 times greater than the minimum terrestrial cost

Ranges of chemical compositions for the major minerals

Table I

High-titanium basalts				
Modal abundance (Vol. %)	Pyroxene 42-60%	Olivine 0-10%	Plagioclase 15-33%	Opaques (mostly ilmenite) 10-34%
Component (Wt. %)				
SiO ₂	44.1-53.8	29.2-38.6	46.9-53.3	<1.0
Al ₂ O ₃	0.6-6.0	-	28.9-34.5	0-2.0
TiO ₂	0.7-6.0	-	-	52.1-74.0
Cr ₂ O ₃	0-0.7	0.1-0.2	-	0.4-2.2
FeO	8.1-45.8	25.4-28.8	0.3-1.4	14.9-45.7
MnO	0-0.7	0.2-0.3	-	<1.0
MgO	1.7-22.8	33.5-36.5	0-0.3	0.7-8.6
CaO	3.7-20.7	0.2-0.3	14.3-18.6	<1.0
Na ₂ O	0-0.2	-	0.7-2.7	-
K ₂ O	-	-	0-0.4	-

Low-titanium basalts				
Modal abundance (Vol. %)	42-60%	0-36%	17-33%	1-11%
Component (Wt. %)				
SiO ₂	41.2-54.0	33.5-38.1	44.4-48.2	<1.0
Al ₂ O ₃	0.6-11.9	-	32.0-35.2	0.1-1.2
TiO ₂	0.2-3.0	-	-	50.7-53.9
Cr ₂ O ₃	0-1.5	0.3-0.7	-	0.2-0.8
FeO	13.1-45.5	21.1-47.2	0.4-2.6	44.1-46.8
MnO	0-0.6	0.1-0.4	-	0.3-0.5
MgO	0.3-26.3	18.5-39.2	0.1-1.2	0.1-2.3
CaO	2.0-16.9	0-0.3	16.9-19.2	<1.0
Na ₂ O	0-0.1	-	0.4-1.3	-
K ₂ O	-	-	0-0.3	-

Highlands rocks				
Modal abundance (Vol. %)	5-35%	0-35%	45-95%	0-5%
Component (Wt. %)				
SiO ₂	51.10-55.4	37.70-39.9	44.00-48.0	0-0.1
Al ₂ O ₃	1.00-2.5	0-0.1	32.00-36.0	0.80-65.0
TiO ₂	0.45-1.3	0-0.1	0.02-0.03	0.40-53.0
Cr ₂ O ₃	0.30-0.7	0-0.1	0-0.02	0.40-4.0
FeO	8.20-24.0	13.40-27.3	0.18-0.34	11.60-36.0
MgO	16.70-30.9	33.40-45.5	0-0.18	7.70-20.0
CaO	1.90-16.7	0.20-0.3	19.00-20.0	0-0.6
Na ₂ O	-	-	0.20-0.6	-
K ₂ O	-	-	0.03-0.15	-

(44¢/kg) mentioned earlier, and 600 to 2,000 times greater than a conceivable lower limit to the lunar-launch costs.

Materials processing in space

A study is underway at the Lunar and Planetary Institute (Houston) concerning both the processing of lunar materials and space manufacturing, in which we consider the following questions:

- What resources can be mined and recovered from the moon?

- What ranges of industrial feedstock can be provided from lunar materials?

- What specific schemes can be identified for physical and chemical processing of lunar materials?

- Can a bootstrap operation be established?

Table I shows the composition of the two major constituents of the mare and highlands regions of the moon [5]. Meteoritic bombardment has tended to homogenize the distribution of minerals in these two regions to great depths. There are no aqueous processes operating on the moon to concentrate minerals or elements. Thus we expect to work with the dust and surface rocks of the moon, rather than look for deep veins of minerals. Table II presents compositional information derived from remote observation of the surfaces of major asteroids [4,6]. It is evident that the chemical/metallurgical industry in space will be substantially different from that on earth, due to scarcity of key elements such as H, C, Na, Cl, etc.

In common with industry on earth, one may anticipate commercial use of both native lunar mineral products (raw or beneficiated) and processed or refined materials (metals, oxides, etc.) for various applications, with price/performance criteria determining use patterns. Native lunar soils may be sintered or fused to obtain a variety of ceramic, cast basalt, and dark-glass products. Free iron may also be recoverable by magnetic methods from lunar soil.

Table III shows elements that are potentially recoverable from the moon. (The designations "major," "minor," and "trace" are ours.) The light trace-elements are mostly due to solar wind bombardment of the lunar surface. Alpha radiation, due to radioactive decay, is responsible for some helium, while impacts of carbonaceous meteorites are responsible for some of the carbon that is present.

The major elements can be recovered using hydrochemical, pyrochemical, electrochemical or physical processes. This can be performed in orbit or on the moon. The chemical plant would also have to be responsible for the recycling of nonlunar materials. The minor elements could either be co-recovered from the major-element processing or be obtained by separate means. In the latter case, the processing could only be performed on the moon, as it would be uneconomical to ship large quantities of soil into space solely for the purpose of obtaining minor constituents.

While the overall abundances of many of the trace elements on the moon do not greatly differ from those on earth, the absence of known concentrated deposits (ore bodies) of such elements makes prospects for their efficient recovery rather dim. Of course, one may still bring critical materials from the earth in modest amounts. Also, note that the major lunar elements constitute the preponderant mass of mineral elements used in earth industry (excepting air, water and fuels).

In 1976, Goeller and Weinberg [7] discussed the molecule "demandite," which was defined as "the average nonrenewable resource humans use." Table IV shows the constituents (in mole fractions) of one molecule of demandite [8]. In Table V, a normalized demandite molecule (fuel deleted) is compared on a weight-fraction basis to an Apollo 15 soil. Almost all of the

Asteroid surface materials:
characterizations [6]

Table II

Asteroid	Mineral assemblage*
Hebe	NiFe > Cpx
Iris	NiFe, Ol, Px
Flora	NiFe \approx Cpx
Metis	NiFe, (Sil (E))
Hygeia	Phy, Opq (C)
Parthenope	NiFe, (Sil (E))
Irene	NiFe, Px
Eunomia	NiFe \sim (Ol) > Px)
Psyche	NiFe, Sil (E)
Thetis	NiFe, Cpx
Melpomene	Sil (O), Opq (C)
Fortuna	Phy, Opq (C)
Phocaea	NiFe, Px, Cpx
Euterpe	NiFe, Px, Cpx
Bellona	Sil (O), Opq (C)
Europa	Phy, Opq (C)
Concordia	Phy, Opq (C)
Ausonia	NiFe, Px
Eurynome	NiFe \sim Cpx
Sappho	Sil (O), Opq (C)
Alkmene	Sil (O), Opq (C)
Io	Sil (O), Opq (C)
Thisbe	Sil (O), Opq (C)
Siwa	NiFe, Sil (E)
Dembowska	Ol, (NiFe)

*Mineral assemblage of asteroid surface material. NiFe (nickel-iron metal), Ol (olivine), Px (pyroxene, generally low-calcium orthopyroxene), Cpx (clinopyroxene, calcic pyroxene); Sil (O) (mafic silicate, most probably olivine), Sil (E) (spectrally neutral silicate, most probably iron-free pyroxene, enstatite), Phy (phyllosilicate, layer lattice silicate, meteoritic clay mineral, generally hydrated, unleached with abundant subequal Fe²⁺ and Fe³⁺ cations), Opq (C) (opaque phase, most probably magnetite or related opaque oxide).

Mathematical symbols (" > ", greater than; " \approx ", much greater than, " \sim ", approximately equal) are used to indicate relative abundance of mineral phases. In cases where abundance is undetermined, order is most abundant to least abundant.

nonfuel demandite can be obtained from the moon (>90%) and the asteroids. Further lunar explorations can be expected to locate higher concentrations of the depleted demandite elements.

Table VI shows a list of useful products, with examples of what could be made at a space manufacturing-facility, primarily from lunar materials. Although not listed, water would be made from oxygen obtained from lunar materials and hydrogen brought from earth. (Hydrogen is also a trace element on the moon, but even though its weight abundance may typically range between 50-100 ppm, its atomic abundance may be 1% that of silicon. If extractable, this hydrogen could be used to produce the water needed to replace that lost in process recycling—since no recycling process is 100% efficient.)

The structural metals listed in Table VI (Al, Fe, Mg, and Ti) will have to be alloyed in order to develop useful mechanical properties. Table I shows that several elements (e.g., Si, Cr, Mn) used in forming commercial

Potential availability of lunar elements

Table III

Major elements \geq 1% lunar
O, Si, Al, Ca, Fe, Mg, Ti
Minor elements 0.1 - 1%
Cr, Mn, Na, K, S, P
Trace elements < 0.1%
H, He, C, N plus all others

(Beneficiation may permit concentrating some trace elements into minor or higher range.)

Demandite [7]: Average nonrenewable resources used in U.S. in 1968

Table IV

Mole fractions

Fuel	CH ₄ - C ₆ H ₁₄ - 0.8022
Building	SiO ₂ - 0.1115, CaCO ₃ - 0.0453
Metals	Fe - 0.0110, Al - 0.0011, Mg - 0.0004 X* - 0.0008, (Cu, Zn, Pb) - 0.0004
Agriculture	N - 0.0076, P - 0.0008, K - 0.0007
Others	O - 0.0053, Na - 0.0053 Cl - 0.0053, C - 0.0023

*X \sim Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, Zr

Properties

Average molecular weight - 23.9
Average recovery energy - 1.25 kWh/kg or 4.5 x 10⁶ J/kg

Average unit cost - 0.014 \$/kg = 1.4 ¢/kg

Total quantity 3 x 10⁹ metric tons
Total value 42 x 10⁹ dollars

Per-capita consumption mass 15.4 metric tons
Energy 18,800 kWh
Power 2.4 kW

alloys of the structural metals are potentially recoverable from the moon. In addition, there is "neutral" iron on the moon that also contains nickel and some cobalt, which could possibly be recovered. Finally, if enough carbon were recoverable from the trace amounts present on the moon (or brought from earth, or possibly obtained from a carbonaceous asteroid), and small amounts of other key alloying elements were imported from earth, one could produce many ferrous and non-ferrous alloys that are commonly used today

In the case of steels, the more important alloying elements not readily available on the moon are C, Ni, Mo, W, V, and Nb (Cb). The physical properties of several commercial alloys containing these elements are generally similar to alloys in which such elements are absent but which instead contain lunar-indigenous elements. (The properties compared included tensile strength, yield strength, hardness, and elongation.) Therefore, for use as structural metals in space, it is possible to produce alloys possessing a broad range of

Demandite compared with lunar sources

Table V

The major problem facing the modern industrial world is to find some source of energy to replace petroleum. Electricity produced by solar energy would do this. A new molecule of nonfuel and nonrenewable elements (nonfuel demandite) can now be defined by subtracting out the fuel in Table IV and introducing the fractions of the elements that compose the remaining substances in Table IV (see columns 1, 2 and 3 below). Surprisingly, 11 of these 16 elements can be obtained from the lunar soil with no more than a factor of ten enhancement over their natural lunar concentrations. The other five elements comprise less than 10% by weight of the nonfuel demandite (columns 4 and 5).

(1) Element	(2) Major use	Weight fractions nonfuel demandite	(4) Apollo-15 Mare	(5) Enhancement required‡
Oxygen (O)		0.4547	0.4130	1.10
Silicon (Si)	Building materials	0.2444	0.2158	1.13
Calcium (Ca)		0.1417	0.0696	2.0
Carbon (C)		0.0574	0.000095	604.0
Iron	Metals	0.0479	0.1535	0.31
Aluminum		0.0023	0.0546	0.042
Magnesium		0.0017	0.0681	0.025
†		0.0020	0.000022	90.0
‡		0.0030	0.0189	0.16
Potassium (K)	Agriculture	0.0021	0.0008	2.6
Phosphorus (P)		0.0019	0.0005	3.8
Nitrogen (N)		0.0083	0.00008	103.0
Sodium (Na)	Chemical processing elements	0.0095	0.0023	4.1
Sulfur (S)		0.0058	0.0006	9.7
Chlorine (Cl)		0.0147	0.0000076	1,934.0
Hydrogen (H)	Plastics	0.0025	0.00007	350.0
Totals		0.99	0.9980	

*Copper, zinc and lead.

†Manganese, titanium, chromium, barium, fluorine, nickel, argon, tin, bromine, zirconium, and boron (mostly titanium and manganese in Column 4).

‡The enhancements, especially for the minor elements, may vary considerably from one lunar landing site to another. H may be at lunar poles. Ref. 2.

properties (as commonly required on earth) by alloying with carbon, lunar-indigenous elements, and/or minor amounts of lunar-deficient elements (LDE).

Several commercial aluminum alloys can be made from lunar-indigenous materials. However, higher strengths, approaching those of the strongest aluminum alloys made on earth, can only be obtained by alloying with small amounts of lunar-deficient elements, particularly Zn.

Only a few commercial alloys of magnesium and titanium can be formed solely from elements recoverable from the moon, but here again, as in the cases of steel and aluminum, significant improvements in properties can be obtained by alloying with minor amounts of lunar-deficient elements. The strongest magnesium alloys will require such lunar-deficient elements as Zn, while the strongest titanium alloys will need Mo.

It is evident that the structural metals to be manufactured in space will consist of alloys that are already in use, are well-characterized, and can furnish almost

any desired property currently available. Nonmetallic materials similarly may be made solely from lunar sources, or modified with additions of lunar-deficient elements.

Product-mix options depend on the type of raw material used and the nature and quantities of finished products required for specific applications. Table VII shows ranges of materials outputs available by varying the mineral input and process conditions. The moon contains large quantities of a variety of minerals, so that the type of industry that might be attempted in space can be chosen after examining the various options available, rather than its being limited by any specific method or process for converting lunar material.

In building a large space manufacturing-facility via bootstrap operations:

1. Some materials almost certainly would have to be brought from earth.

2. The extent of additional structures that could be processed and manufactured in space from lunar materials would depend more critically on fabrication limitations than materials availability.

3. Versatility and properties would demand substantial use of steels, rather than aluminum or magnesium, as structural and magnetic metals and in tooling and manufacturing equipment.

4. Reprocessing and recycling carbon to form baked carbon and graphite products would be difficult in space. If possible, substitutes for such products would be highly desirable.

CHEMICAL PLANT DESIGN

Some factors that must be considered in designing a chemical plant in space are shown in Table VIII. A chemical plant for extraterrestrial materials processing may be expected to use equipment very similar to that employed in earth-based plants. Because of the importance of minimal mass of items to be shipped from earth, most apparatus will be constructed of materials of high specific strength (strength/weight ratio), perhaps using thin linings of corrosion-resistant materials (e.g., even gold)

Equipment must be compatible with the process constraints mentioned earlier, and with the special space environmental factors encountered during transport, assembly and operation. These include an unlimited vacuum sink, an adjustable level of artificial gravity (except on the lunar surface), provision for radiative dissipation of process heat loads, and recycling of lunar-deficient elements used as reagents, solvents or catalysts.

In space, the most practical source of energy is the sun. Solar cell arrays or large solar mirrors (with aluminized surfaces) would be used to concentrate the sunlight and supply electrical and thermal energy to the space manufacturing-facility.

Several different processes for extracting the major elements of lunar soil have been proposed. These have included reagentless processes such as direct electrolysis of raw or beneficiated lunar soils (molten silicates), and magnetic recovery of neutral iron, anhydrous high-temperature processes such as carbo- and silico-thermic reduction and carbochlorination, and lower-tempera-

ture hydrochemical processes such as acidic and basic leaching. (A discussion of some specific processes will appear later.)

Any needed reagents that contain lunar-deficient elements (LDE) must be removed with high efficiency from the output streams of the processing plant and recirculated or regenerated, with efficiencies approaching or exceeding 99%. This is necessary to avoid the necessity of massive earth-lift.

The requirement of high recycle efficiency for LDE has a corollary in that the plant's products must include only the chemical elements present in the feedstock. Since the only nonmetallic elements present in significant quantities from various lunar raw materials are silicon and oxygen, the output streams must necessarily be limited to elements, alloys, silicides, and simple and complex oxides.

The selection of a specific process must await the establishment of criteria for process evaluation, and the formulation of figures of merit to allow comparative "ratings" of alternative systems. Much of the information necessary to evaluate these processes sufficiently to permit rational selection must be obtained by further literature searches and experimental investigations.

Of course, the prime consideration in evaluating space processing and manufacturing systems must center on the cost of producing items in orbital locations vs. the cost of earth-based manufacture and launch into orbit. In such comparisons, it is essential that functional substitutions be considered, since some items such as organics, fiber-reinforced resins, beryllium products, copper, silver, refractory and precious metals, plus materials having appreciable water content, would be difficult to produce from lunar materials. Fortunately, acceptable substitutes exist for any of those substances that would be needed in substantial amounts.

Since the principal motivation for considering orbital or lunar industrialization is to lower earth-launch costs (>\$100/kg) for massive space projects, it is essential that the mass of capital equipment, expendables, reagent inventory and support facilities initially lifted from earth be far exceeded by the annual output mass of such operations. Analysis to date of the materials-processing portion of such operations shows that this requirement is readily met.

The overriding importance of minimal mass makes it imperative that input materials and reagents move expeditiously through the sequence of processing steps without substantial delays and that certain features should probably be avoided or minimized, if possible, including:

1. Steps that require long completion times.
2. Steps in which the input material is present in low concentration.
3. Mass transport of volatiles at very low pressures.
4. Phase separations from viscous suspensions.
5. Reactions with low conversion per pass.
6. Reactions involving handling or storage of large volumes of gas.
7. Reactions involving large transfers of heat, using fluid/vapor heat exchangers.
8. Processes that reject large amounts of process heat at low temperatures (below 200-300°C).

Useful products from lunar sources

Table VI

Structural materials

Metals—steels, aluminum, magnesium, titanium
Reinforced metals—aluminum, magnesium reinforced with silica, steel or alumina
Glasses, fused silica
Ceramics, alumina, magnesia, silica, compounds
Hydraulic cements (need water)

Thermal materials

Refractories plus chromia, titania, titanium silicide.
Same as ceramics above plus castables, ramming cements, insulation, fiberglass, fibrous or powdered ceramics

Electrical materials

Conductors—aluminum, iron, resistance alloys (FeCrAl)
Electrodes—graphite, Fe₃O₄
Magnetic materials, iron alloys, magnetic ceramics
Insulation, glass, ceramics

Fibrous materials

Glass, silica (for apparel, paper, filters, etc.)

Plastics, elastomers and sealants

Soluble silicates, silicone resins (contain some C)

Adhesives and coatings

Anodized aluminum, magnesium, titanium, electroplating (Cr)
Sputtered coatings, etc.

Lubricants, heat-transfer fluids

Sulfides, SO₂, He

Industrial chemicals

Detergents, cleansers, solvents, acids, bases H₂SO₄, H₃PO₄, CaO, NaOH

Biosupport

Oxygen (breathing), 16/18 of water by mass
SiO₂—soil component (includes many trace nutrients)
Constituent elements of life-forms O, Ca, C, Fe, Mg, K, P, N, Na, H and others

9. Processes for which suitable structural materials do not offer reasonable service lives.

Other criteria for process evaluation include reliability, manpower requirements, potential hazards to onsite personnel, adaptability in processing scrap materials, and ease of repair in case of malfunction. Corrosion of parts that can only be replaced from earth supply is naturally far more serious than corrosion of lunar-derived parts.

The original cost of chemical process equipment is expected to be dwarfed by orbital lift costs in almost all cases and thus would be of minor importance. If replacement items for many of these units could be fabricated from lunar materials, this would reduce costs in expansion or replacement operations.

Space environmental factors

Vacuum—The vacuum-sink availability for space processing facilities may be useful for several types of operations. The most generally useful would be the ability to employ refractories and structural materials that are normally sensitive to oxidation, at higher temperatures than would otherwise be possible (except in-

Product-mix options

Table VII

Metal/silica ratio

Equivalents	1 1	Olivine, anorthite, orthosilicates
	0.5 1	Pyroxene, metasilicates
	0 1	Silica
	1 0	Ilmenite, spinel, troilite, etc. Neutral iron

Aluminum/iron ratio

Negative correlation
Approximate range 5:1 to 1:4

Nonstructural-/structural-metal ratio

Ca. (Mg + Fe)	Pyroxenes.	1 1 to 0.1 1
	Ilmenite	0 1

Light-metal/iron ratio

(Al + Mg):Fe Similar to Al:Fe

Silicon/silica ratio

Reduction requirements
Demand conditioned on use of photovoltaic systems

Metal/metal-oxide ratio

Reduction requirements
Depends on demand for metals vs. refractories and pigments

Oxygen/metal ratio

Depending on ratio of oxygen to the structural metal (and silicon) demand. Oxygen may appear as an unneeded byproduct, or iron and other reductants may be surplus materials

Reinforced/normal-metal ratio

- Demand dependent on suitability of reinforced metals to replace a variable portion of reinforced resins in structures

side vacuum furnaces). Thus, ordinary steels could be used for retorts in metals reductions, and such materials as titanium and refractory metals, carbon and carbides, boron nitride and other non-oxide refractories could be used for structural and insulation purposes without danger of excessive oxidation. This should permit improved multilayer radiation-shield insulations for extremely-high-temperature processes (although sublimation may limit the utility of such systems for certain applications).

On the other hand, the use of space vacuum in separation techniques may have very limited application, since the escape of volatiles, particularly water vapor, could rarely be tolerated.

Notwithstanding the availability of vacuum, most of the processing facilities should probably be located in a large container that has an atmosphere and temperature compatible with human activity. This would permit easier inspection, maintenance and operation.

Gravity—The reduced gravitational attraction at lunar-based plants—or the adjustable centrifugal forces for simulated gravity in orbital plants—will allow some mass savings in support structures for process equipment. It seems likely that most of the chemical unit-operations would not operate satisfactorily under conditions of weightlessness, since all mass-transfer operations, except for introduction of pure gases into a vessel,

would be unnecessarily complicated by absence of a gravitational effect. Fixed-volume storage tanks or reactors for solids, liquids or slurries would be difficult to load or unload, and such operations as filtration, distillation, countercurrent extraction or flow, and so on, would be rendered difficult if not impossible.

The most likely uses for weightless processing would be for heating corrosive reaction masses by radiation or induction, using gas-jet or electromagnetic repulsion to prevent contact with the walls of a chamber.

Most elements of an orbital processing system that are relatively safe could likely be located in a large (but possibly segmented) pressure vessel slowly rotated to provide artificial gravity.

Heat sink—The unavailability of massive, external, air or water heat-sinks makes management of process waste-heat especially important. All major heat-rejection loads will ultimately have to be transferred to space radiators. In addition, the poor heat-transfer characteristics of vapor heat-exchange devices make such elements heavy and thus undesirable. Generally, to raise or lower the temperature of a gas stream it will be preferable to adiabatically compress or expand the gas, rather than use wall- or tube-type heat exchangers. Similarly, in distillation operations it will be advantageous to use the heat of condensation to drive the boiler, after heat-pumping it up to a suitable temperature by adiabatic compression. The mass penalty for additional pumping power will usually be far lower than for other alternatives in the disposition or transfer of process heat.*

Unavoidable low- or medium-temperature heat loads, such as from electrolytic cells, may require heat pumping to higher temperatures to avoid excessive space-radiator masses. A simplified analysis indicates that below some temperature—determined by mass/power ratios of space power systems and mass/area ratios of space radiators—it becomes desirable to heat-pump all heat-rejection loads to such baseline temperatures. Similarly, refrigeration equipment for liquefaction of cryogenics should have heat-rejection temperatures at the same baseline level. Preliminary engineering studies show that minimal heat-rejection temperatures are in the 500 to 600 K range.

Recycling requirements

Most earthbound processing plants have a single principal product (or a few coproducts), whose mass-transformation rate is often substantially exceeded by the conversion rates of the reagents, solvents, air and water flows associated with the operations.

Lunar or orbital plants will generally have to recover, reclaim and recycle normally expendable reagents and solvents, due to the general lack of volatiles (except oxygen) available from lunar sources. The problem is more acute than it first seems, because the rate of cyclic transport of water, steam or various reagents may in some cases amount to 10 to 100 times the rate of lunar "ore" passing through the process. Yet the tolerable loss or attrition in these mass loops must be held *in total* to a small fraction of the production rate of useful products, since an earth-mass lift requirement for reagent re-

*See, e.g., "Heat Transfer" A. J. Chapman, Macmillan (1960)

placement approaching that of plant output obviously could not be cost effective.

While recycling operations may require chemical conversions, such as the separation or splitting of salts to yield acids and alkalis, it is simpler to consider recycling on an elemental basis. Thus, for most systems studied to date, only a very few elements must be monitored closely. As an example, for the HF acid-leach process, only H, F, Na and possibly N must be recycled with high efficiency. Even here, usable amounts of Na and H may be recoverable from the lunar raw material.

Recycling losses will probably be more prevalent when lunar-deficient elements are incorporated in solid phases of negligible vapor pressure. This may create difficulties in the use of processes involving reagents at high temperatures—such as slags or liquid-metal phases that may “lock in” lunar-deficient elements.

Reagent and equipment mass

For solution processes, the mass of the solvent system will generally exceed the mass of lunar input material (except where solutions of over 50% by weight are practical). A more typical level may be about 5 to 10% by weight of solute. Further, not all of the solute may be transferred per pass during the various separation or extraction steps, so the ratio of solvent to “active solute” mass is normally much greater than unity.

Fortunately, for aqueous solutions, most of the solvent mass need not be transported from the earth, since the oxygen content, which represents 88.8% of the mass of water, is derivable from lunar materials. Even the hydrogen content may be extracted in sufficient quantities to largely (or entirely) replace that lost in the residual moisture content of products.

Now, let us consider the relative magnitude of equipment and reagent mass for the various units needed for a chemical processing plant. Specifically, one would like to know whether the process vessels, tanks, pipes, etc., weigh more or less than their contents. Analysis shows that, for most cases of equipment that contains 10% or more material in condensed phases, the contents may be expected to far outweigh the container (where the latter is constructed of high-specific-strength materials with minimal safe wall-thickness). Conversely, for gases, the container will invariably outweigh the contents. Furthermore, in the case of gases, the ratio of container to content mass is practically independent of pressure.

This finding reiterates the undesirability of processes that require storage or handling of large volumes of gas. In addition, for processes operating primarily in condensed phases, the mass of the processing operation, apart from power and radiator facilities, will probably be dominated by the masses of reagents involved. These masses, in turn, will depend on reaction and process times for the individual steps.

The engineering characterization of any proposed process may be identified by parameters as shown in Table IX. The sizing (volume) of equipment for any segment may be expressed as:

$$V = \frac{\dot{Q}_i t}{\rho_i v_i} = \frac{\dot{Q}}{\rho_i} t'$$

where \dot{Q}_i is the mass flowrate of component i (kg/s), t is

Chemical plant design

Table VIII

- Selection of process options
- Special space environmental factors
 - Gravity (natural or artificial)
 - Vacuum
 - Heat rejection
 - Recycling of nonlunar-indigenous materials
- Description of unit operations
 - Materials handling
 - Phase separations
 - Heat-exchange
 - Reactors
 - Energy requirements
 - Heat-rejection requirements
- Sizing factors
 - Kinetics limited
 - Heat-transfer limited
 - Momentum limited

a characteristic length (meters) of flowpath in the apparatus, ρ_i is the partial density of component i (kg/m³), v_i is a characteristic velocity of the i th component (m/s), and t' is the process time (s).

Each process step is characterized by an equivalent time (h), representing the time required for the passage of sufficient input material to equal the weights of gross or net contents or container for the step in question.

Summation of the appropriate equivalent times therefore yields the total time required for the passage of sufficient input raw-material to equal the gross or net reagent masses, or the structural masses, for the processing system. Additional equivalent times may be derived to account for masses required for mechanical and thermal power sources; for distribution equipment, motors, pumps, compressors; for heat-transfer equipment, space-radiator facilities; and for other necessary support functions.

Unit operations

Materials handling—Except for storage, these operations are not expected to require substantial masses. Most material can pass through a materials-handling step with velocities of 0.01 to 1 m/s or even higher, so such units would rarely have to handle more than a few minutes' throughput of the operation. Fine grinding using a ball mill or equivalent is somewhat slower, but it is not expected to be necessary for processing of lunar soils. Entrainment of liquids or dust in gas flows may become a problem in lunar gravity or low artificial gravity, but inertial gas or hydrocyclones or other devices may be used to suppress carryover.

Phase separation—The actual physical separation of different phases is usually limited by pressure or inertial considerations, such as foaming or entrainment in distillation columns, or sedimentation velocities in centrifugal filters or in centrifuges, although the material process-time may be limited by heat-transfer rates, growth rates of crystallites or precipitates, etc.

Because of the recycle nature of the various materials flow-loops, it may be preferable to shorten process times (even at the expense of recycling larger-than-normal fractions of intermediate flowstreams) to reduce the masses of intermediate stages. However, at the exit

Engineering design parameters

Table IX

Equipment	Capacity	Typical stream velocity, V_i (or characteristic velocity)	Process time	Other
Motors, pumps, compressors (except vacuum)	10^3 kW m^3	10 to 100 m/s	1 s	$\frac{1 \text{ kg}}{\text{kW}}$ or $\frac{1}{\text{MW}}$
Distillation columns	mass flowrate $1-5 \text{ kg/m}^2 \text{ s}$	1 to 3 m/s (vapor) (entrainment limited)	5-10 s	length: $0.4 - 0.6$ m/plate
Sedimentation centrifuges	volumetric flowrate $0.004-0.08 \frac{\text{m}^3/\text{s}}{\text{m}^2}$	settling velocity ($10 \mu\text{m}$ particles) 10^{-5} m/s X g typical velocity 10^{-2} m/s @ 1,000 g	0.5-2 min	power $50-100 \frac{\text{kW}}{\text{m}^2}$
Rotary kilns	Loading density $0.05 - 0.2 \text{ t/m}^3$	3 to 10 m/h (axial) ($0.0033 - 0.0083$ m/s)	2-10 hr	rotary power $0.1 - 0.2 \frac{\text{kW}}{\text{m}^3}$
Ion-exchange columns	0.5-3 equiv. kg (resin)	0.2 to 0.5 m/min ($0.0033 - 0.0028$ m/s)	5-15 min	
Aqueous-systems heat transfer				
Nucleate boiling	15-240 kW/m ²			$h = 2-16$ kW/m ² K $\Delta T = 10-20\text{K}$
Condensation (inside tubes)	30-1,000 kW/m ²	30 to 150 m/s (vapor)		$h = 3-50$ kW/m ² K $\Delta T = 10-20\text{K}$
Electrolytic cells	$i = 10^3 - 10^4$	ion-migration velocity $10^{-7} - 10^{-5}$ m/s	10-50 h	

stages of the plant, it is important to limit the loss of reagents, especially those containing lunar-deficient elements, so it is necessary to attempt to carry those steps nearly to completion.

As an illustration of the basic problem that might be common to any process that uses water as an intermediate rinse or reagent, we may discuss drying of nonmetallic output streams. Most finely divided metallic oxide or silica solids have an adsorbed or chemisorbed water content that can be removed by application of heat, time and pressure differentials.

Heating and refrigeration—Process-heat requirements may be satisfied by primary electrical or solar thermal sources, or indirectly by using steam or other working fluids, or by exchange with other process flowstreams. If processes are to use solar thermal energy, one may anticipate a substantial mass reduction for equivalent power levels. For example, mass reductions by factors of 30 or more may be possible by substituting solar-thermal for solar-electric power.

The coupling of thermal energy into powdered solids is often troublesome, and can rarely be done efficiently by radiation. One would normally prefer to heat such material by exchange with recirculating gases that are heated in an adjacent unit (by solar-furnace, electric-arc, resistance or induction sources). In certain cases, it may be possible to heat the powdered solids by high-frequency dielectric energy, or perhaps by using microwave energy.

Refrigeration or cooling operations may be required for process steps or for collecting, separating and storing noncondensable gases. Oxygen storage and hydrogen

storage will probably represent the largest power and equipment requirements. Liquefaction of these gases would greatly reduce masses of the storage vessels required to handle them. By subcooling down to the triple point or lower, even further weight reductions are possible [12].

Reaction—The design of reactors is usually dictated by the heat-balance requirements (endothermic or exothermic) and whether internal or external heating or cooling are required. Internally heated or cooled systems would usually be designed in large tubular, cylindrical or spherical vessels, while external heat transfer would usually require a large surface area and at least one short dimension (about 0.2 to 0.5 m). Electrolytic cells usually require a low anode-cathode separation (about 0.1 m or less) to avoid excessive power losses, but the cell may contain multiple anodes and cathodes and thus attain considerable minimum dimensions. However, it is heat-rejection requirements that usually limit the size of electrolytic cells.

Electrolysis of molten silicates

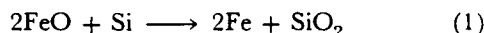
Limited investigations of direct electrolysis of molten silicates of compositions similar to lunar basalts have been performed [14]. The high melting-points and viscosities of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the "reagentless" advantage of the direct electrolysis route and requires consideration of extraction and recovery of fluxing reagents.

The chief objections (or problems awaiting solution)

are the corrosion or durability of anodes used for oxygen recovery, and the purification and separation of cathodic reduction products (which are likely to consist of iron-aluminum-silicon alloys plus minor amounts of additional impurities).

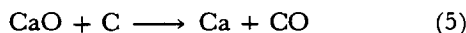
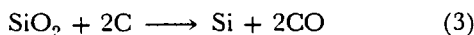
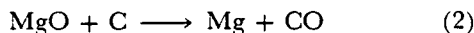
Carbothermic/silicothermic reduction

One of the first serious attempts to define a process option was performed by Phinney, *et al.* [15], at the 1976 NASA-Ames Summer Study, in which silicothermic and carbothermic reduction of bulk lunar soil was discussed. After crushing the raw material, and magnetically separating the ferrous from the nonferrous fractions, reduction could commence. Silicon will reduce iron at 1,300°C. as shown by Eq. (1):



The products can be separated by centrifugation.

The iron-free silicates would be reduced by carbon at 2,300°C, as shown by Eq. (2-5):



By this process, it would be expected that aluminum and silicon would form a melt, while the other reduced metals, including the major impurities Ti, Mn and Cr, would be removed as vapors. However, this reaction scheme is much more complicated. At 2,300°C, condensed compounds, such as SiC, Al₄C₃, and Al₄O₄C are present, along with gases such as Al₂O, SiO, Al, and Si.

The pressures of Al₂O and Al are so high that liquid aluminum cannot be formed at normal operating pressures. Perhaps the greatest defect of the carbothermic reduction process is that although the winning of aluminum on earth via such a process was envisaged as early as the 1940s [16], no plant for producing aluminum by this method has proved practical.

Carbo-chlorination process

At the 1977 NASA-Ames Summer Study, Rao, *et al.* [17], decided quite early that carbothermic reduction would probably be impractical for space processing. They opted for carbo-chlorination of lunar anorthite, CaAl₂Si₂O₈, and lunar ilmenite, FeTiO₃, which could be beneficiated from lunar soil [18]. The desired products are aluminum, iron, silicon (or silica), and titanium.

During our subsequent study at the Lunar and Planetary Institute, it became obvious that carbo-chlorination would create a major plant-size problem. The recycling of chlorine and carbon would require facilities much larger than the basic processing plant. One of the major advantages of carbo-chlorination is that it would require only a minimum of hydrometallurgical operations. Water would be needed, however, for hydrolysis, chlorine regeneration and possibly as a coolant for the system. In order to minimize the size of the heat-rejection radiators, large amounts of heat energy would have to be raised (heat pumped) to about 280°C, to achieve a mass efficient system.

HF acid leach process equations

Table X

1.	$x\text{MO} \cdot \text{SiO}_2 + (4 + 2x) \text{HF} = x\text{MF}_2 + \text{SiF}_4 (\text{aq}) + (2 + x) \text{H}_2\text{O}$
1'.	$x\text{MO} \cdot \text{SiO}_2 + (5 + 2x) \text{HF} = x\text{MF}_2 + \text{HSiF}_3 (\text{aq}) + (2 + x) \text{H}_2\text{O}$
2.	$\text{SiF}_4 (\text{aq}) + n\text{H}_2\text{O} = \text{SiF}_4 (\text{v}) + n\text{H}_2\text{O} (\text{v})$
2'.	$\text{HSiF}_3 (\text{aq}) + n\text{H}_2\text{O} = \text{SiF}_4 (\text{v}) + \text{HF} (\text{aq}) + n\text{H}_2\text{O} (\text{v})$
3.	$(1-y) [\text{SiF}_4 (\text{v}) + 4\text{H}_2\text{O} = \text{Si} (\text{OH})_4 + 4\text{HF}]$
3a.	$(1-y) [\text{SiF}_4 (\text{v}) + 2\text{H}_2\text{O} = \text{SiO}_2 + 4\text{HF}]$
4.	$(1-y'-z) [x\text{MF}_2 + x\text{H}_2\text{O} = x\text{MO} + 2x\text{HF}]$
5.	$y [\text{SiF}_4 + 4\text{Na} = \text{Si} + 4\text{NaF}]$
6.	$y' [x\text{MF}_2 + 2x\text{Na} = x\text{M} + 2x\text{NaF}]$
7.	$z [x\text{MF}_2 + x\text{SiF}_4 (\text{aq}) = x\text{MSiF}_6 (\text{aq})]$
8.	$z [x\text{MSiF}_6 (\text{aq}) + x\text{H}_2\text{O} + \text{electrical energy} = (x/2)\text{O}_2 + x\text{M} + x\text{H}_2\text{SiF}_6]$
8a.	$z [x\text{MSiF}_6 (\text{aq}) + \text{M}'\text{SO}_3\text{R}^* = x\text{M}'\text{SiF}_6 (\text{aq}) + x\text{MSO}_3\text{R}^*]$
9.	$m \text{NaF} + m\text{R}^*\text{OH} = m\text{NaOH} + m\text{R}^*\text{F}$
9a.	$m \text{NaF} + (m/2) \text{Ca} (\text{OH})_2 = m\text{NaOH} + (m/w) \text{CaF}_2$
10.	$m \text{NaOH} + \text{electrical energy} = m\text{Na} + (m/2)\text{O}_2 + (m/2)\text{H}_2\text{O}$
11.	$(1-y) [\text{Si} (\text{OH})_4 = \text{SiO}_2 + 2\text{H}_2\text{O}]$
R* = ion-exchange resin	
m = 4y + 2xy'	

These results led us to believe that processes that rejected less heat at low temperatures and made use of hydrometallurgical operations would tend to be more-useful options for space processing.

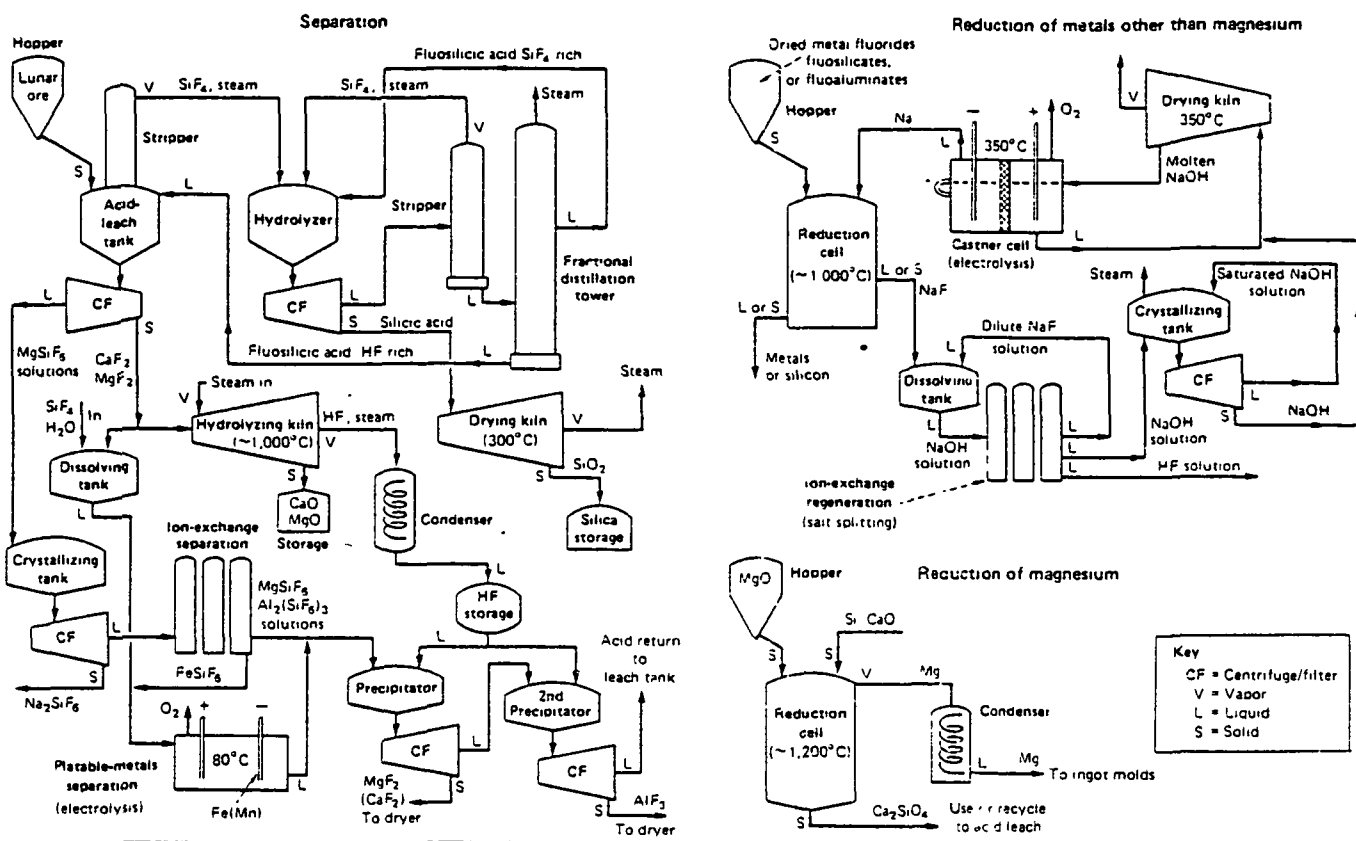
NaOH basic-leach process

A review of the literature [20-23] indicates that anorthite can be decomposed with NaOH in an autoclave; and subsequent treatment of those products with more base can eventually yield alumina and calcium silicate—the latter could be used to make glass or could be hydrolyzed to yield lime and silica. For both basic and acidic leaching, sodium present in lunar soil can probably make up for any sodium lost during recycling. In this process, calcium impurities in the recycled NaOH would not present a problem, inasmuch as base, and not pure NaOH, is needed.

HF acid-leach process

This process uses low-temperature hydrochemical (hydrometallurgical) steps to separate the silica content of the lunar raw material from the other metallic oxides by conversion to fluorides and fluosilicates. This is followed by vaporization of the silica as SiF₄, and separation of the calcium and the structural metals (Al, Fe, Mg, Ti) by a variety of solution, precipitation, ion exchange, or electrolytic steps. Generalized process equations are given in Table X. Iron may easily be recovered from solutions by electrowinning, but the remaining metals, except Mg, are preferably recovered by sodium reduction of the corresponding fluorides, fluosilicates or fluoaluminates. Magnesium may be made by silicon reduction of MgO.

Sodium for the reduction of the metals and silicon can be conveniently obtained by a slight modification of the Castner cell, which at one time was the major



Flowsheet for the HF acid-leach process, proposed to win metals from lunar soil

Fig. 1

commercial device for producing sodium. The Castner cell uses the electrolysis of molten NaOH to produce Na, O₂ and H₂. For lunar operations, the hydrogen is an undesirable byproduct, which can be largely eliminated by using a diaphragm cell and vacuum-drying the anolyte to remove the water formed by discharge of OH⁻ ions.

Metal oxides and silica are obtained, where desired, by hydrolysis of the corresponding fluorides or fluosilicates with steam (or with NH₃, if desired, for SiO₂) or by ion exchange (or permeation) methods. Detailed analyses of the options available for these separations remain to be completed.

A flowsheet for the HF acid-leach process is shown in Fig. 1.

Of the processes studied to date, the HF acid-leach one appears to have the best potential for minimal operating mass, ease of element separations to high purity, and favorable energy and heat-rejection requirements.

A number of details and options remain to be investigated. Many of these specific process steps can be fully defined by straightforward experiments. If any readers are interested in undertaking some of these experiments (many are relatively simple), the authors of this article would be pleased to hear from them.

Separation of the fluoro compounds of the metallic elements by solubilities of fluorides or fluosilicates as a function of pH and F/Si ratio—with or without addi-

tional ion-exchange or electrolytic steps—will require extended literature searches and laboratory investigations. Pyrolytic and hydrolytic behavior of fluorides, fluosilicates and fluoritanates will also require additional research.

Despite these informational gaps, nearly all of the proposed operating steps have been studied on a laboratory scale, and about 75% of the steps have been conducted on a pilot or commercial scale under equivalent or comparable conditions.

Space processing plant

Fig. 2 is an artist's conception of a prototype plant using the HF acid-leach process (shown in color on the cover of this issue). It incorporates the design requirements appropriate to the processing of anorthosite (plagioclase feldspar). This mineral, abundant in the lunar highlands, is an excellent source of aluminum, silicon, silica, oxygen, and other, minor, elements. The chemical plant can process 30,000 metric tons of anorthosite (90% pure) each year.

A 30-MW solar-power array dominates the picture. It is octahedral, approximately 500 meters on a side, and masses 120 metric tons.

The oxide-separation stage shown in the foreground and the electrolytic separation facility in the background have a combined dry mass of 105 metric tons. Approximately 30 metric tons of hydrogen, fluorine, and a small amount of sodium, must be brought from

earth to provide a portion of the working fluids for the liquid-phase hydrolysis scheme used in the plant.

Oxygen and sodium are extracted from the initial runs of lunar soil to provide the full 336 metric tons of water, hydrogen fluoride and sodium hydroxide necessary for full-scale plant operation. Thus, we see that use of lunar materials minimizes the amount of material that must be shipped from earth to start production. Space radiators to reject process heat from the plant are the large flat objects to the left of the oxide separator and electrolysis units. Makeup of the fluorine (up to 30 metric tons each year) will probably constitute the major terrestrial input for 30,000 tons of processed material.

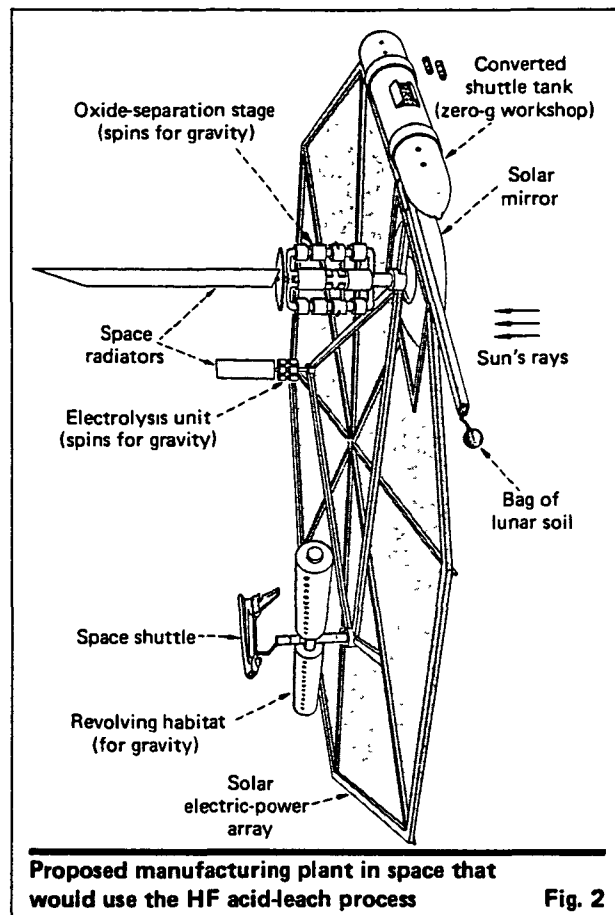
A dual habitat for the construction and operating crews is shown on the bottom of the solar array. Approximately 20 people can operate the plant, assuming round-the-clock operation. Only low temperatures and pressures are used in the processing, so all tanks and lines can be thin-wall, low-mass units. Steel derived from lunar iron should be usable in fabricating future units. The processing units and habitats are spun to provide artificial gravity. A zero-gravity fabrication shop constructed out of one of the shuttle propellant tanks is shown attached to one side of the solar array. A 2,000-ton bag of lunar soil is tethered to the input column of the processing plant.

A rather surprising finding of the study that evolved this particular processing design is the low mass of the space unit. Only 10 to 15 shuttle flights would be required to transport the 290 metric tons of solar array, processing units, and initial working fluids into low earth orbit. Another 10 to 15 flights would be adequate to deploy the 260 metric tons of the habitat and the fabrication unit. This particular plant scales upward in mass in direct proportion to throughput. However, with increasing operating experience, less manned operating involvement will be required. In addition, the trace amounts of free iron in the lunar soil may be used to fabricate additional tanks and plants. If so, the amount of material required to be transported from earth to build successive plants of equal capacity might drop from 290 to 100 metric tons, or less.

Process selection and development

Problems in separation or direct reduction of constituents of complex oxides and silicates prompts one to examine various classes of compounds that can be generated by treating oxide materials with various reagents. The new compounds should be more easily separated, purified or reduced to elemental form than the original material. Separation and purification would be made easier if there were pronounced differences in solubilities in various solvent systems or in vapor pressures of individual constituents.

Solvent systems of interest are either aqueous or non-aqueous. In the former, the water solubility in acid and near-neutral solutions of metallic compounds is of general interest. Most metallic nitrates, chlorides, perchlorates, fluoborates and fluosilicates are water soluble, while there is some limited solubility of fluorides and sulfates for some of the metals. Most of the remaining common anions form insoluble salts with all but the



alkali metals. Nitrate, perchlorate and fluoborate compounds present stability or availability problems that render them less attractive than the other salts for general separation and reduction operations.

In basic solution, only the silica, titania and alumina fractions are likely to have sufficient solubility to be of interest, and these constituents are often rendered insoluble in the presence of polyvalent metallic ions such as Ca^{++} and Mg^{++} . Recycling of base (NaOH) is somewhat more difficult than it is for acids, due to lower volatility.

Most metal chlorides are readily vaporized, while fluorides are much less volatile. Both are easily reduced by active metals or electrochemical action. Sulfides are also potential candidates for metals reduction, but many have very high melting points.

With aqueous solvent systems, one might begin to consider nitrates, chlorides, perchlorates, fluoborates, fluosilicates, fluorides and sulfates. Sulfides, carbonates, phosphates and (to a limited extent) carbonyls might also be usefully employed in certain phases of materials processing loops.

Nitrates and perchlorates present difficulties due to their instabilities toward severe thermal or oxidation-reduction conditions and to the difficulties in resynthesizing such reagents. Fluoborates seem to offer few advantages in comparison with fluosilicates, and require makeup of another lunar-deficient element. Sulfates, carbonates and phosphates seem to present limited

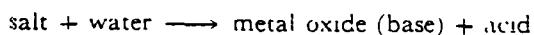
capabilities in general solubility separation operations but might be useful in specific separations.

Ammonia ammonium salt chemistry has a unique advantage in that pyrolysis of ammonium compounds can usefully purify a number of the major and minor lunar elements into readily convertible compounds. The stability of ammonium ion or ammonia is not as great as halides as regards severe oxidation or thermal exposure, but it is better than nitrates or perchlorates, and regeneration is fairly easy in comparison with them.

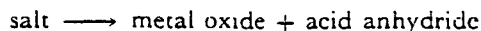
If one examines the free energies of formation for oxides, fluorides, chlorides and sulfides vs. temperature, one observes that the major lunar elements, except for iron, form highly stable compounds. In general, elements further down the free-energy scale form more-stable compounds than elements higher on this scale, and thus are capable of reducing compounds of the latter. Sodium and potassium are more-effective reductants in the halide and sulfide systems than in the oxide system.

A general goal for a plant processing lunar materials would be to obtain separated elements and oxides of commercially useful purities (say 99%) with a minimal reagent loss. The separation requirements seem to demand conversion to soluble or volatile compounds, which then may be separated and reduced or reconverted to oxides. Solvent separation requires a choice of solvents, and there appear to be none producible entirely from lunar elements (with the possible exception of SO_2). Water is one of the best choices in terms of low partial density of lunar-deficient elements (hydrogen) and has the overwhelming advantage in terms of background chemical and engineering data. Water cannot, however, be used as extensively or carelessly as in many earth applications.

The conversion compounds, which may be halides, sulfates, etc., may be considered as salts of the corresponding metallic elements, and that portion not reduced to elemental form must be reconverted to oxides—which may be viewed as a salt-splitting reaction:



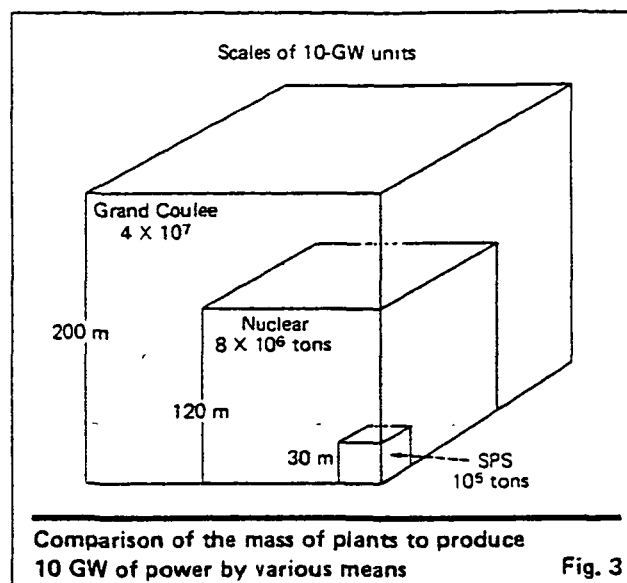
or



The above reactions may be accomplished by hydrolysis or (for some oxy salts) by pyrolysis. In some cases—as, for example, in hydrolysis of halides—it may be more convenient to use acids (or, for silicon halides, bases) instead of water or steam to accomplish the hydrolysis and recovery of HCl or HF. However, such procedures will invariably generate other salts, which must then be split.

Additional salts will be formed if sodium or other active metals are used to reduce halides. These will also have to be salt-split or electrolytically reduced to regenerate the active metal.

Almost any salt may be hydrolyzed with steam, but in many cases the required energy and the mass flow of steam may be prohibitive. Pyrolytic salt splitting may be accomplished with many carbonates, sulfates, and particularly with some ammonium salts such as NH_4F and $(\text{NH}_4)_2\text{SO}_4$ which form NH_3 and acid salts. In the terrestrial economy, salt splitting in an indirect sense is



conducted on a mammoth scale in the chlor-alkali industry. The "best" solution(s) to these requirements for space-based plants will depend on mass, energy, rate and other factors that require additional study.

Oxygen is both a necessary and a desirable end-product of the lunar-materials processing plant, and will probably have to be produced in quantities equivalent to the total of metals, alloys and silicon needed, unless substantial recovery of elemental iron from the lunar soil is achieved. For oxygen production, it appears virtually certain that some electrolytic process will be required, either directly or indirectly. For such a process, especially if conducted at high temperature in a molten or fused salt-bath, the durability or resistance to corrosion of the anode becomes especially important. Graphite appears to be too prone to oxidation at temperatures above 500°C, but Fe_3O_4 or TiO may be possible alternatives in some systems. Lower-temperature systems such as aqueous electrolytic cells or the Castner cell (fused NaOH) have shown satisfactory durability for anodes in commercial service.

Uses of lunar materials

Space power stations (SPS) provide a useful model by which to study the use of lunar materials. Considerable work has gone into the design of systems that could be placed in geosynchronous orbit and scaled to supply a steady stream of power to a terrestrial ground station, with an electrical power output of 10,000 MW (10 GW). This is approximately 10% greater than the maximum expected electric output of the Grand Coulee Dam, which is the largest individual electrical installation in the U.S. Other articles, already cited, provide extensive details on the SPS, so only the factors directly relevant to lunar materials will be discussed. An artist's conception of such a station is pictured on p. 81.

An SPS is projected to have a mass of 100,000 tons and, if constructed as a solar-cell array, a length of 20 km, a width of 3 to 5 km and a grid thickness of several hundred meters [3]. It would be composed of glass (solar cells—52%), aluminum (wiring—6.4%),

graphite composite (structural members-13%), copper and iron (wiring, wave guides and power units-13%) and heat pipe and klystrons (components-7%). These components can all be fabricated from lunar materials, or identical functional requirements can be met by materials supplied from the moon [5]. The remaining 10% or so will require terrestrial materials, at least for the particular systems designs presently available.

sps dimensions appear enormous until they are compared to the scale of engineering that is associated with Grand Coulee or comparable nuclear or conventional coal-fired installations. Grand Coulee is also a very large structure. It is 1.3 km long, 140 m high and has a mass of 40 million tons. This is 400 times as massive as the sps unit. Fig. 3 depicts the mass of Grand Coulee Dam in terms of a cube having a density of 5 t/m^3 . This figure dramatizes the differences in the scale of the materials handling involved in the construction of Grand Coulee, a nuclear plant and an sps unit.

sps power may be beamed to the ground by microwave and intercepted by a large antenna array that is 2 to 5 km in radius. The sophisticated portion of the ground station is composed of millions of identical antenna and receiver units, having a total mass of 5,000 tons. Five thousand tons would be a cube on the order of 10 m on a side. The receivers would be placed in foundation or support structures that would have an integral mass of approximately 2 million tons. Two million tons is one fourth of the mass of a nuclear power station of the same output. Further, the individual foundation units can be very simple compared with the extremely complex structure of a nuclear power station, which must provide radiation and pressure shielding and protect against natural catastrophe.

A 10-GW coal-fired station would have a mass on the order of 2 million tons—a mass between that of the sps ground structure and a nuclear plant. However, a 10-GW coal plant burns a mass of coal approximately equivalent to Grand Coulee Dam every year. In 1976, North America consumed coal equivalent to 14 times the mass of Grand Coulee Dam. This annual usage could rise to 60 times the mass of Grand Coulee by the year 2000 [27].

In comparing the sps to Grand Coulee or a nuclear or conventional power station, one is impressed not with the large physical area of an sps but, rather, with the sps's fantastically efficient use of matter in gathering energy and converting it for use on earth or in space. Far less matter must be manipulated, restructured and emplaced in space to produce useful power on earth than for any other power scheme proposed to date. This includes projected terrestrial solar-power arrays, which must be 6 to 15 times as large in area (due to night and cloud cover) in order to collect the same average energy flux, and which must be more massive per unit of area to withstand the gravity and environmental conditions of earth.

In a practical sense, this means that 90% of the initial materials needed for space power stations can be met with two to four chemical processing units—units that would be on the prototype engineering scale in comparison to most terrestrial bulk-processing plants. This in turn implies that development expenses, and espe-

cially development times, can be small compared with those often encountered in the creation of new, large-scale terrestrial industries.

Despite the relatively small scale of the space processing plant, the economic output can be large (in terms of terrestrial experiences) because a final product such as an sps will have a value of \$200 to \$400/kg, based on power revenues.

Logistics

Comparative studies of the logistics requirements for establishing sps in geosynchronous earth orbit (GEO), using earth-manufactured hardware, or lunar-derived materials and lunar or orbital manufacture, have recently been performed [12]. Under steady-state conditions, and neglecting requirements to establish facilities, the earth-based system would require that 35.4 kg of propellant and payload (consumables) be lifted from the earth for each kg of satellite placed in GEO, while the lunar resource model would require 3.2 kg propellant and payload launched from the earth and 1.75 kg from the moon (if a mass driver were employed) for each kg of working satellite required. These are preliminary figures based on advanced-shuttle-derived vehicles for earth launch and on projected technology for needed lunar and interorbital spacecraft, and of course are subject to change.

Conclusion

Besides being able to obtain material for building an sps or a space habitat, several useful products could be manufactured in space, among these being high-temperature glasses and ceramics [24], and strong-fiber optics for communications. Some possibilities for production of expendables such as propellants are also indicated.

The initial plant being called for by its proponents represents a whole new commercial concept. A pilot plant in space could be an economic boon to mankind, which would obtain benefits from it immediately. Over a period of 20 years, say by 2000, such a prototype plant could seed mature industries in space that would be large even by terrestrial standards. The growth of space industry can proceed quickly, as did the use of coal in the 19th century [25].

Space manufacturing will require the transfer to space of terrestrial technologies and design philosophies not previously associated with space. This application of terrestrial industry to space will be practical when large quantities of lunar materials become available. On the other hand, manufacturing in space will require rigorous recycling of materials available only from earth. Man can make use of parts of this recycling technology developed for space use in order to develop new means to meet terrestrial environmental standards. A source of solar electric power will conserve the depleting supplies of raw materials. And the greater range of control over physical conditions and scale will in time evolve completely new technologies.

The prospects for quasi-permanent human activity beyond the near surface of the earth must initially be based on economic benefit to earth residents sufficient to justify the costs of such enterprises, and ultimately on

the developments of technologies of closed life-support systems and physical economies developed completely by humans and, therefore, understood by them [26]. The judicious implementation of various levels of industrial activity can appreciably lower the cost of accomplishing various industrial and scientific goals in space. Fundamental to such operations is low cost and a diverse source of raw materials and industrial feedstocks. Implementation will also require and enable new parallel technology development in transportation systems, space manufacturing, fabrication, mining and beneficiation.

The studies to date have barely begun to examine the numerous scientific and engineering options available for materials processing in space. It is important that a broader range of expertise be engaged to study the subject and help recommend methods to ensure an orderly and efficient development of the technology. We

solicit interested parties to comment on this report or present ideas on "conventional" or novel approaches to the problem.

Workshops on selected technical topics of interest, such as electrochemistry of space-processing systems, and lunar glass and ceramic technology, will be held in the near future. Prospective participants with a background in these or related areas are being solicited. The authors would appreciate hearing from those interested.

Acknowledgments

This study was performed at the Lunar and Planetary Institute, which is operated by the Universities Space Research Assn., under contract number NAS 09-051-001 (Mod #24) from the National Aeronautics and Space Administration. This is Lunar and Planetary Institute contribution Number 351.

Roy V. Hughson, Editor

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太空工业中 化学工程的作用

THE ROLE OF CHEMICAL ENGINEERING IN SPACE MANUFACTURING

如果人们想开拓太空的潜力，例如建立太阳能发电站（如图所示），就可能要利用月球上开采出来的矿石，并使用大型矿堆运设备，图示如左，伸展至地平线）把它送到太空轨道上的装置中进行加工。

如何把地球以外的物质加工成太空工业所需的原料，化学工程师们将在这方面担当关键性的角色。

月球非常可能是原料的第一个来源地。关于月球，我们已了解得相当详细；我们已知道在月球轨道上怎样设计和进行大规模作业，并且已认识到怎样以低廉的费用把原料运离月球。我们还知道，月球上有各种工业所需的大部分化学元素。

现在已有种种大规模的太空作业计划：如P.E. 格拉顿 [1a, 1b] 关于成系列太阳能发电站卫星的设想 [1c, 3]，及G.K. 沃奈尔 [2] 关于太空工业运用地球以外物质的倡议。对于格拉塞的设想，美国国家航空与航天局（NASA）曾作了前景评价工作。如果这些计划能实现，则人类将在太空中创造出完全是人为的经济结构和太空人类生态学。

从地面到太空

From Earth into Space

即使地球没有大气层，由于地球具有庞大的质量，任何物体想要离开地面而进入太空轨道或进入深远的空间的话，它就

必须有很高的速度（每秒11.2公里）。何况，事实上地球外还有大气层，因它能引起阻力，物体在低空阶段便不能达到高速度。另一方面，物体摆脱引力离开月球时，只需要每秒2.4公里的速度，而且月球没有大气层。

运动物体的总动能和它的速度的平方成正比例。因此，即使不考虑地球的大气层，从地球表面发射一个物体，必须使用从月球发射相同物体所需能量的22倍，这是由于 $(11.2/2.4)^2 = 22$ 的缘故。

生产恰当形式的能量来发射物体要花钱，制造使用这种能量的零部件更要花钱。假使有一个可以100%效率直接使用电力把物体从地面推入太空的装置；若不考虑地球大气层，并假设每千瓦-时的电费是2.5美分，那末由于摆脱引力离开地球时每公斤物质需用17.4千瓦-时的能量，则其费用就等于44美分。这相当于说，发射一个70公斤重的人进入太空需费31美元。从月球发射所用的能量约是从地球发射的5%（即每公斤仅需用0.8千瓦-时），其费用是每公斤2美分，因此发射一个70公斤重的人只需要1.40美元。（当然，现在月球上还没有每千瓦-时价格为2.5美分的电力供应。）

从地球上高效率发射物体的办法，其前景看起来还很渺茫，而从月球上高效率发射则似属可能，为此目的，G.K. 沃奈尔 [2a] 首先设计出部装置，命名为质量推运器（mass driver）。这种装置是由两个部件组成的电动机，外部构型是直线形式。运动部件（电枢）是个超导性线圈环绕的运输器，这些线圈从外部电力线获得加速力，使运输器自铝导轨上升起，这样使有可能达到极高的速度。这种质量推运器的活动模型曾示范表演过，而且其基本理论已与人充分掌握。

By Robert D. Waldron, Thomas E. Erstfeld, and David R. Criswell.
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Magazine, February 12, 1979. Copyright © 1979 by McGraw-
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表2.小行星表面的成分大类 [6]

小行星	矿物共生体*
Hebe	NiFe > Cpx
Iris	NiFe, Ol, Px
Flora	NiFe \geq Cpx
Metis	NiFe, (Sil (E))
Hygiea	Phy, Opq (C)
Parthenope	NiFe, (Sil (E))
Irene	NiFe, Px
Eunomia	NiFe ~ (Ol \geq Px)
Psyche	NiFe, Sil (E)
Thetis	NiFe, Cpx
Melpomene	Sil (O), Opq (C)
Fortuna	Phy, Opq (C)
Phocaea	NiFe, Px, Cpx
Euterpe	NiFe, Px, Cpx
Bellona	Sil (O), Opq (C)
Europa	Phy, Opq (C)
Concordia	Phy, Cpx (C)
Ausonia	NiFe, Px
Eurynome	NiFe ~ Cpx
Sappho	Sil (O), Opq (C)
Alkmene	Sil (O), Opq (C)
Io	Sil (O), Opq (M)
Thisbe	Sil (O), Opq (C)
Siwa	NiFe, Sil (E)
Dembowska	Ol, (NiFe)

* 小行星表面材料所含矿物种类: NiFe (镍铁金属); Ol (橄榄石); Px 辉石, 一般是低钙正辉石); Cpx (斜辉石, 钙辉石); Sil (O) (镁铁硅酸盐, 极可能是橄榄石); Sil (E) (光谱中性硅酸盐, 极可能是无铁辉石, 顽辉石); Phy (叶硅酸盐, 层格硅酸盐, 陨星泥矿物, 一般是水合的, 未沥滤而含有丰富的Fe²⁺和Fe³⁺正离子); Opq (C) (不透明相, 多半是磁铁矿或有关的不透明氧化物)。
用以表示矿物相对含量的数学符号: > 多于; \geq 远多于; ~ 大致相等; 等于。凡是蕴藏含量未确定之处, 排列次序表示含量由多至少。

表3.可得自月球的元素

多量元素——在月球上含量 $\geq 1\%$
O、Si、Al、Ca、Fe、Mg、Ti
少量元素——含量 0.1 - 1%
Cr、Mn、Na、K、S、P
痕量元素——含 < 0.1%
H、He、C、N 及其他
(通过选矿的办法, 痕量元素可能转变为少量元素或甚至多量元素。)

表4.一克分子“需求量”的组分 (根据美国于1968年对不可更新资源的消耗量而统计出的“平均分子”)[7]

单位为克分子分率

燃料	CH ₄ - C ₆ H ₁₄ - 0.8022
建筑	SiO ₂ - 0.1115, CaCO ₃ - 0.0453
金属	Fe - 0.0110, Al - 0.0011, Mg - 0.0004 X* - 0.0008, (Cu, Zn, Pb) - 0.0004
农业	N - 0.0076, P - 0.0008, K - 0.0007
其他	O - 0.0053, Na - 0.0053 Cl - 0.0053, C - 0.0023

*X ~ Mn, Ba, Cr, F, Ti, Ni, Ar, Sn, B, Br, Zr

性质

平均分子量——23.9

开采所需平均能量——1.25 千瓦-时/公斤, 即等于 4.5×10^6 焦耳/公斤

平均单价——1.4 美分/公斤

总消耗量 3×10^9 公吨

总价值 42×10^9 美元

美国每人所消耗的数量 15.4 公吨

能量 18,800 千瓦-时

功率 2.4 千瓦

虽然许多痕量元素在月球上的总含量和在地球上无多大区别, 但这些元素在月球上未知有集中矿藏存在, 因而使经济地开采这些元素的前景十分暗淡。当然, 实在是关键时, 人们仍然可以从地球上运去少量的这些元素。另外还要注意, 月球上的多量元素正是地球上工业中最大量使用的矿物元素 (除去空气、水和燃料)。

在1976年, 戈勒和魏因伯格 [7] 就讨论过所谓的“需求量”分子 (demandite)。它的定义是: “人们用的不可更新资源的平均量”。表 IV 显示组成一个克分子“需求量”的各成分 (以克分子分率计) [8]。表 V 显示, 除去燃料成分后的一个“需求量”分子和阿波罗十五号所载泥土的对比 (单位为重量分率)。差不多所有的非燃料“需求量”成分, 都可以从月球 (>90%) 和小行星群上取得。在进一步探索月球之后, 有希

望找到纯度更高的“需求量”中的稀少元素。

表 VI 显示一些有用产品名单, 它列出以月球材料为主, 在太空制造设施里可以生产哪些产品。水虽然未经列入表内, 但它可用月球材料里获得的氧和从地球运去的氢合成而得。(氢也是月球上的一种痕量元素, 虽然它的重量含量大概介于 50 - 100 ppm 之间, 但它的克原子含量大概是硅的 1%。如果可以提取氢, 则可用它来合成水, 用以补充在循环过程中耗失的水, 因为没有一种循环过程可以回收 100% 的水。)

表 VI 里列出的结构金属 (铝、铁、镁和钛) 必须炼成合金才能具有适当的机械性能。表 I 显示制成工业用结构合金所用的几种元素 (例如硅、铬、锰) 有可能从月球上取得。此外, 月球上还有含有镍和一些钴的“中性”铁, 它也可能加以开采。最后, 如果从月球上现有的痕量碳中可以提取足够数量的碳

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表7.产品合制方案

金属/二氧化硅比率

当量 1 : 1 橄榄石、钙长石、原硅酸盐
0.5 : 1 辉石、硅酸盐
0 : 1 硅石
1 : 0 钛铁矿、尖晶石、陨硫铁等等中性铁

铝/铁比率

负相互关系
大致的范围 5 : 1 至 1 : 4

非结构金属/结构金属比率

钙 : (镁 + 铁) 辉石 : 1 : 1 至 0.1 : 1 钛铁矿 0 : 1

轻金属/铁比率

(铝 + 镁) : 铁 与 铝/铁相同比率

硅/二氧化硅比率

按还原要求
按光电装置的要求而定

金属/金属氧化物比率

按还原要求
依据金属对耐火材料及颜料的相对要求而定

氧/金属比率

依据氧与结构金属 (及硅) 相对需求量而定。氧可能成为不需要的副产品, 铁和其他还原性物质也可能成为过剩材料

增强金属/正常金属比率

需求取决于增强金属的合用程度, 即它是否能代替设备与结构中所用的增强树脂

其中包括无试剂处理法, 诸如: 直接电解月球原土或精选过的土 (熔融硅酸盐电解), 运用磁力收集中性铁; 无水高温处理法, 诸如碳和硅热还原法及氯碳冶金法; 还有低温水溶液化学处理法, 诸如: 酸液或碱液过滤 (有些具体处理法以后还要谈到) 。

含有月球缺乏元素的重要原料在用过之后必须尽可能完全地加以回收, 并循环使用 (需要时予以再生), 其效率要接近或超过 99%。这样就可以避免从地球提运大量的材料。

由于月球缺乏元素的回收率必须尽可能高, 因此, 产品混合物中所含的元素, 除原料中所带来的之外不应再掺入其他元素。又因月球上能多量取得的非金属元素只有硅和氧, 所以在设计产品种类时, 必须只限于元素、合金、硅化物及简单和复杂的氧化物。

设计太空工业生产时, 必须充分掌握各种工艺方法的优缺点, 并掌握对它们的评价方法之后, 才能从中选出一种合适的工艺过程。而为了收集到充分的资料, 以恰当地评选各种工艺方法, 又必须深入分析文献和进行详细的实验工作。

当然, 在评价太空中的加工与制造方法时, 首先要断定, 在空间轨道的装置中制造产品的成本低些, 或是在地球上制造、然后把产品运到太空中的成本要低些。作比较时, 应该考虑到代用材料的问题; 例如, 以月球矿产为原料时, 很难制成有机材料、玻璃钢、含铍制品、铜、银、耐高温金属、贵金属以及含水量较高的各种材料等等。幸而, 上述各种材料即使需要多量使用, 也都可以找到合适的代用品。

在空间轨道或月球上进行工业生产的主要动机在于想节省自地球大量发射物体的费用 (> 100 美元/公斤); 因此, 太空装置每年生产的产品质量, 必须能远远超过初期从地球运过去的生产设备、消耗物资、原料及辅助设施的总质量。迄今对太空材料加工方法的分析结果表明, 上述目标是不难达到的。

由于在太空中尽量减少质量是件至关重要的事, 所以原材料在太空装置中必须能迅速通过各个加工程序, 并须尽量减少延误, 如果可能的话, 应该消除一些不利的因素, 这包括:

1. 需要长时间才能完成的步骤。
2. 投入低浓度材料的步骤。
3. 挥发性物质在很低气压下进行传质过程。

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质及用途所限, 仍须多使用钢材, 而较少使用铝或镁材料。

4. 在太空中把碳加工成碳精电极及石墨制品是一件困难的事。如果可能的话, 最好另外寻找其代用品。

化工装置设计

Chemical Plant Design

在太空里设计化工装置必须考虑的一些因素列于表 VIII。加工地球以外材料的化工装置所用的装备器材可望和以地球为基地的装置十分相似。由于从地球运去的各项物品重量越小越好, 大多数器械仪器都要用强度比率 (即强度重量比) 高的材料制造, 也许要用抗腐蚀材料 (甚至须用黄金) 制成薄衬层。

器材装备必须适合先前说过的种种工艺条件, 也要能适应运输途中和装配及运行过程中遭遇到的特殊太空环境。这包括: 无限大的真空冷源, 各种人为因素对引力的影响 (除去在月球表面), 工艺过程中发生的热量可以辐射方式散发出去, 用作反应物、溶剂或催化剂的月球缺乏元素须循环利用。

太空中最实用的能源是太阳。太阳能电池阵或者巨大的集光镜 (用铝涂面) 可用以集中太阳光, 由此而给太空工业设施供应电能及热能。

有人已经提出了几种从月球的土壤里提炼多量元素的办法。

表8.化工装置设计要素

工艺方案选择

太空环境中的特殊因素

- 引力 (自然的或人工的)
- 真空
- 排热
- 非月球固有材料的循环使用化工单元操作种类
- 物料输送
- 相分离
- 热交换
- 化学反应
- 能量要求
- 排热要求

决定规模大小的因素

- 动力学的限制
- 传热的限制
- 动量的限制

4. 对高粘度悬浮液进行相分离。
5. 每次反应的转化率很低的工艺过程。
6. 需处理或储存大量气体的反应过程。
7. 需用液/气热交换器大量传热的反应过程。
8. 在低温下(200-300℃)放出大量热的工艺过程。
9. 设备结构材料达不到合理的使用寿命的工艺过程。

对太空生产工艺进行评价时,还应考虑到可靠性、人力要求、对生产人员的潜在危险性、废料利用的可能性及设备发生故障时维修的难易程度。如果部件腐蚀后只能从地球运去替用品,则其困难程度必然远大于从月球运去替用品的情况。

制造化工设备的成本比起把它投入空间轨道上的成本简直是微不足道的,这点几乎对一切情况都适用。如果设备中有许多部件可以用月球材料制造,则在扩建设备或更换零件时成本就可降低。

太空环境的因素

Space Environmental Factors

真空——太空加工设备,由于周围有真空冷源,故对几种工艺过程可能是有利的。一般最有利的场合是:一些耐火材料及结构材料在高温下容易氧化而变质,(除去在真空熔炉里使用),而在太空中则无此缺点。因此,普通的钢材也可以用来制造金属还原用容器;又如:钛和耐高温金属,碳和碳化物,氮化硼和其他非氧化物耐高温材料等都可以放心地用于结构和绝热方面,而不致有过份氧化的危险。这样,在极高温条件下便可用先进的多层挡辐射罩来隔热(但升华作用可能使这类隔热罩不适合用于某些用途)。

另一方面,在分离、精选工艺上,太空真空的作用可能极其有限;原因是挥发物质,特别是水汽,因真空度太大而逃逸掉,一般是很不利的。

尽管有真空可以利用,但大多数加工设备大概仍须要放置在一个大容器里。这个容器里要有适合人类活动的大气及温度。这才便于检查、维修和运行。

引力——月球上的装置受到的引力较小,而沿轨道运行的装置又可以调整离心力来增减模拟重力的作用,因此生产设备的支承结构也就不必象在地球上那样庞大。看起来,多数化工过程在失重状态下都不会进行得很好;原因在于,除了把纯净气体引进容器的情况之外,其他的传质过程都要依靠重力的作用来完成,一旦失去重力,情况便要变得十分复杂。例如,固体、液体或泥浆装入或卸自固定容积储罐的过程将难以进行;而过滤、蒸馏、逆流萃取及其他逆流传质过程,即使还可能进行的话,也是十分困难的。

失重工艺的最可能用途是通过辐射或感应法给腐蚀性物料加热,一面运用气流或电磁排斥法阻止它和容器壁相接触。

在沿轨道运行的装置中,大多数较安全的部件都可放在一个大型(可能是分体式的)压力容器,并使该容器缓慢地旋转,以产生人工引力。

冷源——由于太空中不存在空气或水等大量冷源,因此工艺废热的处理变得复杂化。不论废热量有多大,最终都必须通过辐射散热器散发出去。此外,气体热交换器的性能会变得很差,因而需要靠增加面积的办法来弥补,这样就使设备变得庞大而难用。一般来说,克服这个缺点的办法是,若欲改变气体的温度,可通过绝热压缩或膨胀的方法来使它升温或降温,这

样便可避免使用庞大的板式或管式热交换器。同样地,在蒸馏过程中,塔顶蒸汽可先予以绝热压缩,使它在较高的压力和温度下冷凝,同时把冷凝热传给再沸器中沸腾的液体。自然,这样的处理热量或传热方法是需要另加压缩机或膨胀机的,但由此而需增加的设备质量通常要比其他方法少得多(参看一些传热学文献,如“Heat Transfer”, A.J. Chapman, Macmillan, 1960等)。

有一些设备,诸如电解槽等,在运行时不可避免地会变成一种低温或中温热源,它们所产生的热也可能需要用压缩的办法使其升级(即升温),这样可使太空散热器的效率提高,从而减少所需的质量。通过某种简化的分析方法可以看出,在某一种“临界”温度之下(而该温度又随太空设备的质-能比及散热器的质量-面积比而变),所有的放热介质都应该先加以压缩,使其升温之后再放出热量。同样的道理,深冷液化装置中的介质,也应该提高到相同的“临界”温度之上以后,才放出热量。根据初步的工程分析,最低的放热温度应在500-600°K范围内。

物料循环的必要性

Recycling Requirements

大多数地球上的装置都有一种主要产品(或几种一起生产的产品)。这些产品的传质效率常常比有关的反应物、溶剂、空气及水的转化率要低得多。

由于从月球可能弄到的挥发物质(氧除外)一般都较稀少,月球上的或太空轨道上的装置一般必须还原、回收和循环使用。正常情况下可以丢弃的原料及溶剂。这个问题比初看起来更严重,因为水、水汽、或种种物料的循环量在有些情况下可能达到月球“矿物”处理量的10-100倍。然而,这些物质在循环过程中的总损耗量必须比有用产品的产量小得多。否则,如果从地球运去补充的原料数量接近于太空装置产品的产量,在经济上显然是不会合算的。

物料循环使用过程中也须要用到化学转化法予以再生,诸如分解盐类以产生酸和碱等;但这里为简单起见,只考虑元素的循环使用。迄今研究过的大多数生产方式中,只有少数几种元素必须予以严密监控。例如:在氢氟酸过滤过程中,只是氢、氟、钠,也许还有氮必须高效率地予以回收利用。而且,由月球原生材料里也许还可以取得适当数量的钠和氢。

当月球缺乏元素存在于蒸汽压微不足道的固相中时,循环过程中的损耗可能更大。因此,在高温下处理物料也许是困难的。例如:熔渣或液体金属可能把月球缺乏元素“藏”起来。

物料与设备的质量

Reagent and Equipment Mass

对于含有溶液的生产过程来说,溶剂的质量一般会超过原料(溶质)的质量(可使用大于50%重量的溶液时则属例外)。在普通的情况下,溶液的浓度总是在5至10%(重量)左右。加之,在各种分离或萃取过程中,溶液每通过设备一次,并非所有的溶质都能分离出来或被吸收掉;因此,通常所用的溶剂质量要比“有用溶质”的质量大得多。

幸而,对于水溶液,溶剂中的大部分质量都不必从地球运去,因为构成水质量的88.8%的氧可以从月球材料里取得。就连氢也可以从月球上取得足够的数量,以便补偿产品残余水分

表9.工程设计参数

设备	能力	典型流速 V_i (或特征速度)	过程时间	其他
马达、泵、压缩机 (真空泵除外)	10^3 千瓦/米 ³	10至100米/秒	1秒	1公斤/千瓦 或1吨/兆瓦
蒸馏塔	质量流量1—5 公斤/米 ² ·秒	1至3米/秒(汽) (受限于雾沫夹带)	5—10秒	高度每板 0.4—0.6米
固液分离离心机	体积流量0.004— 0.08米 ³ /米 ² ·秒	沉降速(10微米颗粒) 10^{-5} 米/秒×g;典型速·在1000g 下 10^{-2} 米/秒	0.5—2分	功率50—100 千瓦/米 ²
旋转煅烧器	装料量0.05—0.2 吨/米 ³	3至10米/时(轴向) (0.00083—0.0028米/秒)	2—10小时	传动功率0.1— 0.2千瓦/米 ³
离子交换柱	0.5—3当量/公 斤树脂	0.2至0.5米/分 (0.0033—0.0083米/秒)	5—15分	
水相传热				
泡核沸腾	15—240千瓦/米 ²			给热系数2—16 千瓦/米 ² ·°K 温差10—20°K
冷凝(管内)	30—1000千瓦/米 ²	30至150米/秒(汽)		给热系数3—50 千瓦/米 ² ·°K 温差10—20°K
电解槽	$i=10^3—10^4$	离子迁移速度 $10^{-7}—10^{-5}$ 米/秒	10—50小时	

中所带走的大部分(或全部)损失量。

现在,让我们比较一下化工装置各部分的设备及物料的对大小。人们尤其希望知道化工容器、储罐、管道等等比它们所装的东西重些还是轻些。分析结果表明,含有10%以上液相或固相物料的大多数设备,所装物料都远远超过容器的重量(这里说的容器是用高强度材料制的,其壁厚采用安全许可范围内的最小者)。相反,对于气体,其容器一律超过所装物料的重量。此外,就气体说,容器与所装物料之间的质量比率几乎和压力无关。

上述结论再度说明,需要储存或处理大量气体的工艺过程不宜在太空中使用,对于主要在液相或固相下进行的工艺过程。此外,除了动力和散热设备外,总质量多数受物料质量的支配。而物料所需的质量又取决于各个工序的反应和处理过程所需的时间。

各种工艺过程的工程特性可自表IX所列的参数看出。任何设备的大小(容积)可以表示为:

$$V = \frac{Q_i \ell}{\rho_i V_i} = \frac{Q_i}{\rho_i} t$$

式中的 Q_i 是组分 i 的质量流量(公斤/秒), ℓ 是设备中流动路线的特征长度(米), ρ_i 是组分 i 的偏微分密度(公斤/立方米), V_i 是组分 i 的特征速度(米/秒), t 则是处理时间(秒)。

物料每一个处理工序都有一个特征性的当量时间(多数以小时计),它表示投入物料直至其重量等于容器本身或容器内物料毛重或净重时所需的时间。

把各个工序的当量时间加起来,就可以得出整个工艺过程的总当量时间;原材料进设备的时间等于总当量时间之后,其投入量便等于整个装置所容物料或设备本身的毛重或净重。此外,对于机械和热动力源、分配设备、马达、泵、压缩机、传热设备、空间散热器及其他必要的辅助设备,需要时都可求出其当量时间。

化工单元操作 Unit Operations

物料输送——除去储存外,这类操作都不需要大量物质。大多数物料都可以0.01到1米/秒或更高的速度通过物料输送设备,因此这类设备很少需要容纳多于几分钟生产量的物料。用球磨机或同类的机械进行精磨是比较慢些,但预计加工月球泥土不须要使用这类机械。由于月球引力或人工引力都较低,气流中夹带的液体或固体微粒可能引起处理上的难题;但它可用气体或液体的惯性分离器或旋流分离器来加以解决。

相分离——在实际的相分离过程中,压力或惯性力常是关键因素,例如蒸馏塔里的起沫或雾沫夹带问题、离心过滤器或离心机中的沉降速度等,但物料处理时间可能受支配于传热率、结晶或沉淀物的成长率等等。

由于各种工艺常包含循环流程,因此缩短设备内的处理时间或许是有利的(即使由此而需要加大中间的物流循环量),这样做便可减少一些中间工序所含的质量。然而,在装置的出口处,必须使物料的损失量减至最低程度(特别是含有月球缺乏元素的物料),因此各个处理步骤必须尽量进行得彻底。

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试举一个情况为例,以水为中间冲洗剂或反应剂的工艺过程都有一个共同的问题,即干燥产品的问题。大多数细颗粒的金属氧化物或固体硅酸盐中都含有物理或化学吸附的水分,而只要适当地加热、存放或通过压差的办法,这些水分便可除去。

加热和冷冻——工艺上所需的热量,可以得自于电能或太阳能,又可间接通过使用水蒸汽或其他工作流体、或者通过和其他流体进行热交换而获得。如果使用太阳能,可预计能够使设备大量减省质量。例如:用太阳能能代替太阳源电能可以使设备质量减少至1/2或更少。

加热固体粉末常常是件困难的事,用辐射的方法也很难奏效。一般是用循环气流与粉末热交换的方法来完成这项工作,而该气体则需要在另一个设备中用其他方法(如太阳能炉、电弧、电阻或感应加热等)来加热。在某些情况下,固体粉末也许可通过高频电磁场或甚至微波来加热。

冷冻或冷却工艺,在某些处理步骤中或者在收集、分离、及储存不凝气体等方面可能用得着。储存氧及储存氮在动力和装备方面的要求十分大。液化这些气体,将可大大减少所需储存容器的质量。若把它们冷却到三相点或更低温度,则还可进一步减少设备的重量。

反应——反应器的设计通常受热平衡要求(吸热或放热)所支配,还要看是要求从内部或外部加热或冷却而决定。从内部加热或冷却的反应器,一般可设计成大管形、圆柱形或球形;与外部交换热的反应器惯常要求具有大面积的表面及至少一个短尺寸(大约0.2到0.5米)。电解槽通常要求阴阳极之间相距不大(约0.1米或更少些),以免能量损失过多;但每个电槽里可以多放置几个阳极和阴极,以使总体积缩小。然而,排热的要求常常支配着电解槽的大小。

熔融硅酸盐电解

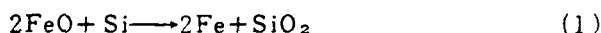
Electrolysis of Molten Silicates

关于成分类似月球玄武岩的熔融硅酸盐的直接电解,曾有少数人进行过研究[14]。由于硅酸盐的熔点及粘度都很高,因而工艺过程较困难,这便促使人们研究添加溶剂的方法。但是,这种办法却能使直接电解法无溶剂的优点消失,并出现回收和循环使用溶剂的问题。这种电解法的主要障碍(或待解决的问题)是析出氧气所用的阳极的腐蚀问题,还有净化及分离阴极上的还原产物问题(它可能是铁铝硅合金,加上少量的杂质)。

碳加热还原法/硅加热还原法

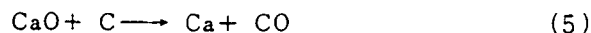
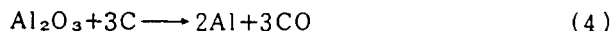
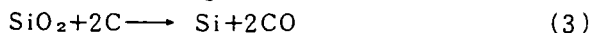
Carbothermic/Silicothermic Reduction

芬奈等人[15]是最早对该法进行认真的定性研究者之一,他们曾在1976年国家航空与航天局的夏季研究会上作报告,讨论对大量月球泥土进行硅/碳加热还原过程的问题。应用这种办法时,先要把原料破碎,并应用磁力把铁质与非铁质分开,然后才进行还原处理。硅可在1,300℃下还原铁,如式(1)所示:



其产物可用离心力将之分开。

不含铁的硅酸盐可用碳在2,300℃下将之还原,如式(2)到(5)所示:



还原过程结束后,可以期望铝和硅形成熔融体;而其他金属,包括主要杂质钛、锰、及铬在内,将变成蒸汽而跑掉。然而,实际的反应过程要比上述的复杂得多。在2,300℃时,液相化合物,诸如:SiC、Al₄C₃及Al₄O₄C和一些气体,诸如:Al₂O、SiO、Al及Si都能一起出现。

Al₂O及Al的蒸汽压力十分高,以致不能在正常操作压力下形成液体铝。碳加热还原法的最大缺点可能是:虽然早在1940年代[16]已显示用这种办法可以在地球上生产铝,但是未曾有过工厂证明用它生产铝是切实可行的。

碳氯冶金法

Carbo-Chlorination Process

1977年,在国家航空与航天局的夏季研究会上,D. B. 晓等人[17]相当早就确定,碳加热还原法对太空作业是不切实用的。他们建议对月球的钙长石(CaAl₂Si₂O₈)和钛铁矿(FeTiO₃)使用碳氯冶金法;这些矿石都可以从月球的泥土中精选出来。所要的产物是铝、铁、硅(或二氧化硅)和钛。

后来,我们在月球与行星研究所的一项研究中发现,采用碳氯冶金法需要用到庞大的设备。氯和碳循环使用所需的设备,要比主要的装置大得多。然而,碳氯冶金法的主要优点之一一是湿法冶金过程用得极少。但是,水还是要用的,它须用于水解、氯再生,也许还要用于冷却系统中。为了尽量减少散热

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表10. HF 酸沥滤法化学反应式

1.	$x\text{MO} \cdot \text{SiO}_2 + (4 + 2x)\text{HF} = x\text{MF}_2 + \text{SiF}_4(\text{aq}) + (2 + x)\text{H}_2\text{O}$
1'.	$x\text{MO} \cdot \text{SiO}_2 + (5 + 2x)\text{HF} = x\text{MF}_2 + \text{HSiF}_3(\text{aq}) + (2 + x)\text{H}_2\text{O}$
2.	$\text{SiF}_4(\text{aq}) + \text{nH}_2\text{O} = \text{SiF}_4(\text{v}) + \text{nH}_2\text{O}(\text{v})$
2'.	$\text{HSiF}_3(\text{aq}) + \text{nH}_2\text{O} = \text{SiF}_4(\text{v}) + \text{HF}(\text{aq}) + \text{nH}_2\text{O}(\text{v})$
3.	$(1-y)[\text{SiF}_4(\text{v}) + 4\text{H}_2\text{O} = \text{Si}(\text{OH})_4 + 4\text{HF}]$
3a.	$(1-y)[\text{SiF}_4(\text{v}) + 2\text{H}_2\text{O} = \text{SiO}_2 + 4\text{HF}]$
4.	$(1-y'-z)[x\text{MF}_2 + x\text{H}_2\text{O} = x\text{MO} + 2x\text{HF}]$
5.	$y[\text{SiF}_4 + 4\text{Na} = \text{Si} + 4\text{NaF}]$
6.	$y'[x\text{MF}_2 + 2x\text{Na} = x\text{M} + 2x\text{NaF}]$
7.	$z[x\text{MF}_2 + x\text{SiF}_4(\text{aq}) = x\text{MSiF}_6(\text{aq})]$
8.	$z[x\text{MSiF}_6(\text{aq}) + x\text{H}_2\text{O} + \text{electrical energy} = (x/2)\text{O}_2 + x\text{M} + x\text{H}_2\text{SiF}_6]$
8a.	$z[x\text{MSiF}_6(\text{aq}) + \text{M}'\text{SO}_3\text{R}^* = x\text{M}'\text{SiF}_6(\text{aq}) + x\text{MSO}_3\text{R}^*]$
9.	$m\text{NaF} + m\text{R}^*\text{OH} = m\text{NaOH} + m\text{R}^*\text{F}$
9a.	$m\text{NaF} + (m/2)\text{Ca}(\text{OH})_2 = m\text{NaOH} + (m/w)\text{CaF}_2$
10.	$m\text{NaOH} + \text{electrical energy} = m\text{Na} + (m/2)\text{O}_2 + (m/2)\text{H}_2\text{O}$
11.	$(1-y)[\text{Si}(\text{OH})_4 = \text{SiO}_2 + 2\text{H}_2\text{O}]$

R* = 离子交换树脂 aq = 水溶 v = 汽
m = 4y + 2xy' electrical energy = 电能

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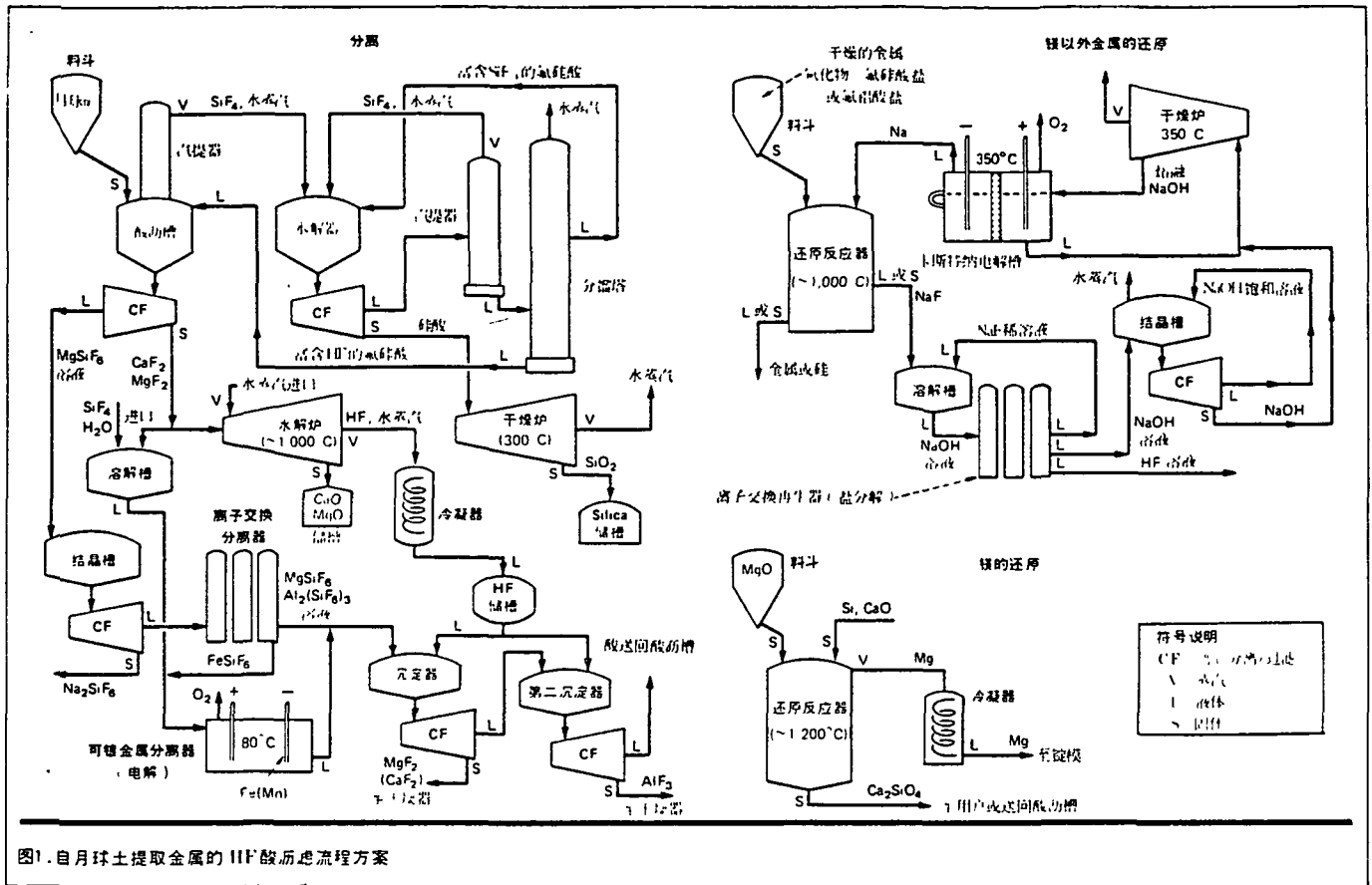


图1. 自月球土提取金属的 HF 酸沥滤流程方案

(上接第36页)

器的尺寸, 需要把大量物料的温度用压缩法提高到 280°C 左右, 方可以较小的散热器放出更多的热量。

这些结果使我们相信, 凡是排出低温热较少并且采用湿法操作的冶金法, 都可能是太空作业中的可取办法。

NaOH 碱沥滤法

NaOH Basic-Leach Process

细读文献[20-23]得知, 钙长石能用 NaOH 在压热器里加以分解; 随后将这些产物再用碱加以处理, 最终便能得到氧化铝和硅酸钙——后者可以用于制造玻璃, 或者可以加以水解以产生石灰和氧化硅。不论采用碱或酸沥滤法, 月球泥土里的钠都用来补偿循环过程中损失的钠。采用碱沥滤法时, 循环使用的 NaOH 中含有杂质钙并不成为问题; 原因是该法所需的只是碱性, 并不需要使用纯净的 NaOH (氢氧化钠)。

HF 酸沥滤法

HF Acid-Leach Process

这种方法是一种低温水溶液化学冶金法 (即湿法冶金), 它通过形成氟化物及氟硅酸盐的途径, 把月球材料中的硅自其他金属氧化物中分离出来。随后, 硅又形成 SiF_4 而挥发出去, 再进一步便可用各种溶解、沉淀、离子交换或电解法等分离出钙与一些结构用金属 (铝、铁、镁、钛等)。总的化学反应式

示于表 X。铁可用电解法轻易地自溶液中分离出来; 至于其余的金属, 除了镁以外, 最好是用钠自氟化物、氟硅酸盐或氟铝酸盐中还原出来。镁则可用硅自氧化镁中还原出来。

只需略微改装一下卡斯特纳 (Castner) 电槽, 就可方便地制取纯钠, 以供还原其他金属及硅之用。以前, 卡斯特纳电解槽曾是多数工厂中用来生产钠的设备。这种电解槽采用电解熔融氢氧化钠的方法来生产 Na、 O_2 及 H_2 。在月球作业中, 氢气是无用的副产品; 但若采用隔膜电解槽, 并以真空干燥法除去 OH^- 离子放电所形成的水, 则所产生的氢气量便可降至最低程度。

金属氧化物和二氧化硅, 需要时, 可以用水蒸汽 (制取 SiO_2 亦可用 NH_3) 水解相应的氟化物或氟硅酸盐而获得; 同样, 用离子交换 (或渗透作用) 法也可取得。至于把它们各个分离开的办法, 则有待于进一步详细研究。

HF 酸沥滤法的流程示如图 1。

在这今已研究过的办法中, 看起来 HF 酸沥滤法所需的质量最少, 元素分离与纯化的过程最简单, 能量利用最合理, 同时放热条件十分好。

目前仍有许多工艺方法及技术细节有待于进一步研究。其中有一些要做起实验来并不很困难。如读者有兴趣做几项这类实验 (其中有许多是相当简单的), 本文作者将乐于听到他们的报导。

由于各种金属氟化物或氟硅酸盐的溶解度随着pH值及F：Si比值而有所不同，所以可以用分步溶解法来分离它们，必要时又可用离子交换法或电解法来补充；但这些方法付诸实现之前，须先广泛查阅文献及进行实验。关于氟化物、氟硅酸盐及氟钛酸盐的高温分解及水解性能，也需要进一步研究才能掌握到。

尽管有这些情报方面的空白，几乎全部适当的太空操作步骤已经以实验室规模进行过研究，而其中大约75%的步骤已经在模拟太空条件下按中试或工业规模进行过实验。

太空加工装置 Space Processing Plant

图2是一位画家设想的HF酸沥滤法太空装置。这个装置适合加工斜长岩（斜长石）。这种矿物在月球高地上蕴藏很丰富，它是铅、硅、二氧化硅、氧以及其他少量元素的理想来源。这套化工装置每年能加工30,000公吨（90%纯度的）的斜长岩。

一个30兆瓦的太阳能发电装置就占据了那张图的大部分位置。它是八面体形的，每边约500米，其质量为120公吨。

前面是氧化物分离器，电解分离设备在后面两者共计净“重”105公吨。大约有63公吨的氢氟及少量钠必须从地球运去，以便在该装置进行液相水解时用作一部分工作流体。

氧和钠是从第一批月球泥土中提炼出来的，以制成装置全盘开工时所需的全部336公吨的水。氟化氢及氢氧化钠。这样，我们看到，使用月球材料就可减少从地球运去的开工材料数量。在氧化物分离器和电解设备左边又大又平的物体是放出工艺热用的空间散热器。补充用的氟每年达30公吨，它将占从地球输入的原料的大部分；但是，该装置每年即可处理30,000吨矿物。

在太阳能发电装置底部可以看到一个供建设和运转人员用的双间住所。假定每天开工24小时，大约20人就可以操作整套装置。工艺过程中仅用低温低压，故全部容器和管线可以是薄壁低密度的设备。从月球铁炼出的钢应可供将来扩充设备时使用。加工设备及人员住所均是旋转着的，以产生人工引力。在太阳能发电装置的一边可以看到有一个用火箭推进剂储罐改造成的无引力工作间。装有2,000吨月球土的袋子拴在加工装置的进料柱上。

在这套加工装置的研究过程中，有一件相当惊人的发现，就是该太空装置所需材料的质量很小。只需要10到15次航天飞行，就可将太阳能发电装置、加工设备和开工用的流体共290公吨运上地球低轨道运行。再有10到15次航天飞行，就足以将260公吨的双间住所和制造设备安装妥当。这种装置本身的质量与其生产能力成正比。然而，当操作经验增多后，就可减少人员操作的需要。此外，月球土层里的微量游离铁，可用以制造需补充的容器和机器。倘若如此，建造下一个同等生产能力的装置时，需要从地球运去的材料的质量可能从290公吨降到100公吨或更少。

工艺方法的选择和发展 Process Selection and Development

由于分离或直接还原复杂的氧化物和硅酸盐时存在许多问

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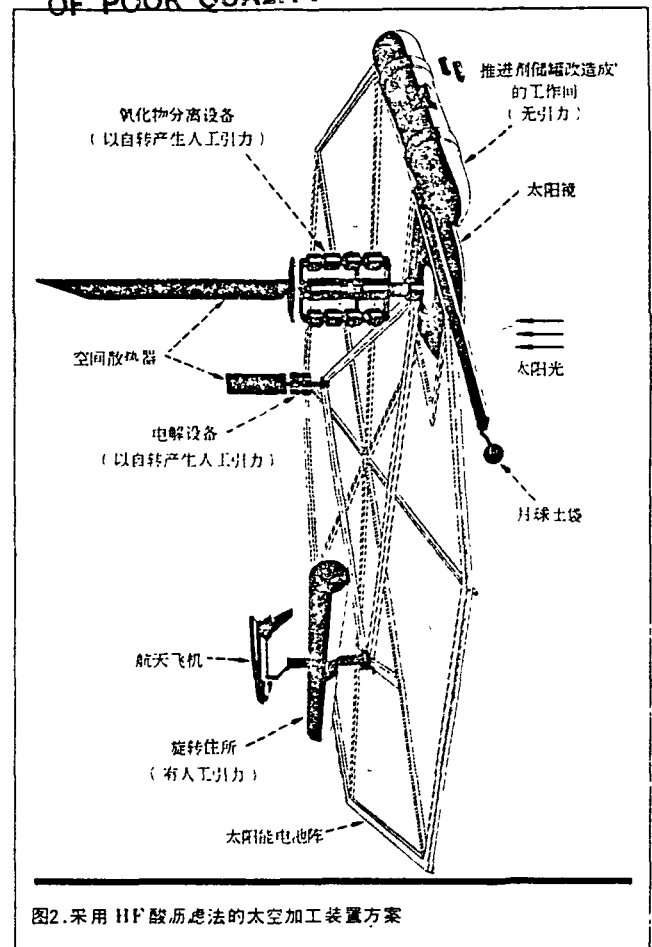


图2. 采用 HF 酸沥滤法的太空加工装置方案

题，这便促使人们用各种化学品来把氧化物转变成其他化合物，试图简化加工过程。他们力求制成一些新化合物，使它们比原始材料容易分离、提纯或还原成元素形态。如果这些化合物在各种溶剂的溶解度方面、或在蒸汽压方面存在明显的差别，分离和提纯就会比较容易进行。

这里涉及的溶液可以是水或非水的。关于水溶液方面，金属化合物在含酸或近乎中性的水里的溶解度，是人们所共同关心的。大多数的金属硝酸盐、氯化物、高氯酸盐、氟硼酸盐及氟硅酸盐都可溶于水，而金属的氟化物及硫酸盐则只有一些具有有限的溶解度。其它大部分常见的负离子都和金属（碱金属除外）形成不溶解的盐。硝酸盐、高氯酸盐及氟硼酸盐的稳定性可能较差，再者它们可能原料来源稀少，因此人们不倾向于把它们用在一般的分离及还原过程中。

在碱性溶液中，仅仅是二氧化硅、二氧化钛及氧化铝具有适当的溶解度；而这些物质若含有多价的金属离子（例如 Ca^{++} 和 Mg^{++} ）时，就常常变得不能溶解。由于碱液（NaOH）的挥发性很低，故它的循环使用要比酸困难些。

大多数金属氧化物容易汽化，而氟化物挥发性则低得多。这两种化合物都易于用活泼的金属或用电化法予以还原。硫化物也很可能变成还原剂金属的原料，可惜许多硫化物的熔点很

高。

就以有水的溶液而言，人们就要考虑使用硝酸盐、氯化物、高氯酸盐、氟硼酸盐、氟硅酸盐、氟化物以及硫酸盐。硫化物、碳酸盐、磷酸盐以及（有限度的）碳酸化合物也可能在材料加工过程的某些方面有用。

硝酸盐以及高氯酸盐对于加热或者处于氧化还原条件时不很稳定，而且这类化合物分解后再合成有困难，因此使用起来不很方便。氟硼酸盐同氟硅酸盐相比似乎少一些有利之处，而且它含有另一种月球缺乏元素。硫酸盐、碳酸盐及磷酸盐在一般的溶解及分离过程中好象性能较差，但在个别的分离过程中可能有用。

氨/铵盐类在化学性质上有一种独特优点，即高温分解铵的化合物可以有效地净化许多月球上的多量与微量元素，使之成为易于进一步加工的化合物。在高温或强氧化条件下，铵离子或氨的稳定性没有卤化物高，但它们比硝酸盐或高氯酸盐稳定些，并比它们较易于再生。

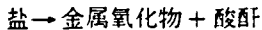
如果我们分析一下氧化物、氟化物、氯化物及硫化物的生成自由能与温度的关系，便可以看出，除去铁以外，月球的其他多量元素都能与之形成高度稳定的化合物。一般说，生成自由能较低的化合物比生成自由能高的化合物要稳定些；因此，前者所含的金属有能力使后者中的金属还原。钠和钾在还原氯化物和硫化物时，比在还原氧化物时更显得有效。

加工月球材料的装置一般的目标是，以最低材料损耗去获得适当纯度（如99%）的一些元素和氧化物。为了要分离各种元素，就需要把原料转化成可溶的或挥发性的化合物，然后便可先把这些化合物逐个分离开，继而又分别予以还原或再转化成氧化物。若使用溶剂分离法，首先要求制备一系列溶剂。但是，看起来没有一种溶剂可以完全从月球元素里（可能SO₂除外）生产出来。因月球缺乏元素（氢）在水中仅占很少比例，故水是最合适的溶剂之一；若以化学及工程数据的丰富程度来说，水更有压倒一切的优点。然而，在太空中水是不能象在地球上那样广泛或胡乱地使用的。

在分离过程的中间阶段，各元素可能要转化成卤化物、硫酸盐等等；它们均可以被认为是金属的盐类；下一步，如果不是将它们还原到元素形态，就须再转化为氧化物——这个过程可以当作是盐类的分解反应：



或



上项反应可以用水解法或（对有些含氧的盐）用高温分解法来完成。在有些情况下——例如在水解卤化物时——比较方便的办法是用酸（对硅的卤化物则用碱）而不用水或水蒸汽，来完成水解作用和回收HCl或HF。然而，这类方法总是要产生新的盐类，随后必须把这些盐类再加以分解。

如果用钠或其它活泼金属来使卤化物还原，则也会形成新的盐类。这些盐类也须加以分解或以电解法还原，以便使活泼金属再生。

几乎任何一种盐都可以用水蒸汽来水解，但是在许多情况下，所要求的能量和蒸汽流量相当巨大，因而可能使这种做法行不通。高温分解盐类的方法可以用诸于许多碳酸盐、硫酸盐，尤其特别适用于某些铵盐，诸如NH₄F及(NH₄)₂SO₄。

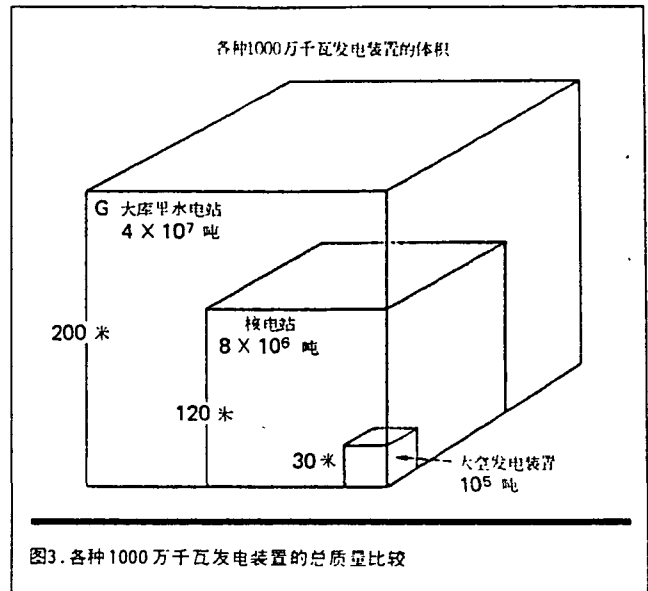


图3. 各种1000万千瓦发电装置的总质量比较

以形成NH₃及酸性盐。在地球的工业生产中，间接意义的盐分解已经大规模地用于氯碱工厂中。对以太空为基地工厂来说，哪一种方法可称为“最佳”盐分解法，将由其所需的质量、能量、效率以及其他因素来决定，这些因素都需要进一步研究。

氧是月球材料加工装置必然要生产的有用产物。除非能从月球土层里直接收集大量的元素铁，否则就要随同成批生产金属、合金及硅而大量生产氧。为生产氧，看来必需要直接或间接采用一些电解工艺。对这类工艺来说，特别是在高温下电解熔融盐时，阳极材料的耐用性或抗腐蚀性变得特别重要。石墨看来在500℃以上太容易氧化了；但在某些场合中使用Fe₃O₄或TiO₂作阳极也许是可行的。在较低温度下，诸如水溶液电解槽或“卡斯特纳”电槽（电解熔融NaOH）中，即使对工业规模生产来说，目前也已有了耐用度适当的阳极材料。

月球材料的用途

Uses of Lunar Materials

通过太空发电站，我们便可来研究月球材料的用途。人们已经探讨过许多种方案，要把发电装置发射到地球同步轨道上，以向地面站连续供应1,000万千瓦的电力。这比大库里坝（Grand Coulee Dam）预计能输出的最高电力大约高10%。大库里坝水电站是美国最大的电力装置。本文引用的其它文章已提到关于太空发电站的细节，因此这里仅讨论同月球材料直接有关的部分。在下一页上有一幅画家设想的太空发电站图。

上述太空站若设计成太阳能电池阵，则其质量将为100,000吨，而长为20公里，宽3到5公里，栅板厚度为几百米〔3〕。它由以下的材料构成：玻璃（太阳能电池，占52%），铝（配线，占6.4%），石墨复合材料（结构部件，占13%），铜和铁（配线，波导器及动力设备，占13%）以及输热管及调速管（各种组件，占7%）。这些零部件都可以用月球材料制造，或者以月球材料来代用〔5〕。剩下的10%左右的零部件需要用地球上的材料，至少对于现有太空站设计情况是这样的。

太空发电站的尺寸显得很庞大，但只要将它和大库里坝水

（下转第12页）

(上接第10页)

电站或相同容量的核电站或常规的燃煤发电站等相比,就要显得十分小。大库里坝水电站也是一个极大的结构,它有1.3公里长、140米高、整体重量为4,000万吨。这便是太空发电站重量的400倍。图3用一种密度每立方米5吨的立方体描绘了大库里坝的质量。这个图使人一目了然地看到,在建造大库里水电站、核电站及太空发电站时,各自所需材料数量之间的差别。

太空发电站产生的动力,可以用微波发射到地面,并用半径2到5公里的大天线阵接收。这种地面接收站的复杂之处在于:它是用上百万个同样的天线和接收器组成的,它们的质量总共为5,000吨,相当于每边10米的一个立方体的质量。接收器将安装在整体质量约200万吨的基础或支撑结构上。200万吨只是一座相同发电量的核电站质量的四分之一。此外,上述地面接收站的各个基础,若和核电站极复杂的结构相比便显得十分简单,后者必须具备辐射及压力的防护罩,还须预防自然灾害。

一个1,000万千瓦的燃煤发电站的质量一般会大于200万吨,——即介于太空发电站的地面结构和核电站两者之间。然而,一个1,000万千瓦燃煤发电站每年的燃煤量大致等于一个大库里坝。1976年,北美洲消费的煤等于大库里坝质量的14倍,这个年耗煤量,到2,000年时可能会增长到大库里坝质量的60倍。〔27〕

将太空发电站与大库里、核电站或常规发电站相比较,给人们留下深刻印象的并不是太空发电站的庞大物体面积,而是太空发电站在聚集能量并将它转化成地球上或太空里可用的形式时,对物质的利用效率十分高。在太空中操作、制造和安装发电站所需的材料质量,远比地球上现有或计划中的任何形式发电站小得多。这包括规划中的地面太阳能电站,这种电站势必要6到15倍于太空站的面积(由于夜间及阴天使效率降低),才能收集到相等的平均能量;而且地面太阳能电站的单位面积重量必须更大些,才能经受得住地球的引力及环境条件的作用。

综上所述可知,建造太空发电站所需的原始材料中的90%,只需由两部至四部地球工业规模的化工装置来供应。由此还可推论,与地球上建造新型工业规模装置所需的研究设计工作量相比,建造太空装置所需的研究设计费用要小得多,特别是研究设计时间要短得多。

尽管太空加工装置的规模相对地小,它的经济效果却可以是大的(这是以地球上的经验来说的),因为最终的产品(例如一个太空发电站),如果按照发电所得收入来算,它的每公斤材料价值将等于200到400美元。

后勤问题 Logistics

关于在地球同步轨道上建立太空发电站的问题,最近已有有人在材料供给方面进行过分析研究〔12〕,以比较一下,在地球上制造设备,及在月球上开采原料、并在月球上或太空中制造设备时,各自的优缺点如何。如果各种条件齐备,并且不需要新建设备,则地球同步轨道上的装置每有一公斤物体,从地球上就需要发射35.4公斤的推进剂与材料(消耗性的)来供给它;但若在月球上开采原料,则同样对于每一公斤太空装置材

料来说,从地球上只需运去3.2公斤的推进剂与材料,另外也只有1.75公斤的材料须从月球上运过去(假定在月球上已建成推运设备)。这些只是粗略的数字,它们是根据拥有最先进的地球航天器及规划中月球与太空轨道用的航天器而得出的结论,自然将来的情况可能有所变化。

结论

Conclusion

除去能够为建造太空发电站或太空住所生产材料外,还有几种有用的产品可以在太空中制造,其中有高温玻璃及陶瓷制品〔24〕和通信用的强化光学纤维材料。还有消耗品的生产(诸如火箭推进剂之类)看起来也可以在太空中进行。

热心人士倡导的第一部太空装置引进了一个崭新的工业概念。在太空里建造一套中间实验装置能在经济上造福于人类,人们将立即从它那里获得好处。再过20年,即2,000年前后,这样一种生产装置可能演变为成熟的太空工业,那时太空中的工厂甚至以地球上的标准来衡量也是大的。太空工业是能够迅速成长的,这犹如十九世纪时用煤的进展一样〔25〕。

在太空办工业,将要求把原和太空无关的地球上的技术和设计原理转用于太空。祇有能够大量使用月球上的材料时,地球上的工业转用到太空才能成为现实。另一方面,在太空中办工业时,祇能从地球运来的材料必须尽量循环使用。不难想象,为太空用途发展起来的材料循环工艺的某些部份,还可反过来运用于地球,以便改善地球的环境。在太空中应用太阳能发电,将会节省地球上日益枯竭的原料。太空探索有助于扩大人类对自然界条件和工业规模的控制幅度,总有一天这将演变成崭新的工艺技术。

人类在地球近空以外进行半永久性活动究竟前景如何,开始时须取决于它对地球上居民可否带来经济利益,花费这么大的费用是否值得;但从长远的前景来看,人类在太空中的这种活动目的是要解决建立自给自足生活体系的技术问题,又要开创出完全是人类创造、完全为人掌握的经济体系〔26〕。只要明智地利用各种工业知识,就可以使太空中办工业和搞科研的成本显著地降低。太空作业中需要考虑的基本问题是降低成本和自多处取得原材料及物资。太空作业的发展,既取决于、又反过来促成交通运输技术、太空制造、装配、采矿及选矿技术的发展。

迄今的研究工作,仅仅是开始分析太空材料加工方面目前所能应用的科学及工程方法。重要的是要动员各方面的专家来研究这个课题,并帮助寻找合理的办法来并然有效地发展这种工艺技术。我们恳请各界有关人士对此报告加以评论,针对上述问题,应如何用“常规”或新颖措施来解决,亦欢迎赐教。

不久的将来要召开一个专题研究会,就某些选定的有关技术专题,例如:太空加工体系的电化学、用月球原料制玻璃及陶瓷的技术,等等进行讨论。敦请与此领域有关的人士出席。本文作者欢迎有兴趣的人士来信联系。

致谢

这项研究是大学太空研究协会在月球与行星研究所进行的,是国家航空与航天局合同号为NAS 09-051-001(Mod #24)的一个项目。本文是月球与行星研究所第351号稿件。

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产品与工艺介绍

新型200安发电直流焊接机组 New 200 Amperes DC Weld/Power Generator

Airco 焊接器械公司宣布，已开始出售一种新型的发电直流焊接机组，电流为200安，可全负荷连续工作，适合于使用焊条的焊接作业。该公司声明，这部机组最适合在现场无电源的地方使用，此外，还适合于建筑工地、农场、造船厂及工厂设备维修场地等。它又可单独作发电机来使用，此时发出的电力是7000瓦、单相、120/240伏、60赫的交流电。用于焊接时，发电机输出的功率可达1500瓦。

这部机组定名为DC Wasp® G-E发电焊接机组。它的输出电流有五个调节范围，各范围之间是互相重叠的，电流可通过控制盘调节，需要时也可加装一套遥控器来调节。所配备的发动机是一台16马力、2气缸的风冷汽油机。它的断路电压可达80伏，使起弧变得十分容易。此外，还可配备以手动或自动的空运行控制器。

若欲获得这部200安Wasp G-E发电焊接机组的详细资料，请去函：Airco Welding Products, Communications Dept., 575 Mountain Avenue, Murray Hill, N.J. 07974, USA.

新型钎焊带 Brazing Foil

Allied Chemical Corporation 研制成功一种均匀而坚韧的钎焊带，并已在不久前获得美国专利权。

据制造厂家说，这种产品已用在多种高质量焊接作业中，如用来制造燃气轮机部件、航空空间装置、热交换器及其它受高应力、高温、强腐蚀的部件。

这种钎焊带是100%金属、100%密实的，其长度及厚度规格有许多种，用途主要是焊不锈钢及镍基合金，包括含有硼、磷与硅的合金在内。

此焊带韧性极佳，弯曲180度也不会断裂；再者，它不像铜焊粉一样需要粘结剂与/或熔剂等焊药来辅助，它直接便可焊接形状十分复杂的构件。

读者欲知悉详情，请写信至：METGLAS Products Operation, Allied Chemical Corporation, 7 Vreeland Road, Florham Park, N.J. 07932 USA.

PRODUCTS AND PROCESSES

Commercial Prospects for Extraterrestrial Materials

Only the United States has the technical expertise and economic ties to quickly develop lunar resources and market the energy produced.

David R. Criswell
Robert D. Waldron
Lunar and Planetary Institute

Why consider going to the moon to obtain raw materials from which to build and supply industry in space?

First, the soil of the moon is composed of 85 to 90 percent of the non-fuel, non-recoverable elements used by United States industries (see Tables 1 and 2). Second, it appears that large quantities of lunar materials might be made available for use in space at a smaller unit cost (\$/kg) than can equivalent materials supplied from the earth. This latter consideration results from the large mass of the earth compared to the moon and to the qualitative capabilities of the space transportation technologies expected to be operating in the 1980s and 1990s.

Non-renewable resources must be extracted from the earth, sea, and air and processed into a form that can be used by industry. "Demandite" is an imaginary molecule that contains the weight fractions of all materials used in the United States in 1968. The properties of Demandite are summarized in Table 1; note that fuels constitute the largest fraction of the Demandite molecule.

Table 1

Use	Weight	
	Fraction	Components
Fuel	0.46	Hydrocarbon (CH_2 to C_6H_{14})
Building Materials	0.45	Calcium carbonate (CaCO_3) Silica (SiO_2)
Metals	0.06	Iron, aluminum, magnesium, manganese, titanium, copper, lead, zinc, other metals
Agriculture	0.01	Nitrogen, potassium, phosphorus
Others	0.02	Oxygen, sodium, chlorine, carbon
<hr/>		
Average Unit Cost	-	1.4¢/Kg
Metals Unit Cost	-	21.0¢/Kg
Total Quantity	-	3 Billion Metric Tons
Total Costs	-	42 Billion Dollars
Average Unit Recovery Energy	-	0.57 Kwhr/Kg

The major problem facing the modern industrial world is to find some source of energy to replace petroleum. Electricity produced by solar energy would do this. A new molecule of non-fuel and non-renewable elements (non-fuel Demandite) can now be defined by subtracting the fuel in Table 1 and introducing the fractions of the elements that compose the remaining substances in Table 1 (see columns 1, 2, and 3 in Table 2).

Surprisingly, 11 of these 16 elements can be obtained from the lunar soil with no more than a factor of 10 enhancement over their natural lunar concentrations. The other five elements comprise less than 10 percent (by weight) of the non-fuel Demandite (see columns 4 and 5 in Table 2).

The huge mass of the earth means that a very high velocity (11.2 km/sec) is required to escape the earth and go into orbit or into deep space. In addition, the presence of the earth's atmosphere induces drag forces and prevents achieving high velocities at low altitudes.

Only 2.4 km/sec is required to escape from the surface of the moon; in addition, the moon has no atmosphere. The total energy of a moving

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Table 2

(1) Element	(2) Major Use	(3) Weight Fractions Non-Fuel Demandite (3)	(4) Apollo 15 Mare	(5) Enhancement Required (c)
Oxygen (O)		.4547	.4130	1.10
Silicon (Si)	Building Materials	.2444	.24158	1.13
Calcium (Ca)		.1417	.0696	2.0
Carbon (C)		.0574	.000095	604.0
Iron	Metals	.0479	.1535	0.31
Aluminum		.0023	.0546	0.042
Magnesium		.0017	.0681	0.025
(a)		.0020	.000022	90.0
(b)		.0030	.0189	0.16
Potassium (K)	Agriculture	.0021	.0008	2.6
Phosphorus (P)		.0019	.0005	3.8
Nitrogen (N)		.0083	.00008	103.0
Sodium (Na)	Chemical Processing Elements	.0095	.0023	4.1
Sulfur (S)		.0058	.0006	9.7
Chlorine (Cl)		.0147	.0000076	1934.0
Hydrogen (H)	Plastics	.0025	.00007	350.0
Totals		.99	1.0	

(a) Copper, zinc and lead

(b) Manganese, titanium, chromium, barium, fluorine, nickel, argon, tin, bromine, zirconium, and boron (mostly titanium and manganese in Column 4).

(c) The enhancements, especially for the minor elements, may vary considerably from one lunar landing site to another. H may be at lunar poles.

Reference (2)

body is proportional to the square of its velocity. Therefore, an object ejected from the surface of the earth must be given $(11.2/2.4)^2 = 22$ times as much energy as a similar object ejected from the moon.

COSTS OF ENERGY

Energy production costs money, and hardware to use the energy properly costs more money.

If one had a device which could take electricity at a rate of 25 mills/kw-hr and directly use this energy with 100 percent efficiency to propel payloads from the surface of the earth into space. then (ignoring the earth's atmosphere) it would cost only 4¢/kg to escape the earth. This corresponds to a cost of \$31 to eject a 70-kg person. Ejection costs from the moon would be approximately 5 percent of the earth cost for the same cost of energy, or 2¢/kg and \$1.40 for ejecting a 70-kg person.

EJECTING MATERIALS FROM THE MOON

It appears possible to build such a device to operate on the moon. The device is termed a mass driver and was first proposed for application to the moon by G. K. O'Neill.¹ The mass driver is a two-part electric motor stretched out into a straight line. The moving portion is a bucket surrounded by superconducting coils that receive accelerating forces from external power lines and levitate the bucket above an aluminum guideway, making possible extremely high velocities.

Much of the technology of the electric power industry is directly applicable to the device. Working models have been demonstrated, and the basic theory is well understood.^{4,5} Large-scale versions of the device are being developed in Germany and Japan for the next generation of high-speed ground transportation. A two-man test version operated by the Japan National Railways achieved 250 km/hr in mid-1978, and commercial operations are expected to start in the mid-1980s.⁶

Such a device cannot operate on the earth's surface to eject materials directly into space. Passage through the atmosphere would quickly reduce the velocity, and extremely intense heating of the payload would occur. The energy cost of launching payloads from the earth is increased greatly over the cost of the minimum energy required because a rocket must be used. Several penalties result. The rocket must be both large and strong enough to carry not only the payload but also the fuel necessary to lift the entire rocket and payload. If it is desirable to recover and reuse the rocket, then additional mass must be included in the form of reentry heat shields, extra structure to withstand reentry and the increased size of the system, and so on.

From a practical standpoint, these penalties are severe. High costs are associated with the complete systems. The space shuttle represents advanced technology applied to this problem.

Advanced Development Will Mean Reduced Cost

The shuttle will carry into orbit approximately 30,000 kg of payload but will have a lift-off weight of 2,000,000 kg including propellants. The payload represents 1.5 percent of the lift-off weight. Payloads will initially be delivered into orbit for \$600/kg. This rate should drop to \$100/kg as advanced shuttle derivatives come into operation.

These are significant decreases in unit costs over the \$2,000 to \$6,000/kg for present expendable launch vehicles. Costs to orbit can be expected to drop to \$15 to \$30/kg by the turn of the century, when large, completely reusable single-stage-to-orbit vehicles come into op-

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eration.⁷ It is also possible that a more exotic proposal to use ground-based lasers to power simple freight rockets into orbit could be translated into hardware.⁸

One thing is clear: Even with these advanced systems, the unit cost to achieve earth orbit or escape to deep space will be greater than the minimum energy cost by a factor of 30 to 100.

JUSTIFYING THE USE OF LUNAR MATERIAL

Several factors must be satisfied to justify using lunar material rather than only terrestrial feedstocks in space. Generally, the same considerations apply as in trade-offs between competing terrestrial industrial processes. A manned lunar base in which lunar soil is excavated, minimally processed and ejected from the moon must be developed and placed in service. This is comparable to finding and establishing a surface mine and transport system on earth. The lunar materials must be collected and delivered to a processing and fabrication facility in space, where they can be formed into feedstock for major projects.

The economic justification becomes easier as progressively larger tonnages of materials are required. In addition, the elements to be obtained from the moon must be adaptable to the major expected products. The cost per unit mass of chemically processing lunar materials must be low compared to the cost of transportation from earth. Finally, research and development of the operating systems and the period before a net economic profit is returned must be short enough that interest on the invested money does not prevent the space system from becoming profitable.

Attempts to meet these challenges can be justified for at least one product. Space power systems (SPS) are relatively large structures that have high intrinsic value and could justify a major space investment.

USES OF LUNAR MATERIALS IN LARGE QUANTITIES

Space power stations provide an appropriate model for the study of lunar materials' uses. Considerable work has gone into designing systems that could be placed in geosynchronous orbit and scaled to supply a steady stream of power to a terrestrial ground station with an electrical power output of 10,000 megawatts (10 GW). This is approximately 10 percent greater than the maximum electric output of the Grand Coulee Dam, the largest individual electrical installation in the United States.

Dimensions of a Solar-power Satellite

An SPS is projected to have a mass of 100,000 tons and, if constructed as a solar cell array, to have a length of 20 kilometers, a width of 3 to 5 kilometers and a thickness of several hundred meters.⁹ It would be composed of glass (solar cells, 52 percent), aluminum (wiring, 6.4 percent), graphite composite (structural members, 13 percent), copper and iron (wiring, wave guides and power units, 13 percent) and heat pipe and klystron components (7 percent).

These components can all be fabricated from functionally equivalent lunar materials.¹⁰ The remaining 10 percent will require terrestrial materials, at least for the particular systems designs presently available.

Size Comparisons

SPS dimensions appear astronomical until they are compared to the scale of engineering associated with Grand Coulee Dam or comparable nuclear installations. Grand Coulee is 1.3 kilometers long, 140 meters high and has a mass of 40,000,000 tons. This is 400 times as massive as the SPS unit.

SPS power will be beamed to the ground by microwave and intercepted by an antenna array 2 to 5 kilometers in radius. The sophisticated portion of the ground station is composed of millions of identical antenna and receiver units with a total mass of 5,000 tons. They must be emplaced in foundation or support structures, which will have an integral mass of about 2,000,000 tons.

Two million tons is similar to the mass of a nuclear power station of the same output. However, the individual foundation units can be simple compared to the extremely complex structure of a nuclear power station, which must provide radiation and pressure shielding and protect against natural catastrophe.

When comparing an SPS to Grand Coulee or a nuclear power station, one begins to be impressed less by its size than by its fantastically efficient use of matter in gathering and converting energy for use on earth or in space. Far less matter must be manipulated, restructured and emplaced in space to produce useful power on the ground than any other power scheme proposed to date.

This claim includes projected terrestrial solar power arrays, which must be six to fifteen times as large in area because of night and cloud cover to collect the same average energy flux; the arrays must also be more massive per unit of area to withstand the gravity and environmental conditions of earth.

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It is not unreasonable to expect further advances in the transmission of power to the ground. One possibility is to use lasers, which may reduce the size and cost of the receiver systems.¹¹

**THE GENERAL SCALE OF
SPS PRODUCTION**

An appreciation of the general scale of a space industry to produce SPS units can be gained by noting estimates that an SPS can be placed into operation for \$2-4/watt and produce power on the ground at 40-80 mills/kw-hour. Thus, a 10-GW SPS will represent an investment of \$200-400/kg.

This figure points out the need to obtain materials in space to work with at costs considerably below \$100/kg. It also indicates why more efficient boosters must be developed for terrestrially launched systems. A total United States market may be 100 to 200 units by the year 2020.¹² The total orbital mass for 200 SPS units would be less than half that of Grand Coulee. Thus, the total market might be \$2-4 trillion before replacement requirements dominate the industry.

Annual cash flows during the growth phase could be \$50-100 billion, comparable to expected expenditures by electric utilities in that period.

**The Materials Industry
Required in Space**

It is interesting to consider SPS production in terms of the materials industry that would be required in space.

To produce 100 SPS units (each with a 100,000-ton mass) between 1990 and 2020, an average 300,000 ton/year must be manipulated in space. Naturally, production would grow with time, and early and later annual production tonnage would move from less to greater than this average value. The figure is moderate by terrestrial standards, whether it includes simply gathering material in a mining operation or chemical processing and fabrication.

The low annual production tonnage makes obtaining the working materials from the moon seem especially possible. It should also reduce the amount of earth materials transported to space by a factor of 10 and possibly could reduce the size of terrestrial launch vehicles needed to provide the 10 percent or less of terrestrial materials for SPS. The launch rate of terrestrial vehicles would certainly be reduced, and economies in SPS production could occur.

LUNAR SUPPLY AND PROCESSING

Obtaining raw materials from the moon and processing them in space into industrial feedstocks are unique in-space operations. Even when materials are supplied from the earth, many must be shipped up as feedstock or semifinished goods to make optimal use of the supply rockets' cargo volumes.

A major study at the NASA-Ames Research Center in the summer of 1977 dealt with establishing a lunar supply base and processing the lunar materials in space and with space manufacturing facilities.¹³ Earlier technical and semipopular articles and texts also describe various aspects of the general approach.¹⁴

AN EXPLANATION OF THE GENERAL CONCEPT

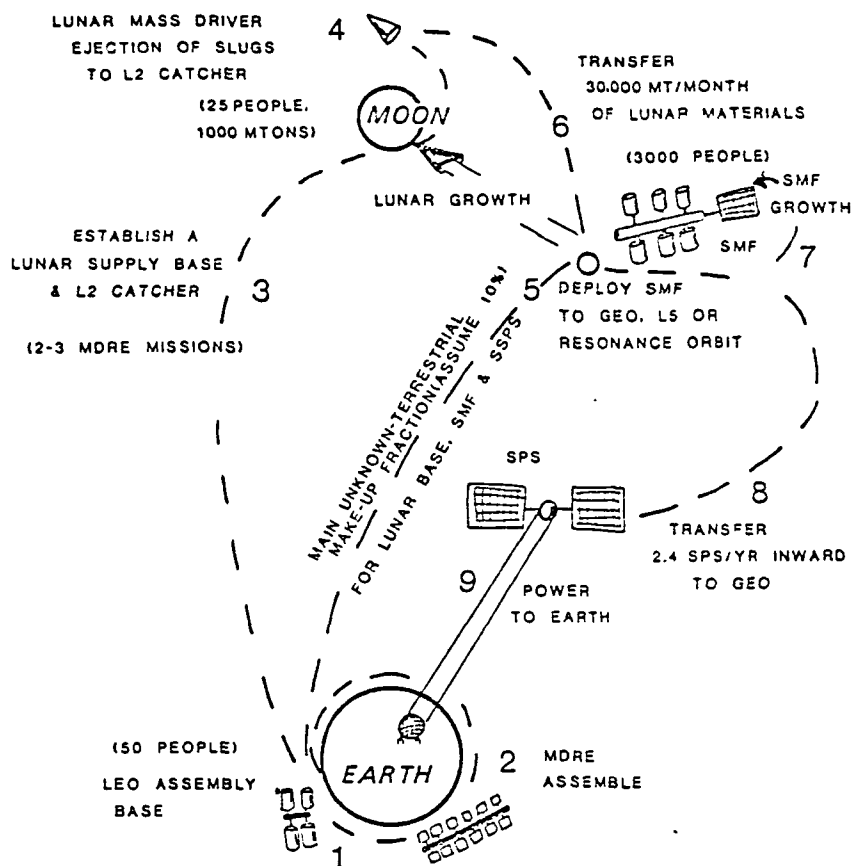
Figure 1 provides the general concept. The numbers indicate the sequence of major operations. Space shuttles would be used extensively in all phases. In the proposed timeline, an assembly base would be constructed in low earth orbit (1) where the first task would be to put together a solar-powered rocket engine based on the mass driver concept (2), called a mass driver reaction engine (MDRE).

This design's main advantage would be that it can generate rocket thrust by throwing out almost any available material rather than requiring specially prepared propellants. Thus, in the initial flights to the moon the MDRE could use aluminum powder produced by grinding up the belly tanks of the space shuttles. These tanks are nominally targeted to burn up in the atmosphere following detachment from the shuttle. However, only a small payload penalty is incurred if they are carried on into orbit.

Each tank has a useful mass of approximately 30,000 tons. A 1,000-ton lunar base is brought in sections from earth to the LEO station, assembled in subunits and moved from low earth orbit to low lunar orbit in two MDRE (3) missions to the moon. Chemical rockets then deliver the construction crew to lunar orbit and transport the base subsections and crew to the lunar surface.

Twenty-five people will be required to place the base into operation over a four-month period. The MDRE will reposition itself at the L2 point, a region of gravitational equilibrium approximately 60,000 kilometers behind the moon, and catch 2,000 tons of lunar soil (4). A portion of the soil will be used as reaction mass for return to earth and another portion as payload.

Figure 1
Lunar Approach



During deployment and construction of the lunar base, the initial small space manufacturing facility (SMF) is assembled as subunits in low earth orbit and then transported to geosynchronous (GEO) orbit or higher by the MDRE (5). The initial SMF will be operated by about 200 people and will be scaled to process 30,000 tons/year of lunar soil (6).

Major tasks of the SMF during the first five-year period will be to build up the capacity of the lunar base (7) by manufacturing additional solar cells to power the lunar mass driver, to provide solar cells and living and production volumes for expansion of the SMF and to construct the first full-size SPS (8).

Terrestrial Mining: A Small Start

The initial lunar base would be a small operation by terrestrial mining standards. Only one small excavator, similar to a backhoe, would be required to operate part-time to gather the 30,000 tons/year of soil needed the first two years. The crew would increase from 10 to 20 people as the ejection rate of lunar soil rose to 300,000 to 700,000 tons/year and the excavation fleet increased to five ten-ton capacity vehicles each.

The original mass driver was designed to accommodate the mature ejection rate, and only additional power is needed to upgrade it. The lunar mass driver would have a total mass of 250 tons and consist of a 300-meter-long acceleration section and 2 km of passive guideways and return track.

A Soil Bucket's Path

The semiprocessed lunar soil would be packaged in 5 to 10 kg units, placed in superconducting buckets and accelerated at 1,000 earth gravities to lunar escape velocity. When a bucket is decelerated, the soil packet is ejected and the bucket returned to a loading facility for reuse. The soil packet coasts downrange through two electrostatic aiming stations; it then follows a ballistic trajectory approximately 60,000 kilometers long to the collecting point at L2.

Orbital analysis indicates that each payload can be made to follow the path of the adjacent payloads and that a stream of soil units can be targeted to pass within a few centimeters of a given target trajectory in the vicinity of L2. A catcher unit approximately 100 meters in diameter can then collect a long string of the soil packets and deliver the collected soil to the SMF.

Cost Estimate for The Ames Proposal

A preliminary estimate of the cost of the scenario proposed at Ames has been done.¹⁴ It indicates that one-time research and development will cost about \$20 billion and that the lunar and SMF installations will require \$40 billion for emplacement and operation over a 10-year program starting in 1985. Lunar soil would be delivered to the SMF at a cost of \$20-25/kg.

Clearly, much more detail is required, but the initial estimates indicate that the concept is worth further investigation. This expenditure would be comparable to that projected for terrestrial deployment of the first SPS.

SIGNIFICANT QUALITATIVE CONSIDERATIONS

A fundamental, pragmatic objection to this approach is based on many years of experience developing major industrial complexes on earth: It is extremely difficult and expensive to develop a mature industrial installation from the concept phase through research and development, prototype proof, construction and debugging in less than 12 to 18 years. Thus, there is an automatic tendency to assume that any use of lunar materials would have to be confined to late in this century or early in the next.

This would not necessarily be the case. Key factors are *the scale of the material operations involved, the economic context of space operations and our knowledge of certain areas of the moon gained during and after the Apollo project.*

Prototype Development

Large industrial facilities on earth generally are scaled to process up to tens of millions of tons of material per year. Enormous efforts ensure that the final plant will operate as planned. Before a final commitment is made to spend billions of dollars to construct the final facility, approximately 1 to 5 percent of that amount is spent in constructing prototype units, which operate at approximately 0.1 to 1 percent of the final throughput rate. These prototype units are normally scaled to inputs of 10,000 to 100,000 tons/year.

Developments and modifications are expected to occur during the prototype stage. Even the output of terrestrial prototype plants has economic significance, though this is unusual and probably confined to new product (market) endeavors. The time scale for prototype development is more often on the order of three to eight years than twelve to eighteen; this is especially relevant to early space manufacturing.

The scale of manufacturing expected during the development phase of SPS production (about 100,000 tons/year) is more in line with prototype operations on earth than with full-scale industrial production. The chemical processing systems can be operating in the 1980s in space. Adequate time is available to scale the prototype systems up to the 300,000 to 700,000 tons/year required for SPS production; this is modest in comparison to terrestrial annual production tonnages. Thus, traditionally long start-up times needn't consign the use of lunar materials to the twenty-first century. Further, the laboratory scale of industrial process development can proceed even faster.

The Commercial Environment For Lunar Material

The earth's competitive commercial environment also produced long development cycles for large industrial installations because the final factory or plant can often be made only slightly more efficient than competing processes. However, early in-space processing operations and lunar supply bases will compete with the cost of launching materials from earth.

As noted, the initial cost per kilogram of processed lunar material should be equal to or slightly better than advanced launch vehicles. As experience is gained in space operations and more of the space products used for internal growth of the space industry, unit costs should steadily decrease to only a few times greater than the cost of the launch energy.

Sufficient Information To Design Hardware

Finally, the Apollo program and extremely careful analysis of samples and data returned from the moon provide us with sufficient information to design chemical processing hardware for the soils found at the last three Apollo landing sites. It is not necessary to return to the moon to obtain additional materials for proving out chemical or thermal processing schemes for lunar soil, which can be synthesized for testing purposes.

We also know enough about the moon to begin detailed planning of an efficient lunar site reconnaissance program using unmanned orbital and surface vehicles. These would survey, select and confirm the suitability of a future mining site by the time it would be needed in the mid-1980s.

Processing Anorthite

Recent process engineering research has identified two schemes for obtaining aluminum, oxygen and silicon from a major lunar mineral, anorthite. Both schemes employ hydrometallurgical processes. One option, *hydrogen fluoride dissolution* of anorthite, involves only low-pressure liquid systems. These minimize plant mass and solve the problems of reusing working fluids and maximizing the fraction of new plants that can be built from lunar materials. Ion exchange membranes also appear able to separate pure oxides of the lunar material with minimum complexity.

Electrolytic techniques appear applicable to separating oxides into their component elements; they may also be adaptable to the direct separation of certain lunar minerals into their elements in one step.

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requiring only electricity and only a small amount of working fluids.¹⁵

The hydrogen fluoride process has been examined in sufficient detail to allow the conceptual design of a plant that would operate in space. A prototype plant capable of processing 30,000 tons/year of anorthite with approximately 98 percent production efficiency with the constituent elements aluminum, silicon, oxygen and calcium would have a mass of 300 tons. It could be deployed into low earth orbit by 20 flights of the space shuttle and would require a crew of about 20 during the checkout period.

Especially significant is the fact that this plant mass is directly proportional to the annual throughput mass. Thus, even smaller versions could be deployed at an earlier time in space or on the moon to check out the entire operation and to produce useful materials. A smaller unit could be flown in a single shuttle mission and could process 500 to 1,000 tons/year of lunar materials.

**Other Minerals
From the Moon**

Other minerals commonly available on the moon may lend themselves even more readily to space processing. Ilmenite—a source of iron, titanium, and oxygen can be separated into its constituent elements. An ilmenite plant might be simpler and less massive than one designed for anorthite processing.

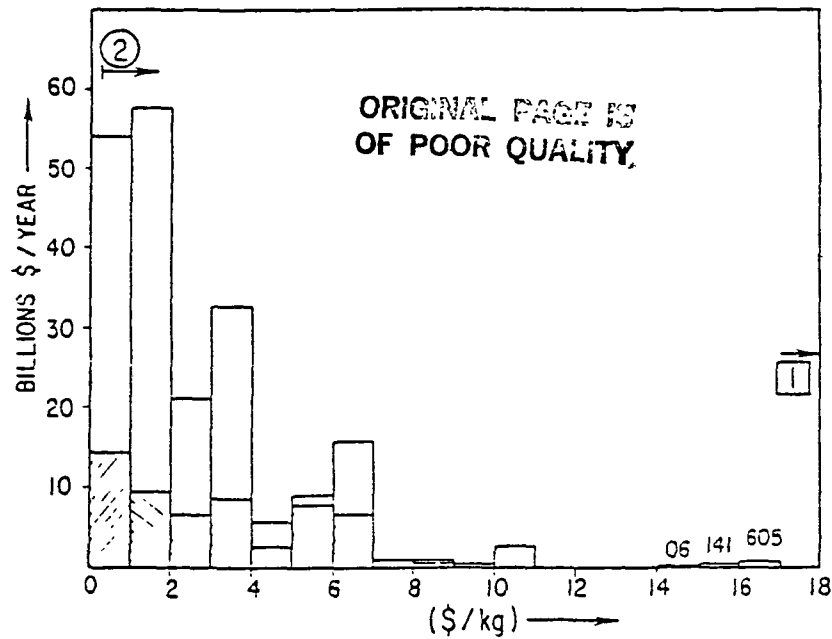
Even the limited studies completed so far indicate that many well-understood techniques for processing terrestrial elements (but not presently in large-scale use due to slight economic disadvantages) can be applied to producing industrial feedstock in space from lunar materials. The problem is to survey the broad range of options and select the most promising ones to develop for the space and lunar environment. Processing in space should cost approximately two to three times the unit cost for similar terrestrial products.

MATURING SPACE INDUSTRIES

Figure 2 provides a general view of the economy of the United States in 1972 and the potential for goods produced in space to find significant markets on earth or to contribute to the creation of economic loops in space similar to those on earth.

This histogram shows the total sales value in billions of dollars each year (vertical axis) versus the cost of producing the goods on a dollars per kilogram (kg) basis (horizontal axis). This was done by determining the value added in 230 Standard Industrial Categories (SIC) in

Figure 2
Potential of Goods Produced in Space



1972.¹⁶ Two general classes of SICs are included: those in which products are composed of elements that can be largely obtained from lunar materials and for which there may be advantages to working in space with either solar thermal or solar electrical power. The SICs include electrometallurgy, glass, ceramic, light and specialty metal working, and fabrication and electronics. These 64 SICs are indicated by the cross-hatched portions of the histogram.

The clear upper portion of each bar in the histogram includes products that contain elements not readily available at the lunar landing sites, which may be available from a special class of asteroids which cross the orbit of the earth and are thought to be retrievable into orbit about the earth at initial costs on the order of \$20/kg.¹⁷

There are 166 SICs in this group, including—pyrometallurgy, rolled or forged steel products, copper, zinc or lead products, industrial chemicals, plastics, textiles and concrete products. Also included are impure fabricated final products such as appliances and vehicles. Excluded are 239 sectors related to agriculture, forestry, food, animals, fossil fuels, asphalt, and non-fuel petroleum products and service industries. All goods included in this histogram had a total value in 1972 of \$202 billion. The goods in the cross-hatched portions of each box had a total value of \$58 billion.

The histogram is deceptive in one very serious way. There are many goods in missiles, electronics and aircraft SICs that have \$/kg values much higher than shown here. However, these products are included with other, cheaper products in the SIC to produce the lower average value.

If a new SIC for space power stations is eventually included in this graph, it will initially be located between \$200 and \$400/kg (far off the right edge) and have a value of \$50-100 billion a year. A new SIC for lunar mining would also be introduced at the right edge of the graph (approximately \$20/kg) that would have an annual output value of \$2-4 billion (note point (1) in Figure 1).

COST OF LUNAR MATERIALS EXPECTED TO DROP

The intrinsic cost (\$/kg) of lunar materials should drop radically as other markets that require large masses of materials are developed. As this happens, the cost in space of lunar materials should eventually approach the cost of ejecting them from the moon.

We noted that the lunar ejection cost could be a few cents per kilogram (.02/kg). This corresponds to point (2) in Figure 2 and implies that approximately 10-15 percent of the present SICs might eventually contain lunar components for use either terrestrially or in space. As a broader range of feedstock elements become available through asteroid resources, additional lunar resources or substitution of materials, most of the SIC shown in Figure 2 could be penetrated by extraterrestrial materials.

However, this historical approach to possible market potential should not distract us from the example provided by the space power systems. New and exotic products and new standard industrial categories for space enterprises will develop, and the products can be made relatively inexpensive as we learn to obtain extraterrestrial raw materials at low unit costs approaching the cost of Demandite (Table 1).

A drop of 1,000 percent in the cost of lunar materials, from \$20/kg to \$.02/kg, may seem rather dramatic unless one realizes that the 380-kg lunar materials returned during the \$25-billion Apollo program could be said to cost approximately \$66 million/kg. There is every reason to think basic cost-reducing feedbacks made possible when mass production is used to meet the needs of mass markets can operate in space as they have on earth for 400 years. Learning curve experience will permit industry to continually drop unit prices.

PUBLIC AND PRIVATE ROLES

Possible roles of private and public enterprises will be heavily influ-

enced by whether a single nation spearheads the growth of space industries or it is pursued as an international effort.

The required scale of investment for research, development and facilities is near the limit of resources that a consortium of large corporations could assemble; this was done for the development of the Alaskan North Slope petroleum reserves. Thus, it is likely that public resources will be used to at least establish the materials supply and the first industrial space park and to ensure various enterprises a period of stable development.

Because the moon is highly visible to all, space law as applied to lunar resources has already received considerable attention in the United Nations.¹⁸ Analogies are often drawn between lunar and seabottom resources.

CONCLUSION

The space power system concept affords the United States' public and private components an especially intriguing opportunity. This nation alone now has the combination of technical expertise in manned space and lunar operations and worldwide economic ties to quickly develop lunar resources and space energy systems and market the energy produced on a national and international level.

This non-polluting source of energy would be extremely valuable to the economies of the developed and underdeveloped nations and could release vast tonnages of petroleum for use as feedstock to the chemical industries. It would be exceedingly difficult for significant competition to develop once economies of scale come into play in space manufacturing as the productive capacity in space increases through use of lunar and, eventually, asteroidal materials.

The opportunity is clearly transitory, because once a commitment is made to use extraterrestrial materials for manufacturing the entire range of skills of an industrial society can be applied to enhancing the growth of the in-space enterprises. There is no single link (for example, earth-to-earth-orbit transportation) that could restrict the growth rate of the combined materials and service segments of the economy.

FOOTNOTES

*This article is the result of work performed at the Lunar and Planetary Institute, which is operated by the Universities Space Research Association under contract number NAS 09-051-001 from the National Aeronautics and Space Administration. This is Lunar and Planetary Institute Contribution Number 344.

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Electrostatic beneficiation of ores on the moon surface

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Abstract. A review of the electrostatic separation processes, the lunar environment as it may affect the techniques, and the data available for two of the important lunar ores – anorthite and ilmenite, points to the lunar environment as being about as ideal as one could imagine for the use of such beneficiation techniques for all types of ores, both magnetic and non-magnetic.

(i) A large amount of the lunar soil is already in fine particulate form suitable for electrostatic processing.

(ii) The observation of the lunar horizon glow and of the motion of the soil grains about the sunset and sunrise terminators of the moon indicate strong electrification properties of the dust.

(iii) The vacuum conditions eliminate the problem of air turbulence entrainment of the very fine particles.

(iv) The low temperature and the absence of water lead to perfect conditions for tribo-electrification.

1. General

Subsequent to the considerable effort put into the exploration of the moon and towards the advancement of man's knowledge of space, the utilisation of extraterrestrial materials, and in particular lunar materials, for industrial purposes in space and the creation of large manned facilities, is now within the range of terrestrial technology (O'Neill 1974, 1975). Among the many contemplated space projects, space solar power stations (SSPS) (to beam power by microwaves to earth and alleviate future energy problems) offer a great immediate incentive.

The construction of such space industries and large habitats would be prohibitively expensive if all materials were to come from earth. The moon and space asteroids offer far more attractive solutions. Based on 1975 estimates (Criswell 1975), the transportation cost of a unit mass of material from the moon to a point in deep space such as the L-5 Lagrangian sphere in the earth/moon system is fifty times less than the corresponding cost of launching the same mass from earth.

Among the thousands of tons of various materials required for building an SSPS, aluminium and silicon are currently considered to involve the largest mass. In addition, other materials will be necessary, such as iron, titanium, oxygen, silica, and a substantial mass for shielding people in deep space habitats.

Following the Apollo explorations of the lunar highlands and maria, the following basic elements, available in the lunar soils, have been identified for possible extraction from soil and rocks:

- (i) seven major elements: Si, Al, O, Mg, Fe, Ca and Ti;
- (ii) six minor elements: Cr, Mn, Na, K, S and P;
- (iii) a few trace elements: H, He, C and N.

From an analysis of various soil samples (less than 1 mm fraction) it has been reported (Criswell 1975) that Al_2O_3 is in substantial concentration in the highlands, SiO_2 is present both in the maria and the highlands, and TiO_2 and FeO are found primarily in the maria.

Electrostatic beneficiation of specific fractions of lunar soils at a mining site offers several valuable advantages. The total number and mass of trucks, conveyors or other devices necessary to transport material from the mine to a central processing facility or launching area can be significantly reduced. Raw feed stocks can be beneficiated to optimal or constant compositions for particular end uses or processing constraints (Waldron 1979). Valuable soil components available at remote locations could be extracted *in situ* and economically transported to a central plant as separate operations.

The vacuum of the outer space and on the moon presents an ideal environment for any electrostatic beneficiation scheme. In such an environment, concepts and ideas which were discarded in the past for earth-based technologies as being economically unjustifiable or too idealistic can now come to light.

Electrostatic separation takes advantage of the natural state of the bulk lunar soil which is that of a finely divided powder with an average grain size of 45–100 μm . It is known by optical observations and direct measurements that electrostatically driven motion of lunar dust does occur due to natural processes which operate rather inefficiently (De and Criswell 1977). Experiments on earth with returned lunar samples, and future *in situ* experiments with small unmanned or manned equipment, can be expected to produce compact, low power beneficiation equipment which will reduce the size of future lunar mining operations and greatly increase the economic value of lunar soils as ores.

2. Electrostatic separation

At the base of any electrostatic separation or beneficiation process for finely divided matter is the interaction between an external electric field and the electric charges acquired by the various particles. In any such processes the external electric field can be easily produced and controlled, whereas the selective charging of the particles to be separated usually requires most of the development effort prior to the building of an industrial installation.

A review of what is known of the environmental conditions on the moon and of the lunar soils and their electrical and magnetic properties, indicates three types of selective electrification processes which will very likely find application in a manufacturing complex:

- (i) tribo-electrification (Incelet and Wituschek 1967, Incelet and Greason 1971);

- (ii) conductive induction (Lawver and Dyrenforth 1973);
- (iii) electron bombardment from heated cathodes in the space vacuum in combination with a conductive discharge (Lawver and Dyrenforth 1973).

Tribo-electrification generates both positively and negatively charged particles, whereas the particle charges produced by conductive induction or electron bombardment are generally of one polarity in a particular installation.

Once the particles are charged selectively, and assuming that they are allowed to fall freely under gravity forces in an applied horizontal, electric field, they will acquire a horizontal acceleration proportional to its charge to mass ratio and to the intensity of the electric field. In case of the unipolar charges produced by conductive induction and/or electron bombardment, the separation is based primarily on the difference in the electrical conductivities of the materials at the time of processing.

In addition to the absence of air turbulence entrainment forces, an important advantage of beneficiation in vacuum is the intensity of the electric field which may be applied. Whereas in air, the electric field intensities are generally less than 30 kV cm^{-1} , in the high vacuum of the outer space the field could be raised to 300 kV cm^{-1} or more.

It is of interest to note that when charged particles are placed in a uniform electric field, the distortion of the field produced by the concentration of the field lines on the particles results in an enhancement of the resultant forces (Inculet 1978).

3. Current expectations for the effectiveness of the electrostatic beneficiation of ores on the moon surface

Generally, in any estimate of an electrostatic beneficiation scheme it is necessary to consider the following data:

- (i) the frequency distribution of the content percentage of the sought mineral in discrete particles for the entire particle-size spectrum in the ore.
- (ii) the tribo-electrification and conductive induction properties of the various particle forming the ore to be processed.

The size of the particles in the lunar soils is in an ideal range for electrostatic beneficiation (Handbook of Lunar Materials 1978). The mean grain size of lunar soils ranges from 40 to $802 \mu\text{m}$ with most falling between 45 and $100 \mu\text{m}$ as seen in figure 1.

For a conjectured estimate of what could be achieved electrostatically in the moon environment, with the moon soils, two minerals have been chosen – anorthite and ilmenite. The two minerals are of major interest as raw materials for chemical production of aluminium, silicon, titanium, iron and oxygen. Although the frequency distribution of the anorthite and ilmenite content percentage in discrete particles is not yet fully documented for all size ranges of particles in the various lunar ores, some assumptions could be made on the basis of what is already available.

At this time there are no earth data for the tribo-electrification and conductive induction properties which could be used for the lunar soils at different temperatures. As a mono-molecular layer of gas adsorbed on the surface of a material is sufficient to substantially change the workfunction of that material, none of the existing data on earth minerals are usable.

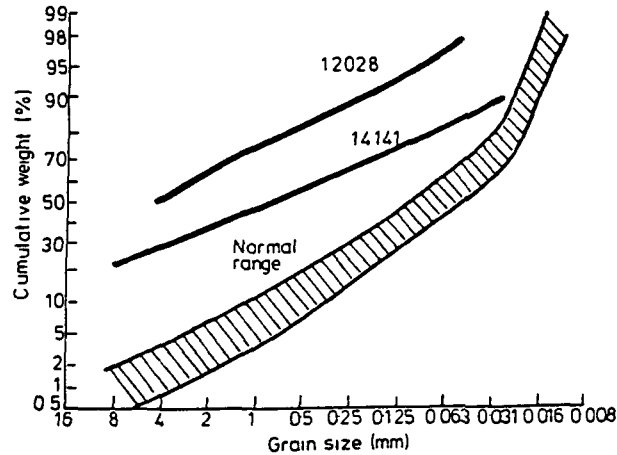


Figure 1. Cumulative grain size distribution for lunar soils. Most soils lie within the envelope. Two particularly coarse soils are also shown. NASA Photo S-76-30404.

However, considering that the lunar environment is an ideal environment for an electrostatic beneficiation process, that is it provides:

- (i) vacuum,
- (ii) low temperature,
- (iii) the gravity acceleration one-sixth of that at the earth's surface,

there is every reason to be optimistic that the efficiencies of beneficiation of the lunar ores (both magnetic and non-magnetic) will surpass anything that is currently achieved in the processing of millions of tons of ore in various facilities on earth.

3.1. Anorthite ($CaAl_2Si_2O_8$)

Anorthite is considered to be the lunar aluminium ore, with silicon and oxygen as by-products.

By weight percentage, the anorthite elements are: 19.4 aluminium; 20.2 silicon; 14.4 calcium; 46.0 oxygen.

Based on the analyses of Al_2O_3 content in the various lunar soils, and assuming a normative percentage of 36.6 for anorthite, it has been estimated that certain soils in the highlands of the moon contain an average 60% of anorthite, whereas in the maria the average anorthite content is 35%.

Let us consider the analyses of the sixteen samples from the Apollo 16 mission which are reported by McKay and Williams (1979). For the 90–150 μm particle size range, if one takes only those discrete grains of anorthite ore which have greater than 90% purity, they represent 43.5% of the ore processed for beneficiation.

In addition to the pure anorthite grains, the anorthite mineral is also distributed in a smaller percentage content in the remainder of the particles.

On the basis of these samples, and assuming the total anorthite content in the lunar highlands to be 60%, one could draw the beneficiation curves shown in figure 2.

Electrostatic beneficiation of lunar ores

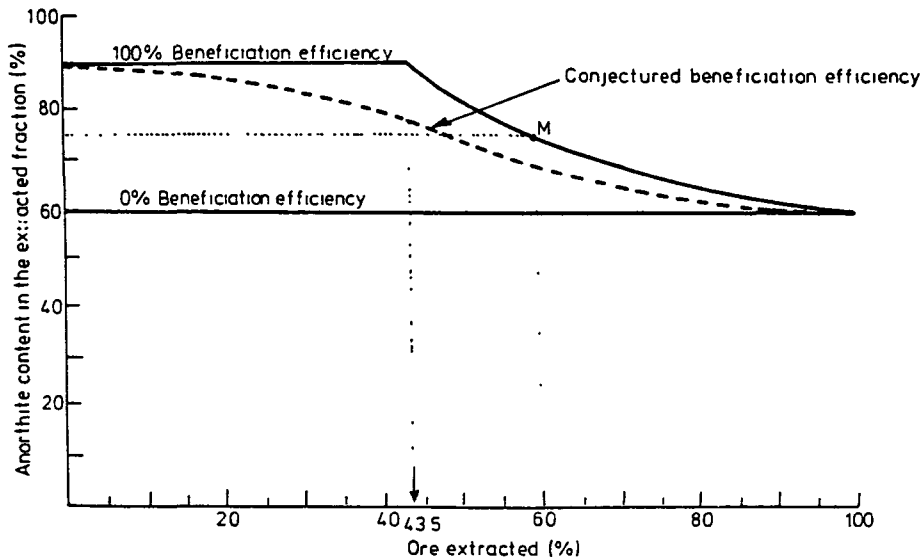


Figure 2 Electrostatic beneficiation of anorthite (90–150 μm fraction) from lunar highlands (Apollo 16 Samples).

The horizontal axis shows the percentage ore extracted defined as:

$$\frac{\text{total amount of ore extracted for future chemical processing}}{\text{total ore (after the coarse sieving) processed in the beneficiation plant or mobile units}}$$

The vertical axis represents the anorthite extract content defined as:

$$\frac{\text{total anorthite in the ore extracted}}{\text{total extracted ore}}$$

The top line represents the ideal case where the electrostatic unit could fully beneficiate the material. In such case, for example, by separating 43.5% of the material, one would obtain more than 90% pure anorthite. In the same ideal case, if one wanted to make use of 60% of the mined material, that amount of ore would have a total anorthite content of 75% (point M on the graph).

The horizontal lower line represents a completely ineffective electrostatic beneficiation.

The broken curve is what the real beneficiation may look like. This curve could only be estimated after the tribo-electrification and the conductive induction properties of the materials are known.

3.2. Ilmenite (FeTiO_3)

The type of ilmenite mineral found on the moon is considered to be, by earth's standards, an acceptable ore for producing titanium. It contains 31.6% titanium and 36.8% iron. It occurs in small amounts in highland rocks and is more abundant in the mare soils.

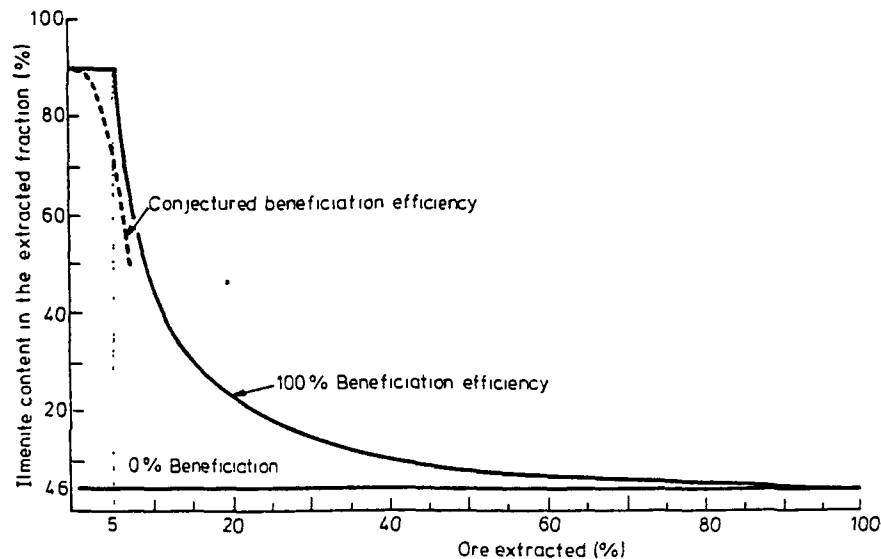


Figure 3. Electrostatic beneficiation of ilmenite (90–150 μm fraction) from lunar maria (Apollo 11 and 17 Samples).

It is estimated (McKay and Williams 1979) that the 90–150 μm fraction of the lunar regolith contains an average of 4.6% ilmenite, and that the same figure is representative of the whole soil.

From various studies it appears that using physical methods, 90% ilmenite concentrates are feasible from the mare soils.

Based on the above, figure 3 shows the possible ilmenite beneficiation curves.

4. Key studies necessary for a definitive evaluation of the applicability of electrostatic separation to lunar soils

Any definitive evaluation will require an in-depth study of:

- (i) the tribo-electrification
- (ii) the conductive induction charging and discharging.

The study must cover the surface properties of the particles in contact, and the factors affecting the charge transfer from particle to particle or from a conveyor surface to the particles.

In the space environment, where the particle surfaces have been conditioned for a very long time by vacuum, temperature and radiation, the only parameter necessary to be thoroughly investigated as to conditioning of such surfaces just prior to any electrostatic beneficiation process may be the temperature. Heating is one of the simplest means by which the energy structure of minerals can be modified.

By introducing radiant heating and also by making use of the temperature variation in the moon's soil from (a) day to night, and (b) from the lunar surface to the mining depth at the time of processing, one may be able to enhance the surface properties of the particles just prior to the electrostatic beneficiation.

An increase in temperature causes a shift in the Fermi-level towards the centre of the forbidden band, enhancing it in the p-type and lowering it in the n-type semiconductors (Carta *et al* 1974).

Heating processes in the earth's atmosphere are generally associated with a change in the relative humidity, in the amount of gases adsorbed by the particles' surfaces.

In the vacuum of outer space one could determine the true tribo-electrification and conductive induction effects generated by temperature changes, and any such studies will be universally valid and reproducible.

5. Conceptual design of a lunar facility for electrostatic beneficiation of ores

It is recommended that the electrostatic beneficiation of the various minerals be carried out with a combination of (mining and beneficiation) mobile units. A conceptual design of such a unit using tribo-electrification as the charging process is shown in figure 4.

Assuming that the lunar terrain is relatively flat, that the mined trench will be approximately 2 m deep and 2 m wide, and that the density of the ore is 1.8 kg dm^{-3} , a 30 ton h^{-1} processing unit will travel at a snail's pace of 4.2 m per hour. The material lifted by the sideloader on to the vibratory screen and conveyor is coarse-sieved. The larger fragments fall back into the trench and the material to be processed goes on to the synton or travelling electric field feeder for the first stage processing in the beneficiation tower. The rejects from the first stage are directed back to the trench and the beneficiated material is lifted up again for a second stage tribo-electrification and processing tower. The final beneficiated material is assumed to be transported by fast moving vehicles to the chemical processing site.

In the mined trench there will be essentially three layers of waste material as shown in figure 4. With relocation of the various beneficiation stages there is no reason why the three waste layers could not be deposited back into the trench in a different order, or fed directly to a second mobile unit following from behind and designed to beneficiate a second mineral.

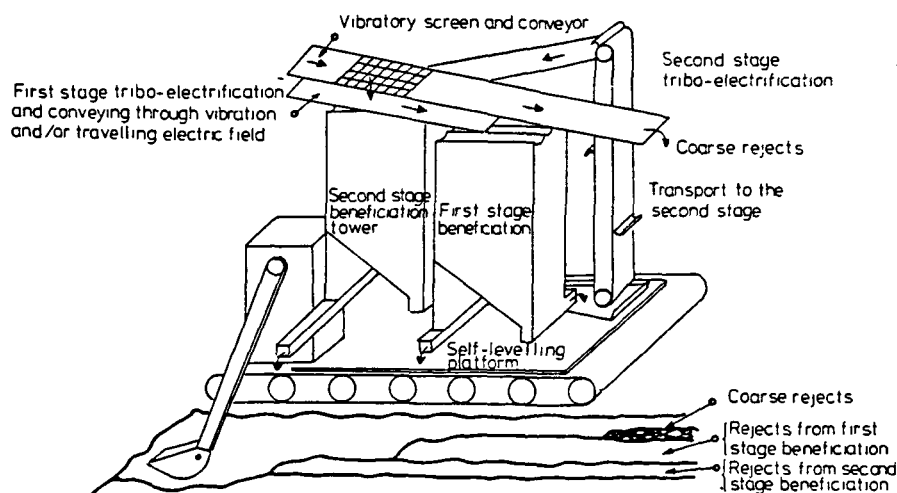


Figure 4. Conceptual design for a mobile unit for simultaneous mining and beneficiation of ores using tribo-electrification as the charging process.

6. Conclusions

(i) The lunar soil is already 'comminuted' in an ideal range for an electrostatic beneficiation of the minerals.

(ii) The lunar environment is about as ideal as one could imagine: (a) sustained high vacuum, (b) low temperature, (c) acceleration of gravity one-sixth of that of the earth's surface.

(iii) The soil may be used directly from the mining trench into the electrostatic beneficiation units. Only an initial coarse screening will be required prior to processing. The ore body being located on more or less flat surfaces and at the very surface of the moon, simultaneous mining and beneficiation may be feasible.

(iv) Three ways of electric charging of the lunar soils for electrostatic beneficiation appear attractive at this time: (a) tribo-electrification, (b) selective conductive induction charging, (c) heated cathode charging and selective conductive, induction discharging.

Acknowledgment

This work was carried out in part at the Lunar and Planetary Institute which is operated by the Universities Space Research Association under contract NSR-09-051-001 from the National Aeronautics and Space Administration. This is LPI Contribution #352.

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Discussion

J Taillet

Do we have a good predicted value of the breakdown field for the vacuum conditions at the surface of the moon?

I I Incullet

Breakdown fields at various vacuum levels and electrode configurations and materials may be found in the literature - however I do not know whether breakdown fields between

electrodes covered with moon dust could be predicted. For the industrial application dealt with in this paper, separation voltages ten times greater than in air, may be safely envisaged.

A C Rose-Innes

Production of the raw silicon is a minor part of the manufacture of solar cells. A factory to manufacture solar cells would include zone refiners, crystal pullers, diffusion furnaces, metal deposition units etc, and the weight of these and their power supplies would almost certainly be greater than the weight of the solar cells produced. In view of this, would it not be more efficient to make the solar cells on earth and transport them into space?

II Inculet

The lower gravitational forces, the vacuum which is already available, and an optimisation of the size of the manufacturing facilities for the production rate which will be necessary to keep pace with the overall completion schedule of the SSPS, will have to be thoroughly re-evaluated prior to a decision to produce the silicon crystals on the moon's surface in addition to the other essential elements such as aluminium, oxygen etc. . . .

Jan van Turnhout

On the moon it would be rather easy to charge the ore grains with an electron gun. This would give a well-defined charging. Would this type of charging be an attractive alternative to tribo-electric charging?

II Inculet

The idea has been considered; it will be a matter of cost and process reliability, whether to use a conductive induction or electron gun charging of the ore particles.

D K Davies

It is well established that the moon dusts are often highly charged by space (solar) radiation. Will this charge significantly influence beneficiation processes?

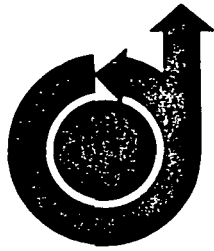
II Inculet

The radiation as a means of charging the lunar ores in a selective way ought to be investigated for both possible use and process control.

For the operation of the proposed beneficiation unit, the normal shielding offered by the structure will very likely be sufficient for retaining the dominance of the tribo-electrifications or of the conductive induction charging whichever is chosen for the process.

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Chapter X, D.



79-1390

Economic Considerations in Space Industrialization

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Reprinted from:

**4th PRINCETON/AIAA CONFERENCE
ON SPACE MANUFACTURING
FACILITIES**

May 14-17, 1979/Princeton, NJ

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ECONOMIC CONSIDERATIONS IN SPACE INDUSTRIALIZATION

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Abstract

The industrial categories of the United States economy are surveyed to identify those which can function using dominantly lunar raw materials or lunar derived feedstocks (LDF) and solar energy. Sixty-four standard industrial categories (SIC) appear to be compatible with LDF inputs; another 166 SIC's might be adaptable to LDF and space industry if substitution of materials and/or terrestrial supplements were introduced. Analytic tools are presented to use in deciding optimal strategies by which a generalized economy can be developed in space in an optimal manner within given constraints of capital, products derived at a given time, local production costs, cost of import from earth and other factors.

Standard Industrial Categories and Lunar Goods

Progressive development of a materials industry in space will depend on acquiring a source of relatively inexpensive material to process into suitable industrial feedstock for the construction of space power stations and other large and small products. Table 1 establishes that a large fraction of a space power station can be constructed from lunar native materials and chemically processed to make appropriate feedstocks. Given a source of bulk processed lunar materials for use in space, and eventually for import of special products to the earth, it is reasonable to first ask what goods in the present United States economy can be produced wholly or in part from lunar materials. The assumption is that the skill to make such goods is adaptable to space even if particular processes and goods are not. This viewpoint will provide a means of evaluating several possibilities:

- (1) Can significant fractions of the developed terrestrial industrial practices be transferred, with minimum research and development expenses, to space to build up a productive space economy?
- (2) What will be the qualitative effect on space industrial possibilities of sharply decreasing the intrinsic cost of obtaining lunar materials for use in cis-lunar space?

These questions are explored by

re-evaluating the total value (billions of dollars - B\$), average intrinsic value (\$/kg) and production energy of the goods outputs of 230 of the 484 Standard Industrial Categories (SIC) of the United States economy in 1967 and 1972. The 230 categories were selected on the basis that the relevant goods might be produced wholly or in part from lunar materials and/or there would be a savings in processing costs through the use of solar energy. The 230 SIC's were divided into two groups. The first group contained 64 SIC's which we deem *most likely* to be producible from lunar materials. Average intrinsic value of goods in these 64 SIC's in 1972 ranged from a high of 11 \$/kg (complete guided missiles) to a low of 0.251 \$/kg (primary aluminum SEC-281 95). Total shipped value of these goods in 1972 was 105 billion dollars, total value added to the products was 60 billion dollars, total consumed mass was 65 billion kilograms and total consumed energy of production was greater than 380 billion kilowatt hours. The cross-hatched bars in Fig. 1 show how the total shipped value of these goods was distributed on a \$/kg basis averaged over 1 \$/kg ranges.

Also shown in Fig. 1 are the clear (top) bars which depict the corresponding distribution of intrinsic value (\$/kg) averaged over 1 \$/kg intervals of 166 SIC's which are deemed *less likely* to be produced wholly or in part from lunar materials (see reference 2 for a detailed listing of these goods). Total shipped value in 1972 of the goods was 310 billion dollars, total value added was 144 billion dollars, total processed mass was 1,577 billion kilograms and total consumed energy was greater than 1,420 billion kilowatt hours.

To the best of our knowledge this is the first time that the value of material goods across a wide range of industries has been examined in this manner. As such, the results are of intrinsic qualitative interest from a terrestrial economic standpoint. It would be interesting to know the long term trends of intrinsic costs and total mass and energy of terrestrial goods. Conversely, the examination of relevant SIC's will provide some indication of what available industrial technologies could be transferred from the earth into space with minimum research and development costs. This approach will also offer a means of identifying which industrial space opera-

tions and practices must be examined in terms of finding alternate materials and/or processes. For example, concrete is the basis of much of the construction industry, but requires massive use of water. In space, glass, ceramics and fiberglass may be evolved to functionally replace concrete.

Successful development of a cis-lunar space economy in the coming decades depends upon rapid development of viable internal and "export" industries to provide an economic justification for the initial investments for each venture. Long-run benefits such as building bases that may play a role in connection with hypothetical future exploration and exploitation of the asteroid belt or the other planets of our solar system must be examined carefully. They may be discounted so heavily as to contribute very little to the benefit side of a current cost-benefit evaluation if long lead times are required.

By definition viable internal or export industries in space must compete successfully with the comparable activity on earth with consideration of up and/or down transport costs. Specifically, production costs must be enough lower in space to compensate for added transportation costs including both acquisition of the raw materials and finished goods transport. Lower production costs may be achievable for any one of a variety of reasons, including the following:

- no grinding of raw materials required
- cheap energy from the sun
- cheap sources of certain bulk materials (from the moon)
- lack of gravity
- cheap vacuum
- cheap means of disposal of waste products

These potential advantages appear to point toward certain industries where one or more of the advantages of a location in space are matched by corresponding disadvantages of earth. For instance, one immediately thinks of

- manufacture of high quality ceramics
- manufacture of high quality glass products
- electrometallurgical processes
- electrochemical processes
- high precision metal-forming
- semi-conductor synthetic gem manufacturing
- micro-electronics
- uranium or plutonium reprocessing

However, while one can make plausible qualitative arguments for some of the above, much more detailed and quantitative analysis is needed to establish even a preliminary case for undertaking major investments. The first step is necessary to ascertain, for all candidate industries, the likely transport costs for both inputs and outputs — which means the mass — in relation to the economic worth of the product. Hence, it is helpful to character-

ize each industry in terms of its average product value per unit mass of inputs (\$/kg). This task (among others) is undertaken in the present paper.

Selection Criteria of Standard Industrial Categories

It will be obvious on reflection that dollar value per kilogram of output is not by itself a sufficient measure. To take a trivial example, industrial diamonds have a very high price (per unit weight), but are unlikely to be found on the moon. Nor is diamond synthesis a plausible activity for a space industry, since the known process (General Electric Co.) involves a combination of ultra high pressures and temperatures that requires very massive production equipment. In this case gravity is not a clear disadvantage.

It is important to consider the source of the inputs to each activity. The standard way of minimizing transport costs on earth is to co-locate producers and consumers of massive or bulky intermediate materials. Thus, rolling mills are co-located with steel furnaces which are almost invariably co-located with blast furnaces, coke ovens and ore sintering plants. So integrated is the iron and steel industry that most of these processes are conventionally lumped together into a single Standard Industrial Category (SIC 3312). But the same principle holds much more generally. For instance, it would usually make no sense to produce a casting of alloy steel on the earth, ship it to a machine shop in space for grinding to specs, and then ship it back to an assembly plant on earth. Nor would it make sense to make paper on earth, ship it to space for printing, and back to earth for binding into books, and so on.

One can exclude as export possibilities lunar based industries for which the bulk of their raw materials *must* come from the earth. To first order, this criterion eliminates as export industries based exclusively on earth materials, all food-processing industries, wood or paper products, tobacco, cotton, wool, and leather products, and fossil fuels *per se*. However, these industries are not eliminated for significant roles in closed loop space industries.

Fossil fuels constitute another complication. Space industry will utilize available solar heat or solar electricity. In principle, energy should be available (and cheap) in space. But familiar solid and liquid hydrocarbon fuels would have to be synthesized from their constituent elements transported from the moon or partially from earth. This will clearly drive up process costs. Consequently, a number of basic industrial processes could not be carried out in a lunar or space environment as they are on earth. One obvious example is the reduction of iron-ore to iron in a blast-furnace, using coke (a form of carbon) as a reductant. The

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newer so-called "direct reduction" processes using coal or natural gas would equally be excluded. Copper, lead, and zinc are also conventionally reduced from oxide ores by similar means. Adoption of these traditional terrestrial processes will require the development of capture and recycle loops for the working fluids. Detailed work is available on applicable processing techniques.³

In the distant future such devices as the plasmarc⁴ may offer promise, but the technology is hardly likely to be applied on an industrial scale until fusion power itself is more fully developed. Electro-metallurgy is a very attractive approach and is being explored for terrestrial use and will be applicable to space operations (Haskin and Lindstrom, this proceedings). Hydrogen is intrinsically scarce in the low latitude soils of the lunar surface and consequently may have to be imported or extracted from dilute lunar reserves.⁵ Open-loop hydrometallurgical processes (acid or alkali leach) can be ruled out of contention because the chemical reagents would also have to be manufactured on site, requiring water. The most direct method of obtaining ferrous metals on the lunar surface is by magnetic separation of metallic iron particles from the regolith.⁶ This reduced material could be further refined to ferroalloys by vacuum melting (with hydrogen recovery). The most plausible means of reduction would seem to be electrolytic cells. However the further metallurgical processes required to manufacture carbon or alloy steel and steel products have not yet been defined, still less developed.

If a steel industry develops on the moon, it may be limited for a long time to the production of alloy steel castings for local use. Low carbon steels suitable for rolling into structural shapes, plate, wire rods, strip, shelp (for pipe and tube) or sheet, are normally produced mainly from pig iron (blast furnace output), obtained from high-grade sintered or pelletized ores, free from ferrous or other metallic impurities. The metallic iron found on the moon is associated with nickel and cobalt, which are extremely difficult to separate.

For the heavier major metals (copper, nickel, zinc, lead) the technology of acid- or alkali-leaching is fairly well-advanced and is becoming competitive in some cases with the older pyrometallurgical processes. Final refining is normally electrolytic. This means of extraction could be implemented in a lunar environment, providing suitable ores were found. However, many of the geochemical processes that have produced economically exploitable ore-bodies on the surface of the earth, have not operated on the moon. Further exploration will be required if suitable sources of these metals are to be found on the lunar surface.

As regards light metals, the regolith

contains substantial fractions (non-hydrated) of alumina (Al_2O_3), silica (SiO_2), iron, calcium and magnesium oxides, and titanium dioxide (TiO_2). The problem is one of efficient physical or chemical separation with minimal water consumption^(3 and Waldron *et al.*, this proceedings). In a lunar or space environment all solvents and most reagents would have to be recycled with very little loss, and further research will be required to overcome difficulties one can expect to encounter.⁷

Nevertheless, since alumina and silica are indubitably present in vast quantities on the moon, it seems reasonable to assume that suitable processes for separating them will be available. Some non-metallic structural materials, notably concrete (based on portland cement) and plaster-of-paris, are unlikely to have any application in a lunar or space environment, since they depend upon a hydration reaction — which means a large amount of water (H_2O) is embodied in the final product. Presumably we can, therefore, rule out all industries based on the use of these traditional materials.

What about chemical products? Organic chemicals are conventionally derived from fossil hydrocarbons, or cellulose. These raw materials are readily available on the earth's surface while hydrogen (at least) is very scarce on the moon. Such limited amounts of hydrogen as can be extracted from lunar soil will most likely be required to make up agricultural and process water losses. Inorganic chemicals are manufactured principally from the following raw materials:

- sodium chloride ($NaCl$)
- potassium chloride (KCl)
- limestone ($CaCO_3$)
- dolomite ($MgCO_3 \cdot CaCO_3$)
- trona ($NaCO_3$)
- sulfur (S)
- fluorspar (CaF_2)
- alumina, from bauxite (Al_2O_3)
- phosphate rock [$Ca_{10}(PO_4)^{3/12}(CO_3)_{6+}$,
(F,OH,Cl)₂]
- silica
- natural gas
- atmospheric nitrogen

Most of these substances are concentrated on the earth's surface by biogeochemical processes — especially associated with the water cycle — that have no counterparts on the moon. For example, the chlorides (salts) accumulate in the oceans by virtue of their extraordinary solubility in water. They are mostly extracted from brines or evaporite deposits. Natural sodium carbonate (trona), as well as magnesium salts, borates and other salts are also obtained from brines or evaporites. Calcium carbonate minerals are obtained from brines or evaporites. Calcium carbonate minerals are obtained from ancient sedimentary deposits (oyster shell, coral) or inorganic precipitate deposits from super-saturated ground water. Fluorspar is often

associated with contact metamorphic zones, a replacement for calcite.⁷ It is increasingly being recovered as a by-product of phosphate rock. Most phosphate rock deposits also originate from phosphates dissolved in and precipitated from ocean water — upgraded in many cases by secondary leaching processes.⁸ Most of the natural sulfur deposits currently being mined are associated with evaporite deposits (salt domes or gypsum), where the sulfur was apparently formed by hydrocarbon reduction of anhydrite.⁹ Sulfur is also increasingly recovered as a byproduct of petroleum and natural gas refining, coal mining and copper, lead and zinc production. All of these activities will probably remain on the earth. However, sulfur is also occasionally found in unconsolidated volcanic rock and is found in the lunar soils. Nitrogen, while not especially rare on the moon, will not be available cheaply there.

In summary, except for alumina, magnesia, silica and (possibly) volcanic sulfur the traditional raw materials for most industrial chemicals are not likely to be found on the moon in deposits concentrated enough to be competitive with earth resources. This fact virtually rules out lunar or space based production for export and major internal growth of all organic chemicals, and most inorganics, including ammonia, chlorine, sodium, potassium, sodium and potassium hydroxide, sulfuric, hydrochloric, hydrofluoric and nitric acids, phosphoric acid, hydrogen cyanide, urea and so on. Only silicon, titanium, oxygen and aluminum-based chemicals appear to be candidates based on the availability of raw materials. However, it does not rule out the possibility of closed loop processes in which make-up losses and initial reagent stocks are acquired in part from the minor and trace elements in lunar soils. Such elements presently known include Na, H, Ca, C, N, P, S and He.

Methodology

Based on the foregoing discussion, we divided the existing U. S. manufacturing sector into three different groups of industries depending on their raw material usage.

- (i) In this group are industries based on raw materials that may eventually be obtainable on the moon, *viz.*, electrometallurgy, glass, ceramics, light and specialty metal working and fabrication, electronics.
- (ii) In this group are industries based on raw materials less likely to be available in concentrated deposits on the moon, requiring significant terrestrial makeup or that require major process modifications from terrestrial practices. Examples include pyrometallurgy (based on coke or hydrocarbons), rolled or forged steel products, copper, zinc or lead products, industrial

chemicals, plastics, textiles, and concrete products. Also, industries whose products are bulky, in relation to value. This applies to certain fabricated final products, such as appliances and vehicles.

(iii) In this group are industries based on raw materials only available on earth, *viz.*, agriculture, forestry, food processing, leather, paper and wood products, and fossil fuels *per se*, plus asphalt, and non-fuel petroleum products. Service industries are also included in this group.

The third group (239 sectors) was omitted from further consideration, while the second group (166 sectors) was included in the analysis. The results are listed separately.² The first group (64 sectors) constitutes those manufacturing industries that, based on present (or anticipated) technology, appear most suitable for lunar or space locations.

To calculate an average product value per unit mass of inputs (\$/kg) there are two basic data requirements, *viz.*, sectoral outputs (in dollars) and sectoral inputs in mass units (kg). The former data are systematically gathered and compiled by the Census and the Bureau of Economic Analysis (BEA) of the Department of Commerce. The major choice to be made for purposes of this paper is the level of aggregation. For reasons that will be explained later, we mainly utilized the 484 sectorization scheme defined by the Commerce Dept., for which input-output coefficients and sectoral outputs are readily available (on magnetic tape or printouts) for the base-year 1967.¹⁰ A slightly more aggregated version of 367 sectors has been published by the Dept. of Commerce.¹¹ "Raw" output data is also available in the Census of Manufactures for 1967 and 1972.¹² These unadjusted data do not correspond exactly to the output figures used in the Commerce I-O model, but can be used for purposes of extrapolation, as will be described hereafter. The major difference is that secondary outputs of all industries are counted twice in the I-O table, first as part of the output of the actual producing industry, and again as part of the output of the industry for which that product is the primary product. This phantom transfer results in an inflation of all sectoral outputs.

The major problem for us has to do with computing material inputs in mass (kg) units. Data on "materials consumed, by kind" are gathered and published for each sector by the Census of Manufactures, but this data is incomplete and difficult to use. First, the quantity measures that are used do not necessarily correspond uniquely with mass. For example, lumber is measured in board-feet, plate glass in square feet, liquids in gallons or barrels, gas in cubic feet, textiles in linear yards, cotton in bales, grain in bushels, electric motors in "units" and so on. While these measures

can be converted roughly to weights, there are no exact numerical equivalences. Different types of fabrics have different weights per yard, and the mix of fabric types produced by a sector might change from one year to another.

Second, there are many omissions in the published Census figures. By law the Census cannot publish data that tend to reveal commercial relationships. Thus, when a commodity is supplied by only one or two firms, the figures are withheld. This results in a tendency to underestimate input quantities.

Third, some input materials are obtained from non-commercial sources. This applies particularly to atmospheric air and process water. To the extent that these materials are used by industry, the "Materials Consumed by Kind" tables are incomplete. Water consumption is covered elsewhere in the Census of Manufactures, but the distinction between water "used up" or water embodied in a product, and water used as a diluent for wastes is inadequately maintained. For the purposes of this paper, the Census data on water use are not helpful.

Fourth and finally, some industries as aggregated by the Census or in the Commerce I-0 table — notably industrial chemicals — manufacture most of their own inputs. That is to say, the Census of Manufactures lists as "inputs" to each subsector of the chemical industry a number of chemicals that are also outputs of other subsectors of the industry. The only satisfactory way of handling the chemical industry is to divide it into individual processes or complexes of processes that are naturally co-located. This is far too difficult a task to undertake within the modest scope of this paper. Considering the unlikelihood of major chemical manufacturing in space from lunar materials, due to raw material unavailability, it does not seem worthwhile to examine this particular industry in greater depth at present.

Of course most industries consume some already processed materials or components manufactured elsewhere. There are several possible approaches, but the one we chose was determined by the fact that a previous study had been carried out by Research Triangle Institute which computed both direct and direct plus indirect consumption of certain finished materials: steel, aluminum, glass, paper, rubber and plastics, in kg, by all 484 Commerce sectors in 1967.¹³ This list covers most of the material inputs to a great many of the "downstream" sectors of the economy through being conspicuously irrelevant to most of the primary materials extraction or processing industries *per se*. For instance, the RTI list includes virtually none of the material inputs to the metallurgical or chemical industries; nor does it cover other minerals such as sand, lime, cement, gypsum, and their products (structural

materials, pottery, ceramics). Nor does it include wood products or textiles of any kind.

It is plausible to assume that all materials on the RTI list are "finished" in the sense that they are recognizable in their final form. Uses by downstream consumers generally involve embodiment in products. Thus steel rods (from the steel industry) are sold to the wire drawing industry where they are drawn into wire; or they are sold to the "screw machine products" sector and machined into screws, nuts and bolts. Later the wire may be made into nails or into galvanized mesh fencing. The nuts and bolts may be used in assembly of auto engines or furniture. When a sector buys a product containing steel from some other sector, steel is an indirect input. When a sector buys raw steel in some form produced by the steel industry itself — say galvanized strip — it is a *direct* input.

Tracing the indirect flows through the economy is very tedious, but this has already been done by RTI. In particular, Ref. 13 contains two tables of interest to us, as follows:

Table B-14 Direct Materials Consumption by Sector (10^6 kg), 1967.

Table B-16 Direct plus Indirect Materials Consumption per Dollar of Final Demand (kg/\$), 1967.

These tables give consumption of each of the specified materials. The data given in Table B-14 of Ref. 12 can be summed up to yield total direct consumption (10^6 kg) of steel, aluminum, glass, paper, rubber and plastics by each sector in 1967 measured. We derived the indirect component of materials consumption for each sector by multiplying the coefficients in Table B-16 by the Total Output (\$) of each sector in 1967, as provided by the Dept. of Commerce (Refs. 10,11).

The 1967 data, derived as noted above, were updated roughly to 1972 by assuming constant relative prices and technical coefficients. Thus, direct materials consumption by each sector was taken to be proportional to the value-added (\$) by that sector. Mathematically, the entries in Table B-14 were multiplied by the 1972/1967 ratio of value-added, adjusted for inflation. Similarly, direct plus indirect materials consumption was taken to be proportional to output (\$), and the entries in Table B-16 — being in units of kg/\$ — were assumed to be equally valid in 1972, as adjusted for inflation and changing sectoral definitions between the two Census years. To obtain total direct and indirect materials consumption for 1972 we multiplied the entries in Table B-16 (summed and adjusted) by a vector of 1972 sectoral outputs.

Unfortunately, the above procedure does not yield a satisfactory estimate of the materials consumption by the primary

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processing sectors which produce metals, glass, paper, rubber and plastics to begin with. Nor does it give material input requirement of industries consuming significant quantities of other materials, such as chemicals, textiles, or ceramics. Based on criteria discussed earlier, we eliminate all sectors primarily processing vegetable or animal products such as food, wood, paper, leather or fossil fuels.

We have, therefore, added (by hand) further direct inputs of all materials not on the RTI list, for which data are available in the "Materials Consumed by Kind" tables in the 1972 Census of Manufactures. Intermediate materials produced and consumed by the same industry (including prompt scrap) were excluded. We used approximate rules of thumb for conversions where area or volume units were used, notably:

cotton	227 kg/bale
fabric	0.5 kg/yd (suggested
(broad curve)	in 1967 Census)
glass	1.33 kg/ft ² (1/4"
	thickness)
wood	1.25 kg/board ft (3/4"
	thickness)
leather	0.4 kg/gal ²
water	3.78 kg/gal
paint	3.78 kg/gal
alcohol	3.6 kg/gal
fuel oil	3.44 kg/gal
naptha	2.68 kg/gal
natural gas	0.0189 kg/ft ³

Energy consumption by sector, in kwh equivalents, are given in the Census of Manufactures. These numbers are included in the data base and printed out for convenience. All fossil fuels have an energy content that can be measured in a variety of units, including BTU, joules, hp. hrs., or kwh. The choice is arbitrary. For consistency electrical energy from all sources is counted in terms of the amount of heat energy (from fossil fuels) that would have been required to generate it.

Tabular Results Described

Table II summarizes the results of the extended computer computations of the inputs from Refs. 11, 12, 13 and 14. The input data were for 1967 and 1972. The results shown in the table are for 1972 only. Table II applies to the *MORE LIKELY* class of goods. The Dept. of Commerce SIC cross references and the previously described *LESS LIKELY* class of goods are presented in (2). The first column is the rank order of the entries where the entries are ranked on a \$/kg basis. The third column is the computed \$/kg value of that particular entry. A short descriptive title of the SIC taken from "Census of Manufactures" constitutes the second column. Total shipped value or price (in 10⁶\$) of the SIC constitutes the fourth column. Total value-added by all the SIC's is given at the end of the two tables. The fifth column is the total mass consisting of direct and indirect mass input to the

SIC as measured in billions of kilograms or millions of metric tons. The sixth and last column is the energy consumption of the SIC in billions of kilowatt hours.

Intrinsic value is based on total shipped value divided by the total mass input which consists of direct and indirect components. "Indirect" in this context implies that the materials passed first through some other sector for processing or fabrication into components. Since we do not wish to count waste materials or combustion products that are discarded in processing (for example, slag from steel mills), the indirect flow analysis only covers finished materials that are likely to be embodied in the intermediate products (steel, aluminum, paper, glass, rubber, plastic).

Among the "more likely" group, the value per unit weight of inputs range from 11\$/kg for "complete guided missiles," down to 0.22 \$/kg for primary aluminum. Discrepancies appear in a few cases (e.g., x-ray apparatus, typewriters) between data for direct and indirect materials inputs. The data have been double checked for all these cases. Almost certainly, the results are spurious, arising from so-called aggregation errors in the I-O tables. Further analysis on a sector basis will be required to eliminate such errors. In one case (Aircraft equipments not elsewhere classified) data was simply unavailable.

Asterisks appear in a few places in table II. An asterisk signifies that the method of extrapolation from 1967 to 1972 of the price coefficients or correction weights yielded a "direct and indirect" consumption for 1972 smaller than direct consumption. This is obviously not realistic; it arises from the fact that different methods of extrapolation were used. Discrepancies introduced in this way are not judged to be quantitatively important. However, the fact that they can occur is unfortunate. If the analysis were to be redone, a different extrapolation rule should be adopted.

The corrected weight used in column 5 of table II is an estimate of the weight of raw or finished materials consumed by the sector, but not included in the RTI study. As previously noted, the RTI study explicitly covered iron and steel, aluminum, glass, rubber, plastic and paper. These materials were chosen because of their importance in packaging. Evidently raw materials of all kinds, as well as building materials, chemicals, wood, textiles and several important metals (copper, zinc, lead, nickel) were omitted. To obtain estimates of the weight of these materials consumed by each sector, we referred to the Census of Manufactures "Materials Consumed by Kind" tables, disregarding those materials in the RTI list. As noted in the text, many of the data are given in volume or other units that have no unique weight equivalent. Our estimates

of average weights per unit are listed in the preceding text.

The number (1) which appears along side entries in the energy consumption column refer to places where data were not available for the 1972 SIC's and energy usage was extrapolated on the basis of changes in sector "total mass" from 1967 to 1972. In all cases the few individual extrapolations were small compared to the total energy consumption in both the *more likely* and *less likely* cases. It is an interesting exercise to examine table I which lists the technical processing operations of which man is capable and ask, "What can be done in space with lunar and eventually asteroidal materials?"

Optimization of Development

For any given scenario leading to space industrialization, specifying a scale of manufacturing operations over time, a certain capital goods and labor requirement is indicated. Having specified the nature of the enterprise (e.g., military vs. civilian) the direct production labor requirement translates into further requirements for housing, household services, recreation, utilities, maintenance and social overhead services all of which have their own (indirect) labor requirements. From these data total population, including dependents and total demand for final goods and services, versus time can be derived.

In the same manner, cumulative requirements for durable goods of all kinds, in place, are implied as a function of time. The latter must have been supplied either from earth, or manufactured at the SMF. Thus, total demand for manufactured products of all kinds (including capital goods) can be estimated in detail for each time period from the initiation of the project.

The question is: which items should be produced in space and which items should be "imported" from earth? This question would be straightforward to answer if there were no economies of scale in manufacturing and no interdependencies between manufacturing activities. Even with increasing returns to scale, the problem is not difficult to solve in the absence of interdependence: one need merely compute the cost of local production at the specified (fixed) level of demand. If it is lower than the cost of production and shipment from earth, the decision will be "make." If it is higher, the decision will be "import."

However, when capital requirements are taken into account interdependence is clearly an important factor and a sophisticated mathematical analysis is required. To produce almost anything in space, machines are needed. The machines themselves must be produced somewhere, either on earth or in space. The fact that each product requires other products as inputs — especially when capital goods are included

— and many products are, *ipso facto*, intermediates in the production of other products. This type of interdependence can be expressed as a set of input-output relationships of the form

$$x_i + y_i - \sum_{j \in I} A_{ij} x_j \geq D_i \quad (1)$$

where D_i refers to annual local (i.e., space) final demand for the i th product, x_i is the annual quantity of local production, y_i is the annual quantity imported and A_{ij} is the annual quantity of the i th product required as an intermediate to locally produce a unit of the j th product. It can be assumed that the A_{ij} are known, from detailed engineering studies. The inequality is an equality in an equilibrium situation when there is no accumulation of inventory. The index i runs over the entire set of products I , including both intermediates (such as capital goods) and "final" goods.

Another type of interdependence that is very important in the mechanical engineering (i.e., machine producing) sectors is *capacity sharing*. This would not matter in the absence of economies of scale, but it is vital where costs drop sharply as output rises, as in this sector. There are important opportunities for cost savings whenever a process element — such as a general purpose machine tool — can be made to play a common role in the production of several different products in place of a number of smaller special purpose machine tools.

Lot size and set-up time for short runs are critical factors in determining the economies of small or medium scale production facilities in an earth environment. However, in a space inventory costs can probably be neglected, in practice, (compared to transport costs) where large lot-size and relatively long runs should be the rule and set-up costs can be minimized. This makes the "scheduling" problem — a bugaboo of most multi-purpose facilities — relatively tractable.

Let us now assume that there are K multi-purpose "process elements" (i.e., items of process equipment or machines) and that for the i th product there is a uniquely defined "technology," i.e., a sequence of process steps. Then

$$\sum_{i \in I} B_{ki} x_i = C_k \quad k \in K \quad (2)$$

where B_{ki} is the amount of processing (in natural measure such as "hours") by the k th process element, per annual unit of output of the i th product, C_k is the total amount of annual processing required on the k th element.

The assumption of a unique technology for each product — no choice — may seem unduly limiting. From the mathematical standpoint this assumption could, in fact, be relaxed. However, we argue that it is justified for products of the engineering

sectors (though not necessarily for chemicals or basic materials). The reason is that each "product" is designed, in practice, to simultaneously achieve multiple objectives: (1) to satisfy some functional requirement and (2) to be manufacturable at the lowest possible cost in the existing industrial environment. There are obviously conflicts between these different objectives and, in the real world, products are never optimized for either of them. (More utility for the consumer is generally achieved only by sacrificing manufacturability and increasing costs.) In the space environment these tradeoffs may be even more acute, though the area of compromise is likely to be different and both product designs and production technology will certainly be different. Moreover, the form of a product that is produced in space from lunar materials may be designed quite differently than the version shipped from earth.* But the essential point is that design of a product and the determination of its manufacturing process (in space or on earth), must occur jointly — with or without the assistance of formal analytical models. We simply assume this has been done, once and for all, and the results are known.

Returning, then, to the "make" vs. "import" question, all that remains is to specify production costs (in space) import prices, and an objective function. The following approach is essentially identical to an approach developed by Westphal and Rhee, of the World Bank, in the study of optimal investment policy for developing countries. The objective function to be minimized is the sum total of net local value added plus import costs of final products of the SMF:

$$U = \sum_{k \in K} f_k(C_k) + \sum_{i \in I} [g_i(x_i) + w_i y_i] \quad (3)$$

where $f_k(C_k)$ is in general a non-linear function of the level of the k th processing activity C_k , $g_i(x_i)$ is a non-linear function of the production level of the i th product, including purchased endogenous inputs and w_i is the import price of the i th product. The sum can be taken over all products (including locally produced intermediate goods), since payment for purchased intermediates are exactly balanced by revenues. The payments might be real — between separately owned enterprises — or, more likely, simply accounting credits and debits.

Both $f(C)$ and $g(x)$ can be assumed to have positive first derivatives and — consistent with the assumption of returns to scale — negative second derivatives. Thus average unit costs are a monotonically decreasing function output. For analytical purposes it is reasonable to assume simple forms for $f(C)$ and $g(x)$.

*To state an obvious difference, products shipped from earth must be made as small and light as possible. Products made in space must, on the other hand, minimize the use of organics and heavy materials.

$$f_k(C_k) = F_k + V_k C_k \quad (4)$$

$$g_i(x_i) = G_i x_i \quad (5)$$

where F_k is the "fixed cost" and V_k is the "variable cost" of the k th processing element. These items can be estimated from engineering analysis though (4) is merely a crude approximation of a non-linear function so the words "fixed" and "variable" should not be interpreted too literally. The coefficient G_i covers only exogenous product-related costs (mainly labor) such as R & D and production "set-up", but excludes locally produced intermediate items (whose prices cannot in any case be determined explicitly without solving the problem we are formulating). We reiterate that, summed over all, $i \in I$, the costs of intermediate goods* produced and used within the SMF contribute nothing to the utility function, since internal payments are exactly canceled by internal revenues (regarded as "credits"). We can now write using Eq. 2:

$$\begin{aligned} U &= \sum_k F_k + \sum_k V_k C_k + \sum_i G_i x_i + \sum_i w_i y_i \\ &= \sum_k F_k + \sum_i [\sum_k V_k B_{ki} + G_i] x_i + \sum_i w_i y_i \\ &= \sum_k F_k + \sum_i (H_i x_i + w_i y_i) \end{aligned} \quad (6)$$

The solution of the optimization problem we have formulated is found by maximizing U , subject to the materials balance constraints.

It can be shown quite easily, first, that with monotonically decreasing unit costs functions the optimal vectors x_i , y_i are orthogonal. That is to say, the choice is dichotomous: make or buy. If it is optimal to produce any amount of the i th product at the SMF, then it is optimal to produce all that is locally demanded. The reason is not difficult to understand. To produce at all, the local unit cost of the minimum scale of production (D_i) must be lower than the price of inputs. Any increase in the scale of output lowers the unit cost, by assumption, and thereby increases the advantage over imports.

Next, a lower bound to the cost of local production at the SMF, (and an upper bound to the scale of output) for every product can be determined by solving a simple linear programming problem, viz.

$$\text{minimize } [U - \sum_k F_k] = \sum_i (H_i x_i + w_i y_i) \quad (7)$$

$$\text{s.t. } x_i + y_i - \sum_{j \in I} A_{ij} x_j \geq D_i \quad (1)$$

where the utility function is the sum of marginal costs of production. In effect,

*By convention, household and consumer goods used by the residents of the SMF are regarded as "final" products, along with the principle export product: solar power satellites

this problem picks out products x_i that can be produced locally at marginal cost shadow prices less than the import price. The corresponding shadow prices can be determined by solving the "dual" problem, viz.

$$\text{maximize } \sum_i p_i D_i \quad (8)$$

$$\text{s.t. } p_i - \sum_{j \in I} A_{ji} p_j \leq H_i \quad (9)$$

$$p_i < w_i \quad (10)$$

All products not satisfying (10) definitely belong to the "import" list. Unfortunately, some products that do satisfy (10) should nevertheless be imported too, since p_i as determined from the above calculation is only a lower limit. Those products not yet definitely assigned to the "import" list must now be examined individually.

The next step is to compile a definite "make" list. To do this, the simplest procedure is to compute an upper limit to the cost of production in the SMF, viz. the cost of production at minimum output, assuming only final demand (D_i) is to be satisfied and all intermediates (such as capital equipment) are to be imported from earth. Any items which satisfy (10) based on this approximation must definitely be on the "make" list. The procedure must be iterated, since the result of the first set of price comparisons will presumably identify some items that will not be imported. Intermediate demand for these items will justify larger outputs and, consequently, lower unit prices. Based on this, a new set of price comparisons should identify further items that qualify for the "make" list. The process continues until there is no further change with further iteration.

Summary

The intrinsic cost (\$/kg) of lunar materials should drop radically as other markets are developed which require large masses of materials. As this happens the cost in space of lunar materials should eventually approach the cost of ejecting it from the moon. If space power stations are eventually included in Fig. 1, they will initially be located between \$200 and \$400/Kg (far off the right edge) and have an annual value of 50 to 100 billion dollars a year. A new SIC for lunar mining would also be introduced at the right edge of the graph, approximately \$20/Kg (point 1), and have an annual output value of two to four billion dollars.¹⁵

We noted at the first of this article that the lunar ejection cost could be the order of a few cents per kilogram (= \$.02/kg). This corresponds to point (2) in Fig. 1, and implies that approximately 10-15% of the present SIC's might eventually contain lunar components for use either terrestrially or in space. As a broader range of feedstock elements become available either

through asteroid resources, additional lunar resources or substitution of materials then most of the SIC shown in Fig. 1 could be penetrated by extraterrestrial materials. However, this historical approach to possible market potential should not distract us from the example provided by the space power systems that new and exotic products and new standard industrial categories for space enterprises will develop and that the products can be relatively inexpensive as we learn to obtain extraterrestrial raw materials at low unit costs.

A drop of 1,000 in cost of lunar materials, from \$20/kg to \$.02/kg, may seem rather dramatic unless one realizes that the 380 kg lunar materials returned by the 25 billion dollar Apollo program could be said to cost approximately 66 million dollars per kilogram. There is every reason to think that the basic feedbacks between mass markets and mass production can operate in space as it has on earth for 400 years. Learning curve experience will permit industry to continually drop unit prices.

Once a commitment is made to the use of extraterrestrial materials for manufacturing, the entire range of skills of an industrial society can be applied to enhancing the growth of the in-space enterprise. There is no single link (as for example — earth to earth orbit transportation) which could restrict the overall rate of growth of the combined materials and service segments of the economy.

Acknowledgment

This work was performed at the Lunar and Planetary Institute which is operated by the Universities Space Research Association under contract number NSR 09-051-001 from the National Aeronautics and Space Administration. This is Lunar and Planetary Contribution No. 377.

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Table I: SUBSTITUTE LUNAR MATERIALS — 10 Gigawatt Space Power Station

RANK	APPLICATION	EARTH BASELINE MATERIAL	EARTH BASELINE MATERIAL MASS (T)	RECOMMENDED LUNAR SUBSTITUTE MATERIAL	EQUIVALENT LUNAR MATERIAL MASS (T)	EARTH ALLOY MATERIAL MASS (T)
a	Photovoltaic cell covers	Borosilicate glass	21,658	Fused silica glass	21,658	0
b	Solar cells	Silicon	14,775	Silicon	14,775	<< 1
c	Photovoltaic cell substrate	Fused silica glass	14,439	Fused silica glass	14,439	0
d	Primary solar array structure	Graphite composite	6,208	Foamed silica glass	12,416	0
e	Solenoid/coil windings, etc.	Copper wire	5,980	Aluminum wire	2,865	0
f	MPTS waveguides	Graphite composite	5,257	Foamed silica glass	5,257	0
g	Klystron heat pipes	CRES tubing	3,892	CRES in Klystron, low alloy steel elsewhere	3,542	350
h	Power transmission busses	Aluminum sheet	3,535	Aluminum sheet	3,535	0
i	Klystron/dc-dc conv. radiators	Aluminum sheet	2,749	Aluminum sheet	2,749	0
j	Klystron solenoid cavity	Copper mach. part	1,820	Aluminum part, copper coated	785	90
k	Klystron poles dc-dc transformer	Iron mach. part	1,758	Iron mach. part	1,758	0
l	Klystron collector radiators	Copper sheet	1,539	Aluminum sheet	779	0
m	Klystron housing	CRES mach. part	1,524	Aluminum cast and mach	515	0
n	Solar cell interconnects	Copper, vacuum deposited	1,456	Aluminum, vacuum deposited	697	0
o	MPTS antenna & other structure	Graphite composite	1,210	Foamed silica glass	2,420	0
			<u>87,300T</u>		<u>88,190T</u>	<u>440T</u>

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Table II: SIC'S MORE LIKELY TO BE PRODUCIBLE FROM LUNAR MATERIALS OR TO TAKE ADVANTAGE OF SOLAR ENERGY

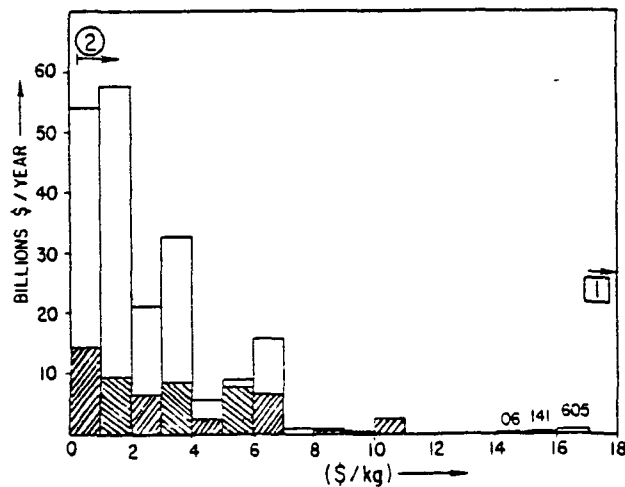
Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁺⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
1	Complete Guided Missiles	11.0	3,348	0.305	NA
2	Industrial Patterns	6.76	161	0.024	NA
3	Optical & Radio & TV & Sighting Equipment	6.17	7,848	1.271	NA
4	Semiconductors	6.03	2,182	0.362	3.3
5	Telephone and Telegraph Apparatus	5.68	3,674	0.647	5.2
6	Porcelain Electrical Supplies	5.55	223	0.040	2.0
7	Calculating, Accounting, Office Machines - NEC	5.29	1,007	0.190	1.9
8	Aircraft Engines & Engine Parts	5.15	3,538	0.687	6.5 (1)
9	Electronic Computing Parts	5.11	5,186	1.015	4.1
10	Vitreous China Food Utensils	4.83	67	0.014	NA
11	Aluminum Rolling and Drawing	4.29	3,338	0.778	25.9
12	Engineering & Scientific Instruments	4.09	846	0.207	2.0
13	Mechanical Measuring Devices	4.02	1,448	0.360	NA
14	Watches & Watch Cases & Clocks	3.89	761	0.196	0.9
15	Industrial Controls	3.85	1,115	0.289	1.7
16	Ophthalmic Goods	3.84	461	0.120	0.9
17	Automatic Temperature Controls	3.82	591	0.155	1.0
18	Small Arms	3.81	320	0.084	NA
19	Non-clay Refractories	3.76	278	0.075	4.8
20	Jewelers Finding & Materials & Lapidary	3.60	264	0.073	NA
21	X-Ray Apparatus & Tubes	3.56	120	0.034	0.3
22	Abrasive Products	3.51	721	0.205	3.9
23	Radio & TV Receiving Sets	3.51	3,605	1.029	2.1
24	Fine Earthenware Food Utensils	3.46	60	0.017	NA
25	Electronic Components - NEC	3.44	3,808	1.106	7.9
26	Primary Non-ferrous Materials - NEC	3.19	325	0.102	6.7
27*	Machine Tools - Metal Cutting Types	3.16	1,152	0.365	3.1
28	Surgical Appliances & Supplies	3.07	1,182	0.385	1.5
29	Hand Saws & Saw Blades	2.98	158	0.053	NA
30	Electron Tubes	2.76	1,142	0.413	2.9
31	Special Dies & Tools & Accessories	2.59	2,985	1.150	7.4
32	Cutlery	2.57	347	0.135	0.9
33	Costume Jewelry	2.57	383	0.149	0.6
34	Pumps & Compressors	2.38	2,254	0.946	4.0 (1)
35	Aluminum Castings	2.27	1,031	0.454	7.4
36	Measuring & Dispensing Pumps	2.10	189	0.090	0.3
37	Non-ferrous Rolling & Drawing - NEC	2.08	1,011	0.486	4.2
38	Hand & Edge Tools - NEC	2.07	1,001	0.483	2.9
39	Other Ordnance & Accessories	1.99	388	0.195	NA
40	Surgical & Medical Instruments	1.95	781	0.400	1.0
41	Ball & Roller Bearings	1.95	1,243	0.636	4.6
42	Engine Electrical Equipment	1.91	1,652	0.864	3.0
43	Ammunition (No Small) - NEC	1.87	1,206	0.644	NA

Table II (continued)

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Sequence Number	Description	S/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
44	Pens & Mechanical Pencils & Marking Devices	1.83	380	0.207	0.6
45	Power Transmission Equipment	1.83	1,225	0.670	3.0 (1)
46	Needles & Pens & Fasteners	1.83	467	0.255	0.9
47	Internal Combustion Engines - NEC	1.80	2,701	1.503	5.1
48	Machine Tools - Metal Forming Types	1.68	563	0.336	1.4
49	Hardware - NEC	1.45	2,634	1.822	5.7
50*	Motorcycles & Bicycles & Parts (SIC-3799)	1.37	536	0.390	0.9
51	Non-ferrous Castings - NEC	1.37	479	0.350	2.5
52	Welding Apparatus	1.36	536	0.309	1.0
53	Games & Toys & Childrens' Vehicles (Exc. Bikes)	1.26	1,412	1.119	2.1
54	Household Cooking Equipment	0.990	751	0.759	1.9
55	Fabricated Metal Products - NEC	0.988	158	1.577	NA
56	Motor Vehicles Parts & Accessories	0.981	14,841	15.132	36.6
57	Metal Foil & Leaf	0.793	232	0.292	0.7
58	Typewriters	0.756	551	0.729	0.8
59	Glass & Glass Products (Except Containers)	0.728	2,868	3.938	41.5
60	Architectural Metal Work	0.525	466	0.887	NA
61	Electrometallurgical Products	0.345	447	1.295	24.0
62	Iron & Steel Foundries	0.285	4,639	16.291	46.2
63	Aircraft Equipment - NEC	NA	3,102	NA	NA
64	Primary Aluminum (SEC - 28195)	0.215	1,591	5.7	84.6
Totals			104,979 MS	70.5	384.0
				$\times 10^9$ kg	$\times 8$ kw-hr

*See page 6



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**Overview of Methods for Extraterrestrial
Materials Processing**

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**FOURTH PRINCETON/AIAA
CONFERENCE ON
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Princeton, N.J./May 14-17, 1979

OVERVIEW OF METHODS FOR EXTRATERRESTRIAL MATERIALS PROCESSING

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Abstract

A brief survey of processing systems suitable for conversion of lunar soil fractions to refined industrial feedstocks are given. Description of a "baseline" process using hydrochemical or metallurgical separation of compounds of major and minor elements using HF acid leaching as the initial step is presented. Rough engineering parameters including power and heat rejection requirements, potential loss of earth supplied reagents during recycling, and mass: output ratios of equipment, reagent inventory, and associated power and radiator facilities are described. Minimal practical scales for such systems and manpower requirements are discussed.

INTRODUCTION

The high costs and engineering difficulties associated with transporting appreciable mass from the earth's surface to earth orbit or deep space have prompted a number of prior studies on the feasibility and techniques applicable to the use of extraterrestrial materials and in particular lunar materials to supply feedstocks for a variety of industrial activities¹. The evolution of space activities can be expected to lead to a progressive increase in the scale of engineering projects with quasipermanent or permanent manned stations in orbit and/or the lunar surface. The benefit:cost ratio of such activity will in large measure depend on the ability to reduce the materials or mass fraction of capital and expendable requirements which must be lifted from earth.

A lunar materials industry, in common with its counterpart on earth, may anticipate commercial use of both native mineral products (raw or beneficiated) and processed or refined materials (metals, oxides, etc.) for various applications, with price/performance criteria determining use patterns. Modified natural products obtained by controlled additions of refined materials may also constitute an important class of materials with a cost intermediate between natural and refined materials.

The input compositional limitations of a lunar materials industry will be constrained by the distribution and composition of various lunar soils and rocks and their respective mineral or amorphous (glassy) fractions. For natural products, the output compositional limitations will be determined by the efficiency of various physical beneficiation methods such as magnetic, electrostatic or thermal separation, while for refined products, the output compounds will depend on the specific chemical transformations incorporated in the processing or refining cycles adopted.

Materials processing in space

A study is underway at the Lunar and Planetary Institute (Houston) concerning both the processing

of lunar materials and space manufacturing, in which we consider the following questions:

- What resources can be mined and recovered from the moon?
- What ranges of industrial feedstock can be provided from lunar materials?
- What specific schemes can be identified for physical and chemical processing of lunar materials?
- Can a bootstrap operation be established?

Table I shows the composition of the two major constituents of the mare and highlands regions of the moon². Meteoritic bombardment has tended to homogenize the distribution of minerals in these two regions to great depths. There are no aqueous processes operating on the moon to concentrate minerals or elements. Thus we expect to work with the dust and surface rocks of the moon, rather than look for deep veins of minerals. It is evident that the chemical/metallurgical industry in space will be substantially different from that on earth, due to scarcity of key elements such as H, C, Na, Cl, etc.

Table II shows elements that are potentially recoverable from the moon. (The designations "major," "minor," and "trace" are ours.) The light trace-elements are mostly due to solar wind bombardment of the lunar surface. Alpha radiation, due to radioactive decay, is responsible for some helium, while impacts of carbonaceous meteorites are responsible for some of the carbon that is present.

(Native products)

Natural mineral products may be obtained from either raw or beneficiated lunar soils or rocks. Native lunar soils may be sintered or fused to obtain a variety of ceramic, cast basalt, and dark-glass products.

Using physical beneficiation methods, one may anticipate recovering specific mineral fractions of pyroxenes, plagioclase, olivine or ilmenite of compositions shown in Table I with admixtures of up to 10% or higher of residual mineral or glassy material. In addition, magnetic separation of lunar soils can be expected to yield from 0.1 to 0.5 wt % of free iron admixed with some nickel-iron alloy. This probably represents the simplest method of obtaining structural metals.

Trace minerals such as spinels, troilite (FeS) and various glasses may also be recoverable by physical methods, while thermal desorption of fine soil particles may permit recovery of light trace elements.

*Lockheed Electronics Co.

(Refined products)

The major elements can be recovered using hydrochemical, pyrochemical, electrochemical or physical processes. This can be performed in orbit or on the moon. The chemical plant would also have to be responsible for the recycling of nonlunar materials. The minor elements could either be co-recovered from the major-element processing or be obtained by separate means. In the latter case, the processing could only be performed on the moon, as it would be uneconomical to ship large quantities of soil into space solely for the purpose of obtaining minor constituents. An exception may be possible for those elements such as Cr, P and S which tend to concentrate in trace mineral fractions if the latter can be efficiently concentrated.

While the overall abundances of many of the trace elements on the moon do not greatly differ from those on earth, the absence of known concentrated deposits (ore bodies) of such elements makes prospects for their efficient recovery rather dim. Of course, one may still bring critical materials from the earth in modest amounts. Also, note that the major lunar elements constitute the preponderant mass of mineral elements used in earth industry (excepting air, water and fuels).

Table III shows a list of useful products, with examples of what could be made at a space manufacturing-facility, primarily from lunar materials. Although not listed, water would be made from oxygen obtained from lunar materials and hydrogen brought from earth. (Hydrogen is also a trace element on the moon, but even though its weight abundance may typically range between 50-100 ppm, its atomic abundance may be 1% that of silicon. If extractable, this hydrogen could be used to produce the water needed to replace that lost in process recycling - since no recycling process is 100% efficient.)

The structural metals listed in Table III (Al, Fe, Mg, and Ti) will have to be alloyed in order to develop useful mechanical properties. Table II shows that several elements (e.g., Si, Cr, Mn) used in forming commercial alloys of the structural metals are potentially recoverable from the moon. In addition, there is "neutral" iron on the moon that also contains nickel and some cobalt, which could possibly be recovered. Finally, if enough carbon were recoverable from the trace amounts present on the moon (or brought from earth, or possibly obtained from a carbonaceous asteroid), and small amounts of other key alloying elements were imported from earth, one could produce many ferrous and non-ferrous alloys that are commonly used today.

In the case of steels, the more important alloying elements not readily available on the moon are C, Ni, Mo, W, V, and Nb (Cb). The physical properties of several commercial alloys containing these elements are generally similar to alloys in which such elements are absent but which instead contain lunar-indigenous elements. (The properties compared included tensile strength, yield strength, hardness, and elongation.) Therefore, for use as structural metals in space, it is possible to produce alloys possessing a broad range of properties (as commonly required on

earth) by alloying with carbon, lunar-indigenous elements, and/or minor amounts of lunar-deficient elements (LDE).

Several commercial aluminum alloys can be made from lunar-indigenous materials. However, higher strengths, approaching those of the strongest aluminum alloys made on earth, can only be obtained by alloying with small amounts of lunar-deficient elements, particularly Zn.

Only a few commercial alloys of magnesium and titanium can be formed solely from elements recoverable from the moon; but here again, as in the cases of steel and aluminum, significant improvements in properties can be obtained by alloying with minor amounts of lunar-deficient elements. The strongest magnesium alloys will require such lunar-deficient elements as Zn, while the strongest titanium alloys will need Mo.

It is evident that the structural metals to be manufactured in space will consist of alloys that are already in use, are well-characterized, and can furnish almost any desired property currently available. Nonmetallic materials similarly may be made solely from lunar sources, or modified with additions of lunar-deficient elements.

Produce-mix options depend on the type of raw material used and the nature and quantities of finished products required for specific applications. Table IV shows ranges of materials outputs available by varying the mineral input and process conditions. Figure 1 illustrates ratios of specific element to total metal equivalents and silica:oxygen equivalents for representative lunar minerals. The moon contains large quantities of a variety of minerals, so that the type of industry that might be attempted in space can be chosen after examining the various options available, rather than its being limited by any specific method or process for converting lunar material.

In building a large space manufacturing-facility via bootstrap operations:

1. Some materials almost certainly would have to be brought from earth.
2. The extent of additional structures that could be processed and manufactured in space from lunar materials would depend more critically on fabrication limitations than materials availability.
3. Versatility and properties would demand substantial use of steels, rather than aluminum or magnesium, as structural and magnetic metals and in tooling and manufacturing equipment.
4. Reprocessing and recycling carbon to form baked carbon and graphite products would be difficult in space. If possible, substitutes for such products would be highly desirable.

CHEMICAL PLANT DESIGN

Process constraints

A successful orbital (or lunar surface) materials processing plant must operate with several constraints which rarely concern industrial plants operating on earth. These include:

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1. Lack of virtually inexhaustible supplies of air and water.
2. Lack of unlimited heat sinks offered by (1).
3. Lack of plentiful fuel supplies: coal, oil, electric, gas, etc.
4. Lack of expendable oxidizing and reducing agents.
5. Lack of expendable acids and bases (except CaO).
6. Lack of key chemicals: ammonia, salt, chlorine, caustic, soda ash, carbon dioxide, sulfuric and phosphoric acids, carbon and graphite and organics.
7. Lack of ordinary solvents.
8. Lack of unlimited inertia in foundations or equipment (except on lunar surface).
9. Lack of support vendors.

Some factors that must be considered in designing a chemical plant in space are shown in Table V. A chemical plant for extraterrestrial materials processing may be expected to use equipment very similar to that employed in earth-based plants. Because of the importance of minimal mass of items to be shipped from earth, most apparatus will be constructed of materials of high specific strength (strength/weight ratio), perhaps using thin linings of corrosion-resistant materials (e.g., even gold).

Equipment must be compatible with the process constraints mentioned earlier, and with the special space environmental factors encountered during transport, assembly and operation. These include an unlimited vacuum sink, an adjustable level of artificial gravity (except on the lunar surface), provision for radiative dissipation of process heat loads, and recycling of lunar-deficient elements used as reagents, solvents or catalysts.

In space, the most practical source of energy is the sun. Solar cell arrays or large solar mirrors (with aluminized surfaces) would be used to concentrate the sunlight and supply electrical and thermal energy to the space manufacturing-facility.

Several different processes for extracting the major elements of lunar soil have been proposed. These have included reagentless processes such as direct electrolysis of raw or beneficiated lunar soils (molten silicates), and magnetic recovery of neutral iron; anhydrous high-temperature processes such as carbo- and silico-thermic reduction and carbochlorination, and lower-temperature hydrochemical processes such as acidic and basic leaching. (A discussion of some specific processes will appear later.)

Any needed reagents that contain lunar-deficient elements (LDE) must be removed with high efficiency from the output streams of the processing plant and recirculated or regenerated, with

efficiencies approaching or exceeding 99%. This is necessary to avoid the necessity of massive earth-lift.

The requirement of high recycle efficiency for LDE has a corollary in that the plant's products must include only the chemical elements present in the feedstock. Since the only nonmetallic elements present in significant quantities from various lunar raw materials are silicon and oxygen, the output streams must necessarily be limited to elements, alloys, silicides, and simple and complex oxides.

The selection of a specific process must await the establishment of criteria for process evaluation, and the formulation of figures of merit to allow comparative "ratings" of alternative systems. Much of the information necessary to evaluate these processes sufficiently to permit rational selection must be obtained by further literature searches and experimental investigations.

Of course, the prime consideration in evaluating space processing and manufacturing systems must center on the cost of producing items in orbital locations vs. the cost of earth-based manufacture and launch into orbit. In such comparisons, it is essential that functional substitutions be considered, since some items such as organics, fiber-reinforced resins, beryllium products, copper, silver, refractory and precious metals, plus materials having appreciable water content, would be difficult to produce from lunar materials. Fortunately, acceptable substitutes exist for any of those substances that would be needed in substantial amounts.

Since the principal motivation for considering orbital or lunar industrialization is to lower earth-launch costs (> \$100/kg) for massive space projects, it is essential that the mass of capital equipment, expendables, reagent inventory and support facilities initially lifted from earth be far exceeded by the annual output mass of such operations. Analysis to date of the materials-processing portion of such operations shows that this requirement is readily met.

The overriding importance of minimal mass makes it imperative that input materials and reagents move expeditiously through the sequence of processing steps without substantial delays and that certain features should probably be avoided or minimized, if possible, including:

1. Steps that require long completion times.
2. Steps in which the input material is present in low concentration.
3. Mass transport of volatiles at very low pressures.
4. Phase separations from viscous suspensions.
5. Reactions with low conversion per pass.
6. Reactions involving handling or storage of large volumes of gas.
7. Reactions involving large transfers of heat, using fluid/vapor heat exchangers without phase change.

8. Processes that reject large amounts of process heat at low temperatures (below 200-300°C).

9. Processes for which suitable structural materials do not offer reasonable service lives.

Other criteria for process evaluation include reliability, manpower requirements, potential hazards to onsite personnel, adaptability in processing scrap materials, and ease of repair in case of malfunction. Corrosion of parts that can only be replaced from earth supply is naturally far more serious than corrosion of lunar-derived parts.

The original cost of chemical process equipment is expected to be dwarfed by orbital lift costs in almost all cases and thus would be of minor importance. If replacement items for many of these units could be fabricated from lunar materials, this would reduce costs in expansion or replacement operations.

Space environmental factors

(Vacuum)

The vacuum-sink availability for space processing facilities may be useful for several types of operations. The most generally useful would be the ability to employ refractories and structural materials that are normally sensitive to oxidation, at higher temperatures than would otherwise be possible (except inside vacuum furnaces). Thus, ordinary steels could be used for retorts in metals reductions; and such materials as titanium and refractory metals, carbon and carbides, boron nitride and other non-oxide refractories could be used for structural and insulation purposes without danger of excessive oxidation. This should permit improved multilayer radiation-shield insulations for extremely-high-temperature processes (although sublimation may limit the utility of such systems for certain applications).

On the other hand, the use of space vacuum in separation techniques may have very limited application, since the escape of volatiles, particularly water vapor, could rarely be tolerated.

Notwithstanding the availability of vacuum, most of the processing facilities should probably be located in a large container that has an atmosphere and temperature compatible with human activity. This would permit easier inspection, maintenance and operation.

(Gravity)

The reduced gravitational attraction at lunar-based plants - or the adjustable centrifugal forces for simulated gravity in orbital plants - will allow some mass savings in support structures for process equipment. It seems likely that most of the chemical unit-operations would not operate satisfactorily under conditions of weightlessness, since all mass-transfer operations, except for introduction of pure gases into a vessel, would be unnecessarily complicated by absence of a gravitational effect. Fixed-volume storage tanks or reactors for solids, liquids or slurries would be difficult to load or unload, and such operations

as filtration, distillation, countercurrent extraction or flow, and so on, would be rendered difficult if not impossible.

The most likely uses for weightless processing would be for heating corrosive reaction masses by radiation or induction, using gas-jet or electromagnetic repulsion to prevent contact with the walls of a chamber.

Most elements of an orbital processing system that are relatively safe could likely be located in a large (but possibly segmented) pressure vessel slowly rotated to provide artificial gravity.

(Heat sink)

The unavailability of massive, external, air or water heat-sinks makes management of process waste-heat especially important. All major heat-rejection loads will ultimately have to be transferred to space radiators. In addition, the poor heat-transfer characteristics of vapor heat-exchange devices make such elements heavy and thus undesirable. Generally, to raise or lower the temperature of a gas stream it will be preferable to adiabatically compress or expand the gas, rather than use wall- or tube-type heat exchangers. Similarly, in distillation operations it will be advantageous to use the heat of condensation to drive the boiler, after heat-pumping it up to a suitable temperature by adiabatic compression. The mass penalty for additional pumping power will usually be far lower than for other alternatives in the disposition or transfer of process heat.

Unavoidable low- or medium-temperature heat loads, such as from electrolytic cells, may require heat pumping to higher temperatures to avoid excessive space-radiator masses. A simplified analysis indicates that below some temperature - determined by mass/power ratios of space power systems and mass/area ratios of space radiators - it becomes desirable to heat-pump all heat-rejection loads to such baseline temperatures. Similarly, refrigeration equipment for liquefaction of cryogenics should have heat-rejection temperatures at the same baseline level. Preliminary engineering studies show that minimal heat-rejection temperatures are in the 500 to 600 K range.

Recycling requirements

Most earthbound processing plants have a single principal product (or a few coproducts), whose mass-transformation rate is often substantially exceeded by the conversion rates of the reagents, solvents, air and water flows associated with the operations.

Lunar or orbital plants will generally have to recover, reclaim and recycle normally expendable reagents and solvents, due to the general lack of volatiles (except oxygen) available from lunar sources. The problem is more acute than it first seems, because the rate of cyclic transport of water, steam or various reagents may in some cases amount to 10 to 100 times the rate of lunar "ore" passing through the process. Yet the tolerable loss or attrition in these mass loops must be held *in total* to a small fraction of the production rate

of useful products, since an earth-mass lift requirement for reagent replacement approaching that of plant output obviously could not be cost effective.

While recycling operations may require chemical conversions, such as the separation or splitting of salts to yield acids and alkalis, it is simpler to consider recycling on an elemental basis. Thus, for most systems studied to date, only a very few elements must be monitored closely. As an example, for the HF acid-leach process, only H, F, Na and possibly N must be recycled with high efficiency. Even here, usable amounts of Na and H may be recoverable from the lunar raw material.

Recycling losses will probably be more prevalent when lunar-deficient elements are incorporated in solid phases of negligible vapor pressure. This may create difficulties in the use of processes involving reagents at high temperatures - such as slags or liquid-metal phases that may "lock in" lunar-deficient elements.

Reagent and equipment mass

For solution processes, the mass of the solvent system will generally exceed the mass of lunar input material in a specific vessel (except where solutions of over 50% by weight are practical). A more typical level may be about 5 to 10% by weight of solute. Further, not all of the solute may be transferred per pass during the various separation or extraction steps, so the ratio of solvent to "active solute" mass is normally much greater than unity.

Fortunately, for aqueous solutions, most of the solvent mass need not be transported from the earth, since the oxygen content, which represents 88.8% of the mass of water, is derivable from lunar materials. Even the hydrogen content may be extracted in sufficient quantities to largely (or entirely) replace that lost in the residual moisture content of products.

Now, let us consider the relative magnitude of equipment and reagent mass for the various units needed for a chemical processing plant. Specifically, one would like to know whether the process vessels, tanks, pipes, etc., weigh more or less than their contents. Analysis shows that, for most cases of equipment that contain 10% or more material in condensed phases, the contents may be expected to far outweigh the container (where the latter is constructed of high-specific-strength materials with minimal safe wall-thickness). Conversely, for gases, the container will invariably outweigh the contents. Furthermore, in the case of gases, the ratio of container to content mass is practically independent of pressure.

This finding reiterates the undesirability of processes that require storage or handling of large volumes of gas. In addition, for processes operating primarily in condensed phases, the mass of the processing operation, apart from power and radiator facilities, will probably be dominated by the masses of reagents involved. These masses, in turn, will depend on reaction and process times for the individual steps.

The engineering characterization of any proposed process may be identified by parameters as shown in Table VI. The sizing (volume) of equipment for any segment may be expressed as:

$$V = \frac{\dot{Q}_i \ell}{\rho_i v_i} = \frac{\dot{Q}}{\rho_i} \tau$$

where \dot{Q}_i is the mass flowrate of component i (kg/s), ℓ is a characteristic length (meters) of flowpath in the apparatus, ρ_i is the partial density of component i (kg/m³), v_i is a characteristic velocity of the i th component (m/s), and τ is the process time (s).

Each process step is characterized by an equivalent time (h), representing the time required for the passage of sufficient input material to equal the weights of gross or net contents or container for the step in question.

Summation of the appropriate equivalent times, therefore yields the total time required for the passage of sufficient input raw-material to equal the gross or net reagent masses, or the structural masses, for the processing system. Additional equivalent times may be derived to account for masses required for mechanical and thermal power sources; for distribution equipment, motors, pumps, compressors; for heat-transfer equipment, space-radiator facilities; and for other necessary support functions. A summary of the equivalent times for a specific process are developed in a later section.

Unit operations

(Materials handling)

Except for storage, these operations are not expected to require substantial masses. Most material can pass through a materials-handling step with velocities of 0.01 to 1 m/s or even higher, so such units would rarely have to handle more than a few minutes' throughput of the operation. Fine grinding using a ball mill or equivalent is somewhat slower, but it is not expected to be necessary for processing of lunar soils. Entrainment of liquids or dust in gas flows may become a problem in lunar gravity or low artificial gravity, but inertial gas or hydrocyclones or other devices may be used to suppress carryover.

(Phase separation)

The actual physical separation of different phases is usually limited by pressure or inertial considerations, such as foaming or entrainment in distillation columns, or sedimentation velocities in centrifugal filters or in centrifuges, although the material process-time may be limited by heat-transfer rates, growth rates of crystallites or precipitates, etc.

Because of the recycle nature of the various materials flow-loops, it may be preferable to shorten process times (even at the expense of recycling larger-than-normal fractions of intermediate flowstreams) to reduce the masses of intermediate stages. However, at the exit stages of the plant, it is important to limit the loss of reagents, especially those containing lunar-deficient elements, so it is necessary to attempt to carry those steps nearly to completion.

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As an illustration of the basic problem that might be common to any process that uses water as an intermediate rinse or reagent, we may discuss drying of nonmetallic output streams. Most finely divided metallic oxide or silica solids have an adsorbed or chemisorbed water content that can be removed by application of heat, time and pressure differentials. For many cases in which industrial drying of solids is practiced, the observed drying rate or rate of weight loss is initially nearly constant, but below a certain moisture content, the rate drops and often becomes nearly proportional to the "excess residual water content" or content in excess of the equilibrium level corresponding to the local temperature and pressure³. For such a dependence, drying would continue at a progressively slower rate for an infinitely long time and never reach constant weight. For a practical process, the operation must be terminated at some reasonable time or residual moisture content. One can derive an optimum drying time or moisture content in terms of the minimized total mass of drying equipment and replacement mass to supply hydrogen for water lost. Using typical operating parameters, the optimum residual moisture content may be expected to fall below 0.1%, but one can tolerate mass losses of 5-10 times that level.

Since the same mathematical dependence often occurs for chemical reactions approaching equilibrium, the preceding technique may be employed to calculate optimum process times and convergence (toward equilibrium) for chemical reactors.

(Heating and refrigeration)

Process-heat requirements may be satisfied by primary electrical or solar thermal sources, or indirectly by using steam or other working fluids, or by exchange with other process flowstreams. If processes are to use solar thermal energy, one may anticipate a substantial mass reduction for equivalent power levels. For example, mass reductions by factors of 30 or more may be possible by substituting solar-thermal for solar-electric power.

The coupling of thermal energy into powdered solids is often troublesome, and can rarely be done efficiently by radiation. One would normally prefer to heat such material by exchange with recirculating gases that are heated in an adjacent unit (by solar-furnace, electric-arc, resistance or induction sources). In certain cases, it may be possible to heat the powdered solids by high-frequency dielectric energy, or perhaps by using microwave energy.

(Heat transfer)

In heat exchange in which gas flow in one or both streams plays a part, one would like to operate at very high velocities or Reynold's numbers since the heat transfer coefficients in turbulent flow are roughly proportional to the 0.8 power of velocity or Reynold's number⁴. Heat transfer involving fluids in boiling or condensing flow are much higher than when no phase change is involved, so when liquids must be heated it is advantageous to operate under conditions of solution pressure and heater temperature to produce nucleate boiling at the interface when vapor pressures permit such operating modes.

Refrigeration or cooling operations may be required for process steps or for collecting, separating and storing noncondensable gases. Oxygen storage and hydrogen storage will probably represent the largest power and equipment requirements. Liquefaction of these gases would greatly reduce masses of the storage vessels required to handle them. By subcooling down to the triple point or lower, even further weight reductions are possible⁵.

(Reaction)

The design of reactors is usually dictated by the heat-balance requirements (endothermic or exothermic) and whether internal or external heating or cooling are required. Internally heated or cooled systems would usually be designed in large tubular, cylindrical or spherical vessels, while external heat transfer would usually require a large surface area and at least one short dimension (about 0.2 to 0.5 m). Electrolytic cells usually require a low anode-cathode separation (about 0.1 m or less) to avoid excessive power losses, but the cell may contain multiple anodes and cathodes and thus attain considerable minimum dimensions. However, it is heat-rejection requirements that usually limit the size of electrolytic cells.

SPECIFIC PROCESSES

Previous studies of extraterrestrial materials processing have generated proposed processes ranging from reagentless electrolysis to various high and low temperature thermochemical or electrochemical separations. We have reexamined these systems based on the selection criteria discussed earlier and briefly review their principal features and problems in this section. In addition, we present a description of two hydrochemical processes involving basic or acidic leaching of lunar ore. The latter system which we designate the HF acid leach process seems to offer the best prospects for efficient processing of lunar materials and we have designated it as our "baseline" process for more extended analysis and engineering studies to develop models for space industrialization.

Electrolysis of molten silicates

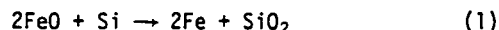
Limited investigations of direct electrolysis of molten silicates of compositions similar to lunar basalts have been performed⁶. The high melting-points and viscosities of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the "reagentless" advantage of the direct electrolysis route and requires consideration of extraction and recycling of fluxing reagents.

The chief objections (or problems awaiting solution) are the corrosion or durability of anodes used for oxygen recovery, and the purification and separation of cathodic reduction products (which are likely to consist of iron-aluminum-silicon alloys plus minor amounts of additional impurities).

Carbothermic/silicothermic reduction

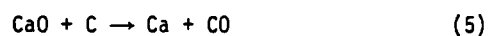
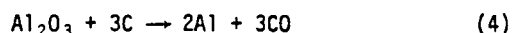
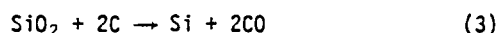
One of the first serious attempts to define a process option was performed by Phinney *et al.*⁷,

at the 1976 NASA-Ames Summer Study, in which silicothermic and carbothermic reduction of bulk lunar soil was discussed. After crushing the raw material, and magnetically separating the ferrous from the nonferrous fractions, reduction could commence. Silicon will reduce iron at 1,300°C, as shown by Eq. (1):



The products can be separated by centrifugation.

The iron-free silicates would be reduced by carbon at 2,300°C, as shown by Eq. (2-5):



By this process, it would be expected that aluminum and silicon would form a melt, while the other reduced metals, including the major impurities Ti, Mn and Cr, would be removed as vapors. However, this reaction scheme is much more complicated. At 2,300°C, condensed compounds, such as SiO, Al₄C₃, and Al₄O₄C are present, along with gases such as Al₂O, SiO, Al, and Si.

The pressures of Al₂O and Al are so high that liquid aluminum cannot be formed at normal operating pressures. Perhaps the greatest defect of the carbothermic reduction process is that although the winning of aluminum on earth via such a process was envisaged as early as the 1940s⁸, no plant for producing aluminum by this method has proved practical.

Carbo-chlorination process

At the 1977 NASA-Ames Summer Study, Rao *et al.*⁹ decided quite early that carbothermic reduction would probably be impractical for space processing. They opted for carbo-chlorination of lunar anorthite, CaAl₂Si₂O₈, and lunar ilmenite, FeTiO₃, which could be beneficiated from lunar soil¹⁰. The desired products are aluminum, iron, silicon (or silica), and titanium.

During our subsequent study at the Lunar and Planetary Institute, it became obvious that carbo-chlorination would create a major plant-size problem. The recycling of chlorine and carbon would require facilities much larger than the basic processing plant. One of the major advantages of carbo-chlorination is that it would require only a minimum of hydrometallurgical operations. Water would be needed, however, for hydrolysis, chlorine regeneration and possibly as a coolant for the system. In order to minimize the size of the heat-rejection radiators, large amounts of heat energy would have to be raised (heat pumped) to about 280°C, to achieve a mass efficient system.

These results led us to believe that processes that rejected less heat at low temperatures and made use of hydrometallurgical operations would tend to be more useful options for space processing.

NaOH basic-leach process

A review of the literature¹¹⁻¹⁴ indicates that anorthite can be decomposed with NaOH in an autoclave; and subsequent treatment of those products with more base can eventually yield alumina and calcium silicate — the latter could be used to make glass or could be hydrolyzed to yield lime and silica. For both basic and acidic leaching, sodium present in lunar soil can probably make up for any sodium lost during recycling. In this process, calcium impurities in the recycled NaOH would not present a problem, inasmuch as base, and not pure NaOH, is needed.

HF acid-leach process

This process uses low-temperature hydrochemical (hydrometallurgical) steps to separate the silica content of the lunar raw material from the other metallic oxides by conversion to fluorides and fluosilicates. This is followed by vaporization of the silica as SiF₄, and separation of the calcium and the structural metals (Al, Fe, Mg, Ti) by a variety of solution, precipitation, ion exchange, or electrolytic steps. Generalized process equations are given in Table VII. Iron may easily be recovered from solutions by electro-winning, but the remaining metals, except Mg, are preferably recovered by sodium reduction of the corresponding fluorides, fluosilicates or fluo-aluminates. Magnesium may be made by silicon reduction of MgO.

Sodium for the reduction of the metals and silicon can be conveniently obtained by a slight modification of the Castner cell, which at one time was the major commercial device for producing sodium. The Castner cell uses the electrolysis of molten NaOH to produce Na, O₂ and H₂. For lunar operations, the hydrogen is an undesirable byproduct, which can be largely eliminated by using a diaphragm cell and vacuum-drying the anolyte to remove the water formed by discharge of OH⁻ ions.

Metal oxides and silica are obtained, where desired, by hydrolysis of the corresponding fluorides or fluosilicates with steam (or with NH₃, if desired, for SiO₂) or by ion exchange (or permeation) methods. Detailed analyses of the options available for these separations remain to be completed.

A flowsheet for the HF acid-leach process is shown in Fig. 2.

Of the processes studied to date, the HF acid-leach one appears to have the best potential for minimal operating mass, ease of element separations to high purity, flexibility, and favorable energy and heat-rejection requirements.

A number of details and options remain to be investigated. Many of these specific process steps can be fully defined by straightforward experiments. If any readers are interested in undertaking some of these experiments (many are relatively simple), the authors of this article would be pleased to hear from them.

Separation of the fluoro compounds of the metallic elements by solubilities of fluorides or fluosilicates as a function of pH and F:Si ratio — with or without additional ion-exchange or

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electrolytic steps — will require extended literature searches and laboratory investigations. Pyrolytic and hydrolytic behavior of fluorides, fluosilicates and fluotitanates will also require additional research.

Despite these informational gaps, nearly all of the proposed operating steps have been studied on a laboratory scale, and about 75% of the steps have been conducted on a pilot or commercial scale under equivalent or comparable conditions.

(Thermochemistry)

The heat transfer requirements of the HF acid leach process may be derived from existing thermochemical data for the compounds present in the process equations. These may be used to prepare the ΔH vs T map shown in Fig. 3. In this figure the enthalpy changes involved in water transfer — distillation and condensation — have been omitted. The electrolysis heat load represents only the ohmic heat loss of the process step.

The total input power requirement is projected to total 4100 KWH/metric ton. For the plant sizing analysis, this was increased to 7130 KWH/metric ton to allow for various losses.

(Plant sizing)

The techniques of plant sizing and mass estimation developed in the preceding discussion were applied to the HF acid leach process. The results are shown in Table VIII. By summing the equivalent times for containers, net masses of lunar deficient elements and extra inventory and equipment, one obtains a total equivalent time of 81 hrs. If one uses gross instead of net reagent mass, the total becomes 155 hrs. In either event, the plant should be able to process more lunar ore than its total mass each week, or on an annual basis it could supply more than 50 times the earth lift mass of the plant.

(Reagent replacement mass)

The principal lunar deficient elements used in the HF acid leach process are H, F, Na and optionally N. (Sodium is probably not a serious consideration since it is a minor lunar element and frequently occurs at levels exceeding 2.5% of the total metallic equivalents in feldspar fractions from mare soils.) These recycling elements will occur principally as chemically or physically combined water or hydroxyl ion (H) or fluoride ion (F) and as ammonia or ammonium ion (N).

The hydrogen and nitrogen content of vacuum dried, calcined refractory oxides or other compounds can be reduced to almost any desired level given sufficient time and temperature at low pressure although mass efficient operation may not be served by drying to less than 0.1% as discussed earlier. If we assume a conservative residual content of 0.5% H_2O and 0.1% NH_3 for the non-metallic output streams and zero for these impurities in metal outputs, the ratios of reagent replacement mass:input mass for H and N may be expected to fall in the ranges $3.7 - 7.4 \times 10^{-4}$ and $4.1 - 8.2 \times 10^{-4}$ depend on amount of reduced products. The moisture content or dew point of oxygen can be held to insignificant levels.

The residual fluorine level will occur principally as residue from steam hydrolysis of refractory fluorides, and cannot be oaked out in a practical manner. Analytical studies¹⁵ suggest that the fluorine content of pyrohydrolyzed fluorides can be reduced to 0.25 to 0.5% without undue extension of the process. Vacuum cycling may possibly lead to lower residual levels. We may anticipate F replacement mass:input mass ratios in the range of $1 - 2 \times 10^{-3}$ and possibly lower with improved vacuum desorption.

Total reagent replacement mass:input mass can probably be held below one part in 300 with further improvements likely. At this rate, the reagent replacement mass requirement would equal the initial net plant mass in 3 to 6 years. It may be noted that replacement mass need not be supplied in elemental, toxic or hazardous forms.

(Minimum scaling)

There is no fundamental reason why the chemical processing facility could not be reduced down to laboratory bench scale. Table VIII indicates a total process time of less than 36 hrs. The longest process time other than electrolysis is 3 hrs. for which the corresponding units would contain 3 kg of lunar ore at an average throughput of 1 kg/hr or 7.13 metric tons/year with an 81% duty cycle. At a very small scale, the mass:throughput and power:throughput ratios may be expected to increase — perhaps by as much as a factor of two.

The concept of bootstrap growth of processing capacity can increase the annual output mass:net plant mass ratio by an amount limited by the reagent requirements for lunar deficient elements. For the HF acid leach process, the LDE net reagent mass represents 28% of the net plant mass, so the annual output:net plant mass ratio could be nearly quadrupled by expanding equipment capacity using lunar materials. Even greater increases may result from process revisions or modifications of operating cycles which can reduce the equivalent times required for LDE reagents.

The Lunar and Planetary Institute is operated by the Universities Space Research Association under Contract No. NSR 09-051-001 with the National Aeronautics and Space Administration. This paper is LPI Contribution No. 373.

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High-titanium basalts				
Modal abundance (Vol.%)	Pyroxene	Olivine	Plagioclase	Opaques (mostly ilmenite)
	42.60%	0-10%	15-33%	10-34%
Component (Wt.%)				
SiO ₂	44.1-53.8	29.2-38.6	46.9-53.3	< 1.0
Al ₂ O ₃	0.6- 6.0	-	28.9-34.5	0 - 2.0
TiO ₂	0.7- 6.0	-	-	52.1-74.0
Cr ₂ O ₃	0 - 0.7	0.1- 0.2	-	0.4- 2.2
FeO	8.1-45.8	25.4-28.8	0.3- 1.4	14.9-45.7
MnO	0 - 0.7	0.2- 0.3	-	< 1.0
MgO	1.7-22.8	33.5-36.5	0 - 0.3	0.7- 8.6
CaO	3.7-20.7	0.2- 0.3	14.3-18.6	< 1.0
Na ₂ O	0 - 0.2	-	0.7- 2.7	-
K ₂ O	-	-	0 - 0.4	-
Low Titanium basalts				
Modal abundance (Vol.%)	42-60%	0-36%	17-33%	1-11%
Component (Wt.%)				
SiO ₂	41.2-54.0	33.5-38.1	44.4-48.2	< 1.0
Al ₂ O ₃	0.6-11.9	-	32.0-35.2	0.1- 1.2
TiO ₂	0.2- 3.0	-	-	50.7-53.9
Cr ₂ O ₃	0 - 1.5	0.3- 0.7	-	0.2- 0.8
FeO	13.1-45.5	21.1-47.2	0.4- 2.6	44.1-46.8
MnO	0 - 0.6	0.1- 0.4	-	0.3- 0.5
MgO	0.3-26.3	18.5-39.2	0.1- 1.2	0.1- 2.3
CaO	2.0-16.9	0 - 0.3	16.9-19.2	< 1.0
Na ₂ O	0 - 0.1	-	0.4- 1.3	-
K ₂ O	-	-	0 - 0.3	-
Highlands rocks				
Modal abundance (Vol.%)	5-35%	0-35%	45-95%	0-5%
Component (Wt.%)				
SiO ₂	51.10-55.4	37.70-39.9	44.00-48.0	0 - 0.1
Al ₂ O ₃	1.00- 2.5	0 - 0.1	32.00-36.0	0.80-65.0
TiO ₂	0.45- 1.3	0 - 0.1	0.02- 0.03	0.40-53.0
Cr ₂ O ₃	0.30- 0.7	0 - 0.1	0 - 0.02	0.40- 4.0
FeO	8.20-24.0	13.40-27.3	0.18- 0.34	11.60-36.0
MgO	16.70-30.9	33.40-45.5	0 - 0.18	7.70-20.0
CaO	1.90-16.7	0.20- 0.3	19.00-20.0	0 - 0.6
Na ₂ O	-	-	0.20- 0.6	-
K ₂ O	-	-	0.03- 0.15	-

Table I (LEFT)

Ranges of chemical compositions for the major minerals

Table II Potential availability of lunar elements

Major elements ≥ 1% lunar
O, Si, Al, Ca, Fe, Mg, Ti

Minor elements 0.1 - 1%
Cr, Mn, Na, K, S, P

Trace elements < 0.1%
H, He, C, N plus all others

(Beneficiation may permit concentrating some trace elements into minor or higher range.)

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Table III Useful products derivable
primarily from lunar sources

STRUCTURAL MATERIALS	
Metals	Steels, aluminum, magnesium, titanium and alloys
Reinforced Metals	Metals above reinforced with silica, steel, alumina or titanium silicide
Glasses	Calcium, magnesium, aluminum, or titanium silicates, fused silica, foamed glasses
Ceramics	Alumina, magnesia, silica, complex oxides, fused basalts
Hydraulic Cements	(Need water)
THERMAL AND SPECIALTY MATERIALS	
Refractory and Hard Materials	Ceramics above plus chromia, titania, titanium silicides
Abrasives	Alumina, garnets, silicon carbide, titanium carbide (limited by C)
Insulation	Ceramics above plus fiberglass, fibrous or powdered ceramics
ELECTRICAL MATERIALS	
Conductors	Aluminum, magnesium, iron, resistance alloys (FeCrAl), silicon
Electrodes	Fe ₃ O ₄ , TiO, graphite (limited by C)
Magnetic Materials	Iron alloys, magnetic ceramics (ferrites, magnetoplumbites)
Electrical Insulation	See glasses, ceramics and thermal insulation
FIBROUS MATERIALS	
	Glass, silica, synthetic mineral wool For apparel, paper, filters, etc.
PLASTICS AND ELASTOMERS	
	Silicone resins (limited by C)
SEALANTS, ADHESIVES AND COATINGS	
	Soluble silicates Anodized coatings On aluminum, magnesium, titanium Electroplating Chromium, etc. Sputtered or vacuum deposited coatings

Table III (cont'd.)

LUBRICANTS, HEAT TRANSFER FLUIDS	
	Sulfides, graphite (limited by C) SO ₂ , He
INDUSTRIAL CHEMICALS	
	Detergents, cleansers, solvents, acids, bases H ₂ SO ₄ , H ₃ PO ₄ , CaO, NaOH
BIOSUPPORT	
	Oxygen (breathing), 16/18 of water by mass SiO ₂ - soil component (including trace nutrients) Bioelements O, Ca, C, Fe, Mg, K, P, N, Na, H others

Table IV Product-mix options

Metal/silica ratio		
Equivalentents	1:1	Olivine, anorthite, orthosilicates
	0.5:1	Pyroxene, metasilicates
	0:1	Silica
	1:0	Ilmenite, spinel, troilite, etc. Neutral iron
Aluminum/iron ratio		
	Negative correlation Approximate range 5:1 to 1:4 (whole soils)	
Nonstructural-/structural-metal ratio		
Ca:Al	Plagioclase: ~ 1:2	
Ca:(Mg+Fe)	Pyroxenes: 1:1 to 0.1:1	
	Ilmenite: 0:1	
Light-metal/iron ratio		
(Al+Mg):Fe	Similar to Al:Fe	
Silicon/silica ratio		
Reduction requirements Demand conditioned on use of photovoltaic systems		
Metal/metal-oxide ratio		
Reduction requirements Depends on demand for metals vs. refractories and pigments		
Oxygen/metal ratio		
Depending on ratio of oxygen to the structural metal (and silicon) demand. Oxygen may appear as an unneeded byproduct, or iron and other reductants may be surplus materials		
Reinforced/normal-metal ratio		
Demand dependent on suitability of reinforced metals to replace a variable portion of reinforced resins in structures		

Table V Chemical plant design

Selection of process options

Special space environmental factors

- Gravity (natural or artificial)
- Vacuum
- Heat rejection
- Recycling of nonlunar-indigenous materials

Description of unit operations

- Materials handling
- Phase separations
- Heat exchange
- Reactors
- Energy requirements
- Heat-rejection requirements

Sizing factors

- Kinetics limited
- Heat-transfer limited
- Momentum limited

Table VI Engineering design parameters

Equipment	Capacity	Typical stream velocity, V_j (or characteristic velocity)	Process time	Other
Motors, pumps, compressors (except vacuum)	$\frac{10^3 \text{ kW}}{\text{m}^3}$	10 to 100 m/s	1 s	$\frac{1 \text{ kg}}{\text{kW}}$ or $\frac{\text{t}}{\text{MW}}$
Distillation columns	mass flowrate $1-5 \text{ kg/m}^2 \text{ s}$	1 to 3 m/s (vapor) (entrainment limited)	5-10 s	length: 0.4 - 0.6 m/plate
Sedimentation centrifuges	volumetric flowrate	settling velocity ($10 \mu\text{m}$ particles) $10^{-5} \text{ m/s} \times g$ typical velocity: $10^{-2} \text{ m/s} @ 1,000 g$	0.5-2 min	power $50-100 \frac{\text{kW}}{\text{m}^2}$
Rotary kilns	Loading density $0.05 - 0.2 \text{ t/m}^3$	3 to 10 m/h (axial) (0.0033 - 0.0083 m/s)	2-10 hr	rotary power $0.1 - 0.2 \frac{\text{kW}}{\text{m}^3}$
Ion-exchange columns	0.5-3 equiv. $\frac{\text{kg}(\text{resin})}{\text{kg}(\text{resin})}$	0.2 to 0.5 m/min (0.0033 - 0.0028 m/s)	5-15 min	
Aqueous-systems heat transfer				
Nucleate boiling	15-240 kW/m^2			$h = 2-16$ $\text{kW/m}^2\text{K}$ $\Delta T = 10-20\text{K}$
Condensation (inside tubes)	30-1,000 kW/m^2	30 to 150 m/s (vapor)		$h = 3-50$ $\text{kW/m}^2\text{K}$ $\Delta T = 10-20\text{K}$
Electrolytic cells	$i = 10^3 - 10^4$	ion-migration velocity $10^{-7} - 10^{-5} \text{ m/s}$	10-50 h	

1. $xMO \cdot SiO_2 + (4 + 2x) HF = xMF_2 + SiF_4 (aq) + (2 + x) H_2O$
- 1'. $xMO \cdot SiO_2 + (5 + 2x) HF = xMF_2 + HSiF_5 (aq) + (2 + x) H_2O$
2. $SiF_4 (aq) + NH_2O = SiF_4 (v) + nH_2O(v)$
- 2'. $HSiF_5 (aq) + nH_2O = SiF_4 (v) + HF (aq) + nH_2O(v)$
3. $(1-y) [SiF_4 (v) + 4H_2O = Si(OH)_4 + 4 HF]$
- 3a. $(1-y) [SiF_4 (v) + 2H_2O = SiO_2 + 4HF]$
4. $(1-y'z) [xMF_2 + H_2O = xMO + 2xHF]$
5. $y [SiF_4 + 4Na = Si + 4NaF]$
6. $y' [xMF_2 + 2xNa = xM + 2xNaF]$
7. $z [xMF_2 + xSiF_4 (aq) = xMSiF_6 (aq)]$
8. $z [xMSiF_6 (aq) + xH_2O + \text{electrical energy} = (x/2)O_2 + xM + xH_2SiF_6]$
- 8a. $z [xMSiF_6 (aq) + M'SO_3R^* = xM'SiF_6 (aq) + xMSO_3R^*]$
9. $mNaF + mR^*OH = mNaOH + mR^*F$
- 9a. $mNaF + (m/2) Ca(OH)_2 = mNaOH + (m/w) CaF_2$
10. $mNaOH + \text{electrical energy} = mNa + (m/2)O_2 + (m/2)H_2O$
11. $(1-y) [Si(OH)_4 = SiO_2 + 2H_2O]$

Table VII HF acid leach process equations

R* = ion-exchange
m = 4y + 2xy'

Table VIII Equipment and reagent masses - process and equivalent times

Step	t Process Time(hr)	R _m	r _m	R' _m	h ₁ =tR _m	h ₂ =tr _m	h ₃ =tR' _m
		Contents Equiv. input	Mass Ratios Container Equiv. input	Net contents(LDE) Equiv. input	Equivalent Times* (hr) Container	Contents	Net(LDE)contents
Acid Leach	.5	.2	.48	7.95	11.1	.24	3.97
Sedim.centrifuge/ Distill	.0167	22.2	28.8	7.95	.371	.48	.133
Hydrolyze	.5	44.9	.96	14.7	22.5	.48	7.36
Sedim. Centrif.	.0167	44.9	42.6	14.7	.75	.71	.207
Distill/ Condense	.00278	7.06	86.4	2.14	.0196	.24	.006
Distill(1/2)	.00278	22.5	86.4	7.36	.0625	.24	.020
Hydrolyze/dry	3.0	3.0	.55	.728	9.0	1.66	2.18
Distill	.00278	7.63	86.4	1.36	.021	.24	.004
Electrolysis	27.5	1.45	.173	.036	40.05	4.75	1.0
Metals reduction	3.0	1.76	.48	.7	5.28	1.43	2.1
Regeneration(est).	.5	5.0	.48	.7	2.5	.24	.35
Misc.	.5	1.0	.4	1.0	.5	.2	.5
Subtotal	35.54				92.15	10.91	17.83
EXTRA MASS		(metric tons @ 4.21 ton/hr input)			equiv. time (hr)		
Reagent Inventory			20			4.7	
Compressors			10			2.4	
Heat Exchangers			10			2.4	
Pipes, Valves			5			1.2	
Electrical			6			1.4	
Structural & misc.			25			5.94	
Radiators (20 MW)			24			5.7	
Elec. Power (30 MW)			120			28.5	
Subtotal			220			52.24	

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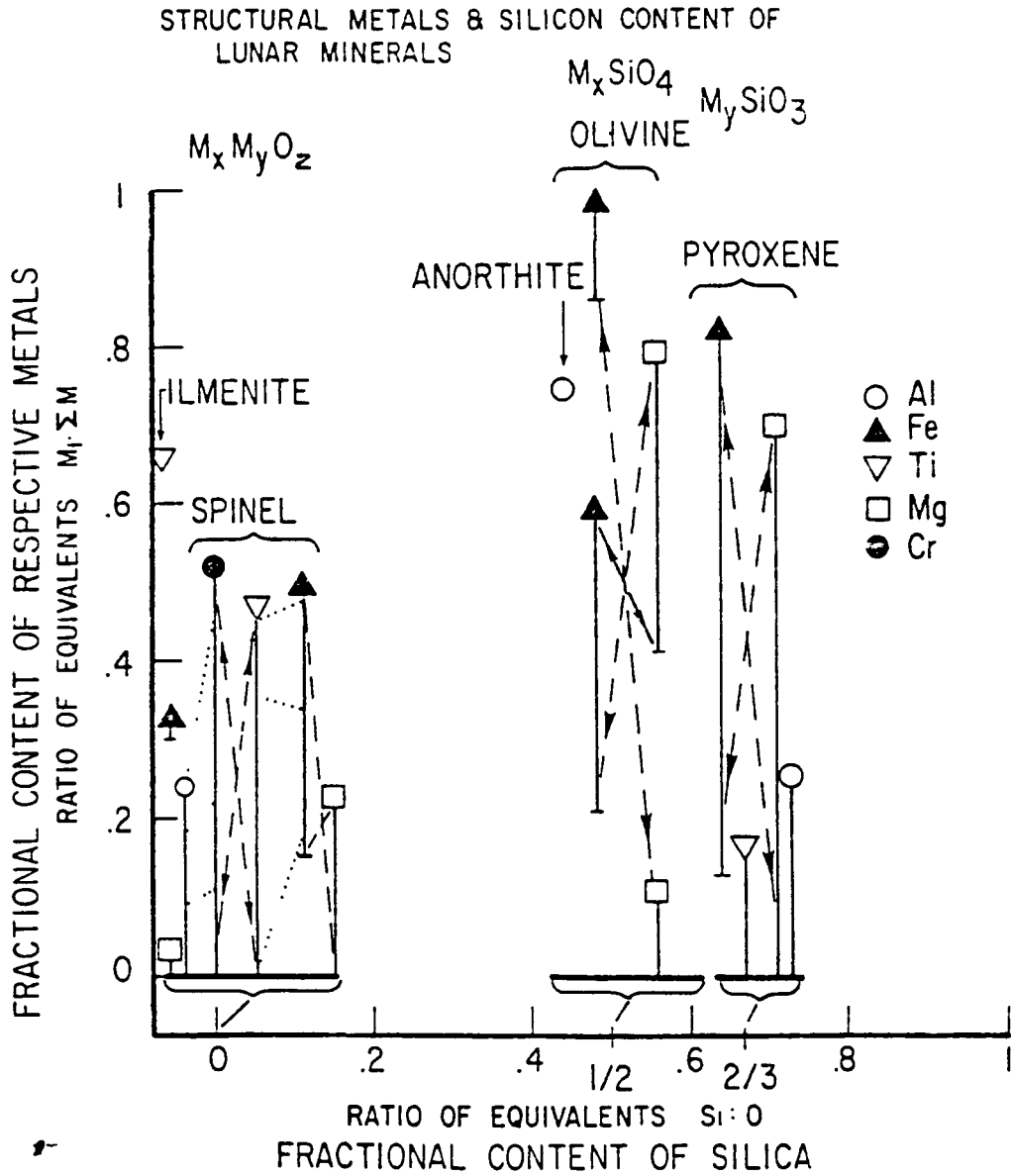


Figure 1.

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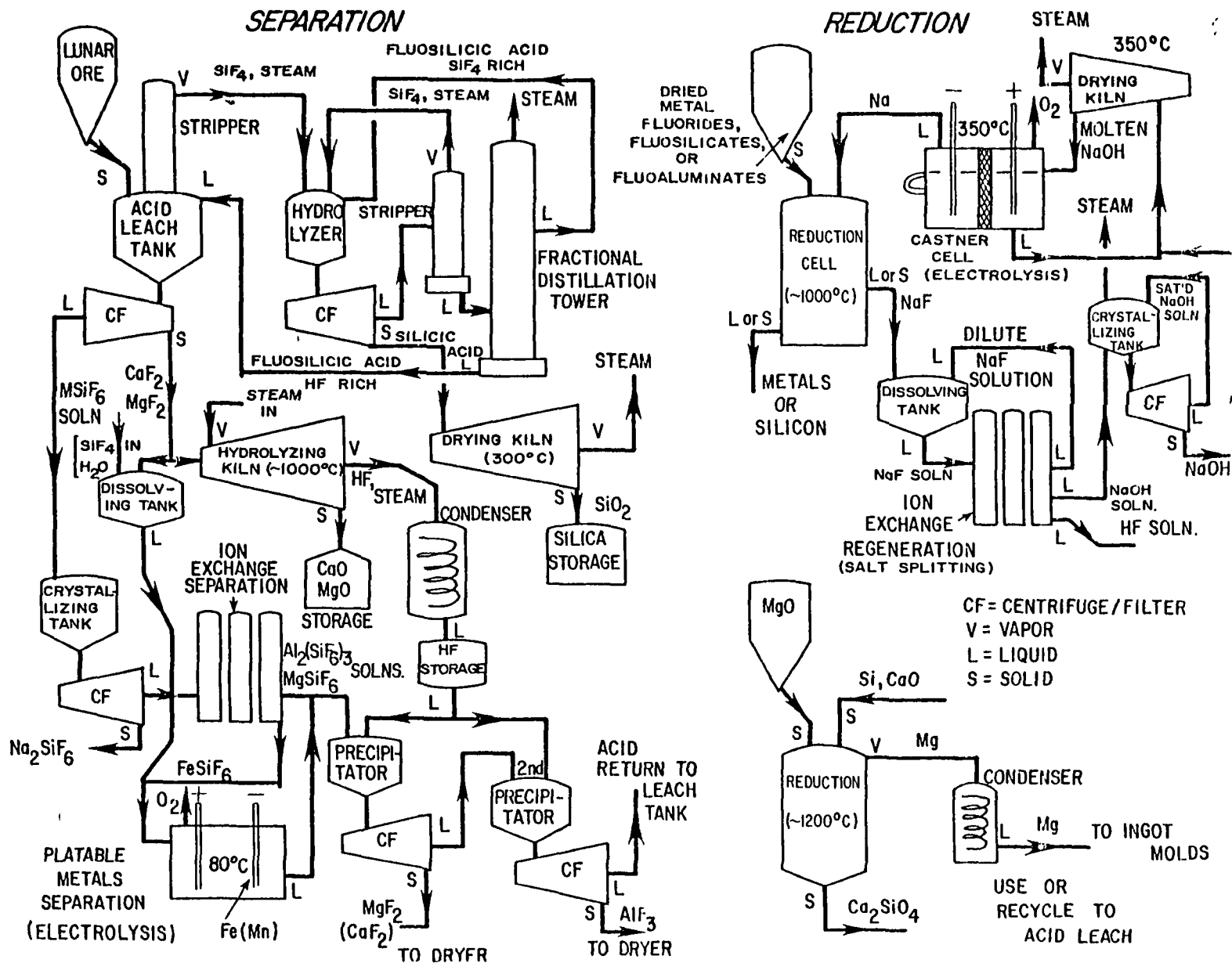
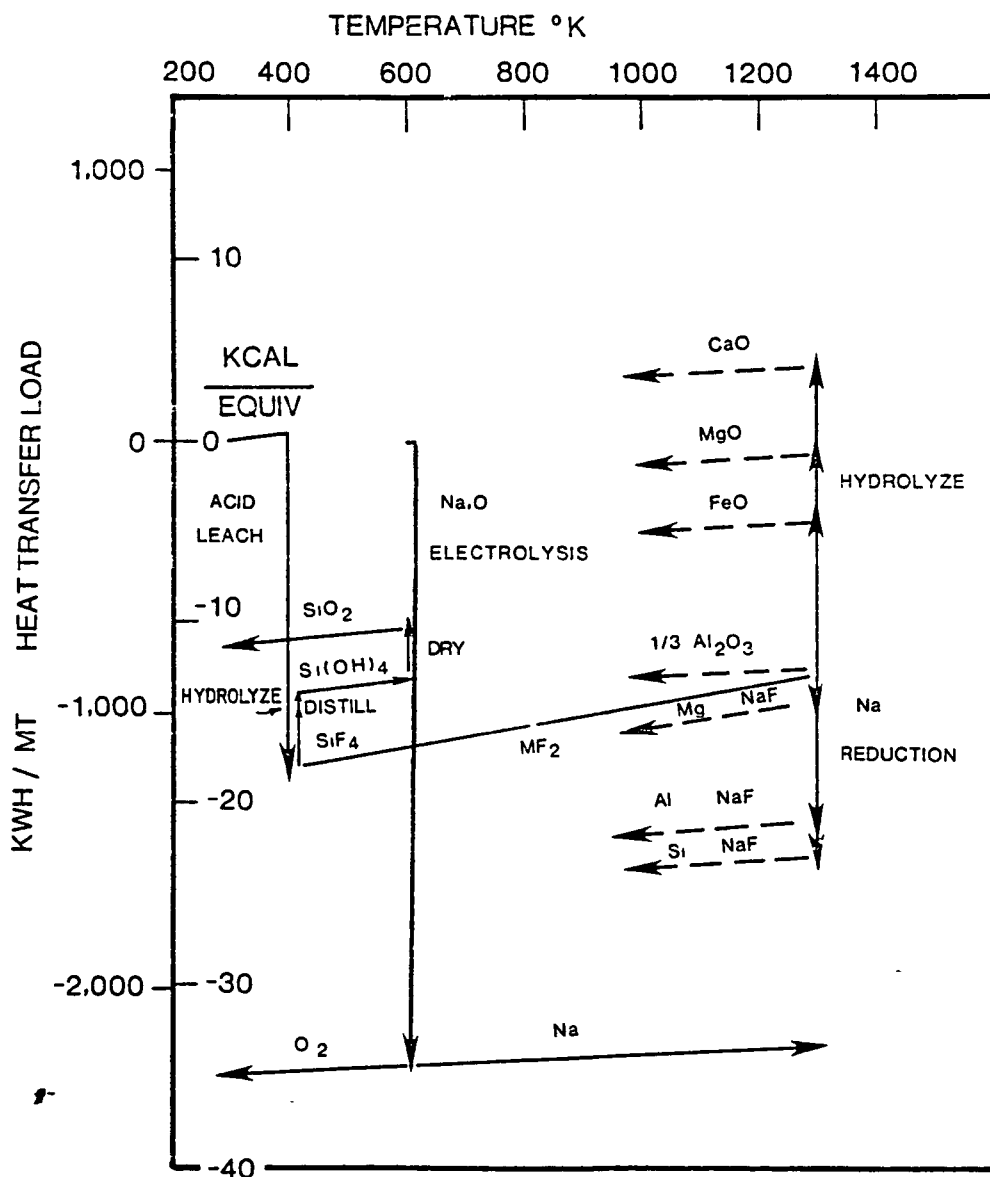


Figure 2. PICTORIAL FLOW CHART FOR HF ACID LEACH PROCESS

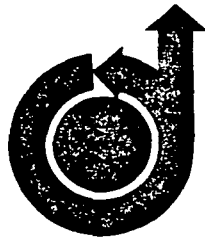
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TEMPERATURE/HEAT LOAD DIAGRAM FOR HF ACID LEACH PROCESS

Figure 3



79-1391

**Scaling and the Start-Up Phase
of Space Industrialization**

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Planetary Institute, Houston,
Texas

Reprinted from:

**4th PRINCETON/AIAA CONFERENCE
ON SPACE MANUFACTURING
FACILITIES**

May 14-17, 1979/Princeton, NJ

SCALING AND THE START-UP PHASE OF SPACE INDUSTRIALIZATION

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Abstract

By terrestrial standards very little mass is needed to construct the space portion of a 10,000 megawatt (10 GW) power system. Use of lunar materials makes it reasonable to consider alternatives to silicon solar cells for conversion of sunlight to electricity and thereby avoid present major problems associated with solar cell production. Machinery needed on the moon to excavate lunar materials and deliver them to a transport system, to beneficiate lunar materials, to produce glasses and ceramics from lunar materials and to chemically process lunar materials into their major oxides and elements are minor mass fractions of the total mass of equipment needed in space to produce an SPS. In addition the processing equipment can throughout several hundred times their own mass each year with very little requirement for makeup mass from earth.

Space Power System Masses Compared to Terrestrial Units

Space solar power stations appear to be ideal candidates for initial products of an early space industry because of their expected high intrinsic value (200 - 400 \$/kg) and the vast potential terrestrial market the order of one trillion dollars over the next thirty years. It is now clear that space power stations can be constructed of approximately 90% lunar derived materials even without redesign of the terrestrially based models. ¹ With redesign this fraction might be increased somewhat and more importantly the fabrication processes might be substantially simplified.

It is important to pursue the subject of the scale of the SPS as a candidate for construction in space because it provides a dramatic model by which to appreciate how efficiently mass can be used in space and on earth to convert solar energy into electricity. Figure 1 is a scaled sketch of the Grand Coulee Dam in Washington state. Grand Coulee Dam is of interest because it is the largest single producer of electrical power in the United States. Its maximum electrical output will be 9,200,000 kilowatts (9.2 GW) or approximately 10% less than the projected ground output of an SPS. The metropolitan area of Houston consumes 10 GW. Grand Coulee was, and still is, a very large structure with a length of 1.3 km, a height of 0.1 km and a mass of approximately 40,000,000 tons (T). It was planned during the 1920's and constructed in the 1930's. It was clearly a sophisticated engineering challenge. Incidentally, Grand Coulee is powered by solar energy with rain water being the transducer of solar energy to mechanical energy. The energy collector area of Grand Coulee is the drainage basin for the eastern portion of the Columbia

River and is approximately 300,000 km². ³

Compared to Grand Coulee little mass is required in space for solar collectors and transmitting antennas to construct an SPS. The concrete mass equivalent (5 T/m³) of an SPS would be contained in the small, elongated box of concrete along the top left hand portion of the dam. The 10 by 10 by 200 meter section of concrete has a mass of 100,000 T or the same as one SPS. Alternatively, 100,000 T is a 3 meter thick slide across the dam. SPS is an extremely efficient mechanism for the collection of and conversion of solar energy to electricity.

The ground receiving array can be divided into two parts — the sophisticated and expensive electronics for power reception and the support structures of the electronic elements. ⁴ The sophisticated components have a total mass of approximately 4,500 T and occupy a volume of equivalent mass of concrete of 10 by 10 by 9 meters. The mass of ground antenna supports is large. Recent estimates indicate 2,000,000 tons of concrete pedestals which correspond to 5% of the mass of Grand Coulee. However, there is a very significant difference in that the support structure for the receiving antennas is constructable as many small individual units of concrete and/or metal stands rather than a monolithic structure such as the containment vessel of a nuclear power plant.

Space power systems appear very attractive on a mass standpoint in comparison to nuclear and coal fired plants of similar electrical output. A 10 GW nuclear plant will have an overall mass of the order of 8,000,000 T including foundations, radiation shield, reactors, generators, and ancillary equipment.

A coal fired plant composed of 20 units of 0.5 GW output would have a mass the order of 2,000,000 T or approximately the mass of the support structure of the receiving antenna for a space power system. However, the coal fired plant must burn approximately 35,000,000 T of coal each year. Thus, one 10 GW coal station must transport the mass equivalent of Grand Coulee Dam each year. Presently, the U. S. consumes 16 Grand Coulee's of coal each year. In order to increase the national energy dependence on coal to 40% by the year 2000, we must invest approximately 80 B\$ in new mines and transportation systems. We would then be burning approximately 60 Grand Coulee's of coal annually. ⁵

Viewed in comparison to Grand Coulee Dam, one begins to be impressed not with the large physical area or size of an SPS (5 by 20 by 0.1 kilometers) but rather, with the fantastically efficient use of matter that an SPS affords in gathering energy and

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converting it for use on earth or in space. Far less matter must be manipulated, re-structured and emplaced in space to produce useful power on the ground than any other power scheme proposed to date. This includes projected terrestrial solar power arrays which must be 6 to 15 times as large in area due to night and cloud cover to collect the same average energy flux and which must be more massive per unit of area to withstand the gravity and environmental conditions of earth. Finally, it is not unreasonable to expect further advances in the transmission of power to the ground to substantially reduce the size and costs of the receiving systems. Viewed in another way one realizes that Grand Coulee contains sufficient mass-equivalent to construct 400 to 500 SPS units. This quantity of electric energy could satisfy all United States power demands well into the next century.

Attention must also be given to overall system scales which must be created and operated if SPS is to be deployed from the earth versus constructed from lunar materials. A feeling for the relative sizes is also contained in Fig. 1. Proposals exist for fully reusable two-stage boosters to be used to ship semi-finished or feedstock materials from earth to low earth orbit to manufacture an SPS unit.^{4,6} If these boosters utilize hydrogen and oxygen for propellants, then theoretically the exhaust product could be pure water. The quantity of water exhausted from the launches of all the heavy lift launch vehicles (HLLV) to transport 100,000 T to low earth orbit is indicated in Fig. 1-3 as effluent from Grand Coulee Dam. The effluent could form a body of water 10 meters deep by 300 meters wide by 660 meters long. Theoretical designs are available of boosters which are scaled to accommodate this quantity of liquid propellant usage over the course of 250 flights. Other boosters which utilize hydrocarbons and liquid oxygen would have an effluent approximately four times as massive. Bulk liquid handling technology is available to handle this magnitude of propellant. It is used commonly on earth with petroleum at many ports. However, the terrestrial systems are large by traditional aerospace standards and these new launch vehicles must operate in the severe environment of the launch from earth to low earth orbit and return safely many times with minimum refurbishment required between launches. Inert mass of the two-stage fully reusable booster would be the order of 1,000 T. The first stage would have an inert mass of approximately 800 T; the second stage 400 T. The second stage would lift a payload to orbit of 400 T. Half of the fuel in each flight would be used simply to boost the inert mass of the second stage into orbit.

If hydrogen and oxygen were burned stoichiometrically in fuel cells on the moon and used to eject with 60% efficiency 100,000 T into space by means of an electromagnetic mass driver then only 13,000 T of water would be produced which corresponds

to 0.7% of the water effluent of the terrestrial boosters. It is not being suggested here that hydrogen and oxygen be used with fuel cells on the moon to produce power to launch payloads in space. Our objective is to illustrate the great difference in the practical scales of propellant and materials handling, at least a factor of 150, which can be expected between utilizing lunar versus only terrestrial materials to construct an SPS or other large space structures. In point of fact, it is anticipated that solar energy will be utilized to power the lunar mass driver and that considerable use will be made of the earliest solar cell production of a space manufacturing facility to increase the ejection capacity of a lunar supply base.¹⁵

Raw Materials Scale

Figure 2 gives a more detailed depiction of the scale of the raw materials handling and the distribution of processed materials for one 10 GW SPS. We assume for this figure that highland soil essentially equivalent to the whole rock composition of highland rocks is available at the mining site. The major mineral will be plagioclase. The minor mineral will be ilmenite mixed with opaque glasses.^{7,8} The oxide compositions of these constituents are approximated as: plagioclase (SiO_2 - 45% by weight, Al_2O_3 - 35%, CaO - 20%) and for the opaques (Al_2O_3 - 20%, TiO_2 - 30%, FeO - 40% and MgO - 10%). It is assumed that magnetic, electric and physical separation techniques have been applied to the soils to produce a 90% plagioclase and 10% residue of opaques and ilmenite for the mineral fractions and which composes approximately 65% of the soil. The remaining 35% is the glass fraction which is used to make native glass components of the SPS. The compositions are in general agreement with modal analyses of the soils returned from the Apollo 17 site.⁹

A total of 215,900 tons of selected lunar material must be transported off the moon and thermally and chemically processed to form 90% of a space power station.² Depending on the exact highland landing site it will be necessary to beneficiate up to approximately twice this much soil to produce the ratios of native glass, opaque minerals and plagioclase. It is reasonable to assume that the soil has a bulk density of 2 tons/ M^3 . Thus, we must be prepared to beneficiate 431,800 tons of soil or 216,000 M^3 . This corresponds to a 10 M deep square of soil which is 103 M on a side. If the ultimate objective is to supply materials for the construction of one 10 GW SPS per year, then the excavation and beneficiation rates are the order of 740 tons per day (24 hours) on an 80% operations level or 31 tons per hour. This is a moderate excavation rate by terrestrial standards if the 1/6 gravity of the moon is taken into account. It is advantageous to start with a small operation on the moon and build up to this excavation rate.

Lunar Base

The magnitude of equipment which must be employed on the moon in the initial gathering and processing of lunar material is depicted in Fig. 3. It is highly desirable to minimize the mass of equipment necessary to start operations in space and to make maximum use of space materials to build up further capabilities. The rationale and design of the base was developed during the 1977 Summer Study on space industrialization conducted at the NASA Ames Research Center. ^{15a} Initial mass on the moon of the base would be approximately 800 tons. Approximately 4000 tons of landers, fuels and payload would have to be ejected from low earth orbit to the moon to land the base. We estimate that 20 - 30 people could install the base in four to six months and ten people could operate it. It would begin ejecting 30,000 tons/year of bulk lunar soil and grow in launch capacity to 0.6 Megton/year (≈ 3 SPS) over five years. Growth would be provided by the addition of solar cells, habitats and mining equipment.

The initial mining operations would be very small by terrestrial standards. The first excavation is a few meters deep and less than 50 meters in width. It is being worked by a single backhoe which is a small and versatile piece of excavation equipment which can be operated in a semiautomatic mode and monitored from earth. It is estimated that under nominal conditions only one front-end loader (25 T mass) with 12.5 tons of payload will be required to excavate and haul all the soil to a transportation point for ejection from the moon. This assumes the use of beneficiation at the site of the excavation. Approximately 80 MW-hr/yr will be required to operate the equipment. Subsequent introduction of 10 T or 50 T (payload) haulers will increase haulage and efficiency. Few personnel on the moon will be associated with operation of the equipment. Less than one manyear of maintenance per year should be required.^{10,14}

The four partially covered tanks are the liquid hydrogen sections of shuttle belly tanks converted to use as habitats, maintenance facility, mass driver loading facility and soil packaging facility. Each tank is approximately 24 meters long.

Under nominal conditions with at-the-mine beneficiation less than 300 tons of mining equipment would be required on the moon over 30 years to deliver 16 million tons of ore to the launcher. Pending the performance of engineering tests of various separation techniques in a quantitative manner on available lunar soils we can only estimate the mass of apparatus required. The calculations of Incullet ¹¹ are modified for the assumptions of 80% duty cycles, an annual mining rate of 432,000 T rather than one magaton and the need for only one stage of beneficiation. Under these assumptions two beneficiation units would be required. A total mass the order of 40 tons and power of 14 kilowatts during operation or approx-

imately 98 MW-hr/yr would be required. These beneficiation techniques should be highly automated and require only maintenance support from lunar personnel. It may well be that the use of physical and magnetic separation processes will require even less power and mass than estimated here. Non-destructive tests on lunar soils can provide far more accurate knowledge of efficiencies.

One cannot send the combination of minerals from the moon which would exactly fulfill the elemental requirements for the construction of an SPS. We assume that the proper mix of native glass to silicon tonnage can be established by the low energy beneficiation processes on the lunar surface. However, the need for silicon to use in solar cells forces one to export from the moon more oxygen, aluminum, calcium, titanium and magnesium than are required by the SPS. It is apparent that the absolute value of this excess is artificial. Substitution of materials will allow the use of aluminum, titanium and magnesium in the construction of SPS units as structural elements and the use of calcium as an electrical conductor under some conditions. ¹² In addition, the by-products of the refining process are far from useless in space. All these excess elements can be employed in support of non-SPS functions to great advantage. For example, the oxygen can be used in propulsion and life support; aluminum, iron, calcium, titanium and magnesium can be used in the construction of bootstrapped facilities, spacecraft and other devices for use in space such as radio telescopes, communications equipment and as inputs to products to be used on earth.

Three different materials processing challenges are presented by the major blocks of Fig. 2. These are glass and ceramics production of 34,700 tons/year (or 120 tons per day at 80% utilization), total chemical processing of the lunar soils to separated oxides and separated elements of 181,200 tons/year (or 620 tons/day at 80% utilization) and the preparation of 14,950 tons/year of semiconductor-grade silicon. We will address only the first two problems. However, it is possible that the chemical processing scheme proposed in the following section may be capable of providing the silicon of the required purity level of use in solar cell manufacturing without further secondary refining. ¹³

Chemical Processing Facility

Considerable detailed analysis has gone into the conceptual development of a chemical processing facility which could accept any of the major lunar minerals (pyroxenes, plagioclase, olivine or ilmenite with some modifications) and produce virtually complete separation of the oxides or the elements of the minerals.^{13,14,15,16} The system presented here ¹³ is designed to utilize process steps which are or have been employed in production plants, in prototype industrial operations or depend on well

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established principles of chemical engineering. Much emphasis has been placed on minimizing process temperatures, using low pressure aqueous solutions (avoid the use of high pressure gases), minimizing the loss of process chemicals which must be imported from earth and maximizing the use of lunar materials in both the process chemistry and in the construction of the facility. *It is especially important that the facility can be scaled in output versus size over a wide range of input flow rates.* This means that small benchtop units can be quickly developed, modified for use in Spacelab and deployed on the moon and in orbit as both test articles and productive units.

Figure 4 shows the approximate appearance of the first industrial scale unit appropriate to the start of SPS production. The plant is optimized to process anorthosite (90% pure) at the rate of 30,000 tons/year. A 30 MW solar-power array dominates the picture. It is octahedral, approximately 500 meters on a side, and masses 120 tons. This particular processing facility should have a rather surprisingly low mass. The processing units will mass 105 tons, initial reagent inventory 65 tons, and the solar cells 120 tons. These masses could be placed in orbit by 10 to 15 Shuttle flights. Another 10 to 15 Shuttle flights could deploy the 260 tons for the habitat and fabrication units used primarily during development. The bag of soil entering the plant has a mass of 2,000 tons.

The oxide separation stage shown in the foreground and the electrolytic separation facility in the background use as initial working fluids approximately 65 tons of hydrogen, fluorine and a small amount of sodium to provide a portion of the working fluids for the liquid-phase hydrolysis scheme used in the plant. Additional oxygen and sodium are extracted from the initial runs of lunar soil to provide the full 340 tons of water, hydrogen fluoride and sodium hydroxide necessary for full-scale plant operation. Thus, we see that use of lunar materials minimizes the amount of material that must be shipped from earth to start large scale production. In this plant the makeup loss of hydrogen fluoride would probably constitute the major terrestrial input and is expected to be less than 30 tons per year for 30,000 tons/year output of processed materials. In other words, the facility is estimated to process 1000 times the makeup loss. This may well be improved by further use of lunar materials. If the Shuttle is used to bring the hydrogen fluoride to space then this would contribute 70¢/kg to the processing costs at 20 M\$ per Shuttle flight.

It is estimated that as lunar derived iron becomes available it will be possible to construct plants such as this primarily out of lunar materials and that less than 100 tons of equipment need be imported from earth. It should be noted in Fig. 2 that the "excess materials" needed to construct an SPS contain on the order of 600 tons of

iron and that six plants of the above capacity could process in one year the 180,000 tons of lunar materials necessary to fabricate 90% of an SPS. The potential of the bootstrapping approach now becomes apparent. Once the skill is established to create and operate the first prototype scale of a space processing facility (30,000 tons/year) then the subsequent five units needed for full production can be brought into production with less than 15 to 20 additional Shuttle flights. This is very powerful leverage. The challenge is to develop the fabrication techniques for working in space.

Glass and Ceramic Production

There is no doubt that a wide range of glasses and ceramics can be produced from lunar materials. 15c, 15b, 17, 18 Glasses and ceramics occur naturally on the moon and have been produced from oxide compositions that are identical to natural bulk compositions of the lunar soils. 17 Duplicated compositions include those at the Apollo 11 (mare, high titanium), Apollo 12 (mare, low titanium), Apollo 16 (highland) soils (see Mackenzie - these proceedings). Glass and ceramic production can benefit from mineral separation as well as from the availability of refined silica and silicon fractions of the lunar soil.

One can be certain that the production of clear window glass, refractory and chemically inert containers, fiberglass wool, reinforced fiberglass strands and ropes, and light pipe fibers is possible. Light pipe fibers for use in communications systems on the earth and in space are especially interesting because they presently cost on the order of 100,000 \$/kg for the glass element. Blocks of totally anhydrous lunar glass could be returned to earth for fiber production. Special notice is taken of the use of solar energy and the possibility of glass production by sintering of amorphous powders.

The Lunar and Planetary Institute conducted a workshop on 14-17 April 1979 (proceedings in progress) entitled "Glass and Ceramics Industries in Space Based on Lunar Materials." 19 There were participants from industrial, governmental and university laboratories who are active in the production of and research on glass and ceramics. A suitable point of focus for the meeting was to estimate the equipment and people that would have to be placed on the moon in order to use local lunar materials in order to create a facility for the production of 35,000 tons per year (100 tons/day) of glass products. Major products were to be those needed by the SPS. The products included foamed structural elements, fiberglass and fiberglass with metallic coatings for use in composite structures and in contaminating atmospheres, and substrate glass used for solar cell support. In addition, the plant was to allow for the use of magnetic beneficiation of the feedstock and limited production of iron and oxygen by electrolysis of a portion of the glass melt in a secondary reactor. The oxygen was to be used in

foaming, other process uses, and for life support. One major determination of the group was that the technology does exist to produce useful products for these applications from the native glass components and minerals of the lunar highlands. In addition, it is reasonable to expect that a wide range of glasses can be produced (clear glass to very dark glass) with only beneficiated lunar constituents. The anhydrous nature of the lunar glasses would make them superior in mechanical properties and more stable in their other properties than glasses made of terrestrial oxides.

Figure 5 is a preliminary schematic of the proposed glass processing facility. The facility was assumed to be on the moon or in a one-sixth pseudo gravity environment in space. If the plant were in space only the beneficiated ores would be sent from the moon. Lunar soil is introduced (<500 tons/day) into a conveyor system that moves the soil under a powerful permanent magnet. The magnetic component is attracted to the magnet and held against a second conveyor that transports the magnetic fraction (approximately 1 to 5% by weight) to a small melting and electrolysis pot. Free iron and oxygen are collected and the residue is saved for further use as a mixer or disposed of. The other stream of material is introduced into a modifier or blender to adjust the composition and then introduced into the melt tank. On earth a melt tank capable of handling 100 tons/day would be approximately 3.3 by 3.3 by 33 meters in internal volume and have alumina (Al_2O_3) walls approximately 2/3 to 1 meter in thickness and have a mass the order of 1000 tons. Heating is 90% by direct solar.

Table 1 summarizes the estimates of the masses of critical components that would have to be imported from earth in order to construct a plant on the lunar surface in one year. The primary challenge is to provide the alumina bricks which make up the glass melting tank. For this there must be a small chemical processing plant that can produce the alumina at a rate of approximately 1000 tons/year or a total input on the order of three times that rate. The plant would be that previously described and would be approximately 10% the size of the space unit. Cost estimates must be very vague due to the preliminary nature of this analysis. However, if the equipment masses cost on the order of 20,000 \$/kg (this excludes the habitats development), then approximately three billion dollars would be required to design and emplace and operate the system. It was felt that the Shuttle was a far more difficult research and development challenge.

Items 1 (chemical plant) and 6 (machine shop) were extremely important to the bootstrapping operation. It was argued that given sources of iron (item 8) and aluminum (or titanium) a semi-automated machine shop could produce the bulk of mechanical items necessary to build up the glass plant and greatly increase the capacity of the exca-

vation fleet and magnetic beneficiation system in one year.

Glass and ceramic production involves many empirical control factors which must be resolved experimentally. This is especially true when ambient conditions are changed from atmospheric pressure to vacuum and in some cases from terrestrial to one-sixth or zero gravity. Availability of the extensive data on lunar soils make it entirely reasonable to begin a series of terrestrial and Spacelab experiments to establish general procedures for the production of a wide range of glass and ceramic products. Terrestrial experiments can very quickly establish the needed key experiments to be performed early in zero-gravity to allow final design of lunar and space production equipment.

A technique developed at Los Alamos Scientific Laboratories (LASL) might be of use in forming habitats, tunnels, pipelines or conduits directly in the regolith and greatly reduce the mass necessary from earth to establish habitats and facilities. Over 1 kilometer of glass lined pipes have been formed directly in basaltic rock by pressing a white hot molybdenum tip into the rocks and soils.²⁰ The system can be scaled up to large size and heat is generated either by electricity or solar energy. The moon is more suited than the earth to this process due to the lack of water or atmosphere. Following melting the lunar soil could be formed into very thick glass lined walls which could be relatively easy to seal against leaks (if necessary) and would be extremely strong. Figure 6 is a picture of a short tunnel formed in a sandy soil as part of the LASL "Subterranean* Program." The individual glass pipes are approximately 10 cm in diameter and are fused together. In lunar operations a much larger diameter tool would be used which would produce a continuous tunnel.²¹

It was noted by several of the workshop participants that the soil of the moon, in place, is an exceedingly good thermal insulator. It may well be that power for a lunar base can be supplied by turbines in which the working fluid is heated by heat stored in a pool of molten lunar soil. The soil melts to a lava with a rather low viscosity. Solar concentrators could be used during the lunar day to elevate the lava to approximately 2000°K and then heat could be extracted and the pool allowed to cool to 1500°K over the lunar night. Adequate power to operate a lunar base could be provided by a pool of lava the order of 60 meters in diameter. Most of the system components could be manufactured on the moon.

Near-Term Bootstrapping

It is completely clear that the use of lunar materials will greatly reduce the size of transportation systems that are required to provide the materials inputs to an SPS program. At the level of several hundred thousands of tons of materials a

year the savings can be enormous. In fact, if the lunar option is used then the major expense and pacing activity is the research and development tasks that must be done to design and activate the production facilities (Fig. 7, Ref. 2). The dilemma is that the size of the production facilities and propellants (130,000 tons) are of the same order of magnitude as a single SPS (Fig. 8, Ref. 2).

The challenge is to determine how to use the vast (100 B\$) and available aerospace research and development base developed over the last 20 years to get back to the moon and use bootstrapping with lunar materials to decrease the costs of construction activities. These early small scale operations will serve to remove the uncertainties of having to extrapolate estimates of our true capabilities in space over several orders of magnitude. As a specific example, we know how to build rocket engines which can be powered by liquid oxygen and hydrogen. The development and operation of such systems between the lunar surface and lunar orbit would be relatively cheap to accomplish (<1 B\$ - Ref. 22). Such systems could put the tonnages into space necessary to construct major facilities. However, at this point in time it is necessary to plan to bring from earth the required hydrogen which severely degrades the cost advantage. An alternative rocket system which could use lunar oxygen and calcium or aluminum would be a major development challenge (>5 B\$), would have less specific impulse than H_2/O_2 systems, and would require the early installation on the moon of a capability to process 400,000 tons per year of lunar soil to make the reactants. There has been much interest in the possibility of enhanced concentrations of hydrogen in the polar regions of the moon.²³ If this is the case then bootstrapping can be used from the very first in the creation of a major industrial capability in space and on the moon. This fact can be determined at a moderate cost by remote observations by a lunar polar orbiting satellite. Several advantages would result. The Shuttle and lunar rockets could provide all the transport needs; construction systems could grow in size steadily as experience was gained, rather than having to be planned from the first for maximum size and then executed in one step, and major production experience could be acquired on the moon initially where the working materials are more readily available.

Figure 9 provides a generalized schematic diagram of the development and flow of mass, people and capital in a space industry. Space industries will have a greater incentive to conserve working fluids and recycle all process and production mass than does terrestrial industry. Pollution control will not simply be a virtue but a necessity. In Fig. 9 the lower case letters correspond to the total extraterrestrial and terrestrial masses in kilograms extracted from the lunar (or asteroidal) surface (m'), transported into space (m) from the moon (or asteroid). The earth/space export ratio is

(d_e). The mass is either lost (l), processed (d_g, d) or exported to make other productive facilities in space (e_p), support space activities (e_o) or exported to earth (e_e) as products.²⁴ These quantities can change with time as indicated by the "dot" derivative. The mass flow of personnel to and from space is given by p and p' respectively. Terrestrial dollar values are associated with the transport of people ($T(\$/kg)$), demandite fractions necessary from earth ($D_e(\$/kg)$), the capital invested in the goods ($C_e(\$/kg)$) and the value of the imported goods ($E_e(\$/kg)$). There will be costs in space associated with the gathering ($M'(\$/kg)$), transport ($M(\$/kg)$), first processing ($P(\$/kg)$), internal production of goods in space ($D(\$/kg)$) and maintenance of life-support loops ($R(\$/kg)$). Attention will always be focused on decreasing the cost of obtaining a mix of elements which can supply the material needs of the space economy. This average mix might be called "Demandite" in analogy to its use to describe the analogous quantity in the terrestrial economy.²⁵ This formulation emphasizes the fact that space industry will be a producer of "new wealth".^{26,29}

The first step, the original deposition on the moon of masses totaling $m_0(kg)$ deserves very special attention. As we saw earlier, it is not unreasonable to expect that the early mass will grow additional productive capacity at a rate equal to 100 times itself in the first year if the need to send more mass into space can be minimized (i.e., minimize $d_e(kg/kg)$). If this can be done then the capital cost of the original investment can be minimized. O'Neill^{27,28} first drew attention to the possibility of bootstrapping a generalized economy in space on the materials available to us. The studies by O'Leary and others^{15d,e,f} have demonstrated that relatively small machines can retrieve to the vicinity of the earth very large quantities of materials to use in space operations. There is clearly much room for advancement in minimizing the first step. The legacies of the Apollo program are two-fold: we have detailed knowledge of a vast subset of the available lunar resources; we have the skills to perform successfully lunar and cis-lunar operations which could be 10 to 20 times larger in people and machinery than was the Apollo program.³⁰ The power of the space Shuttle is that it will let us accomplish these more extensive and permanent lunar operations at considerably less cost than Apollo.

The Lunar and Planetary Institute is operated by the Universities Space Research Association under Contract No. NSR 09-051-001 with the National Aeronautics and Space Administration. This paper is LPI Contribution No. 378.

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Table 1.

A. BOOTSTRAP EQUIPMENT REQUIRED FROM EARTH

Item	Mass Tons
1. Small chemical plant to produce SiO ₂ (a) plant (b) fluids	50
2. Equipment for forming refractories	10
3. Heating equipment and molybdenum electrodes	24
4. Forming equipment for pipes, blocks, etc.	5
5. Forming equipment for glass rope	5
6. Machine shop	50
7. Volatiles separator	2
8. Magnetic separator	2
9. Control equipment	2
10. Habitats (3)	150
Total	350 tons

B. PERSONNEL REQUIRED BY FUNCTIONS
(Two shifts)

Item	People
1. Ore separation	2
2. Chemical plant	10
3. Construct and operate (a) glass tank (b) rope production, (c) glass blocks, and (d) volatile separator	20
4. Materials handling and maintenance	8
Total	40

Figures:

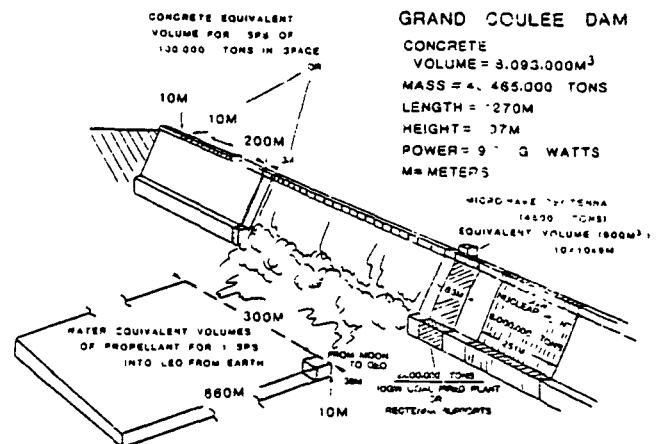


Figure 1

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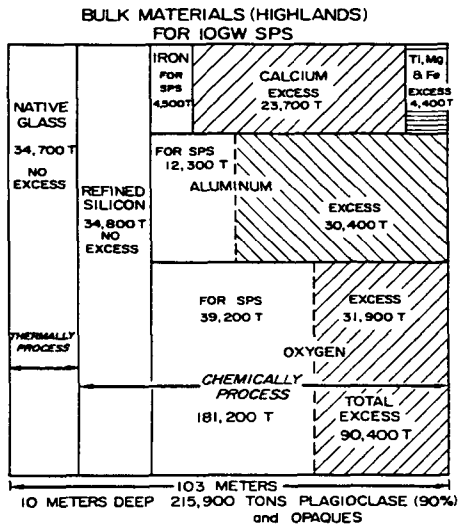


Figure 2

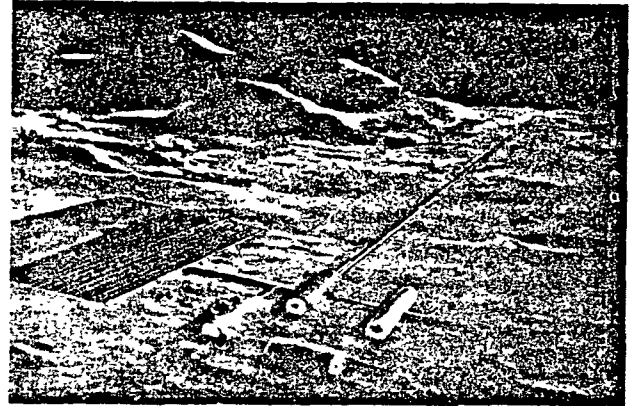


Figure 3 (Ref. 14)

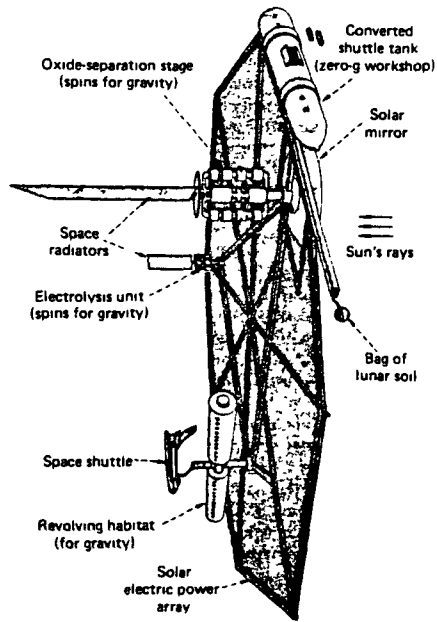


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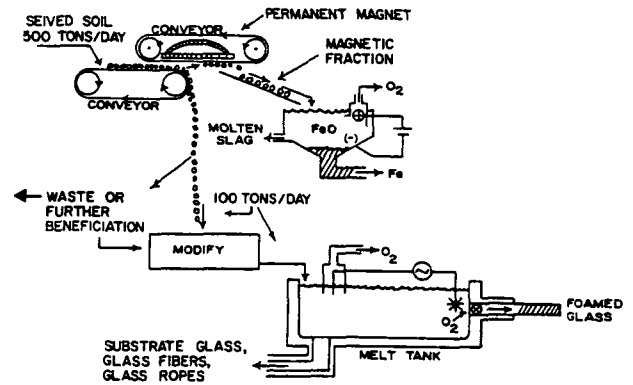


Figure 5

Figures (continued)

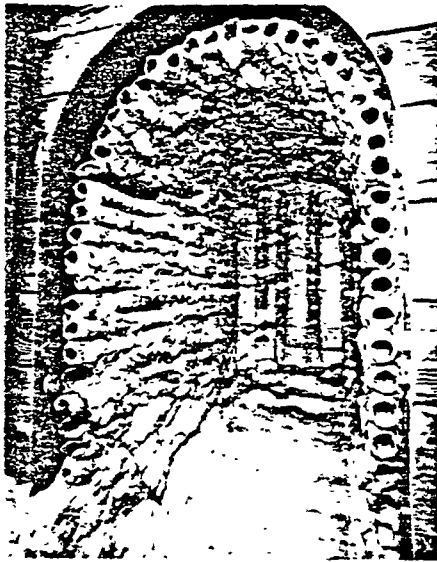
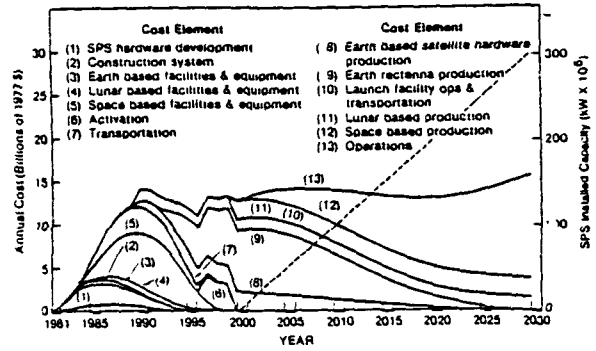


Figure 6 (Ref. 20)

LRU CONCEPT B ANNUAL EXPENDITURES
Nominal Estimate



• Similar results obtained for LRU Concepts C & D

Figure 7 (Ref. 2)

START-UP PHASE

- Deliver all facilities to their use locations
- Deliver initial propellant supplies & vehicles
- Deliver personnel for checkout and operations

Mass Estimate For LRU Concept B

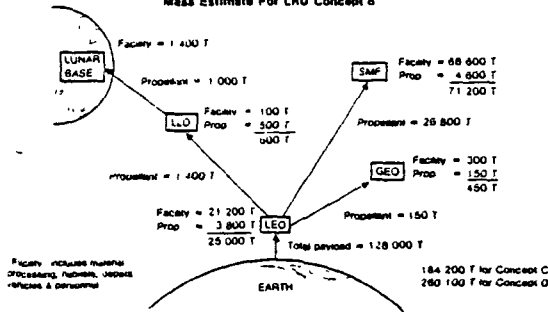


Figure 8 (Ref. 2)

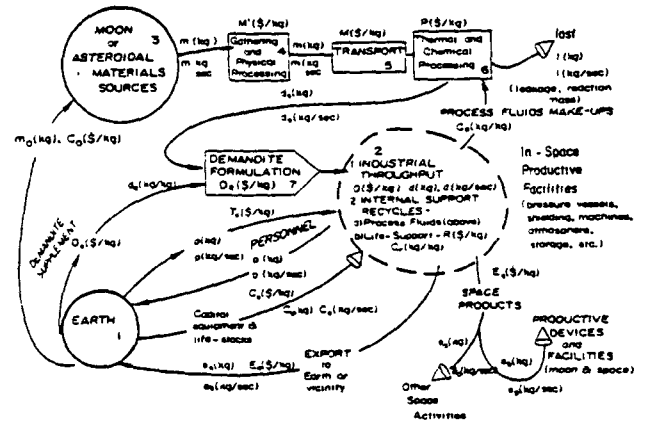


Figure 9 (Ref. 14)

Chapter X, G.

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79-1376
Excavation Costs for Lunar Materials
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Princeton, N.J./May 14-17, 1979

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EXCAVATION COSTS FOR LUNAR MATERIALS

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Abstract

A lunar strip mining system is presented which is capable of excavating and transporting 3 million metric tons of ore per year to a central processing plant on the moon's surface. The mining system would grow from a single front-end loader in the first year, to a fleet of ten haulers in the 30th year. The cumulative mass of equipment transported from the earth to the moon by the 30th year would range from 160 to 780 tons, depending on the assumptions and conditions. The net energy required per year would grow from an initial 8 MW-hr to a range of 160 to 930 MW-hr by the 30th year, again depending on the assumptions. Lunar personnel requirements would consist of a single individual, whose primary function would be to perform maintenance. All of the mining equipment would either operate automatically or by remote control from earth. The projected cost for the lunar mining system is approximately \$12 to \$37 per ton of ore over the life of the mine. Consequently, the cost of the mining system is an important part of the overall economics of exploiting lunar resources.

Introduction

The National Aeronautics and Space Administration and the Department of Energy are currently studying the feasibility of an energy system based on solar power satellites. These satellites would be in geosynchronous orbit and would consist of huge arrays of solar cells which would generate electricity directly from sunlight. The electricity would then be converted into a microwave beam for transmission to earth, where it would be reconverted to electricity. Each satellite would produce approximately 10 GW of power.

The amount of mass required for such a satellite system is enormous compared to earlier space programs. Each satellite would have a mass of approximately 100,000 tons and more than 100 satellites would be constructed. There are three possible sources of materials for construction of the satellites: the earth, the moon, or a passing asteroid which would be captured and placed in earth orbit. All three sources are currently being studied.

Investigations of the samples returned from the moon during the Apollo program have demonstrated that, after beneficiation, the top few meters of lunar soil contain almost all of the basic raw materials

needed to construct the solar power satellites, especially aluminum, silicon, and oxygen. This paper describes a strip mining system which could be used to excavate the ore and transport it to a central processing plant on the lunar surface.

The mining system would consist of a front-end loader and a fleet of haulers. This system was chosen over other methods primarily for two reasons: flexibility and maintenance.

Flexibility: This system can easily expand to accommodate the desired quantity of ore. In addition, if various sources of materials must be exploited, then the equipment can simply be re-directed to the different mine locations as required.

Maintenance: With this system, all of the pieces of equipment can be returned to the plant and maintenance can be performed in an enclosed shelter in a shirt-sleeve environment. This is a critical requirement.

Mining Plan

Mining Rate

A Satellite Manufacturing Facility (SMF) has been proposed to assemble the solar power satellites in earth-orbit. The SMF, as presently conceived, would require a feedstock of approximately 600,000 tons per year of beneficiated lunar ore. This beneficiated ore is expected to represent 20% of the total lunar ore mined. Thus a gross mining rate of 3,000,000 tons/yr will be required to supply the SMF. All of the lunar ore will be strip mined from the lunar surface without requiring any overburden removal.

The current scenario presumes that this gross mining rate would be achieved in the fifth year of lunar operations, growing from an initial rate of 30,000 T/yr. The mining rate and the cumulative ore mined over the 30-year life of the mine is presented in Table 1. This same information is shown graphically in Fig. 1 for the first few years of the operation. Although this scenario requires the mining rate to increase by a factor of one hundred over a period of five years, in fact the quantity of ore is not large by terrestrial standards and can be easily accomplished in the allotted time.

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TABLE 1.
LUNAR MINING PLAN

Mining Year	Gross Mining Rate (T/yr)	Net Ore To SMF (T/yr)	Cumulative Ore Mined (T)	Cumulative Ore to SMF (T)
1	30,000	30,000*	30,000	30,000
2	150,000	30,000	180,000	60,000
3	600,000	120,000	780,000	180,000
4	1,500,000	300,000	2,280,000	480,000
5	3,000,000	600,000	5,280,000	1,080,000
7	3,000,000	600,000	11,300,000	2,280,000
10	3,000,000	600,000	20,300,000	4,080,000
15	3,000,000	600,000	35,500,000	7,080,000
20	3,000,000	600,000	50,300,000	10,100,000
25	3,000,000	600,000	65,300,000	13,100,000
30	3,000,000	600,000	80,300,000	16,100,000

*No beneficiation during first year

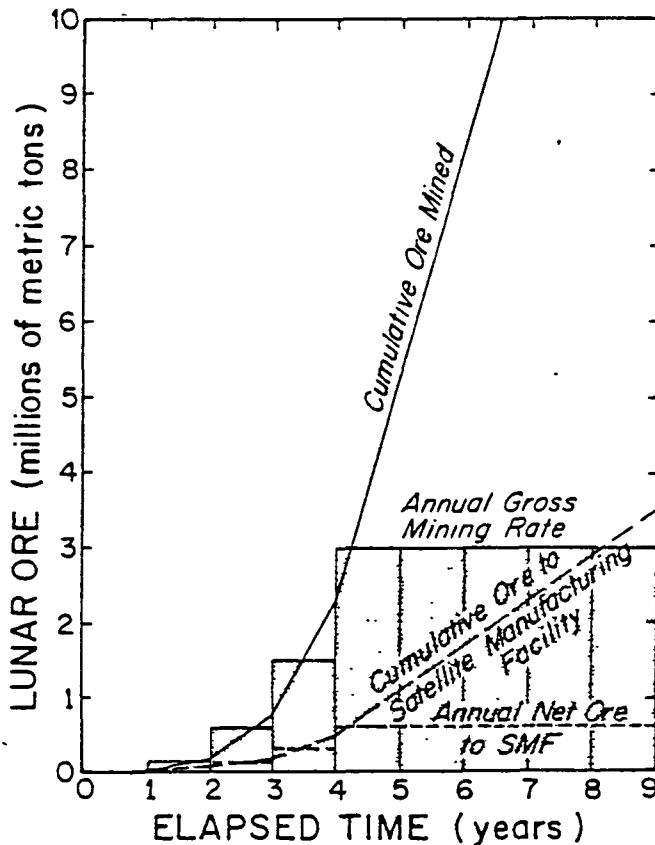
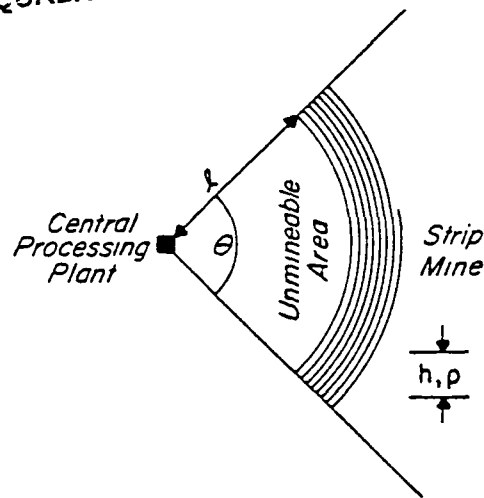


Fig. 1 Lunar Mining Plan

Mine Geometry

Of course, the location of the lunar plant and mine have not been determined yet. For purposes of this study, a hypothetical mine layout has been assumed, as shown in Fig. 2.

The lunar soil is assumed to be unmineable for a radial distance of 2 km from the plant. Beyond that point is the mine, subtending an angle of $\pi/2$ radians. The



l Radial Distance from Plant to Mine over Unmineable Area

θ : Mine Angle

h : Thickness of Mineable Ore

ρ : Bulk Density of Ore

Fig. 2 Mine Lay Out

thickness of the mineable ore is taken as 2 m, which is a rather arbitrary assumption; future exploration will likely yield a greater depth.

The bulk of the ore is taken to be 1.8 T/m^3 . This is considered to be a very reasonable estimate, and is based on many direct measurements. (1)

Early Years of Mining

During the first two years of the mine, all of the ore will be excavated and transported to the plant by a front-end loader. Using a front-end loader to transport the ore a distance of more than 2 km would not normally be considered a very efficient method. However, a single front-end loader is the least amount of equipment needed to start ore flowing into the plant. Furthermore, the amount of ore is not large during the first two years, and can easily be handled by a front-end loader.

Starting in the third year, haulers would be brought to the moon for transporting the ore from the mine to the plant. The front-end loader would remain in the mine and load the haulers.

As presently envisioned, electrostatic beneficiation of the ore would begin in the second year of mining. Other investigators are studying whether or not this beneficiation could be performed concurrently at the mine. Even if it could, it has been assumed in this paper that the beneficiation module would remain at the plant during the second year. It would then be moved to the mine with the front-end loader in the third year.

Number of Haulers and Excavators

General Expression

The following expression has been derived for determining the number of haulers, N, required at any time during the life of the mine:

$$N = \frac{M'f}{TmAE} \left[\frac{w(4\ell^2 + \frac{8M}{B\theta h\rho} \times 10^{-6})^{\frac{1}{2}}}{SV_{max}} + \frac{1}{3600} \left(\frac{Mtes}{Fpge} + t_{sl} + t'_l + t_d + t'_u \right) \right] \dots\dots (1)$$

Each of these factors is defined in Table 2. A range of values for each factor has been selected which reflects ideal, nominal, and unfavorable conditions. In this way, the minimum, most likely, and maximum number of haulers can be calculated. These values are also summarized in Table 2.

TABLE 2.
FACTORS USED TO CALCULATE NUMBER OF HAULERS
REQUIRED FOR MINING PLAN

Factor	Symbol	Units	Conditions		
			Ideal	Nominal	Unfavorable
Gross mining rate	M'	T/yr	See Table 1		
Fraction of ore returned to plant	f	--	Case 1*	0.2	0.2
			Case 2	1.0	1.0
Time available to mine per year	T	hr	8766	4185	3987
Payload of each Hauler	m	T	Varies from 5 to 200		
Availability of Equipment	A	--	0.8	0.95	0.85
Efficiency of Equipment	E	--	1.0	0.83	0.67
Wander Factor	w	--	1.0	1.1	1.15
Radial Distance from plant to Mine	ℓ	km	2	2	2
Cumulative ore mined	M	T	See Table 1		
Mineability factor	B	--	1.0	0.98	0.95
Mine angle	e	radians	π/2	π/2	π/2
Depth of mineable ore	h	m	2	2	2
Bulk Density of Ore	ρ	T/m ³	1.8	1.8	1.8
Maximum Speed of Hauler	v _{max}	kph	68	33	23
Speed Factor	S	--	0.9	0.85	0.7
Grade	Δ	--	0	+0.03	+0.05
Rolling Resistance	μ	--	0.02	-0.05	-0.07
Cycle time for front-end loader	t _e	s	30	45	60
Swell factor	s	--	1.0	1.15	1.3
Bucket fill factor	F	--	1.0	0.95	0.9
Spotting time to Load	t _{sl}	s	0	10	20
Re-load time at Plant	t _l	s	Case 1	0	0
			Case 2	10	30
Dump time	t _d	s	15	25	40
Unload time at Mine	t _u	s	Case 1	0	0
			Case 2	15	40

* Case 1: With concurrent electrostatic beneficiation
Case 2: Without concurrent electrostatic beneficiation

The most important factors in this expression are:

- Gross mining rate (M')
- Distance from plant to mine (ℓ)
- Fraction of ore transported to plant (f)
- Time available to mine per lunar day (T)
- Payload of each hauler (m)
- Maximum speed of hauler (v_{max})

Of these, the single most important factor is the fraction of ore transported to the plant. If electrostatic beneficiation can be performed at the mine, then as much as 80% of the ore will remain in the mine area and only 20% will require transport to the plant. This factor has such an enormous influence that two cases have been considered: with and without concurrent electrostatic beneficiation.

Number of Haulers Required

By substituting the appropriate factors from Table 2 into Equ. (1), the number of haulers required, N, can be calculated for any case and condition. This has been done and is summarized in Table 3.

As can be seen in Table 3, the payload of each hauler is significantly less for Case 1 than for Case 2. As noted above, electrostatic beneficiation at the mine has an enormous influence on the ore transport system.

Examining Table 3 further, it can be seen that for any given hauler payload, the number of haulers required under ideal conditions is typically about one-tenth of that required under unfavorable conditions. This large range is primarily due to two factors: (1) the time available to mine; and (2) the speed of each hauler. Under ideal conditions, it has been assumed that mining can occur during lunar day and night, and that the haul road is level and well-compacted. As a result, the time available for mining is more than double and the speed of each hauler is nearly quadruple the respective parameters under unfavorable conditions.

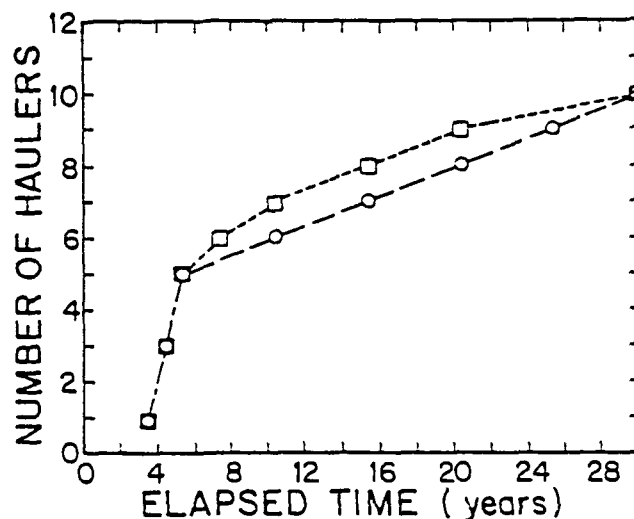
Ideal conditions define the absolute minimum number of haulers required to transport the lunar ore, and as such, are rather unrealistic. At the other extreme, unfavorable conditions define the maximum number of haulers required if everything is adverse: reduced time available for mining, steep grades and loose soil, poor equipment efficiency, and extra time required for loading and unloading.

TABLE 3. NUMBER OF HAULERS REQUIRED

Mining Year	Case 1. With Concurrent Electrostatic Beneficiation						Case 2. Without Concurrent Electrostatic Beneficiation								
	m=10			m=20			m=50			m=100			m=200		
	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U
3	1	1	2	1	1	1	1	1	3	1	1	2	1	1	1
4	1	3	6	1	2	3	1	3	6	1	2	3	1	1	2
5	1	5	12	1	3	6	2	5	12	1	3	6	1	2	3
7	2	6	13	1	3	7	2	6	14	1	3	7	1	2	4
10	2	6	15	1	3	8	2	7	16	1	4	8	1	2	4
15	2	7	18	1	4	9	2	8	19	1	4	10	1	2	5
20	2	8	21	1	4	11	2	9	21	1	5	11	1	3	6
25	2	9	23	1	5	12	2	9	23	1	5	12	1	3	6
30	2	10	25	1	5	13	2	10	25	1	5	13	1	3	7

m: Payload of Each Hauler (Tons)
I: Ideal Conditions
N: Nominal Conditions
U: Unfavorable Conditions

Consequently, for planning purposes, nominal conditions have been assumed. Referring to Table 3, a hauler payload of 10 tons with concurrent electrostatic beneficiation results in a reasonable fleet size, even after 30 years. Similarly, a hauler payload of 50 tons is appropriate without concurrent electrostatic beneficiation. The growth in the number of haulers for these two cases over the life of the mine is shown in Fig. 3. In both cases, the initial requirement for haulers is small. However, the fleet increases rapidly to five haulers in the fifth year. The growth slows down then, and a maximum fleet of 10 haulers is required by the 30th year.



- Case 1: With Concurrent Electrostatic Beneficiation (Hauler Payload, m = 10 Tons)
- Case 2: Without Concurrent Electrostatic Beneficiation (Hauler Payload, m = 50 Tons)

Fig. 3. Number of Haulers Required Under Nominal Conditions

Hauler-Excavator Match

It has been presumed that it will require four passes by the front-end loader to fill the hauler. The bucket capacity, q_e , has been calculated to be:

$$q_e = \begin{matrix} \text{Ideal} & \text{Nominal} & \text{Unfavorable} \\ 6.9m^3 & 8.4m^3 & 10.0m^3 \end{matrix}$$

This is not a wide variation, and for convenience, the bucket capacity will be taken as $10.0m^3$. Allowing for swell, the mass per bucketful would be 12.5 tons. This applies to both Case 1 and Case 2,

since the total amount of ore mined is the same whether or not concurrent electrostatic beneficiation can be performed.

Mass of Mining Equipment

Mass of Haulers

A plot of empty vehicle mass, m_h , versus payload, m , for a variety of terrestrial haulers is presented in Fig. 4. As can be seen, there are numerous haulers available which have a payload of 10 to 50 tons. In fact, the largest commercially available hauler has a capacity of nearly 320 tons. Note also that the points in Fig. 4 tend to fall along a straight line; the ratio of payload to vehicle mass, m/m_h , is approximately 1.3 over a wide range.

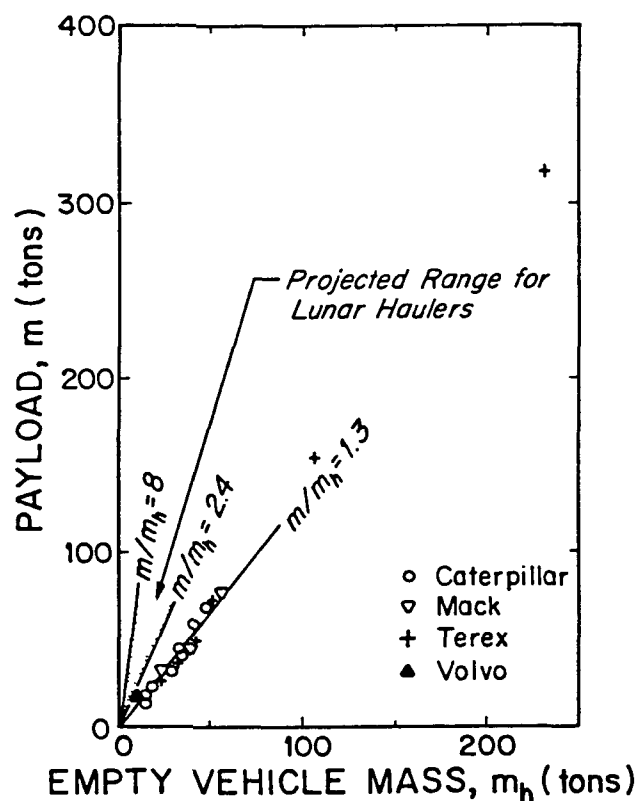


Fig. 4 Mass of Terrestrial Haulers

Most of the mass of the hauler is devoted to structural support of the payload. Because of the reduced lunar gravity, an equivalent mass payload on the moon would impose one-sixth as much structural load as on earth. Consequently, as a first approximation, it should be possible to design lunar haulers with one-sixth as much mass, or $m/m_h = 8$.

By comparison, the Lunar Roving Vehicle (LRV) of the Apollo project had a ratio of $m/m_h = 2.4(2)$. The LRV obviously falls at the low end of the scale, with an empty vehicle mass of only about 0.2 tons.

These two ratios have been assumed to be upper and lower bounds. The mass of each lunar hauler can then be estimated to fall in the following ranges:

Case	Payload	Vehicle Mass
1	10 T	1.2 to 4.2 T
2	50 T	6.2 to 20.8 T

Mass of Front-end Loader

Unlike the haulers, the mass of a front-end loader is independent of the gravity field. This is because the vehicle mass is used as a counter-balance to prevent it from tipping over when the bucket is loaded and extended. Thus, without greatly changing the geometry of the vehicle (and thereby reducing its maneuverability), the mass of the lunar front-end loader would be essentially the same as its terrestrial counterpart.

A plot of tipping mass versus empty vehicle mass for a variety of terrestrial front-end loaders is presented in Fig. 5.

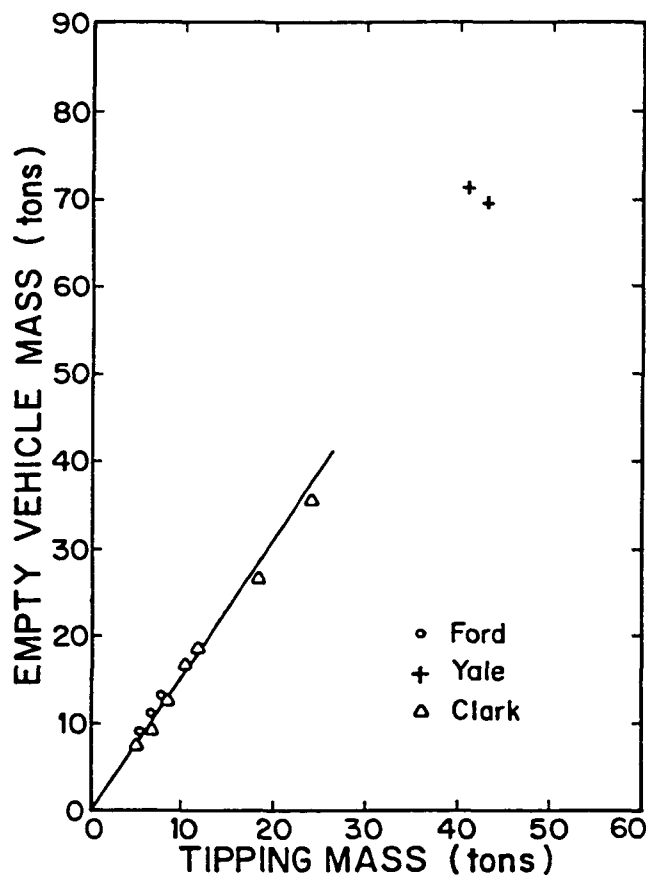
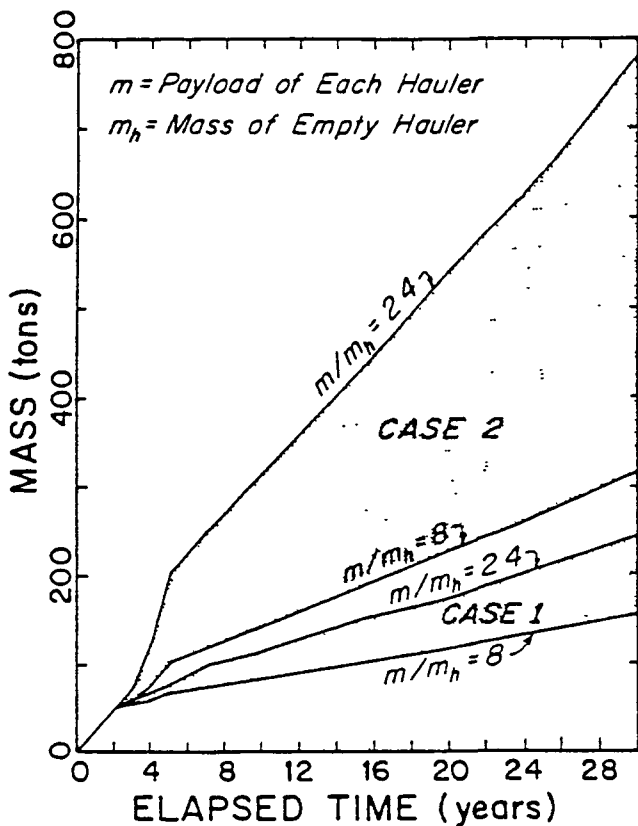


Fig. 5 Mass of Terrestrial Front-End Loaders

As with the haulers, the points tend to fall along a straight line. It is the usual terrestrial practice to multiply the bucket load by a factor of 2.0 to determine a safe tipping mass⁽³⁾. The lunar equipment will presumably incorporate automatic sensing systems to prevent tipping over, and a factor of safety of 1.2 should be adequate. Thus, using a bucket load of 12.5 tons, a tipping mass of 15T is used to enter Fig. 5, from whence a vehicle mass of 23.5T is found.

Cumulative Mass of Mining Equipment

The cumulative mass of the mining equipment, including an allowance for back-up vehicles and spare parts, has been evaluated and is presented in Fig. 6.



Including Back-Up Vehicles and Spare Parts
Nominal Conditions

Case 1: With Concurrent Electrostatic
Beneficiation (m = 10 Tons)

Case 2: Without Concurrent Electrostatic
Beneficiation (m = 50 Tons)

Fig. 6 Cumulative Mass of
Mining Equipment

In the first two years of the mine, only front-end loaders, plus spare parts, are transported to the moon. Thus, in either Case 1 or Case 2, a mass of 26T must be shipped the first year, and an additional 26T the second year. Beyond that point, the cumulative masses for the two cases diverge owing to the heavier haulers required for Case 2. By the 30th year, the cumulative mass can range from a minimum of 160 to 240 tons for Case 1, to 320 to 780 tons for Case 2.

Energy Required For Mining System

Hauler Transport

The energy required to excavate the lunar ore at the mine is trivial compared to the energy required to transport it from the mine to the plant. Consequently, the excavation energy has been neglected in the analysis that follows.

The net energy (i.e., neglecting losses due to energy storage or conversion) required for a single hauler to transport a load of ore to the plant and return to the mine is given by:

$$E = (0.139) w (4\ell^2 + \frac{8M}{B\theta hp} \times 10^{-6})^{1/2} a m_h$$

$$\left[\left(1 + \frac{m}{m_h}\right) (\mu + \Delta) + \left(1 + \frac{(f-0.2)m}{m_h}\right) (\mu - \Delta) \right] \dots \dots \dots (2)$$

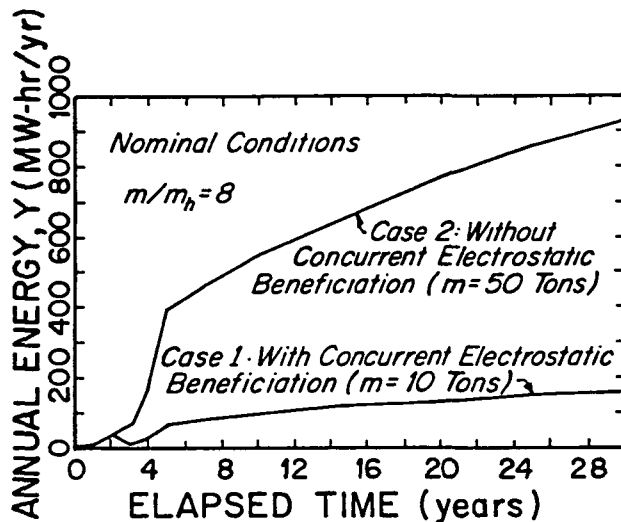
where, E = net energy per load (kW-hr/load)
a = acceleration of lunar gravity = 1.63 m/s²
and all of the other terms have previously been defined.

The net energy required for any given mining year, Y, is then approximately given by:

$$Y = E \frac{M'f}{m} \dots \dots \dots (3)$$

Once again, by substituting all of the appropriate factors into Equations (2) and (3), the net energy required for the mining system can be calculated. This has been done and is presented in Fig. 7. The energy required in the first two years is the same for Case 1 or Case 2, because a front-end loader is used to transport the ore in both cases. After that, the energy required for Case 2 is considerably greater, owing to the use of larger haulers, and the necessity to transport waste back to the mine.

Note that for Case 1, the energy requirements actually decrease during the third and fourth years. This is because beneficiation at the mine commences with the third year, and the fact that the haulers are much more efficient for transportation than the front-end loader.



m = Payload of Each Hauler
 m_h = Mass of Empty Hauler

Fig. 7 Net Energy Required for Mining System

The large differences between ideal and unfavorable conditions are primarily due to the differences in rolling resistance plus grade: unfavorable conditions assume a total resistance of 12%, whereas ideal conditions assume 2%, or a ratio of six.

For the third and subsequent mining years, the net energy requirements presented in Fig. 7 have been calculated assuming a payload to hauler mass ratio of $m/m_h = 8$. A ratio of $m/m_h = 2.4$ would require approximately 30% more energy.

Personnel

Lunar-Based Personnel

In the previous sections, the amount of mass and energy required to operate the lunar strip mining system has been discussed in detail. In this section, the personnel requirements are considered. Of these three factors, personnel is by far the most important and challenging. It is extremely expensive to transport people to the moon and to supply them with the basic requirements of life. Consequently, it is imperative that the number of people required to operate the mining system be kept to an absolute minimum. It is believed that the entire system can be operated by one person on the moon, with support and assistance from earth, of course. Obviously, this one individual would have to be rotated back to earth, similar to the other personnel at the plant.

The primary function of this person would be to perform maintenance on the

mining equipment during lunar night. During lunar day, he would be available for monitoring the mining activities and trouble-shooting if required. All of the equipment would either be automatic or remote-controlled, and thus, no other personnel would be required to operate the mining system.

Automatic Haulers

The haulers can undoubtedly be designed to operate in an automatic mode, only requiring occasional re-programming. Prior to mining, orbital photographs would document the topography in great detail. A family of haul roads would be selected and stored in each hauler's on-board computer memory. Using inertial guidance, radar, laser ranging, electronic guideposts, satellite tracking, or a combination thereof, the hauler could navigate back and forth from the mine according to a programmed sequence. Earth-based personnel would monitor the performance of the haulers and would have the capability to switch to remote control if necessary. The haulers could also be either remotely or manually controlled on the lunar surface.

Such a system should be readily attainable with present technology. In fact a child's toy is presently being sold which will follow a simple programmed path.

Remote Controlled Front-End Loader

There are many variables associated with excavation and it is doubtful that the front-end loader could operate automatically. However, it should be possible to remotely control it from earth. The front-end loader would be equipped with television cameras and various sensors to monitor its performance and location. This data would be displayed to an earth-based technician who would control the operations. As with the haulers, the front-end loader could also be either remotely or manually controlled on the lunar surface.

Again, the technology already exists for designing such a system. On a small scale, remote-controlled excavation on the moon and Mars have already been accomplished in the Surveyor and Viking programs. On earth, large draglines have been equipped with digital displays so that the operator can better monitor his own performance. Because of safety requirements, simple remote-controlled equipment has been designed for use in underground mines on earth. One study by a terrestrial equipment manufacturer suggests that in the future, most soil-moving and surface mining projects will be performed by remote control, again because of increasing safety standards⁽⁴⁾.

Cost

In the preceding sections, three important cost components of the lunar mining system have been identified: mass, energy and personnel. An approximate estimate of the cost can be made using the following assumptions:

- The cost to transport mass from the earth to the lunar surface will be \$2K/kg.
- The cost of energy supplied on the moon will be 5¢/kW-hr.
- Personnel on the moon will require 10 kg/day of consummables transported from earth. At \$2K/kg, this amounts to \$20K/day to support one person on the moon.

To these three cost components, a fourth component must be added: the cost of money. To simplify the analysis, constant dollars have been used, i.e., zero inflation. Hence, an interest rate of 3% has been used in the calculations.

Using these parameters, it is then a straightforward exercise to calculate the total cost of the lunar mining system. Under nominal conditions, the total cost over the 30-year life of the mine varies from a minimum of nearly \$1B (Case 1, $m/m_h = 8$) to a maximum of almost \$3B (Case 2, $m/m_h = 2.4$). Thus, the effect of the larger haulers, which are required in Case 2 to transport unbeneficiated ore, is to triple the total cost. In either case, the cost for transport of mass to the moon is the single largest component, representing 60 to 90% of the total. Personnel is the second most important, representing 10 to 40% of the total. The cost for energy is negligible, amounting to less than 1%.

In terms of the total ore mined, the cost amounts to \$12 to \$37 per ton over the life of the mine, which is high by terrestrial standards. Furthermore, in terms of the beneficiated ore, the cost jumps by a factor of five to \$60 to \$185 per ton. Thus, the cost of the mining system is an important part of the overall economics of exploiting lunar resources. It is believed that technological advances can reduce these costs significantly. Additional research and studies need to be performed.

Conclusions

This study has demonstrated the feasibility of a lunar mining system utilizing a remote-controlled front-end loader and a fleet of automatic haulers. One person would be required on the moon to monitor operations and to perform maintenance during lunar night. Cost estimates range from \$1B to \$3B to excavate a total of 16 million metric tons

of ore over the 30-year life of the mine.

Acknowledgements

This study was supported by the Lunar and Planetary Institute. The author gratefully acknowledges this support and the assistance of Dr. David R. Criswell of the LPI.

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Chapter X, H.

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Glass and Ceramics from Lunar Materials
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DRR

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Abstract

The possibilities of producing a variety of glass and ceramic products directly from lunar soil are discussed. These include glass fibers, glass wool, glass containers, foamed glass panels, fine grained glass-ceramics for tiles, pipes and electrical insulators. Anorthite can be melted to form windows and mirrors. Silica, alumina, magnesia can be fired singly or in combination to give bricks and refractories. The uniqueness of production in space is discussed and specific examples given.

1. Introduction

The importance of glass and ceramic as materials of engineering is well-known. The most common examples are found in building materials and in components of equipment for industrial manufacturing processes. Most glass and ceramics are based on silicates. It is of interest to note that lunar surface materials are practically all silicates. Thus for colonization of space it is logical to consider using lunar materials as resources for glass and ceramic products. Indeed the utilization of lunar materials for the production of glass windows, glass fibers and sintered ceramic bodies has already been suggested.^{1,2} The objectives of this report are to select a few lunar materials which are the most likely candidates for the manufacture of glass and ceramic products on the lunar surface or in space to evaluate the difficulties and uniqueness of extraterrestrial processing and to propose some feasible techniques of manufacture.

2. Lunar Materials of Importance as Glass and Ceramic Products

From available literature on lunar materials and from knowledge on the manufacture of similar materials on earth, the following are of obvious importance:

- (a) Lunar soil as found
- (b) Anorthite from purified plagioclase
- (c) Silica from silicon oxidation
- (d) Alumina and Magnesia

(a) Lunar Soil as Found. The chemical compositions of three samples of lunar soils³ (Apollo 11, Apollo 12 and Apollo 16) are shown in Table 1 together with those of basalts and shale found on earth. The similarity in chemical compositions between the lunar soils and especially basalt is striking. Basalts and shale are fairly low melting solids (liquidus temperatures 1200° to 1300°C). Both basalts and shale have been melted and processed into glass fibers (long strands) and glass wool (short lengths).^{4,7} Because of the high concentration of iron oxides, glasses from basalt and shale are dark brown in color. The fibers and wool are thus light brown in color. For thermal insulation and

for reinforcement the color is not of importance. The chemical and mechanical properties of such basalt and shale fibers are comparable of those of common colorless E-glass fibers. Lunar soils, as found, that is not separated into lithic fragments, mineral fragments, glass and agglutinates¹, is thus a very feasible raw material for the manufacture of glass fibers and glass wool. Glass containers are another possible product and so is light weight foamed glass panels. Some preliminary experiments have been carried out in our laboratory on the melting of oxide mixtures corresponding to the chemical compositions of Apollo 11, Apollo 12 and Apollo 16 samples. The first two were readily melted at 1350°C and easily cast into glass blocks. The sample corresponding to Apollo 12 was easily made into glass wool. Figure 1 shows the glass wool and glass made. Because of the high content of alumina, sample 3 of Table 1 had to be melted at 1500°C but the melt also formed glass readily on cooling. Our raw materials were made up of oxides and carbonates which, after melting, showed the compositions of Table 1. The actual lunar soil may melt at lower or higher temperatures.

Considerable work has been done by the Russians on the production of glass-ceramics from basalts.⁸ (Glass ceramics are fine-grained polycrystalline ceramics made by the controlled crystallization of glass). Because of their superior mechanical strength and chemical inertness, such basalts have been melted and crystallized to form tiles, pipes and other building products. Shale has also been converted to glass-ceramics with high tensile strength and good chemical durability. We have recently been able to convert the glass based on the Apollo 12 soil composition into a glass-ceramic. It appears that the high concentration of iron oxide constitutes the nucleating agent necessary for the formation of glass-ceramics. Lunar soil, as found, will thus be a good raw materials source for the production of glass-ceramics. Because of their superior mechanical properties (with tensile strengths in excess of 50,000 p.s.i., for instance, such lunar glass-ceramics can probably be used as structural components of buildings in space or on the moon. Samples with low contents of iron oxide and titanium oxide are likely candidates for electrical insulator bushings.

(b) Anorthite from Purified Plagioclase

Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_7$) obtained from plagioclase, has been suggested as a raw materials for colorless glass since the FeO content is less than 0.1%.¹ If colorless glass is easily made in large quantities from the fusion of anorthite, then obviously glass windows will be a logical product. Although glasses have been prepared in small quantities from the melting of anorthite¹⁰, it appears that the glass can be readily crystallized from 980° to 1100°C.¹¹ The melting temperature of anorthite is 1550°C. It is not

possible to predict if anorthite alone can be used to produce glass windows since devitrification can occur. Secondly, the melting temperature is relatively high. Thirdly, the activation energy for viscosity is likely to be high and there is little industrial experience on such glass forming systems. However, the melting temperature can be decreased to 1350°C by the addition of small amounts of CaO and the probability of devitrification can be reduced by the addition of SiO₂. The transparency of modified anorthite glass sample is seen in Figure 2. Table 2 shows the chemical compositions of glasses made in our laboratory. In general then, it can be concluded that colorless glass windows can be produced from basically anorthite alone or with small additions of CaO and/or SiO₂. The expansion coefficient of such glasses is likely to be less than that of common window glass. This should be an asset for windows which will experience large changes in temperatures. Thin glass sheets can be processed into mirrors and mounted on a foamed glass panel as focussing mirrors in heliostats.

(c) Silica from Silicon Oxidation. Silica (SiO₂) is obtainable from the oxidation of silicon.¹¹ If glasses or other ceramic products are to be produced, refractories must be employed as containers and/or furnace parts. Vitreous silica is an ideal refractory material because of its high glass transition temperature (1200°C). For short times up to a few hours, for instances, silica glass can be used up to 1700°C before distortion of shape becomes serious. At 1500°C, silica glass does tend to devitrify to cristobalite but the rate is extremely small.¹³ At this temperature, the rate is only 2×10^{-6} cm/min or about 0.1 cm per year.

For refractory applications, the quality of silica glass need not be of the "transparent clear fused quartz" standard. The SiO₂ powder can be sintered (or fused) together at about 1750°C to form bricks or crucibles. Because fused silica has very low expansion, such sintered products can undergo rapid heating and cooling. The rate of corrosion by molten glass such as basalt is very low even at 1400°C. Thus fused silica is recommended as a refractory material for extraterrestrial glass and ceramic production.

(d) Alumina and Magnesia. If fused silica does not have sufficient stability at temperatures in excess of 1700°C for long times, alumina (Al₂O₃) and/or magnesia (MgO) can always be used. The melting temperatures of alumina and magnesia are 2050°C and 2800°C, respectively. For refractory applications, the powder can be sintered into bricks or crucibles for use in glass melting. In addition, other common refractory compounds such as spinel and mullite can be formed.

3. Processing of Lunar Materials - General Considerations

In the above section, it has been suggested that glass (fibers, containers and windows) and glass-ceramics (pipes, tiles, electrical insulators and load-bearing structures) can readily be made from lunar materials. Container and refractories can be made from silica, alumina and magnesia. In this section, the uniqueness of processing such materials on the moon and/or in

space are briefly reviewed. Specific examples are described in the next section.

Industrial productions of glass fibers, containers, windows, glass-ceramics and refractories on earth are all highly complex technologies based on many years of learning and experience. Such technologies are successful, and only successful, if the conditions of Table 3 are strictly adhered to. If one or more of such conditions are altered, both research and development must be done prior to firstly a pilot plant-scale process before large-scale production can be attempted. However, not all the new conditions are totally unpredictable or unacceptable.

Of all the conditions listed in Table 3, the processing of fiber glass under high vacuum is the most difficult one envisaged. Because of vaporization losses, it is likely that glasses can only be made properly under one atmosphere. The processing of fiber glass by common technique is to allow molten glass to run down freely from nozzles in the form of liquid streams. If the gravitational forces are now reduced drastically, the production rate must be decreased significantly. Thus an established earth process can no longer work and an alternative must be developed. Zero gravity permits containerless melting. Its advantage have been described by Happe.¹⁴ Although containerless melting will undoubtedly minimize refractory corrosion, it is not always easy to apply it to glass products. For instance, in flat glass manufacture, highly viscous molten glass may be pulled upwards to form sheets. The bulk of the melt must be retained in the furnace while the sheet is being pulled upwards. contact with refractory is unavoidable. The availability of high vacuum and zero gravity can on the other hand be exploited in the production of vapor deposited amorphous solids of high purity. There are thus advantages as well as disadvantages of processing glass and ceramics in space.

Processing of glass and ceramics on earth usually requires large quantities of cooling water. For lunar operations, it is obvious that innovative cooling techniques must be developed. If the amount of water needed in a normal process is to be reduced, not only the processing rate is altered but machinery must be modified. In the manufacture of glass fibers (long strands) and glass wool (short strands), if yarn and mats are the intended end-products, an organic binder must be sprayed on to the glass fibers and wool.¹⁵ The amount of organic binder needed is approximately 1-2% by weight of the glass processed. This will presumably have to be transported from earth. On the other hand, if only loose glass wool is to be produced for insulation, the organic binder is not necessary.

Practically all industrial processes in use today in the production of glass and ceramics utilizes oil or gas as energy sources. Large scale uses of electric melting are uncommon although recently there are increasing developments in this field.¹⁶ It is likely that if and when large scale melting of glass is ready for implementation in space, the necessary technology will be ready for adaptation. Direct utilization of solar energy through focussing

TABLE 1

CHEMICAL COMPOSITIONS OF LUNAR SOIL COMPARED
TO EARTH MATERIALS IN WEIGHT PERCENTS

	1	2	3	4	5	6
	Apollo 11	Apollo 12	Apollo 13	Basalt	Basalt	Basalt
SiO ₂	42.0	46.4	44.9	49.1	45.4	45.00
TiO ₂	7.5	2.7	0.6	3.2	0.6	----
Al ₂ O ₃	13.9	13.5	26.7	13.9	16.6	15.0
FeO	15.7	15.5	5.5	14.0	11.0	3.0
MgO	7.9	9.7	6.0	5.3	11.1	10.0
CaO	12.0	10.5	15.6	9.4	13.0	20.0
Na ₂ O	0.4	0.6	0.5	3.1	3.6	5.0
K ₂ O	0.1	0.3	0.1	1.3	—	3.0

Nos. 1 - 3 According to D.R. Criswell³
 No. 4 --- Basalt from Pullman, Washington⁴
 No. 5 --- Basalt from Armenia, U.S.S.R.⁵
 No. 6 --- Inorganic portion of oil-shale from Colorado⁶

TABLE 2

Possible compositions for colorless transparent
window glass derived from lunar materials

	Anorthite Beneficiated to 99% (w/o)	Modified Anorthite (w/o)
SiO ₂	42.8	42.3
Al ₂ O ₃	36.2	10.8
CaO	20.0	46.3
Na ₂ O	0.5	0.15
MgO	0.1	0.03
FeO	0.1	0.03

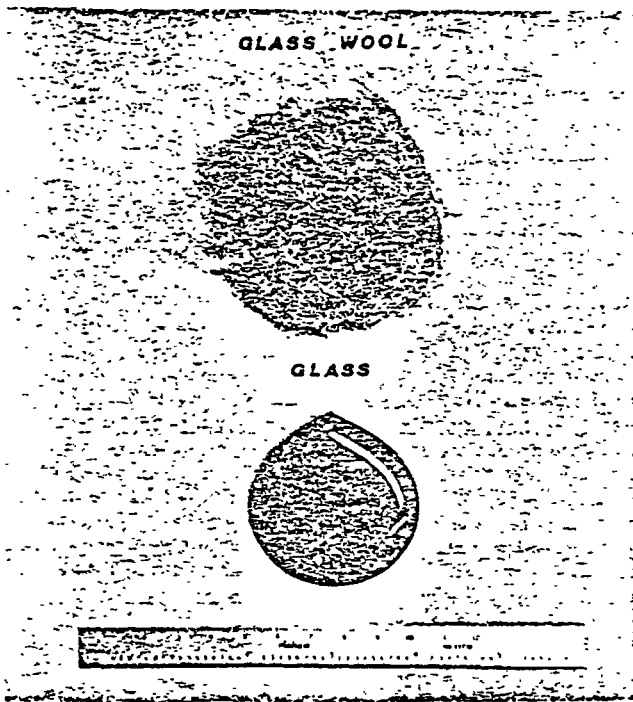


Figure 1. Glass wool and glass from the melting of oxide mixtures corresponding to Apollo 12 composition

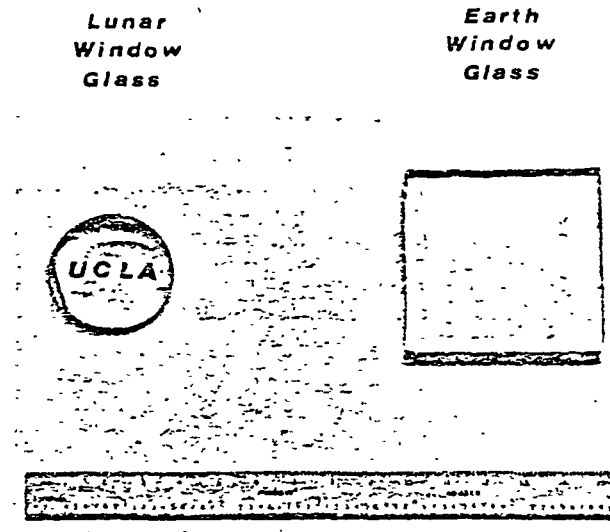


Figure 2. Optical transparency of "lunar window" glass compared to that of common window glass.

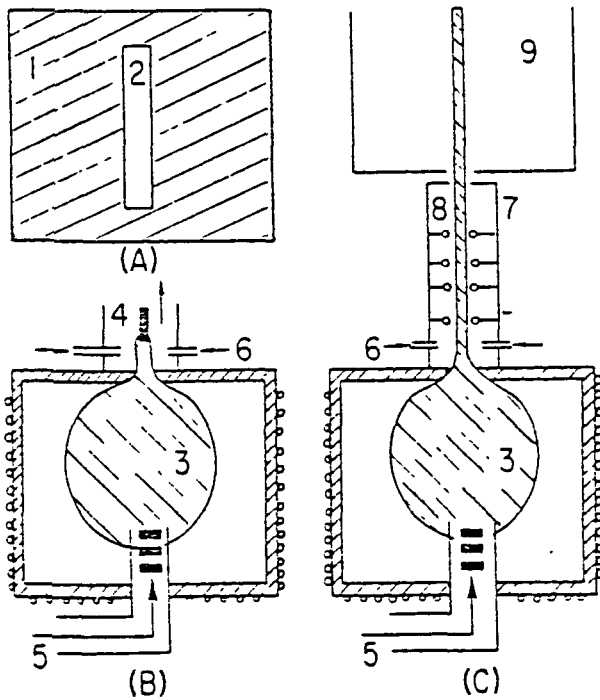


Figure 3. Possible design of an up-draw window glass melting furnace for space application.

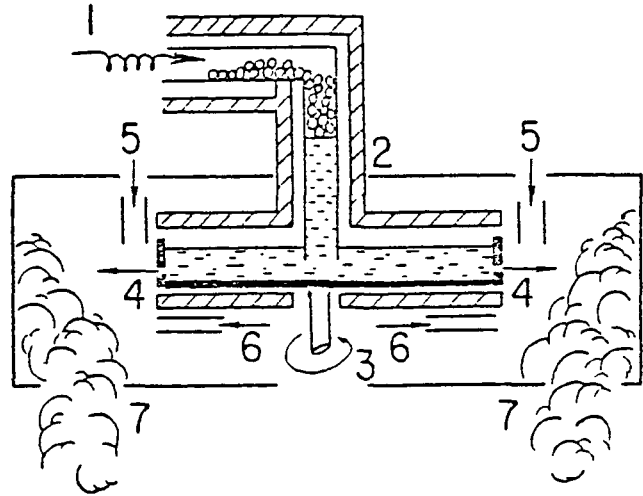


Figure 4. Possible design of a glass wool production furnace to be used on the moon or in space.

Chapter X, I.

CHEMICAL PROCESSING
OF LUNAR MATERIALS

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Paper Number 79-116

XXXth CONGRESS OF THE

INTERNATIONAL AERONAUTICAL FEDERATION

16 - 22 September 1979

Munich, Germany

79-116

Abstract

Many of the characteristics of the low latitude lunar soils and rocks are very well established by studies conducted on samples returned from the moon by Soviet and American missions. Several chemical, thermal and physical processing schemes can be defined and tested on earth and in-earth orbit and then utilized on the moon and in space. These various systems can produce a wide range of industrial feedstocks from the lunar soils and rocks.

The following report highlights recent work on the general problem of processing lunar materials.

LUNAR SOURCE MATERIALS

Table I shows the composition of the two major constituents of the mare and highlands regions of the moon.⁵ Meteoritic bombardment has tended to homogenize the distribution of minerals in these two regions to great depths. There are no aqueous processes operating on the moon to concentrate minerals or elements. Thus we expect to work with the dust and surface rocks of the moon, rather than look for deep veins of minerals. It is evident that the chemical/metallurgical industry in space will be substantially different from that on earth, due to scarcity of key elements such as H, C, Na, Cl, etc.

Table II shows elements that are potentially recoverable from the moon. (The designations "major," "minor," and "trace" are ours.) The light trace-elements are mostly due to solar wind bombardment of the lunar surface. Alpha radiation, due to radioactive decay, is responsible for some helium, while impacts of carbonaceous meteorites are responsible for some of the carbon that is present.

REFINED PRODUCTS

Table III shows a list of useful products, with examples of what could be made at a space manufacturing-facility, primarily from lunar materials. Although not listed, water would be made from oxygen obtained from lunar materials and hydrogen brought from earth. (Hydrogen is also a trace element on the moon, but even though its weight abundance may typically range between 50-100 ppm, its atomic abundance may be 1% that of silicon. If extractable, this hydrogen could be used to produce the water needed to replace that lost in process recycling — since no recycling process is 100% efficient.)

The structural metals listed in Table III (Al, Fe, Mg, and Ti) will have to be alloyed in order to develop useful mechanical properties.

Table II shows that several elements (e.g., Si, Cr, Mn) used in forming commercial alloys of the structural metals are potentially recoverable from the moon. In addition, there is "neutral" iron on the moon that also contains nickel and some cobalt, which could possibly be recovered. Finally, if enough carbon were recoverable from the trace amounts present on the moon (or brought from earth, or possibly obtained from a carbonaceous asteroid), and small amounts of other key alloying elements were imported from earth, one could produce many ferrous and non-ferrous alloys that are commonly used today.

In the case of steels, the more important alloying elements not readily available on the moon are C, Ni, Mo, W, V, and Nb (Cb). The physical properties of several commercial alloys containing these elements are generally similar to alloys in which such elements are absent, but which instead contain lunar-indigenous elements. (The properties compared included tensile strength, yield strength, hardness, and elongation.) Therefore, for use as structural metals in space, it is possible to produce alloys possessing a broad range of properties (as commonly required on earth) by alloying with earth) by alloying with carbon, lunar-indigenous elements, and/or minor amounts of lunar-deficient elements (LDE).

Several commercial aluminum alloys can be made from lunar-indigenous materials. However, higher strengths, approaching those of the strongest aluminum alloys made on earth, can only be obtained by alloying with small amounts of lunar-deficient elements, particularly Zn.

Only a few commercial alloys of magnesium and titanium can be formed solely from elements recoverable from the moon; but here again, as in the cases of steel and aluminum, significant improvements in properties can be obtained by alloying with minor amounts of lunar-deficient elements. The strongest magnesium alloys will require such lunar-deficient elements

as Zn, while the strongest titanium alloys will need Mo.²

It is evident that the structural metals to be manufactured in space will consist of alloys that are already in use, are well-characterized, and can furnish almost any desired property currently available. Non-metallic materials similarly may be made solely from lunar sources, or modified with additions of lunar-deficient elements.

MOTIVATIONS FOR USING LUNAR MATERIALS

The high costs ($\geq 100\$/\text{Kg}$) and engineering difficulties associated with transporting appreciable mass from the earth's surface to earth orbit or deep space have prompted a number of prior studies on the feasibility and techniques applicable to the use of extraterrestrial materials and in particular, lunar materials to supply feedstocks for a variety of industrial activities. The evolution of space activities can be expected to lead to a progressive increase in the scale of engineering projects with quasi-permanent or permanent manned stations in orbit and/or the lunar surface.

Table IV shows the approximate power, capital mass, and expendable requirements of a range of different productive functions which could be operated in space or on the moon. We see that most of these functions are significantly more efficient in the use of energy and mass in the production of feedstocks or products than are rockets designed for lifting goods from earth. Admittedly, the working environments of space and the moon are significantly different in many ways from earth. However, differences such as high vacuum, a predictable environment, control in space of gravity and the availability of solar energy will favor many processes.

It is reasonable to anticipate that the early machines of production can be used to produce other machines. In this manner new capital can be created from lunar materials with a minimal drain on the present terrestrial resources. In turn, growth by using native lunar materials implies that

"time" and "skills" in the initial efforts may be substituted for large terrestrial expenditures. Thus one may be able to avoid the deployment of massive quantities of machines of production from earth in relatively short periods of time. New options for industrial developments in space will be realized and then created.

Several general considerations must be taken into account in the difficult, but potentially rewarding challenge of making the maximum use of lunar materials for creating productive systems.

1. Some materials almost certainly would have to be brought from earth.
2. The extent of additional structures that could be processed and manufactured in space from lunar materials would depend more critically on fabrication limitations than materials availability.
3. Versatility and properties would demand substantial use of steels, rather than aluminum or magnesium, as structural and magnetic metals and in tooling and manufacturing equipment.
4. Reprocessing and recycling carbon to form baked carbon and graphite products would be difficult in space. If possible, substitutes for such products would be highly desirable.

GENERAL CONSIDERATIONS

A lunar or space processing plant faces several constraints which rarely concern terrestrial plants. There is a lack of virtually inexhaustible air and water and the heat sinks provided by these fluids. Plentiful supplies of traditional fuels such as coal, oil or gas are missing and initially, electricity will be scarce. Expendable oxidizers, reductants, acids and bases (except CaO) are missing. There is a lack of many key chemicals such as: ammonia, salt, chlorine, caustic, soda ash, carbon

dioxide, sulfuric and phosphoric acids, carbon and graphite and organics. There are no common solvents. In space there are no foundations of unlimited inertia. Finally, there will be few support vendors, initially.

The sun will be the dominant source of direct (heat) and derived (electrical) energy. Any needed reagents that contain lunar deficient elements (LDE) must be recovered with high efficiency (>99%) from the output stream and recirculated or regenerated. This is necessary to avoid the necessity of massive earth lift of reagents.

The overriding of importance of minimal mass makes it imperative that input materials and reagents move expeditiously through the sequence of processing steps without substantial delays and that certain features should probably be avoided or minimized, if possible, including:

1. Steps that require long completion times.
2. Steps in which the input material is present in low concentration.
3. Mass transport of volatiles at very low pressures.
4. Phase separations from viscous suspensions.
5. Reactions with low conversion per pass.
6. Reactions involving handling or storage of large volumes of gas.
7. Reactions involving large transfers of heat, using fluid/vapor heat exchangers without phase change.
8. Processes that reject large amounts of process heat at low temperatures (below 200-300°C).
9. Processes for which suitable structural materials do not offer reasonable service lives.

Other criteria for process evaluation include reliability, manpower requirements, potential hazards to onsite personnel, adaptability in processing scrap materials, and ease of repair in case of malfunction. Corrosion of parts that can only be replaced from earth supply is naturally

far more serious than corrosion of lunar-derived parts.

The original cost of chemical process equipment is expected to be dwarfed by orbital lift costs in almost all cases and thus would be of minor importance. If replacement items for many of these units could be fabricated from lunar materials, this would reduce costs in expansion or replacement operations.

PHYSICAL PROCESSING

Using physical beneficiation methods, one may anticipate recovering specific mineral fractions of pyroxenes, plagioclase, olivine or ilmenite of compositions shown in Table I with admixtures of up to 10% or higher of residual mineral or glassy material. In addition, magnetic separation of lunar soils can be expected to yield from 0.1 to 0.5 wt % of free iron admixed with some nickel-iron alloy. This probably represents the simplest method of obtaining structural metals.

Trace minerals such as spinels, troilite (FeS) and various glasses may also be recoverable by physical methods, while thermal desorption of fine soil particles may permit recovery of light trace elements.

A very wide range of glass and ceramic products can be made from soils, soil fractions and the oxides and element combinations derived from processed lunar soil (Table III). In addition, many trace elements can be obtained by heating (and melting) fine grain fractions of the lunar soil.

CHEMICAL PROCESSING

Previous studies of extraterrestrial materials processing have generated proposed processes ranging from reagentless electrolysis to various high and low temperature thermochemical or electrochemical separations. We have investigated hydrochemical processes involving basic or acidic leaching of lunar ore. The latter system, which we designate the HF acid leach process, seems to offer the best prospects for efficient processing

of lunar materials. We have designated it as our "baseline" process for more extended analysis and engineering studies to develop models for space industrialization.

Electrolysis of molten silicates:

Limited investigations of direct electrolysis of molten silicates of compositions similar to lunar basalts have been performed.⁷ The high melting-points and viscosities of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the "reagentless" advantage of the direct electrolysis route and requires consideration of extraction and recycling of fluxing reagents.

The chief objections (or problems awaiting solution) are the corrosion or durability of anodes used for oxygen recovery, and the purification and separation of cathodic reduction products (which are likely to consist of iron-aluminum-silicon alloys plus minor amounts of additional impurities).

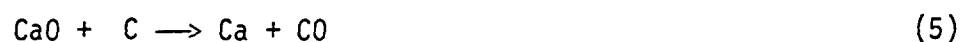
Carbothermic/silicothermic reduction:

After crushing lunar material and magnetically separating the ferrous from the nonferrous fractions, reduction can be done. Silicon will reduce iron at 1,300°C, as shown by Eq. (1):



The products can be separated by centrifugation.⁵

The iron-free silicates would be reduced by carbon at 2,300°C, as shown by Eq. (2-5):



By this process, it would be expected that aluminum and silicon would form a melt, while the other reduced metals, including the major impurities Ti, Mn and Cr, would be removed as vapors. However, this reaction scheme is much more complicated. At 2,300°C, condensed compounds, such as SiO, Al₄C₃, and Al₄O₄C are present, along with gases such as Al₂O, SiO, Al, and Si.

Carbo-Chlorination Process:

Rao *et al.*,⁵ decided quite early that carbothermic reduction would probably be impractical for space processing. They opted for carbo-chlorination of lunar anorthite, CaAl₂Si₂O₈, and lunar ilmenite, FeTiO₃, which could be beneficiated from lunar soil. The desired products are aluminum, iron, silicon (or silica), and titanium.

Subsequent study has revealed that carbo-chlorination would create a major plant-size problem. The recycling of chlorine and carbon would require facilities much larger than the basic processing plant. In order to minimize the size of the heat-rejection radiators, large amounts of heat energy would have to be raised (heat pumped) to about 280°C, to achieve a mass efficient system.

These results indicate that processes which reject less heat at low temperatures and made use of hydrometallurgical operations would tend to be more useful options for space processing.

NaOH Basic-Leach Process:

Anorthite can be decomposed with NaOH in an autoclave; and subsequent treatment of those products with more base can eventually yield alumina and calcium silicate — the latter could be used to make glass or could be hydrolyzed to yield lime and silica. For both basic and acidic leaching, sodium present in lunar soil can probably make up for any sodium lost during recycling. In this process, calcium impurities in the recycled NaOH would not present a problem, inasmuch as base, and not pure NaOH, is needed.^{1,2}

HF Acid-Leach Process:

This process uses low-temperature hydrochemical (hydrometallurgical) steps to separate the silica content of the lunar raw material from the other metallic oxides by conversion to fluorides and fluosilicates. This is followed by vaporization of the silica as SiF_4 , and separation of the calcium and the structural metals (Al, Fe, Mg, Ti) by a variety of solution, precipitation, ion exchange, or electrolytic steps. Iron may easily be recovered from solutions by electrowinning, but the remaining metals, except Mg, are preferably recovered by sodium reduction of the corresponding fluorides, fluosilicates or fluoaluminates. Magnesium may be made by silicon reduction of MgO .

Sodium for the reduction of the metals and silicon can be conveniently obtained by a slight modification of the Castner cell, which at one time was the major commercial device for producing sodium. The Castner cell uses the electrolysis of molten NaOH to produce Na , O_2 and H_2 . For lunar operations, the hydrogen is an undesirable by product, which can be largely eliminated by using a diaphragm cell and vacuum-drying the anolyte to remove the water formed by discharge of OH^- ions.

Metal oxides and silica are obtained, where desired, by hydrolysis of the corresponding fluorides or fluosilicates with steam (or with NH_3 , if desired, for SiO_2) or by ion exchange (or permeation) methods. Detailed analyses of the options available for these separations remain to be completed.

A flowsheet for the HF acid-leach process is shown in Fig. 1. Of the processes studied to date, the HF acid-leach one appears to have the best potential for minimal operating mass, ease of element separations to high purity, flexibility, and favorable energy and heat-rejection requirements.

DEVELOPMENTAL APPROACHES

Several options for chemical processing of lunar materials are well within the state of the art of applied chemistry and chemical engineering to begin development based on the extensive knowledge of lunar materials. Both systems analyses of proposed flow-sheets and bench top experiments are completely reasonable to begin.

There is no fundamental reason why the chemical processing facility for the HF process could not be reduced down to laboratory bench scale. The estimated total process time is less than 36 hours. The longest process time, other than electrolysis, is three hours for which the corresponding units would contain 3 kg of lunar ore at an average throughput of 1 kg/hr or 7.13 metric tons/year with an 81% duty cycle. At a very small scale, the mass:throughput and power:throughput ratios may be expected to increase — perhaps by as much as a factor of two.

The concept of bootstrap growth of processing capacity can increase the annual output mass:net plant mass ratio by an amount limited by the reagent requirements for lunar deficient elements. For the HF acid leach process, the LDE net reagent mass represents 28% of the net plant mass, so the annual output:net plant mass ratio could be nearly quadrupled by expanding equipment capacity using lunar materials. Even greater increases may result from process revisions or modifications of operating cycles which can reduce the equivalent times required for LDE reagents.

It is very likely that the applied science and technology which results from the development of lunar/space processing plants will find widespread application on earth. The challenges of refining the common lunar minerals with minimum loss of working reagents is similar to the terrestrial challenge of refining low grade terrestrial ores and doing so with a minimum of pollution.

The ultimate terrestrial importance of the development of space resources may turn out to be, not the materials or the energy which will flow from space to the earth, nor the new habitats created in space, but rather the certain, tangible, and visible knowledge that secure, new, expanding wealth can be created by humanity from the commonly available energy of the sun, the soil of the ground beneath our feet (whether we stand on the earth, the moon, or any other celestial body), and the cumulative and shared skills of the entire human race.⁶

ACKNOWLEDGMENT

The Lunar and Planetary Institute is operated by the Universities Space Research Association under Contract No. NSR 09-051-001 with the National Aeronautics and Space Administration. This paper is LPI Contribution No. 396

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Table I

RANGES OF CHEMICAL COMPOSITIONS FOR THE MAJOR MINERALS

High Titanium Basalts					Highlands Rocks				
Modal Abundance (Vol. %)	Pyroxene 42 - 60%	Olivine 0 - 10%	Plagioclase 15 - 33%	Opagues (Mostly Ilmenite) 10 - 34%	Modal Abundance (Vol. %)	Pyroxene 5 - 35%	Olivine 0 - 35%	Plagioclase 44 - 48%	Opagues (Mostly Ilmenite) 0 - 5%
Component (Wt. %)					Component (Wt. %)				
SiO ₂	44.1-53.8	29.2-38.6	46.9-53.3	< 1.0	SiO ₂	51.10-55.4	37.70-39.9	44.00-48.0	0 - 0.1
Al ₂ O ₃	0.6- 6.0	-	28.9-34.5	0 - 2.0	Al ₂ O ₃	1.00- 2.5	0 - 0.1	32.00-36.0	0.80-65.0
TiO ₂	0.7- 6.0	-	-	52.1-74.0	TiO ₂	0.45- 1.3	0 - 0.1	0.02- 0.03	0.40-53.0
Cr ₂ O ₃	0 - 0.7	0.1- 0.2	-	0.4- 2.2	Cr ₂ O ₃	0.30- 0.7	0 - 0.1	0 - 0.02	0.40- 4.0
FeO	8.1-45.8	25.4-28.8	0.3- 1.4	14.9-45.7	FeO	8.20-24.0	13.40-27.3	0.18- 0.34	11.60-36.0
MnO	0 - 0.7	0.2- 0.3	-	< 1.0	MgO	16.70-30.9	33.40-45.5	0 - 0.18	7.70-20.0
MgO	1.7-22.8	33.5-36.5	0 - 0.3	0.7- 8.6	CaO	1.90-16.7	0.20- -0.3	19.00-20.0	0 - 0.6
CaO	3.7-20.7	0.2- 0.3	14.3-18.6	< 1.0	Na ₂ O			0.20- 0.6	
Na ₂ O	0 - 0.2	-	0.7- 2.7	-	K ₂ O			0.03- 0.15	
K ₂ O	-	-	0 - 0.4	-					
Low Titanium Basalts									
Modal Abundance (Vol. %)	42 - 60%	0 - 36%	17 - 33%	1 - 11%					
SiO ₂	41.2-54.0	33.5-38.1	44.4-48.2	< 1.0					
Al ₂ O ₃	0.6-11.9	-	32.0-35.2	0.1- 1.2					
TiO ₂	0.2- 3.0	-	-	50.7-53.9					
Cr ₂ O ₃	0 - 1.5	0.3- 0.7	-	0.2- 0.8					
FeO	13.1-45.5	21.1-47.2	0.4- 2.6	44.1-46.8					
MnO	0 - 0.6	0.1- 0.4	-	0.3- 0.5					
MgO	0.3-26.3	18.5-39.2	0.1- 1.2	0.1- 2.3					
CaO	2.0-16.9	0 - 0.3	16.9-19.2	< 1.0					
Na ₂ O	0 - 0.1	-	0.4- 1.3	-					
K ₂ O	-	-	0 - 0.3	-					

Table II

POTENTIAL AVAILABILITY

Major Elements $\geq 1\%$ Lunar

O, Si, Al, Ca, Fe, Mg, Ti

Minor Elements 0.1 - 1%

Cr, Mn, Na, K, S, P

Trace Elements $< 0.1\%$

H, He, C, N plus all others

(Beneficiation may permit concentrating some trace elements into minor or higher range).

Table III

USEFUL PRODUCTS

STRUCTURAL MATERIALS

Metals — Steels, aluminum, magnesium, titanium
Reinforced Metals — Aluminum, magnesium
Reinforced with silica, steel or alumina
Glasses, fused silica
Ceramics, alumina, magnesia, silica, compounds
Hydraulic cements (need water)

THERMAL MATERIALS

Refractories plus chromia, titania, titanium silicide. Same as ceramics plus incl. castables, ramming cements insulation, fiberglass, fibrous or powdered ceramics

ELECTRICAL MATERIALS

Conductors — Aluminum, magnesium, iron, resistance alloys (FeCrAl)
Electrodes — Graphite, Fe_3O_4
Magnetic materials, iron alloys, magnetic ceramics
Insulation, glass, ceramics

FIBROUS MATERIALS

Glass, silica (for apparel, paper, filters, etc.)

PLASTICS, ELASTOMERS AND SEALANTS

Soluble silicates, silicone resins (contain some C)

ADHESIVES AND COATINGS

Anodized aluminum, magnesium, titanium, electroplating (Cr)
Sputtered coatings, etc.

LUBRICANTS, HEAT TRANSFER FLUIDS

Sulfides, SO_2 , He

INDUSTRIAL CHEMICALS

Detergents, cleansers, solvents, acids, bases
 H_2SO_4 , H_3PO_4 , CaO, NaOH

HUMAN/AGRICULTURE RELATED

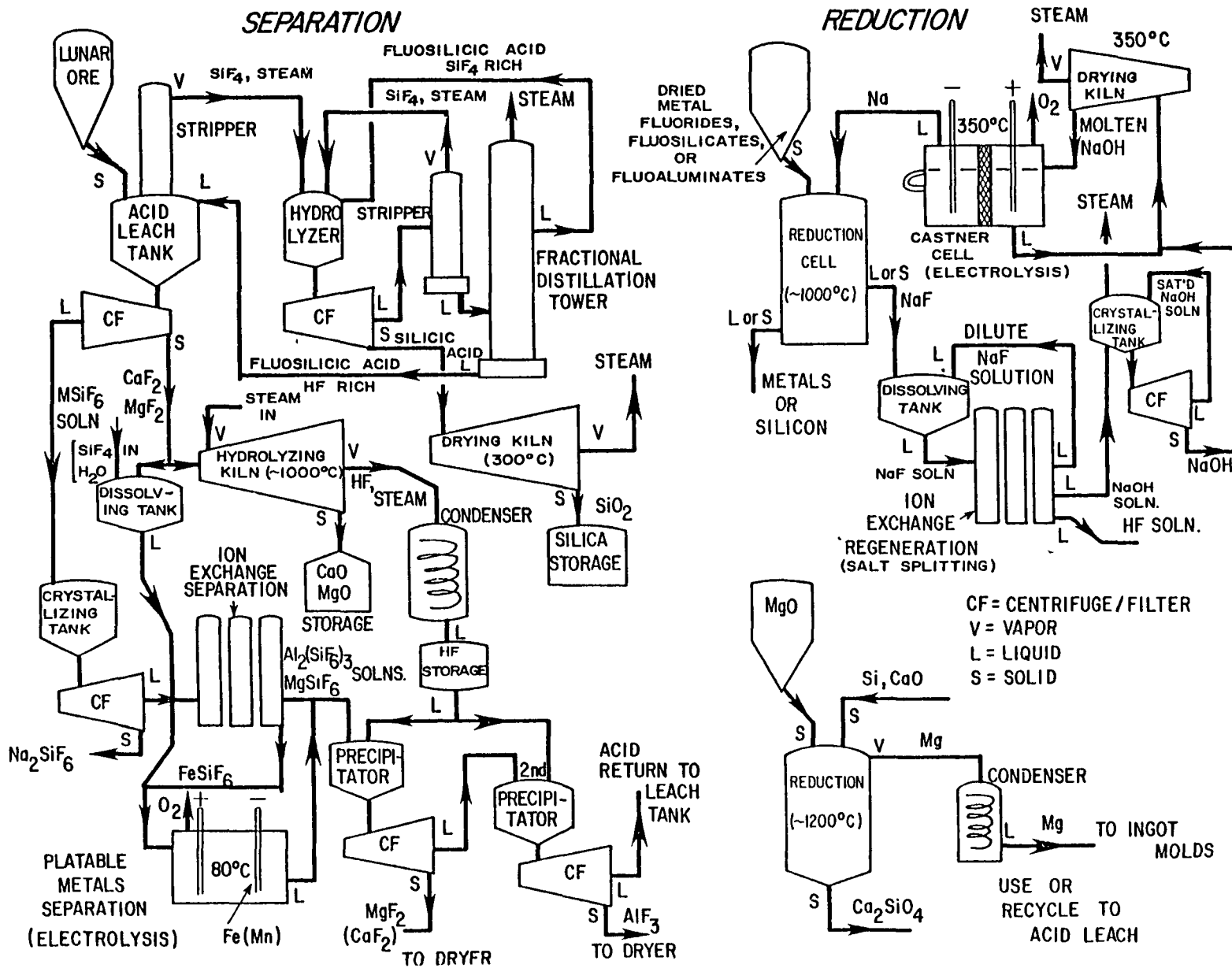
Oxygen (breathing), 16/18 of water by mass
 SiO_2 — Soil component (includes many trace nutrients)
Constituent elements of life-forms: O, Ca, C, Fe, Mg, K, P, N, Na, H
and others

Table IV

<u>Function</u>	<u>TONS CAPITAL</u>	<u>MEGAWATTS</u>	<u>TONS CONSUMABLES</u>
	TON/HOUR	TON/HOUR	TON/HOUR
Soil Excavation or Beneficiation	0.1-1	10^{-4}	$<10^{-7}$
Cold Drawing	10	0.1	Small
Lunar Mass Driver	50	1	0.01
Cold Macro Assembly	100	0.1	Small
Welding, Hot Fusion Forming	1-10	$10^2-(10^3)$	Small
Chemical Refining	100	10	0.01
Lunar Chemical Rocket	150	10-20*	2
Solid State — Micro Components	3000	50	0.1
Terrestrial Chemical Rocket	>2000	>100*	20

*With propellant production

Figure 1



PICTORIAL FLOW CHART FOR HF ACID LEACH PROCESS

HF ACID LEACH PROCESS EQUATIONS

- $$\left\{ \begin{array}{l} 1. \quad xMO \cdot SiO_2 + (4 + 2x)HF = xMF_2 + SiF_4(aq) + (2 + x)H_2O \\ 1'. \quad xMO \cdot SiO_2 + (5 + 2x)HF = xMF_2 + HSiF_5(aq) + (2 + x)H_2O \end{array} \right.$$
- $$\left\{ \begin{array}{l} 2. \quad SiF_4(aq) + nH_2O = SiF_4(v) + nH_2O(v) \\ 2'. \quad HSiF_5(aq) + nH_2O = SiF_4(v) + HF(aq) + nH_2O(v) \end{array} \right.$$
- $$3. \quad (1-y) [SiF_4(v) + 4H_2O = Si(OH)_4 + 4HF]$$
- $$3a. \quad (1-y) [SiF_4(v) + 2H_2O = SiO_2 + 4HF]$$
- $$4. \quad (1-y'-z) [xMF_2 + xH_2O = xMO + 2x HF]$$
- $$5. \quad y [SiF_4 + 4Na = Si + 4NaF]$$
- $$6. \quad y' [xMF_2 + 2x Na = xM + 2x NaF]$$
- $$7. \quad z [xMF_2 + xSiF_4(aq) = xMSiF_6(aq)]$$
- $$8. \quad z [xMSiF_6(aq) + xH_2O + elec. \text{ energy} = (x/2)O_2 + xM + xH_2SiF_6]$$
- $$8a. \quad z [xMSiF_6(aq) + M'SO_3R^* = xM'SiF_6(aq) + xMSO_3R^*]$$
- $$9. \quad m NaF + mR^*OH = mNaOH + mR^*F^-$$
- $$9a. \quad m NaF + (m/2)Ca(OH)_2 = mNaOH + (m/w)CaF_2$$
- $$10. \quad m NaOH + elec. \text{ energy} = mNa + (m/2)O_2 + (m/2)H_2O$$
- $$11. \quad (1-y) [Si(OH)_4 = SiO_2 + 2H_2O]$$

R* = ion exchange resin

m = 4y + 2xy'

THE ROLE OF SPACE TECHNOLOGY IN THE DEVELOPING COUNTRIES*

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I. INTRODUCTION

The space era began just a little over two decades ago with the launch of Sputnik I, the first artificial satellite of the Earth, by the Soviet Union in October 1957. Within a short time, more historic events followed: the first orbital flight of a human being, then of two, then of three. Then, within an astonishingly short time, the first voyage of human beings to the surface of another planetary body, the Moon, was successfully accomplished by the United States. Including these historic events, altogether some 2500 satellites and space probes have been launched from 24 sites around the globe.

As an arena for human endeavors, space is still widely believed to be of little consequence; its contributions have been perceived as beneficial primarily to the developed countries. Yet the whole world has been changed irrevocably as a result of the quest to explore and to utilize the new frontier of outer space. New concepts have been explored; new technologies have been developed to permit the exploration of space by machines and by people; and the options available to human civilization have been expanded and multiplied.

The spectacular successes of the manned lunar landings have now been eclipsed by the applications of space technology to practical activities here on Earth. As President Carter stated in the U.S. Space Policy of October 1978, "more and more,

*Presented at NGO Forum on Science and Technology for Development, Vienna, Austria, August 19-29, 1979.

space is becoming a place to work." The utilization of the space environment and the growing consciousness of this new dimension for utilitarian, economic, and social ends have had profound consequences for all of humanity, and we have as yet barely begun to transform space from a scientific curiosity into practical human endeavors. Since 1965, when satellites first emerged from the experimental stage into routine use as a practical and valuable tool in the field of communications, we have seen the remarkable growth of satellite communications systems encircling the globe. Successful use of communications satellites has been demonstrated for voice, video, and electronic data transmission. Peace missions, the printing of newspapers, teaching people of all ages in remote villages, teleconferences, diagnosis of illness and the prescribing of medical treatment, the broadcast of Olympic games, and the provision of emergency rescue and disaster relief services have already been accomplished successfully via communications satellite and have already affected the lives of the Earth's peoples.

At present, at least two international and five regional satellite communications systems are in operation, as are a multitude of satellite systems for specialized purposes, such as aeronautical and maritime navigation and communications, broadcast, data relay, and meteorology. One of the greatest success stories in international cooperation is the INTELSAT agreement which was signed in 1964, under which 11 nations entered into a unique partnership to provide global communications services via satellites. INTELSAT is a triumphant display of the use of space and communications technology for multilateral benefit, serving an operational need of all the world economically, effectively, and efficiently. Not the least of its attractive features is that it is a successful and profitable business enterprise reaping financial rewards for all of its participants. (Net investment in INTELSAT is currently \$400 million, with revenues in 1978 of about \$180 million, paying a return of 14% per year on investments to its owners.) Still more remarkable is the example INTELSAT sets for future international endeavors in space of 102 nations working together purposefully and peacefully for their common benefit.

Through advances in technology, the present generation of INTELSAT V satellites has 100 times the capacity of the first INTELSAT satellites, and substantially increased lifetime. The cost of placing into orbit a communications capability equivalent to one telephone circuit for 1 year has decreased from about \$30,000 to \$3000 over the past 10 years. Simultaneously, rapid advances in the development of microelectronic circuitry have reduced the cost and size of ground stations which transmit and receive signals to and from the communications satellites.

Besides the proven advantages of space for communications purposes, outer space has unique advantages for observation. Weather satellites have already been of inestimable economic value in the developed countries; once adequate capabilities for communication of weather information to villages have been implemented, they will provide early warning of typhoons to low-lying areas throughout developing countries as well as allow farmers to plant crops at the best time in relation to the onset of the monsoon rains, with major benefit to the human condition at minimal cost.

A strong case can be made that the avoidance so far of nuclear war over the last 30 years or more has depended heavily on the availability to the major nuclear powers of precise information indicating the lack of preparation by potential opponents for such a war. Military surveillance and reconnaissance satellites have made major contributions toward providing such information. Neither the Nuclear Test Ban Treaty prohibiting the testing of nuclear explosive devices in the waters of the

oceans, in the atmosphere, or in outer space, nor the Strategic Arms Limitation Treaty could have been achieved without the availability of such satellites. The technology developed for these satellites, originally for the goal of national survival, is now being turned to directly peaceful purposes through the development of satellites for the measurement of temperature and wind velocity distributions in the atmosphere, of patterns of land use, of ground water, of forest coverage and vitality, of deforestation, of the salinity of water, of ocean temperatures and wave heights and directions, and of mineral concentrations including petroleum.

II. SOME ULTIMATE POSSIBILITIES IN SPACE

So far we have mentioned what has already been achieved in space or what will be implemented very soon. Let us turn now to a brief consideration of what space could ultimately mean to all of us.

Because space programs in more than a dozen nations around the globe are no longer "news," further expansions of the potential capabilities of space activities for the improvement of the human condition have not yet been appreciated by most of the Earth's population. Within the past decade, the expansion of scientific knowledge and of the technical capability has reached the point that the nations of Earth can, and should, consider opening resources of energy and materials in space many thousands of times greater than all the resources of the Earth; this can be done within a very short time-scale, as little as one or two decades. The resources in question are *energy*, now wasted, which streams outward from the Sun endlessly, in the form of intense, unvarying sunlight in space outside the Earth's shadow, and *materials*, now totally unused, in the form of lunar soils and the asteroids of the solar system.

The unlimited energy available in space may be harnessed for use here on Earth in several different ways. Large, very lightweight mirrors in orbit around the Earth could illuminate, on demand, specific areas on Earth on either the daylight or the night sides of the planet. Such orbiting mirror systems could be used for illumination of crops near the freezing point to reduce losses to frost; for illumination of urban areas, reducing or eliminating the need for street lighting systems; for illumination to permit night harvesting or to assist night operations in disaster relief and rescue; to stimulate the growth of crops for biomass energy conversion; or for direct conversion of more intense sunlight (available 24 hours a day in this manner) into electricity by well-known means on the ground.

Alternatively, full-time sunlight could be captured in geosynchronous Earth orbit, converted into some acceptable form such as low-density microwaves for transmission to a receiver station on the surface of the Earth, and its conversion on the ground into useful forms to provide a full-time renewable energy source. In highly industrialized regions, such Solar Power Satellites would likely be used to provide electricity. Elsewhere, the energy delivered from space could be used to produce synthetic liquid or gaseous fuels, such as methanol (produced from air and water) or hydrogen (by electrolysis from water), to produce synthetic fertilizers such as ammonia (from air and water), or to desalinate ocean water for human consumption and for agriculture. At the present time, a number of uncertainties concerning the environmental acceptability, economics, and technical practicability of Solar Power Satellites remain to be resolved, but the idea clearly merits serious consideration.

An alternative approach to the construction of such Solar Power Satellites has been developed in a series of four conferences, three government-supported techni-

cal studies, and several reviews by academic- and aerospace-contractors funded by agencies of the U.S. government. These studies have all concluded that, at least in the long run and possibly even quite early, the construction of these satellites can be accomplished at least cost and with minimum adverse environmental impact by using raw materials obtained from the surface of the Moon and refined in space using solar energy. The National Science Foundation, in close cooperation with the National Academy of Sciences, is now undertaking still another independent review of this possibility under mandate by the U.S. Congress.

Still other studies during the past 10 years, particularly in the United States, recently substantiated by reviews carried out in other countries, now make it virtually certain that in the long run the vast energy and material resources of space will be of far greater importance to humanity than will all the resources available within the biosphere of Earth. It has become clear that these resources can be put to use most easily in space itself, creating and supporting orbital factories, agricultural establishments, and human habitats. Such a development, however, probably represents an ultimate rather than an initial state.

Although the highly-visible American-Russian race for the Moon began as a peaceful expression of technological capability and national power, it is fortunate that the first human landing on the Moon's surface was followed by a series of flights whose purpose was scientific. These expeditions returned to scientists in many countries on Earth an enormous wealth of data, much of it still under analysis, far more abundant, quantitative, and accurate than all prior suppositions about the Moon up to that time. We learned, for example, that random lunar soil samples from the six sites visited contain an average of 30% metals by weight (including iron, aluminum, magnesium, and titanium); 20% silicon (a material from which photovoltaic solar cells can be made); and 40% oxygen (perhaps the most vital element for human survival, being the essential component of our atmosphere and making up nearly 90% of the weight of ordinary water). In retrospect, we are coming to view the greatest value of the lunar explorations to be geological prospecting for resources.

Earth approaching asteroids have also been suggested as a competitive source of raw materials for space manufacturing. The available resource is enormous. In many cases, the energy required to transfer an asteroid (or a portion of an asteroid) to a manufacturing site in high orbit around the Earth is comparable to that for raw materials obtained from the lunar surface. The cost for asteroidal materials may be many times less for logistical reasons: due to the very weak gravitational pull of an asteroid, no complex propulsion engines are necessary for soft landings; and solar energy would be available continuously at an asteroid for processing and for propulsion. Studies of the light reflected from some of these asteroids reveal that their chemical compositions may be similar to those of meteorites which have landed on Earth. Some apparently contain large quantities of metallic iron and nickel, while others are rich in carbon, nitrogen, and hydrogen, elements which appear to be very scarce on the Moon. Discoveries of new asteroids over the next few years will allow selection of a variety of raw materials with numerous alternative retrieval missions possible. Techniques for retrieving asteroidal materials have been subjected to a number of engineering studies, which confirm earlier suggestions that the retrieval costs for these materials may become less than \$1 per kilogram.

The projected requirements for replacing losses of air and water at orbital facilities for the construction of Solar Power Satellites and the projected expansion of agricultural facilities in orbit supplying the construction workers are sufficiently large to suggest that the bulk of the raw materials for these purposes should come from the

asteroids rather than from the Earth, while the availability of free metals in asteroids would eliminate many of the complex steps of chemical processing needed for fabrication of Solar Power Satellites from lunar materials.

The possibility of retrieving metals from asteroids for delivery to the Earth's surface has also been discussed. One study has shown that the cost of delivering fragments of a nickel-iron asteroid may be economically competitive almost immediately. The separated metal would be melted with solar energy, made into a metal/vacuum foam, shaped into a lifting body, deorbited by a variety of technical means to land in the ocean just offshore, and towed ashore for use in conventional industries. It is interesting to note that approximately half of the total world production of nickel between 1961 and 1965 came from the Sudbury Astrobleme in Ontario, Canada. This deposit is probably asteroidal in origin, so that it is likely that non-terrestrial materials are already in use here on Earth.

In the more distant future, perhaps as little as three decades from now, the apparent attractiveness of space agronomy offers the possibility of raising food in orbit more economically and reliably than here on Earth, assuming a highly developed program of space industrialization will have been implemented. Large quantities of mature crops could be dehydrated, loaded inside lifting bodies made of metal/vacuum foam, and delivered offshore from potential consumers. As population growth continues here on Earth, as water resources become more scarce in some major agricultural regions of Earth, as fossil fuels and fertilizers become more expensive, and as drought and other adverse climatic factors continue to cause major fluctuations in food production on Earth, it is possible that the costs of food produced in space and delivered to the Earth may become cheaper than conventional farming down here.

Although these estimates and possibilities are clearly preliminary, they indicate that a healthy and vigorous economy in space, independent of the biosphere of Earth, may permit the delivery to Earth of a virtually unlimited and reliable supply of materials, food, and energy for future generations as little as 30 years from now. These possibilities could relieve the immense pressures the human race now perceives in its attempts to manage its Earthly endowment of nonrenewable energy and material resources and its food supply. The promise of such advanced concepts in space utilization merit serious attention by all the nations of the Earth.

III. NEEDS OF THE DEVELOPING COUNTRIES

What are some of the key problems and needs of developing countries as they struggle to raise the quality of life for their peoples? Most of the developing countries suffer from a lack of accessible (or identified) material and energy resources, from a lack of sufficient numbers of skilled workers in a wide variety of fields, from a lack of usable information, and from a lack of adequate communications and transportation facilities, both domestically and internationally. Further problems in many developing countries include lack of potable water, lack of medical personnel and facilities, lack of financial credit for agriculture, and (in some cases) inequitable land distribution patterns. All of these factors can create serious impediments to efforts to raise the standard of living of the population and to slow down the rapid increase in population which can dilute the effects of increases in national economic production. In the next section, we wish to indicate some of the possibilities which the utilization of space resources in the next one to three decades can offer to help alleviate some of these problems in developing nations. We do not wish to suggest that outer space

technologies can solve or even address every one of these problems, but rather to encourage serious consideration of the ways in which space programs could be integrated into plans for development in virtually every developing country on Earth.

IV. SPACE ACTIVITIES AIDING DEVELOPMENT

The role of communications satellites in development is multiple: their use in providing education for all ages in remote villages and in providing medical consultation with major medical facilities in the same country or in a developed country has already been demonstrated. These capabilities will soon become sufficiently inexpensive to become widely available during the next 5 to 10 years. Communications satellites are particularly well-suited for basic communications services within countries of very large area, difficult terrain, or multiple islands where adequate land-based communications infrastructures have not yet been installed or where these would be prohibitively expensive. Rapid access to global trading information will play an important role as developing countries strive to become more integrated in world trade.

Navigation satellites planned for deployment in the 1980's will be useful for developing countries as well, providing accurate navigational information for shipping in coastal waterways and between islands and by-passing much of the expense of installing air navigation beacons in remote areas. Such satellites will also make extensive surveying projects for road and railroad construction and other major civil engineering programs less expensive and time-consuming.

Remote sensing satellites (such as the LANDSAT and SEASAT series) can provide a wealth of information on physical and biological conditions in any country. Some examples of proven techniques or soon-to-be-available techniques include cartographic surveying of remote areas; periodic surveys of urban areas to analyze changes in land use; inventory analyses of surface and ground waters; observations of forest population distributions, health, and cutting rates; monitoring of waters for turbidity, septic runoff, or industrial pollution; changes in coastlines and lagoons; and constant updating of information on agricultural conditions and crop yields. Some of these applications of remote sensing satellites have been used in Bangladesh (coastline changes), Canada (monitoring of log debris on Williston Lake in British Columbia), Jamaica (mineral resource surveys), Brazil (lagoon variations), and Japan (marine pollution in Tokyo Bay).

Of great importance is the investment being made by the United States and other technologically active nations to develop and prove the operational value of the data received from such remote sensing satellites. Increasingly, data on any given condition of the Earth's surface can be interpreted in a reliable manner with less and less examination of conditions on site. If a method of surveying forest cutting rates has been confirmed (after considerable developmental expense) to apply to a given type of tree distribution and land type in one country, for example, that method can then be transferred for use in a less developed country at considerably less expense, requiring far less commitment of resources including money, trained personnel, or equipment. Thus it is possible for highly complex space systems, data receiving technologies, and data interpretation methods to bear immediate returns in developing countries.

On a longer term basis, it is clear that the ground systems necessary to use observations and services available from space hardware are rapidly becoming less expensive and less difficult to use as the space systems grow in size, power, and

sophistication. As a general theme, the world wide character of space systems will make them available to any country at a minimal cost, perhaps on an "as-needed" or an "as-used" rental basis, enormously reducing the expenditures of capital and people needed to carry out the same functions from the ground.

We have already mentioned briefly the possibility of constructing large Solar Power Satellites in geosynchronous Earth orbit to harness the abundant solar energy available in space full-time for delivery to Earth. While these were originally conceived as a source of electrical power on the ground in industrialized regions of the Earth, they offer great promise for many rural areas of developing countries as well, where the primary need for energy is for fuels suitable for cooking, heating of homes, and small labor-intensive industries. Cooking needs alone amount to the equivalent of 1 ton of firewood per person per year. In this context, electricity produced at receiving stations for Solar Power Satellites could be distributed to ten or twelve chemical synthesis plants at distances to 50-100 km from each receiving station. That electricity could then be used to produce methanol from the carbon dioxide in air and from water in large quantities. Methanol is a liquid fuel which can be burned in an environmentally very safe manner, using existing low-technology stoves, ovens, and furnaces. Initially, the synthetic fuels could be distributed by labor-intensive methods or by pipelines built gradually by labor-intensive methods to supply villages with fuels at prices considerably lower per unit of energy than current prices for presently available fuels (kerosene, firewood, or dried cow dung). Such a program could provide enormous numbers of jobs for unskilled workers, especially during the construction phases, in regions of chronic rural unemployment. The standard of living of rural families would be raised directly by reductions in the heavy burden of fuel costs. One Solar Power Satellite used in this manner should provide sufficient liquid fuel to provide for the cooking and heating needs for populations of 5 to 15 million people, depending on the climate.

It is possible that in some cases the receiving stations for Solar Power Satellites may have to be constructed as large floating platforms just offshore. In the conversion of microwave power into electrical power, a small amount of heat will be generated. With appropriate designs, that heat could be used to warm the surface layers of ocean water to encourage growth of marine plants and animals in the immediate vicinity of the floating platforms, providing the basis for large scale mariculture operations. Previous studies of mariculture have found the costs of floating platforms to be prohibitive; in this case, however, since the floating platforms would be economically justifiable because of the energy received from space, the additional costs for establishing a large mariculture operation providing major new sources of edible proteins would be very much smaller.

As the developed countries replace electrical generating plants which burn fossil fuels with Solar Power Satellites, their demand for petroleum should shrink, reducing the costs of traditional energy sources required for transportation and food production in the developing countries. The costs of petroleum by-products (including fertilizers, pesticides, plastics, industrial solvents, and pharmaceutical products, to name a few) should also decline. Meanwhile, as the absolute costs of primary energy sources decline, industrial countries will be able to utilize less concentrated sources of terrestrial minerals as inputs to industrial processes, reducing competition for limited reserves of more concentrated scarce minerals.

Countries having advanced space capabilities will find tremendous economic incentives to create the new technologies permitting them to use whatever material resources are available in space for the construction of machinery and habitats in

space. Early construction on the Moon will very likely use the common soil of the outer lunar surface. Since it is likely that the accessible portions of the lunar soil have no deposits of high grade minerals, techniques will have to be developed for the extraction of economically useful elements from low grade ores. These techniques will in many cases prove applicable to extraction of useful elements from low grade ores available in abundance on Earth, further reducing tensions of competition for resources here on Earth.

One additional possibility should be mentioned here: the potential use of equatorial sites or low-latitude sites in developing countries as spaceports, especially if these are combined with tariff-free trade zones. Logistically, such launch and recovery sites can provide major improvements in rocket performance and thus in operating costs. A spaceport combined with a free-trade zone would provide major benefits to the host country, including stronger links with international trade, a new impetus for tourism, and a natural focus for the development of a technical and scientific cadre within the host country. Such possibilities are being explored by a number of developing countries in conjunction with the Earthport Project in Santa Barbara, California.

It must be emphasized in this discussion that, although the technologies for these advanced possibilities are expensive and are being developed at the present time for the benefit of the developed countries which can presently afford them, their impact will be far greater and far more dramatic in the developing countries. To add one Solar Power Satellite to the electrical system in a country such as the United States would change its capacity by 2%; to add one Solar Power Satellite to the electrical system in India would increase India's electrical capacity by 40%. Clearly, the deployment of a communications satellite system in a country like Indonesia, which is scattered across hundreds of islands stretching over 8000 km of ocean, will be of far greater benefit than to provide such a satellite for continental Europe. It would thus be a serious error for developing countries to dismiss space technology as irrelevant to their needs.

IV. POLICY QUESTIONS

Many important issues must be examined if some of the ideas presented above are to be taken very seriously by developing countries:

1. By investing in space development, is the world being deprived of some of the most urgent resources needed for solving mundane problems? Space expenditures by the industrialized countries currently use only a small fraction of one percent of the Gross National Products of those countries. The benefits to developing countries have already been inestimable.
2. Are the countries advanced in space technologies ready to share their knowledge and benefits with other countries? In many cases, the past record already answers this question positively. In other cases (such as Solar Power Satellites), economic self-interest will encourage advanced countries to make the new technologies available at the earliest opportunity.
3. Is it necessary and possible to bring total international control over all space developments? Because of the vastness both of the resources and of space itself, it seems unnecessary and, perhaps, impossible to effect total control.
4. What will be the impact of large-scale space industrialization on the terrestrial environment? This is a question under active research in the United States. In

many cases, such as asteroidal mining of metals, the effects would be highly beneficial by removing highly-polluting activities from the Earth's biosphere.

5. Is it possible to control military developments in space? This question has no simple answers, but deserves careful consideration from all sides.
6. Finally, how can terrestrial and space science and technology be combined for maximum benefits to all of humanity? This question is open ended; perhaps it is best addressed on a case-by-case basis during the early design stages of new projects, whether on Earth or in space, whether the project is being implemented in a developed country or a developing country. To ignore either space technology or Earth-based technology in the effort to improve the human condition would be foolish.

Careful consideration of these issues by those working toward the advancement of the developing countries will, we are confident, convince them that space technology has much to offer these nations.

V. RECOMMENDATIONS

As research scientists closely identified with the possibilities of advanced space technologies discussed earlier, our primary purpose in writing this paper has been to make known to the citizens of all nations the new possibilities now emerging, and to urge upon all nations the importance of avoiding three tragic mistakes:

1. The mistake of thinking that the new resources beyond the biosphere of Earth are limited in quantity and thus concluding that it is appropriate to restrict their use. Such a mistake would delay the use of these resources at all and would thus delay their use to relieve problems of the developing countries.
2. The mistake of ignoring these resources and thus, by inaction, permitting their possible misuse by a limited number of nations solely for their own benefit.
3. The mistake, through ignoring these new resources and thus the importance of their environment, of idly standing by, while outer space becomes merely an extension of petty nationalistic military confrontations which still afflict the surface of the Earth for historical reasons and for the defense of "limited" territory and resources.

To avoid these mistakes and to foster greater international cooperation, we urge the peoples and the governments of the developing countries to seize every opportunity to join in this new direction of economic and technological growth by the use of space technologies in their own countries; by the encouragement of progress in the development of space resources at the earliest date; and by participation by some of their own citizens in the development of space for the benefit of all humanity. One major way in which a developing country can make use of the growing opportunities in space at reasonable cost is to establish and maintain (perhaps in connection with an appropriate governmental department or a university) a satellite receiving terminal capable of receiving remote sensing data for that country direct from space. With a limited number of personnel trained to use this equipment who can keep abreast of developing technology, the received information can be used to the benefit of that country while a sense of trust in, and expectation for, the use of space observation systems grow throughout the government and the people.

In view of the enormous benefits which may result from vigorous utilization of the vast resources of outer space, we urge the developing nations to gather information on the new possibilities discovered in the past decade for the use of these resources

for the improvement of the human condition everywhere on Earth.

We further recommend that the nations of the Earth consider and, if they so choose, adopt the following ideas as working principles:

- A. That the United Nations should vigorously press for the adoption of legal principles by which the resources beyond the biosphere of the Earth can be used as soon as possible, in a manner to relieve human suffering and to speed economic development in the developing nations. The United Nations may wish to consider making it a condition for the legal use of non-terrestrial resources that some portion of production be turned over to the ownership, or for the use, of developing countries. Care should be taken not to summarily ban private companies from activities in space, as such a course may seriously delay any benefits from space to every nation on Earth.
- B. That all nations should recognize the opportunity presented by the development of the resources beyond the biosphere. Use of these resources peacefully and cooperatively will constitute a triumph of the human spirit, an extraordinary human adventure, and a transition without parallel in human history. With this recognition, it should be an urgent goal to establish first the study and then, if proven feasible, an actual space program to use those resources as a peaceful, cooperative, and international program under the auspices of the United Nations or some other suitable international organization. At the present time, we would strongly suggest consideration of Solar Power Satellites as an important candidate for study.
- C. That the developing nations should take an active part in research directed at the utilization, as soon as possible, of the virtually unlimited resources of energy and materials now known to be available beyond the biosphere. It appears to us that such an active role can be played most effectively by research within each developing country by its own nationals. Much of that research would have potential for immediate useful applications within developing countries. (For example, the development of closed-system agriculture under controlled conditions could lead to practical methods for intensive controlled-environment agriculture at the village level, allowing increased food supplies, protection of drinking water from contamination, and reduced needs for urbanization or the rapid development of a transportation infrastructure. Such research could also point the way for the manufacture in space of new construction materials suitable for use in developing countries for housing, water supply, and light industry.)
- D. Since the development of resources beyond the biosphere will profoundly alter our human outlook, opening for the first time the possibility that new territory can be constructed out of abundant unused resources rather than obtained by conquest, that men and women representing every nation on Earth work actively in any such program from the earliest practical moment, in space as well as on Earth.
- E. That renewed efforts be made by the United Nations to ban offensive weapons from space, especially high-orbital space and all celestial bodies. Ideally, all space from high Earth orbits outward should be preserved as non-military regions free of all weapons, military installations of any kind, and military spacecraft whether manned or unmanned. Realistically, however, recognizing the positive contribution that certain military satellites (reconnaissance and surveillance satellites in particular) have made to international stability, and the possibility of future defensive systems in orbit reducing the risk of nuclear

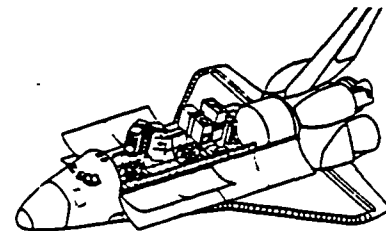
war on Earth, we would urge the nations of Earth to study and discuss carefully the implementation of further limitations on military activities in space.

VI. CONCLUSIONS

The changing nature of space technology is projected to result in routine and productive activities in space related to the needs of terrestrial society. Routine, inexpensive access to space through the use of new transportation systems (such as the U.S. Space Shuttle and the European Space Agency's *Ariane* launch vehicle) will bring about economically valuable returns from a wide variety of potential applications. One analysis conservatively estimates annual revenues from space activities of \$15,000 million in the year 2000, and more than \$70,000 million in the year 2010, producing almost 2 million new jobs just in the United States in 2010. These figures cannot begin to indicate the significance such new possibilities will have for developing nations.

The potentials of outer space for the improvement of the human condition everywhere are unlimited. Developing countries cannot afford to neglect space technology and space science. Although the highly industrialized countries will necessarily make the initial investments to develop the resources available beyond the biosphere of the Earth, such ventures should become international in scope and character so that their benefits can reach all of humanity at the earliest possible time.

The ultimate terrestrial importance of the development of space resources may turn out to be, not the materials or the energy which will flow from space to the Earth, nor the new habitats created in space, but rather the certain, tangible, and visible knowledge that secure, new, expanding wealth can be created by humanity from the commonly available energy of the Sun, the soil of the ground beneath our feet (whether we stand on the Earth, the Moon, or any other celestial body), and the cumulative and shared skills of the entire human race.



AAS-78-143

LUNAR BASE HABITAT
EXPLORATION DESIGN STUDY

G. TROTTI

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LUNAR AND PLANETARY INSTITUTE

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OCTOBER 30—NOVEMBER 2, 1978
HOUSTON, TEXAS

OUTLINE FOR AN EXPLORATORY STUDY ON THE DESIGN OF LUNAR BASE HABITATS

All structures in space are pneumatic, no matter if they are built of aluminum, steel, fabric, or something else.

The moment an architect has to provide a crew with a shirt-sleeve environment that will protect them against the vacuum of space, the structure becomes pneumatic.

Despite the fact that pneumatic structures, previously designed out of steel and rubber, have not been proven effective, the advance of technology has given us the necessary materials.

We know that any pressurized environment must be cylindrical or spherical. New plastic based materials make it easy to use curved surfaces when designing a pressurized environment.

The problem we encounter on the lunar environment are the 1/6 gravity, radiation, temperature, night and day cycles, and monochromatic landscape. Building a shirtsleeve environment for a structure in orbit confronts the same basic problems.

On earth, we can build pressurized containers out of steel or aluminum, because we don't have any volume or weight limitations. In space welding, bending, rivetting, and sealing these materials, although possible, would be very difficult.

The shuttle, which is the workhorse of the immediate future, has limitations of weight and volume. Pneumatic structures are designed to expand after deployment. Each structure will be several times larger than the volume of the shuttle bay. The new light weight materials will help us solve the weight problems. We see this system work like a rubber life raft, wherein the instant it touches the water, it deploys and provides a safe

shelter. Many of these rafts include food and water for a limited number of people. In a somewhat similar way a pneumatic structure can be deployed in orbit or on the surface of the moon.

With pneumatic structures we can possibly transport several modules in one trip. These modules could be designed to fit together or to be used independently after deployment. Since we cannot depend on car tire technology to build habitats in space, we have turned away from rubberized steel mesh, which is bulky and hard to fold. DuPont makes a fiber which is strong as steel and several times lighter. Kevlar 29 has the characteristics of dacron and is much easier to fold than steel mesh (DuPont, personal communication). Therefore, we feel Kevlar opens the door to the successful use of pneumatic structures.

The interior of these light weight modules does not have to be cramped, since we can afford more free volume. The texture of the walls does not have to be metallic anymore. With this system we could soften up the interior walls; they could have a quilt-like surface. Interior shapes could be varied easily and color fabric would be easily available.

The use of pneumatic structures gives us many possible solutions to basic habitability problems. After all, nobody wants to live in a metal cave.

It is conceivable that for the lunar environment a similar system can be designed, which arrives on the surface of the Moon in a relatively small package and then is deployed to provide a large pressurized volume with life support systems to support a population of 12 people.

Let me show you an example of a concept which we are studying with that purpose in mind. It consists of two basic elements — a membrane which will support the internal pressures of the environment, and a rigid pallet which will house all the life support systems (Fig. 1).

This system allows for a maximum payload which results in a structure considerably larger than the volumetric constraints of the shuttle bay.

Several of these pallets can be transported in one shuttle flight, the number will depend on the final characteristics of the habitat designed. It is expected that this approach will allow for maximum payload utilization of the up-leg of the shuttle. The shuttle will be weight rather than volume limited. The membrane will be manufactured of teflon covered Kevlar. It will be a two layer membrane with a 66 cm foam core to provide rigidity (Fig. 2) in case of depressurization of the environment. The shelter will keep its shape supporting three meters of soil on top of it.

The foam comes in two separate chemical bags which break at the time of deployment and mix. The foam then fills in the space between the membranes.

All interior and exterior walls will be of double skin fabric. The interior wall thickness of the foam is 6 cm, which will provide sound and temperature insulation from room to room. These walls do not provide structural strength to the membranes; therefore, they carry very little loads. The interior walls material is not Kevlar, but nylon or polyesters which are lighter and cheaper. These walls will be pre-sewn to the membrane when necessary. When the shelter is deployed all internal partitions stand in place.

The design might allow for some furniture to be part of the wall system and therefore, be made out of fabric.

Hard surface furnishings such as table tops, bathroom fixtures, doors, etc., will be brought up in the same shuttle flight in a separate package. Each pallet will have its own 'kit' of rigid parts which will be easily attached to the module after deployment.

The pallets (Fig. 3) will be constructed of a light aluminum frame of 4.5 m x 8.5 m. It will house all the LSS, waste management system, communication system, etc. These systems could be incorporated as part of the structure of the pallet in this way lightening it.

It is possible that some of the stationary furniture such as beds, tables, cabinets, etc., could be unfolded from the top wall of the pallet.

The bottom wall will be curved to help carry the internal pressure loads, and at the same time the curve will facilitate the transportation of the module on the lunar surface. When the module is unloaded from the lunar tug it will be pulled like a 'sled' by a lunar surface vehicle to its final destination. Once in their permanent position the modules will be interconnected to create a small network of specialized environments (Fig. 4). Some of these modules can act as independent units from the main network.

When the desired configuration is completed the modules will be covered by three meters of lunar soil for radiation and temperature insulation.

The pallets will be placed below grade, in trenches dug by an automated LSV before the arrival of personnel to the moon.

This will facilitate the covering of the shelters.

There are three ways in which we can connect these pneumatic modules:

1. Membrane to membrane, where various modules are attached directly through the skin to create large internal volumes.
2. Frame to frame, where the modules have a 'doorway' type frame where they will attach to another module with the same type system, in this way creating two separate but directly connected spaces such as different rooms under one roof in a typical home.
3. Transportation tunnel, where a cylindrical tube can be connected to the previously described frames to create a long corridor. This system will be used for remote spaces which will have frequent traffic such as a maintenance facility. The circulation tunnel will add 'free volume' to the base, therefore making it psychologically larger than it really is.

These structures could be designed as bellows, or telescopic, all to save volume in the shuttle bay. The diameter of these tubes — tunnels — is about two meters to permit traffic of large objects. These tunnels will not be equipped with their own LSS, although they are furnished with light fixtures and communication systems.

The air-lock (Fig. 5) is a smaller module designed with the same structural concept. It connects directly to one of the larger modules through frame type connections which are identical in all modules.

This module (Fig. 6) is not only used as an air-lock, but is used as a 'dirt-room' too. One of the biggest housekeeping problems on the moon is to leave all the fine lunar soil outside of the shelter. The 'dirt-room' is designed specifically for that purpose. It is composed of two areas — the suit cleaning and the suit storage areas. The first one is equipped with an air shower, grid floor and a suit vacuum system where the astronauts can clean their suits before hanging them up. The second area is furnished with a soft floor, seating for two people, and storage compartments for space suits and equipment.

Dining/Kitchen Module

The food management (Fig. 7) scheme in this design is man-to-food-to-table, where the person gets his or her tray of food from the food preparation area and then walks to the dining area to eat.

In this specific arrangement within one 4.5 x 8.5 meter module, seating for the 12-man crew is provided. Six extra places are provided for visitors. Food storage preparation and distribution areas are within the same module (Fig. 8).

Food selection will be made from several tray combinations which will vary day to day. Once in the dining room (Fig. 9) the tray is attached to a light frame which provides support for them. When trays are not in place only the frame is visible, in this way making the dining room more spacious.

The dining room serves as a projection room where films are shown periodically for the entertainment of the crew. The floor surface must be soft to reduce noise levels, but must be smooth for easy cleaning. The walls are made out of fabric which could be designed in bright colors.

Living Module

This module is designed to create private spaces for the crew members. It provides a private sleeping and passive recreation area (Fig. 10).

The bathroom, with the exception of the lavatory, is shared with one other person; this is done through a utility wall system that divides the two rooms. It consists of a toilet, shower, storage closet and lavatory areas.

On the other side wall (Fig. 11) of the room there is a fold-out table which can be used for work or passive recreation. Next to this table is the bed which is designed with a thin foam mattress; the blanket (Fig. 12) side of the envelope is made out of stretch material. To go in and out of the bed the blanket is provided with a zipper which helps reduce the housekeeping time. Attached to the bed there is a small pivoting tray containing T. V. screen, radio, and communication system.

Minimal Configuration for 12 People Coexisting

Six 4.5 x 8.5 meter modules with a total area of 219 m² are able to house 12 in comfortable quarters (Fig. 13).

This type of configuration is transported in two shuttle flights, including furnishings, and it is assembled and deployed in one earth day.

The more we study the structural problems of pneumatic structures, we find out that if the geometry or shape of the skin is continued without any rigid members, it becomes much more efficient. The case might be that the best solutions will be the ones where the skins are made of Kevlar all around, and the floor could float inside the shelter. An example is shown in this space

station (Fig. 14) which we designed several years ago, where the floors and partitions are connected to an interior frame all the sides of the partitions could be used as working areas (Fig. 15).

Other ways in which we are trying to solve the problem of providing large pressurized volumes in a few shuttle flights is with foldable flat plates that can be assembled in space by astronauts in a hard-hat role. An example is shown in (Fig. 16) where the first shuttle brings the core with all the LSS and Research and Development equipment. The core is lifted by a hydraulic rotisserie type hoist which then turns it, while the astronauts lift the plates from the shuttle bay and hook them together to enclose the first volume. When the first volume closure is completed, the bay is pressurized, making it habitable and locking the plates in place. One subsequent shuttle flight will bring the addition of six saddle units which will be placed around the core (Fig. 17). These examples are purely conceptual, but we feel that they could serve as stepping-stones for the development of structures which are directly focused on the shuttle constraints.

In conclusion pneumatic and foldable systems offer adaptability to the transportation restraints.

They can provide interior spaces which are much larger and more dynamic environments than the typical tin cans. The different design possibilities provide flexibility to counteract the extreme temperature variations, different gravity conditions, radiation, and isolation in space. We believe that our ability to create humane environments to lead a healthy and exciting life in space is limited only by our imagination.

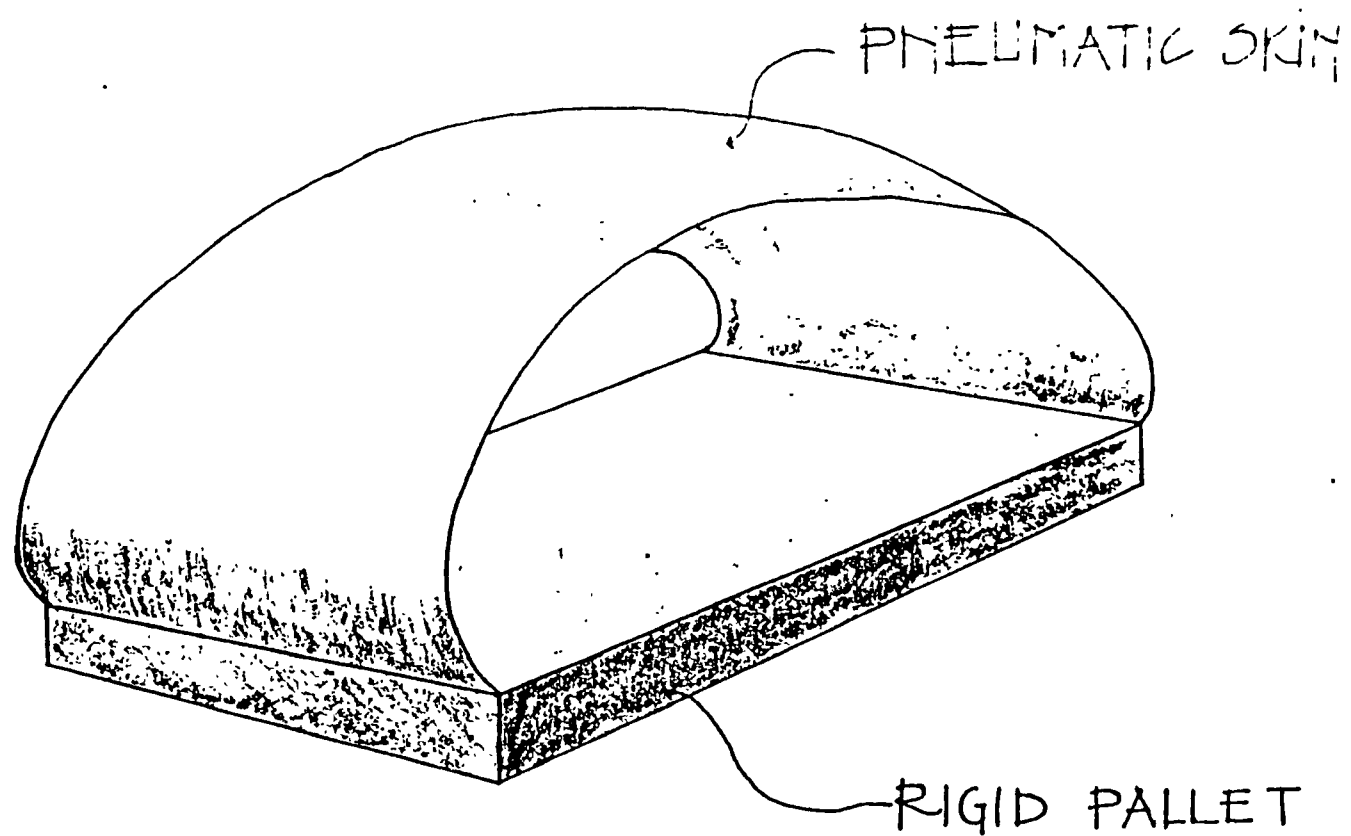
LUNAR BASE HABITAT
EXPLORATION DESIGN STUDY

Figure Captions

- (Fig. 1) Basic Pneumatic Module
- (Fig. 2) Exterior Wall Section
- (Fig. 3) Possible Module Design (Section)
- (Fig. 4) Minimal Configuration 3 Pallets
- (Fig. 5) Air-Lock Module Floor Plan
- (Fig. 6) Air-Lock Module Interior View
- (Fig. 7) Food Preparation and Dining Module
- (Fig. 8) Food Preparation Area, Interior View
- (Fig. 9) Dining and Projection Room, Interior View
- (Fig. 10) Living Module for Four People, Floor Plan
- (Fig. 11) Interior View of Bedroom
- (Fig. 12) Isometric View of Bed
- (Fig. 13) Six Modules Configuration Capable of Housing 12 People.
Delivered in Two Shuttle Flights
- (Fig. 14) Pneumatic Space Station Section
- (Fig. 15) Pneumatic Space Shuttle Outside View
- (Fig. 16) Shuttle Section Showing Hydraulic Lifting Space Shuttle
Core, Flat Plates are Shown on Bottom of SH Bay
- (Fig. 17) Outside View of Hexagonal Flat Plate Space Station

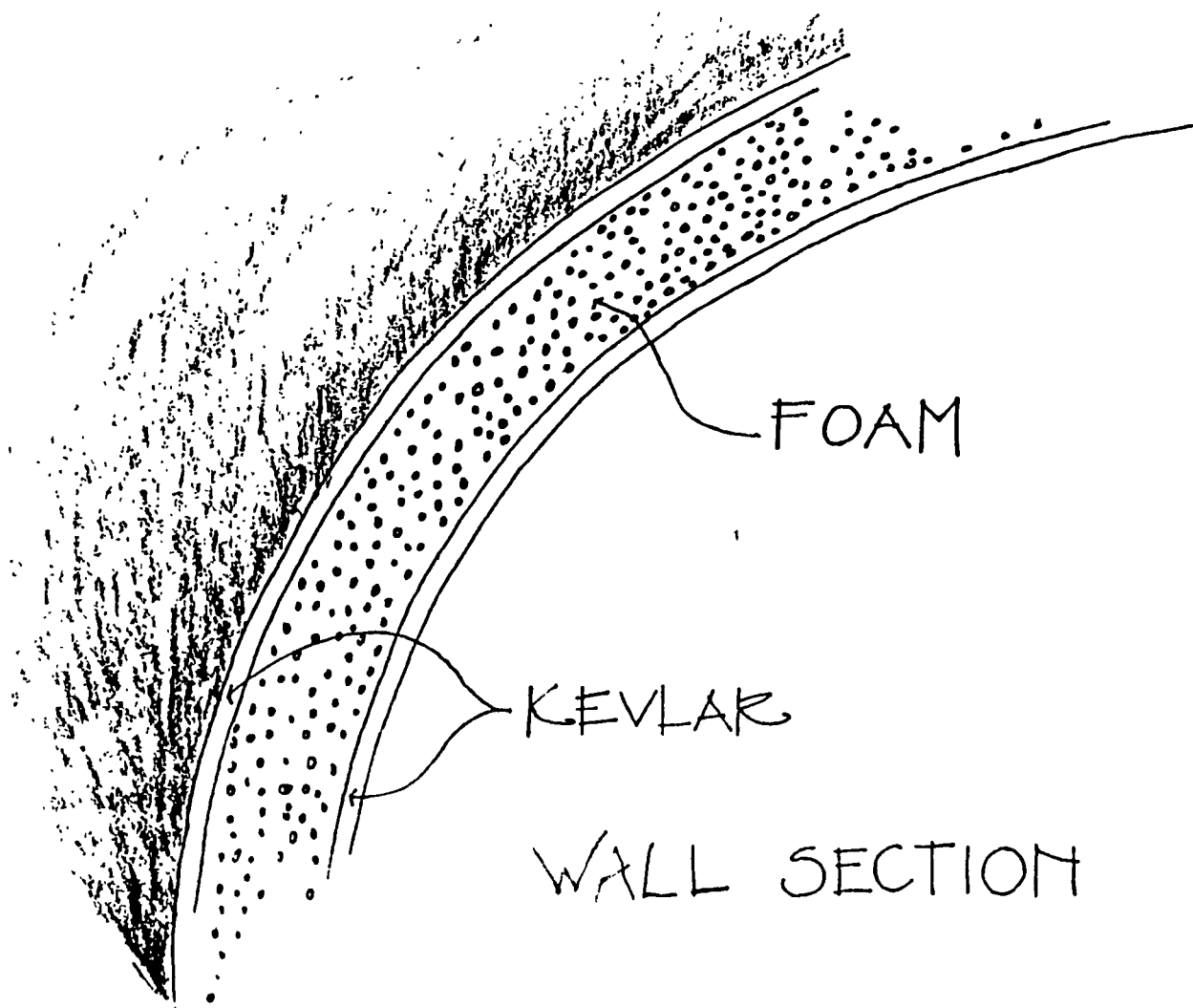
Acknowledgments

This work was performed at the Lunar and Planetary Institute, which is operated by the Universities Space Research Association under contract No. NSR-09-051-001 with the National Aeronautics and Space Administration. This paper constitutes the Lunar and Planetary Institute Contribution No. XXX.



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Figure 1



WALL SECTION

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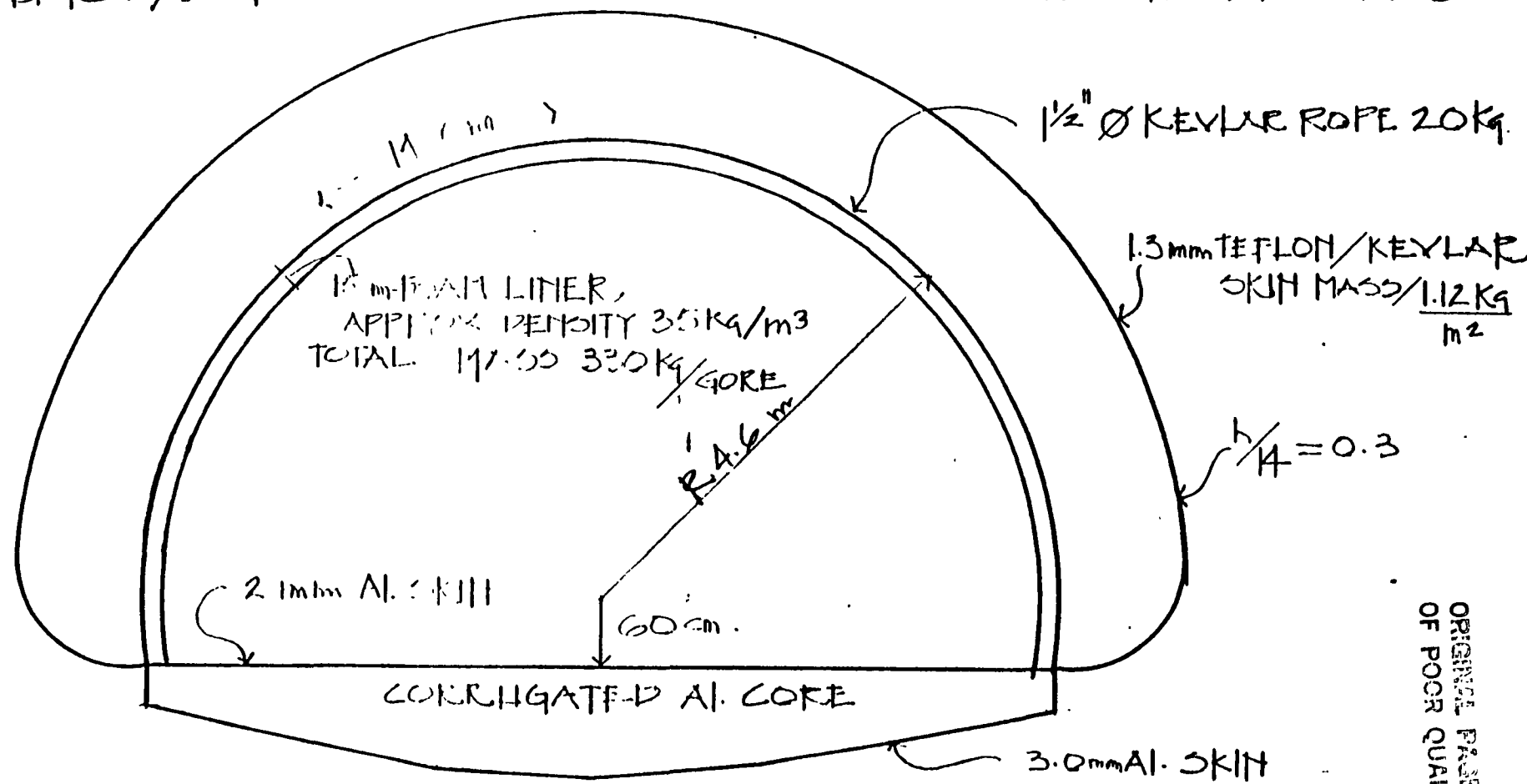
Figure 2

IM OF MOIST SOIL, APPROX.
 $1.60 \times 10^3 \frac{\text{nt}}{\text{nt}^2}$

TOTAL WEIGHTS:

FLOOR	733 kg
SKIN	60 "
FOAM	330 "
ROPE	40 "
MODULE TOTAL	<u>1363 "</u>

EXPANSION RATIO
 FABRIC .75:1

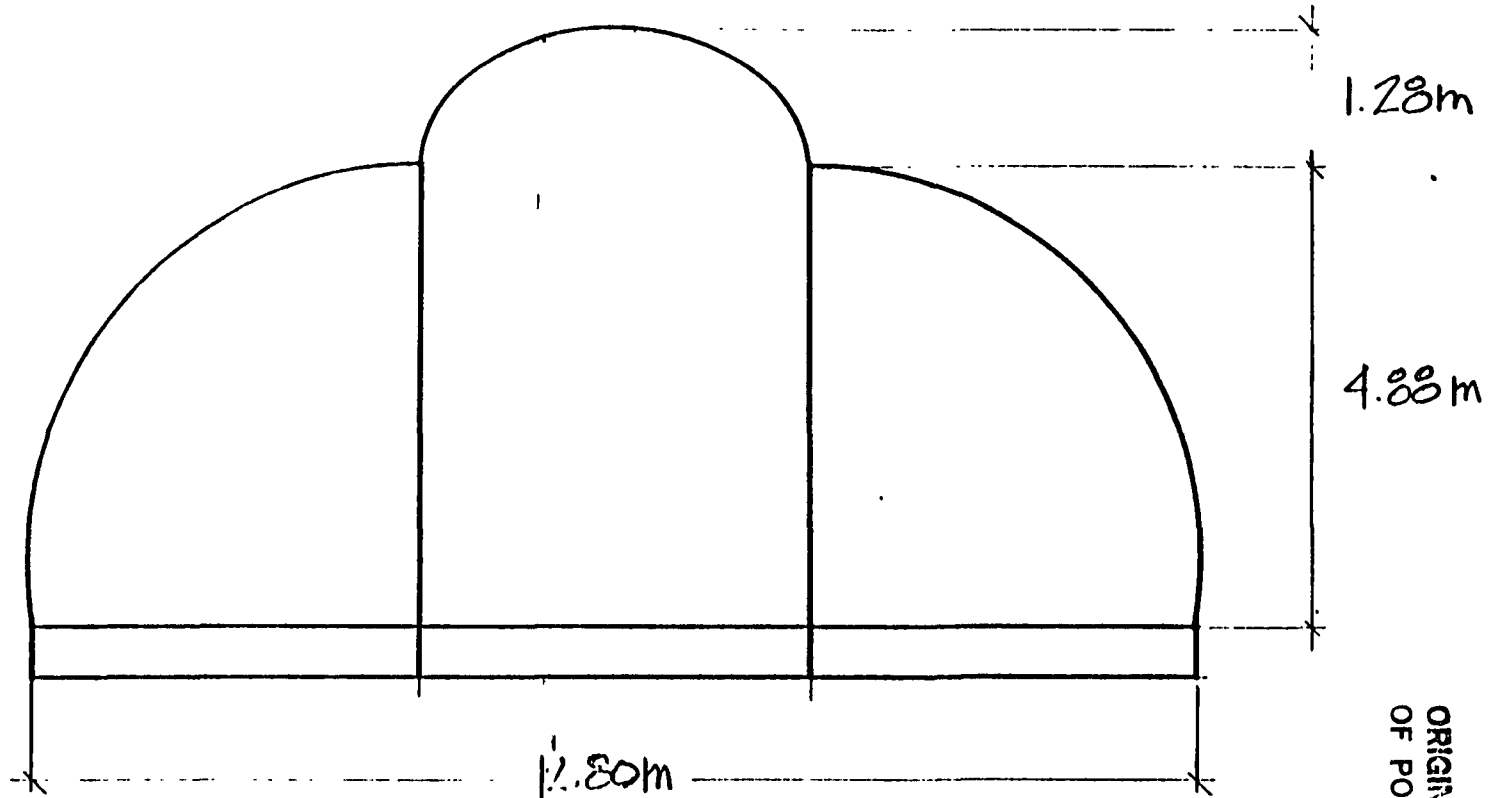


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POSSIBLE MODULE DESIGN

Figure 3

MINIMAL CONFIGURATION: SINGLE TORUS MODULE W/ ZEPH MOPHIT



MINIMAL CONFIGURATION TOTAL WEIGHT:

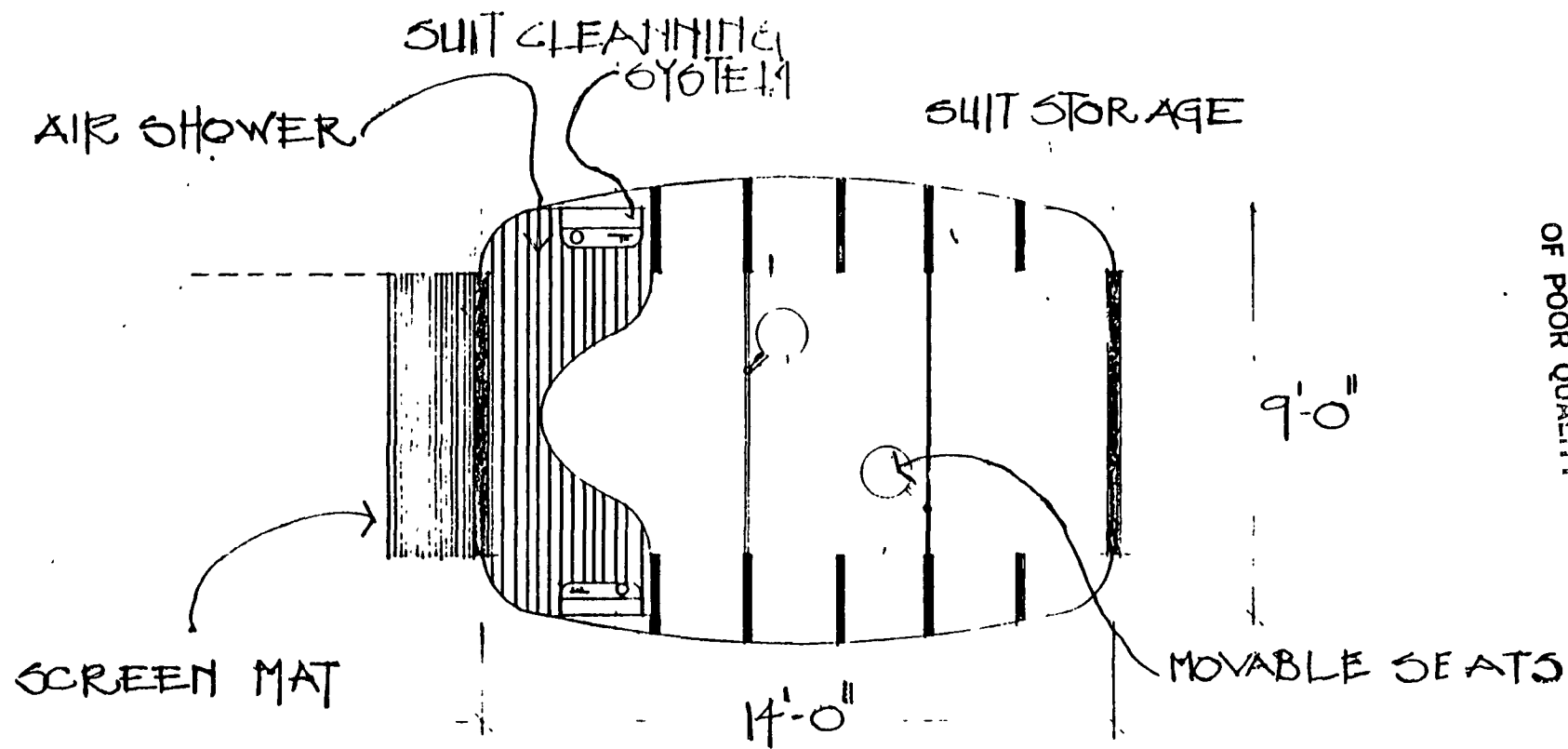
FLOOR	3000	Kg
FOAM	1000	"
CABLES	40	"
SKIN	200	"
TOTAL	<u>4240</u>	Kg.

$$AREA = 110 \text{ m}^2$$

$$\frac{MASS}{\text{m}^2} = \frac{4240}{110} = 39$$

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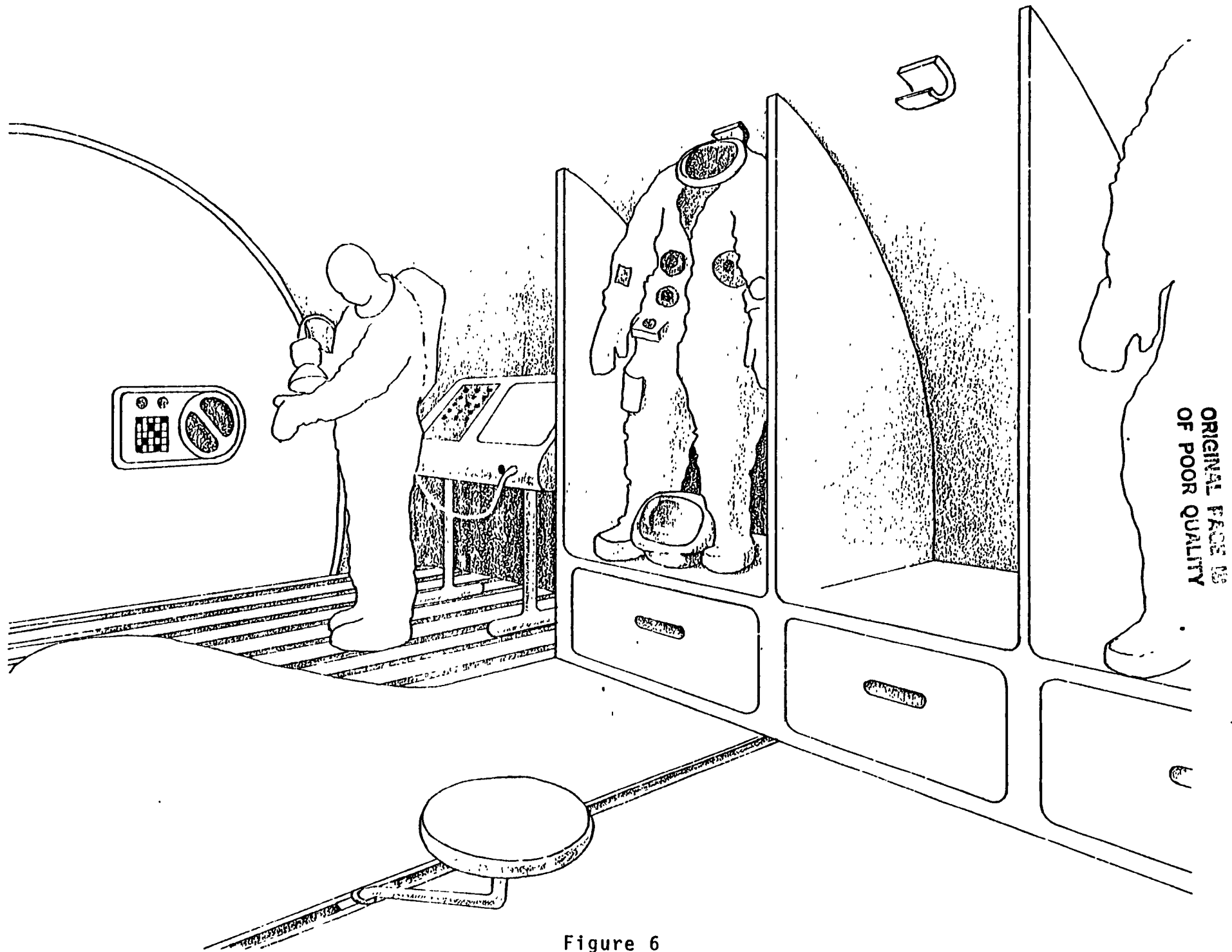
Figure 4



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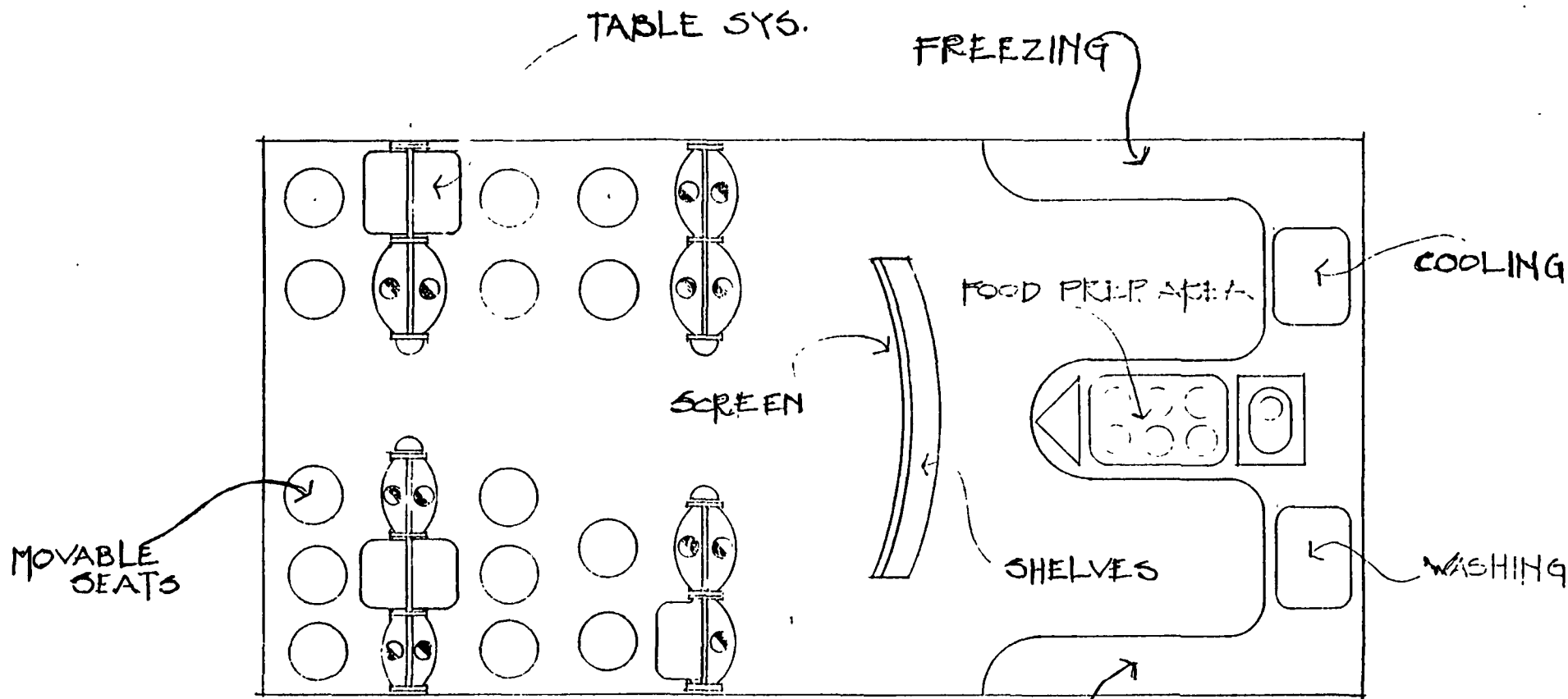
AIRLOCK & SUIT STORAGE MODULE

Figure 5



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Figure 6



MAN TO FOOD TO TABLE CONCEPT

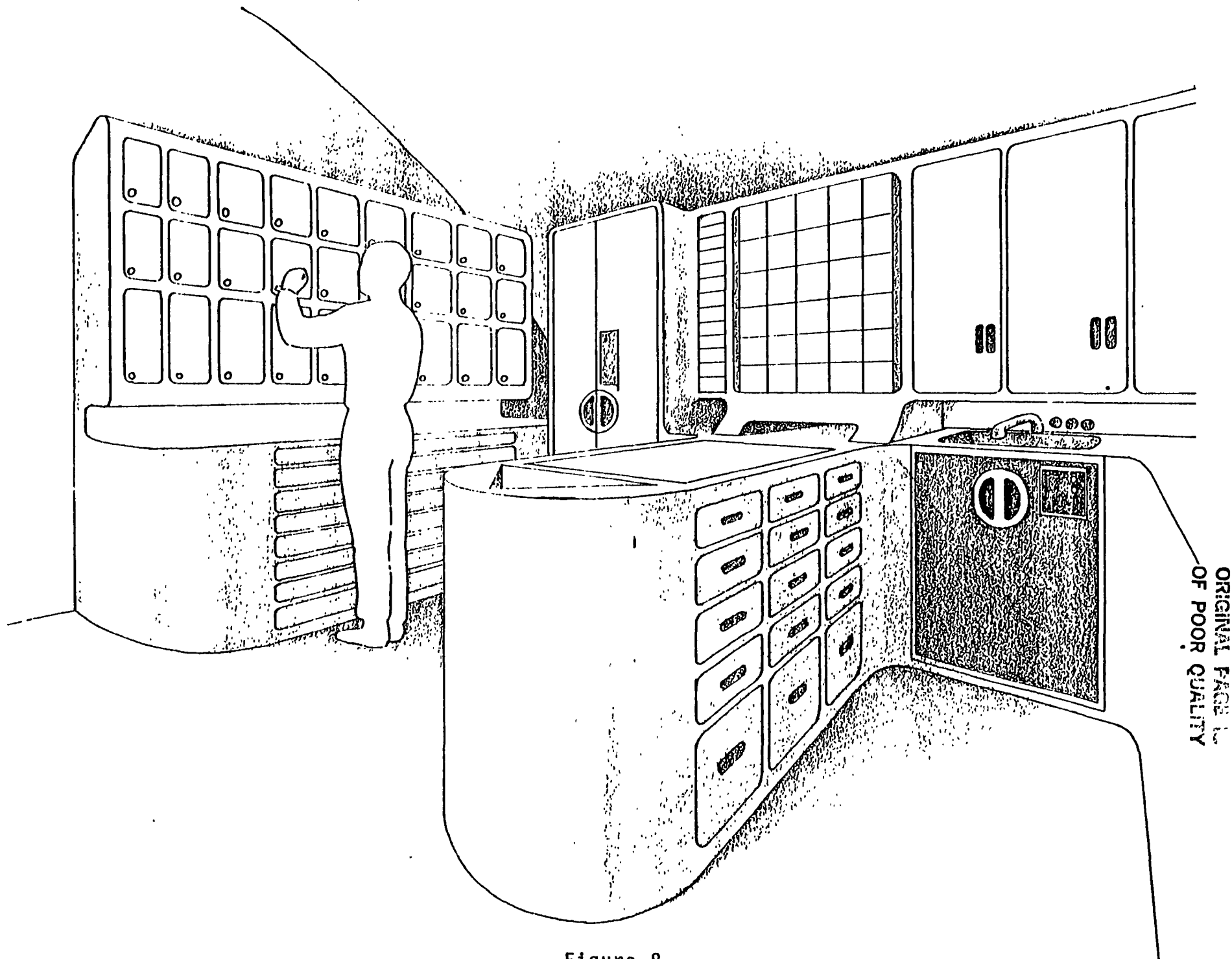
392 # TOTAL AREA

SEATING 12 MAN CREW + 6 EXTRA VISITOR PLACES

DINING - PROJECTION ROOM COMBINATION

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Figure 7



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Figure 8

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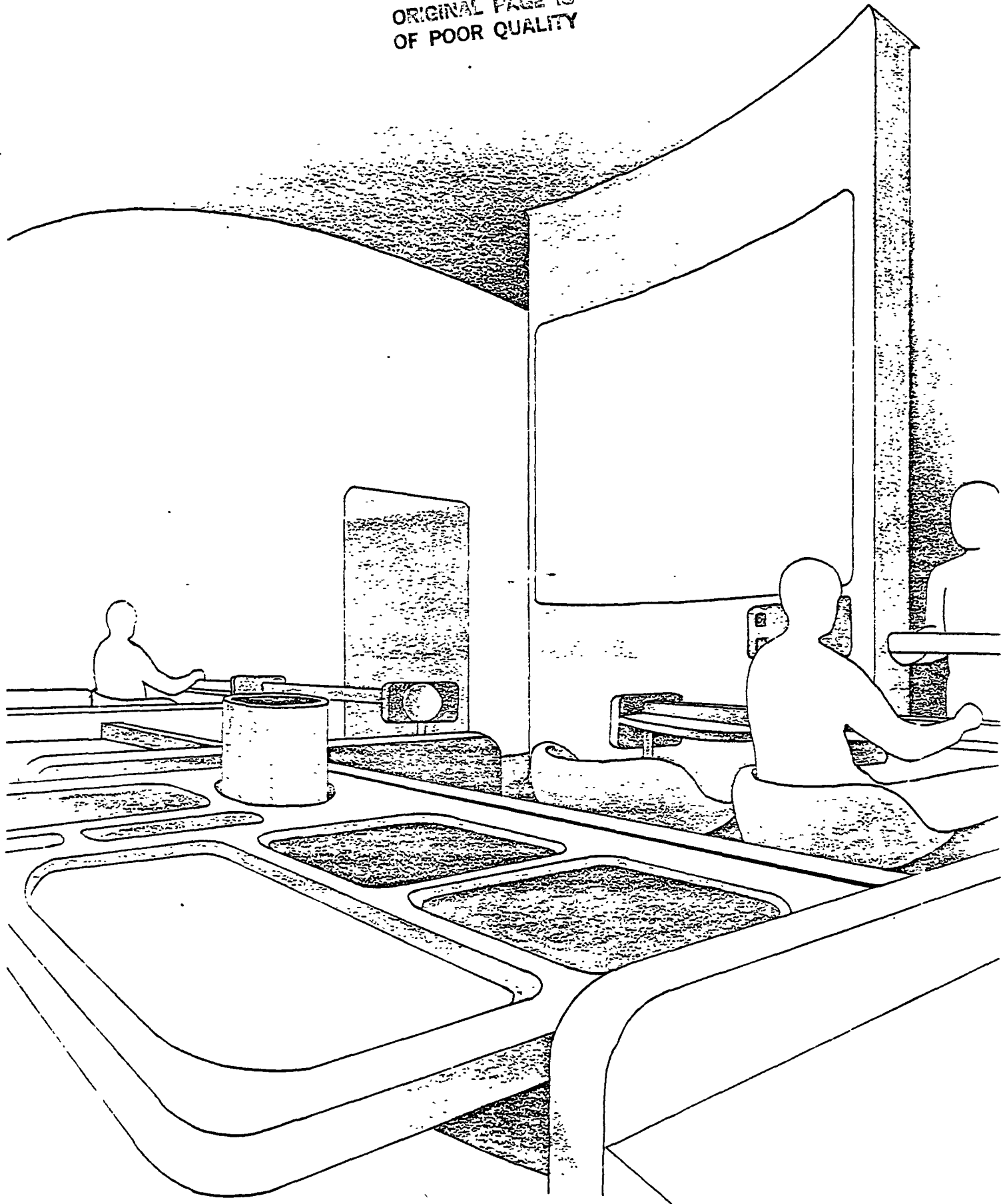
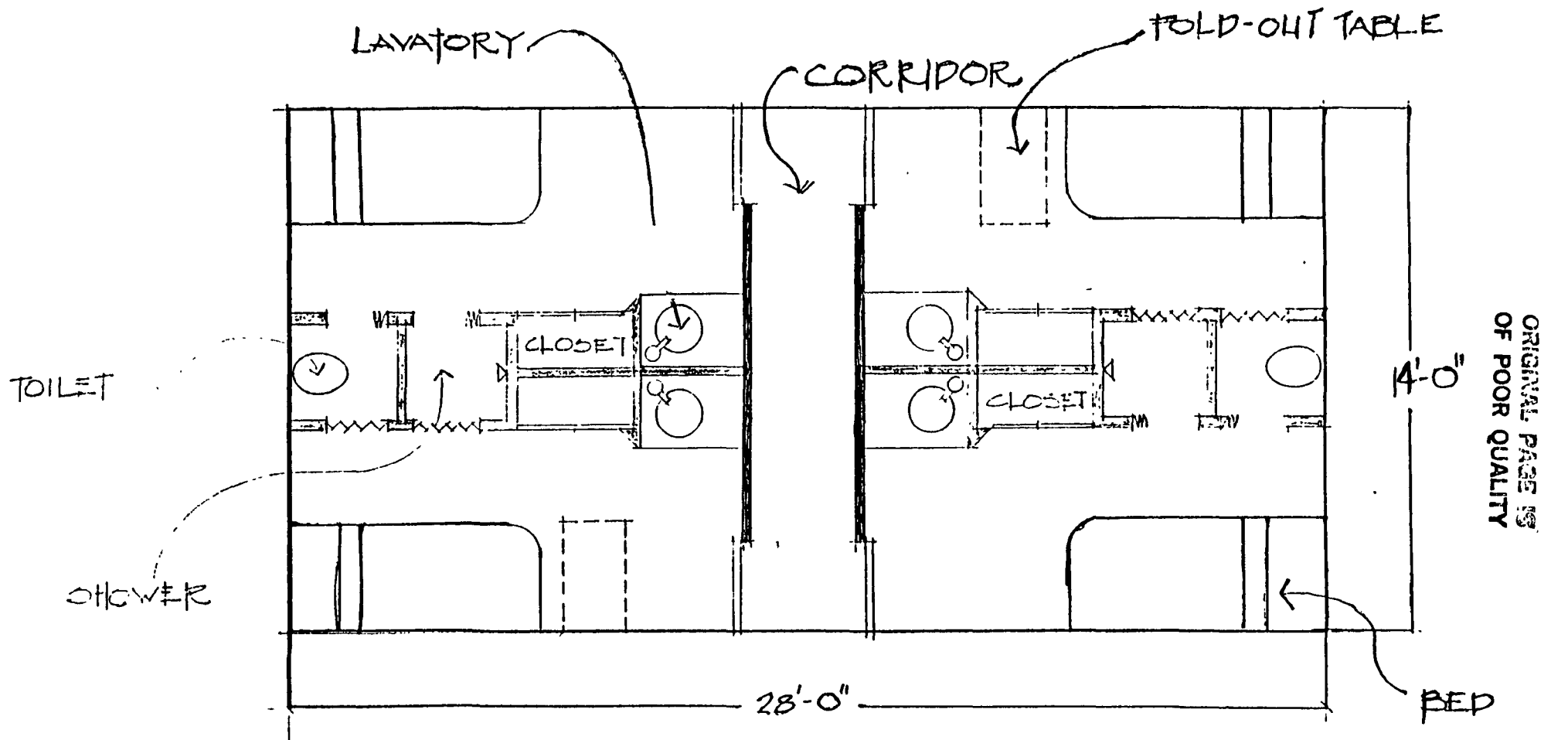


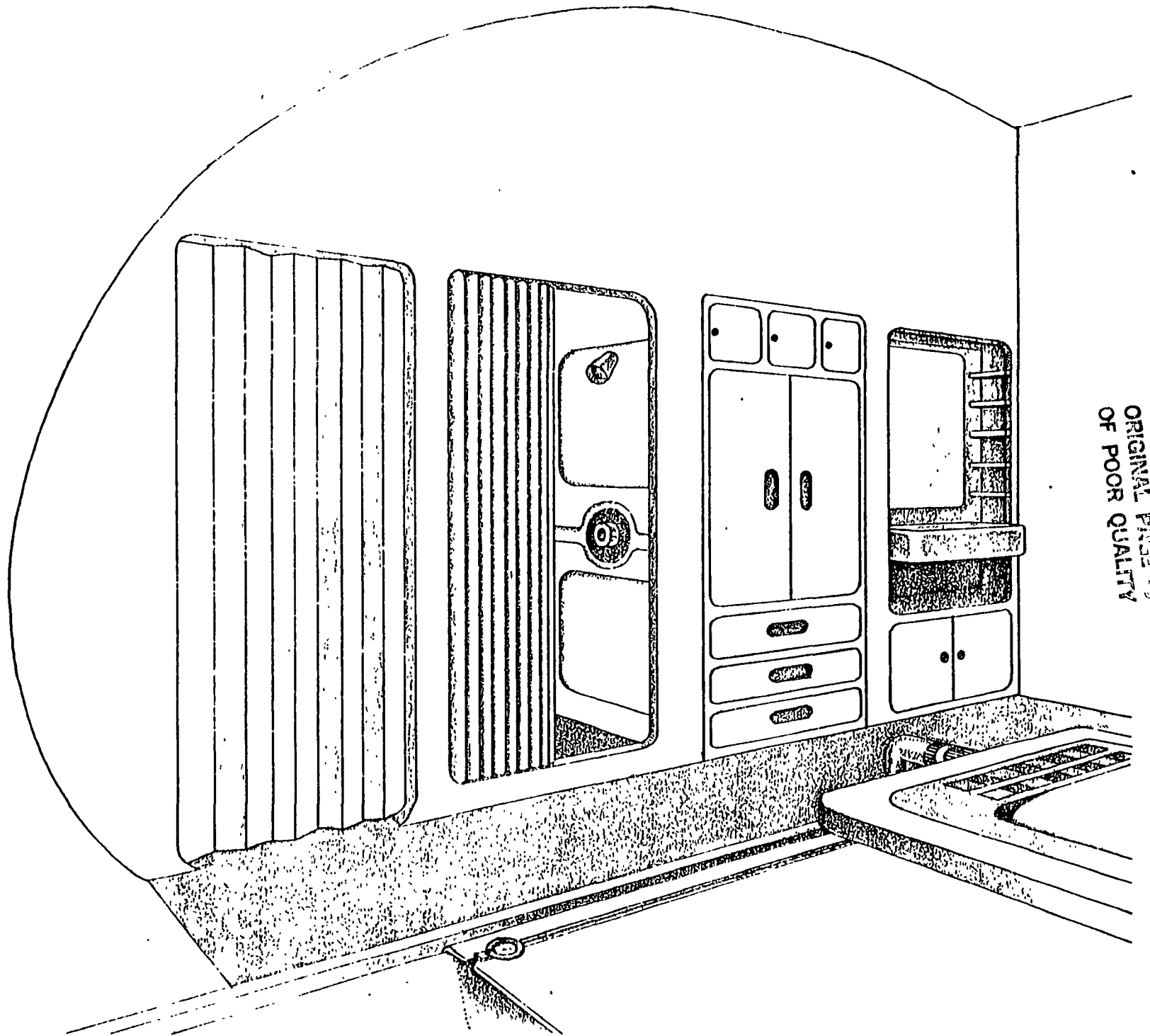
Figure 9



MODULE TOTAL # = 392 #
 - 25% CIRCULATION = 98
 CREW OF 4 $\frac{294}{4} = 73.5$
PER MAN

LIVING MODULE

Figure 10



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Figure 11

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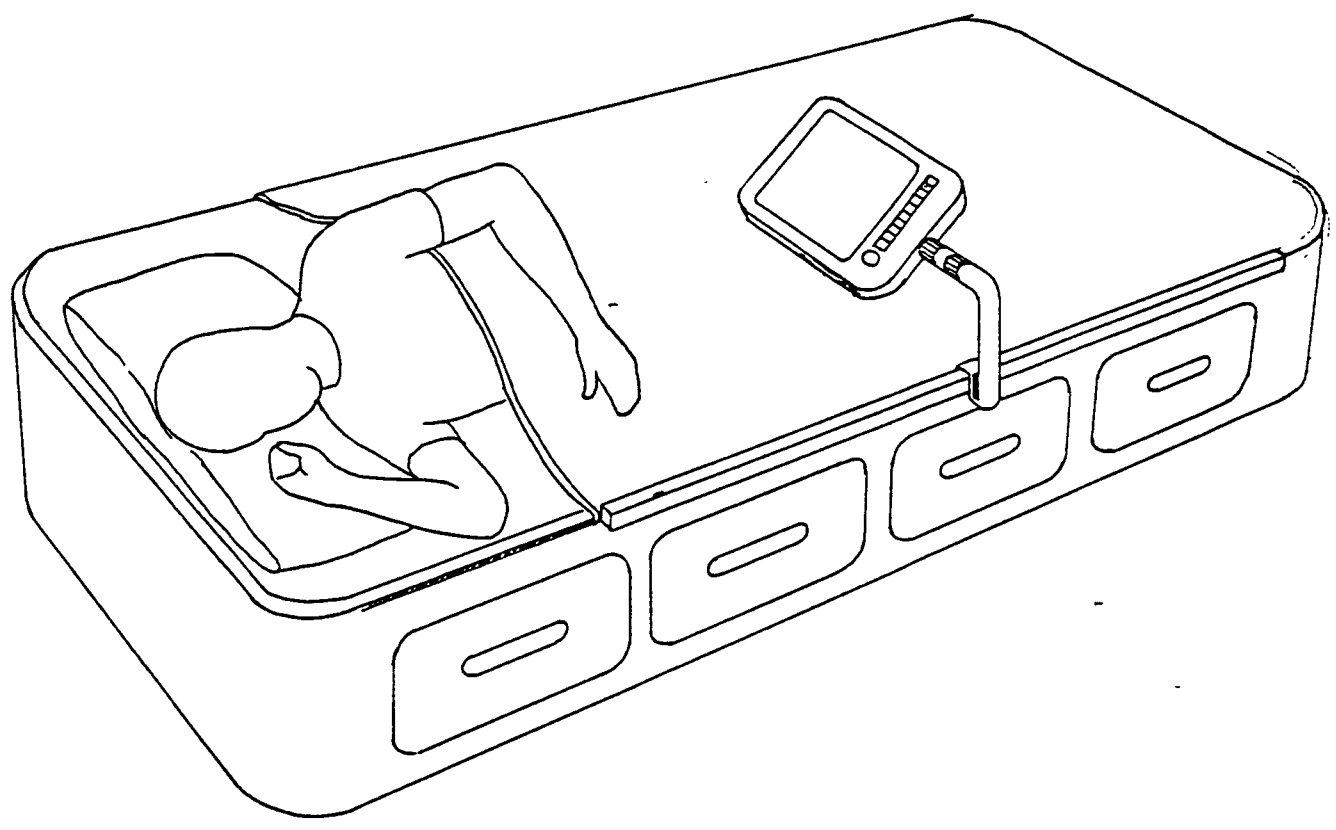
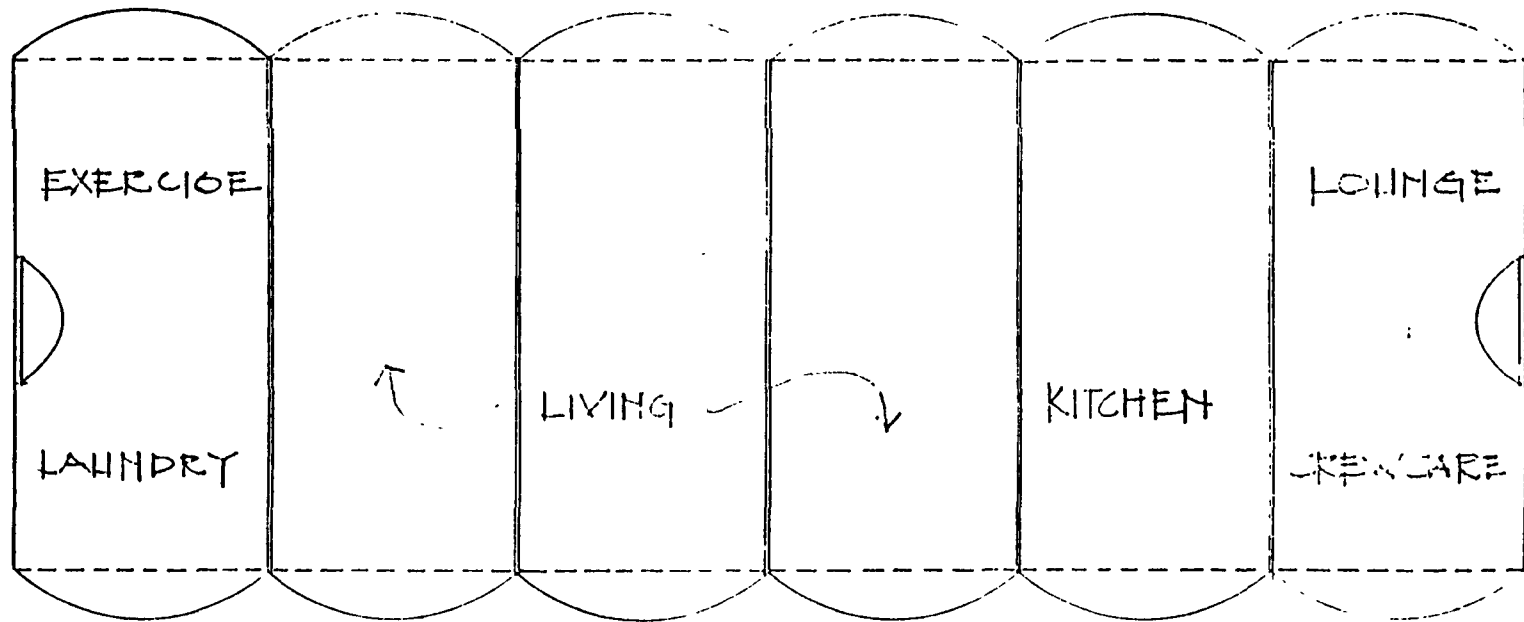
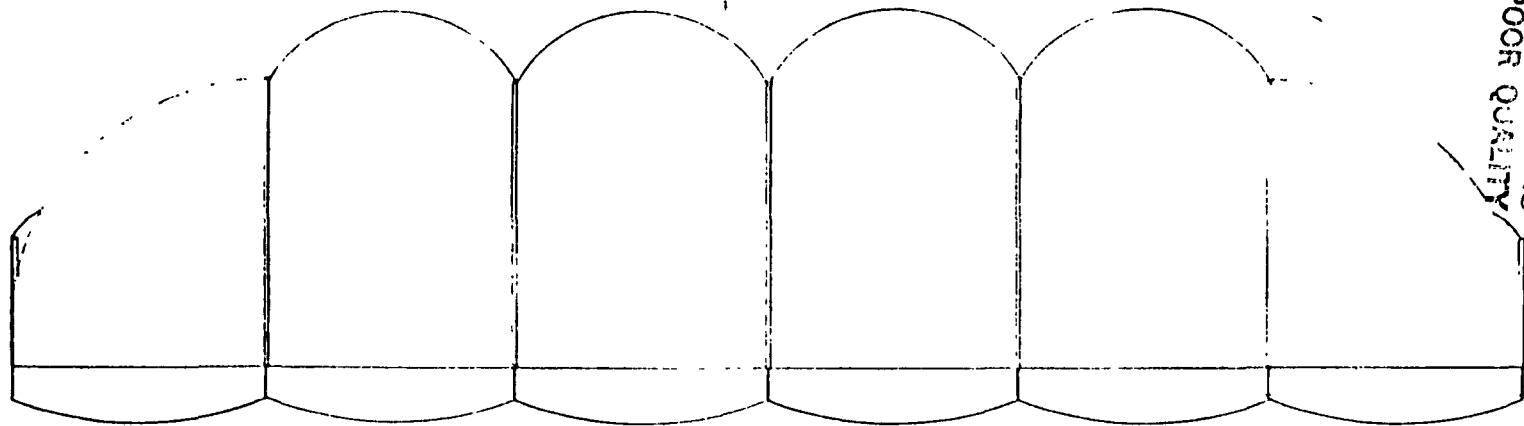


Figure 12



PLAN VIEW

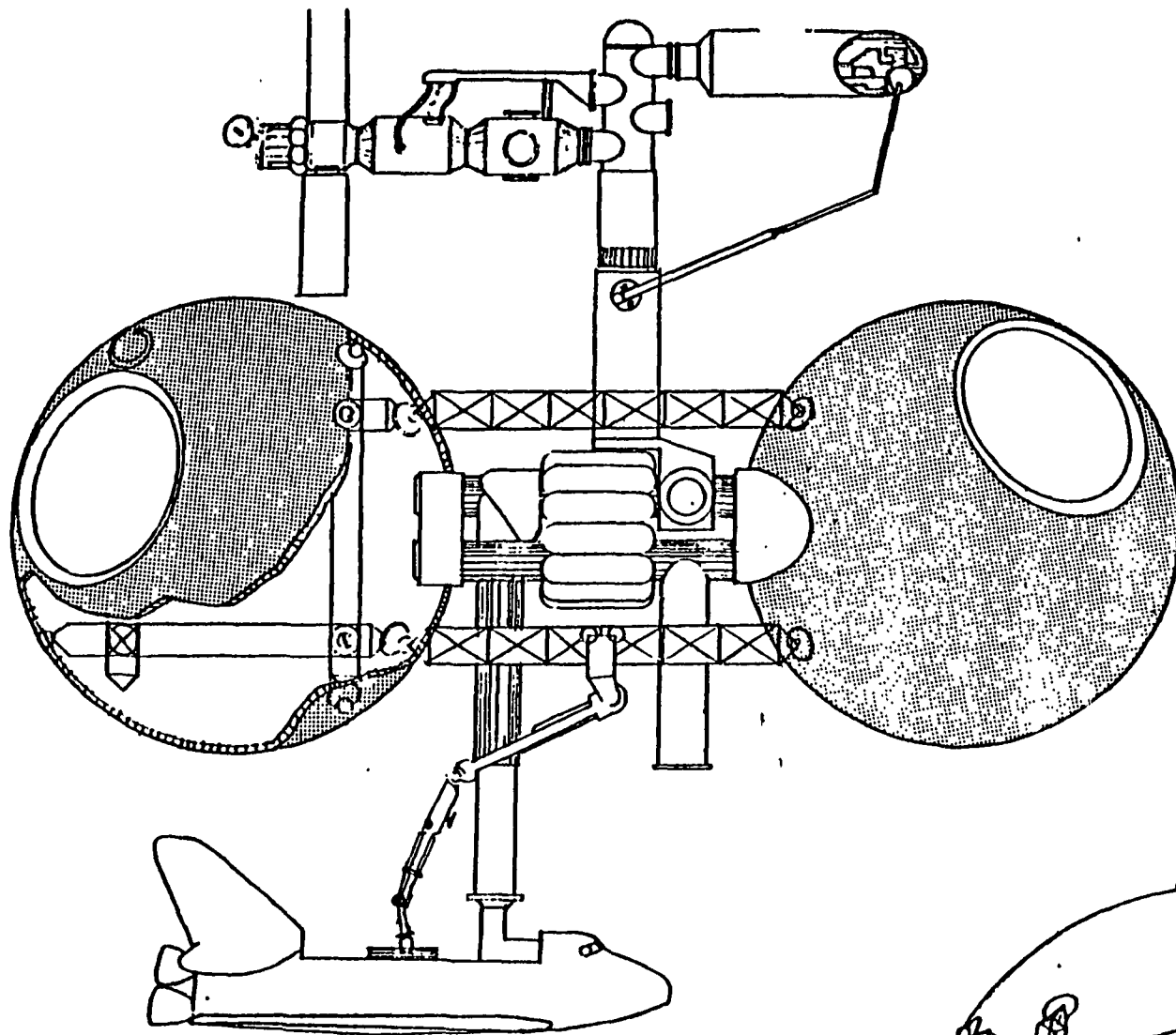


SIDE VIEW

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OFF-DUTY ACTIVITY HABITAT, FOR 12 MAN CREW

Figure 13



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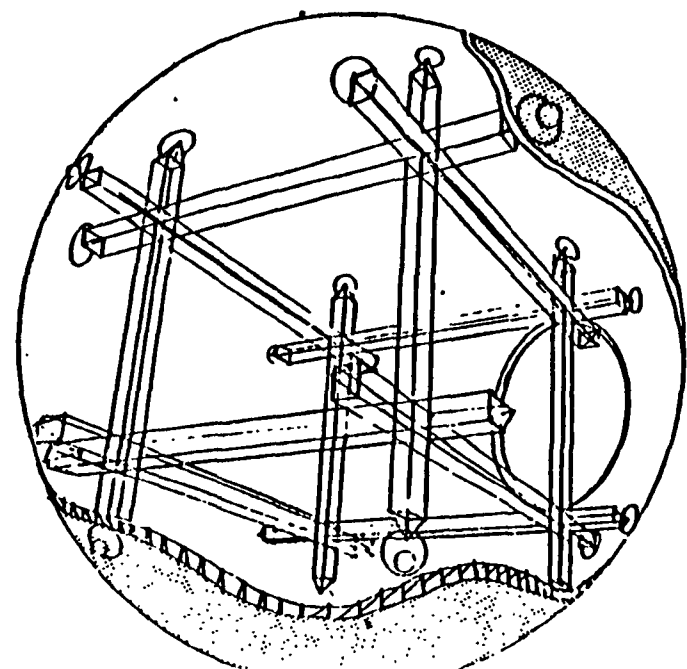


Figure 14

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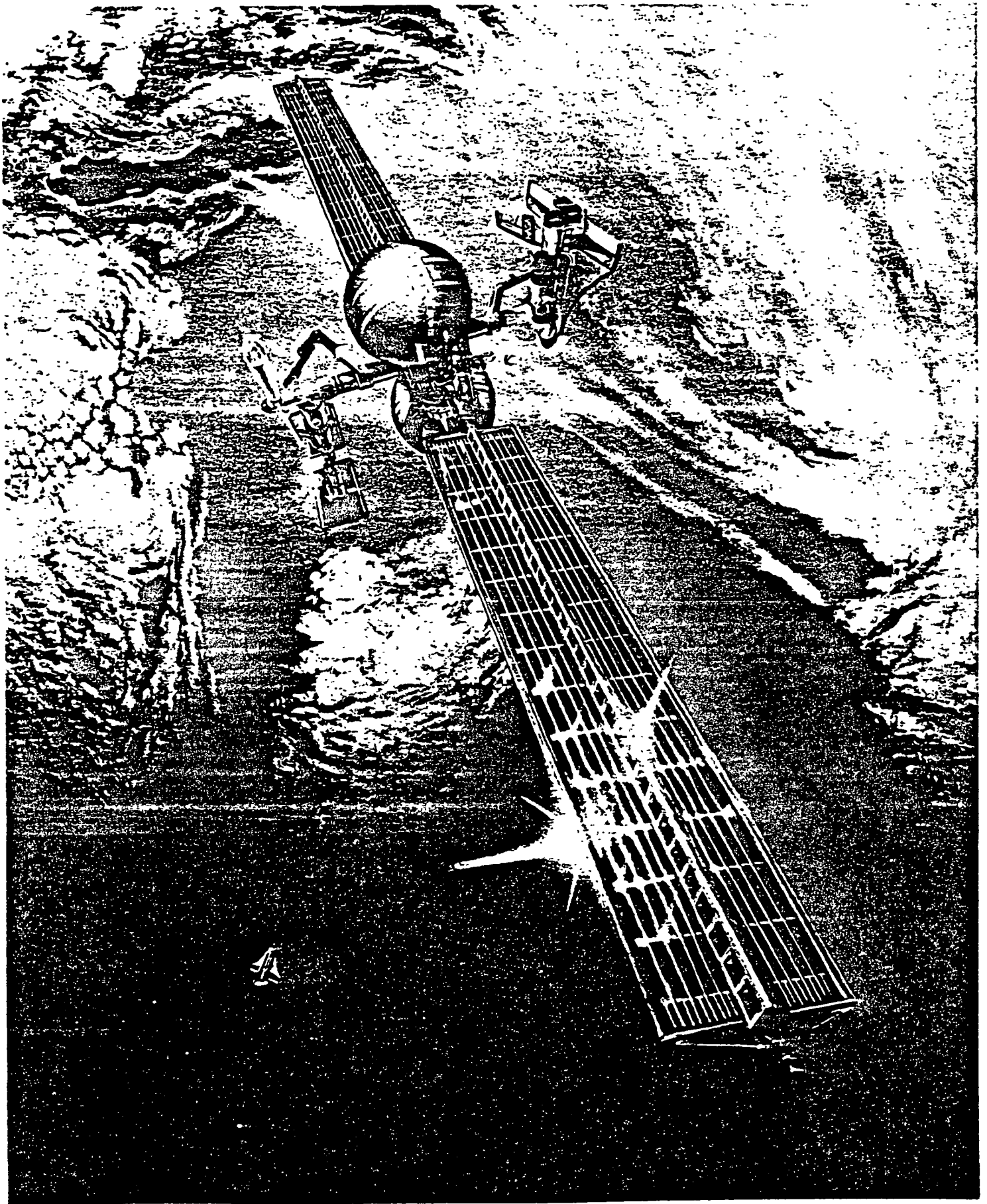
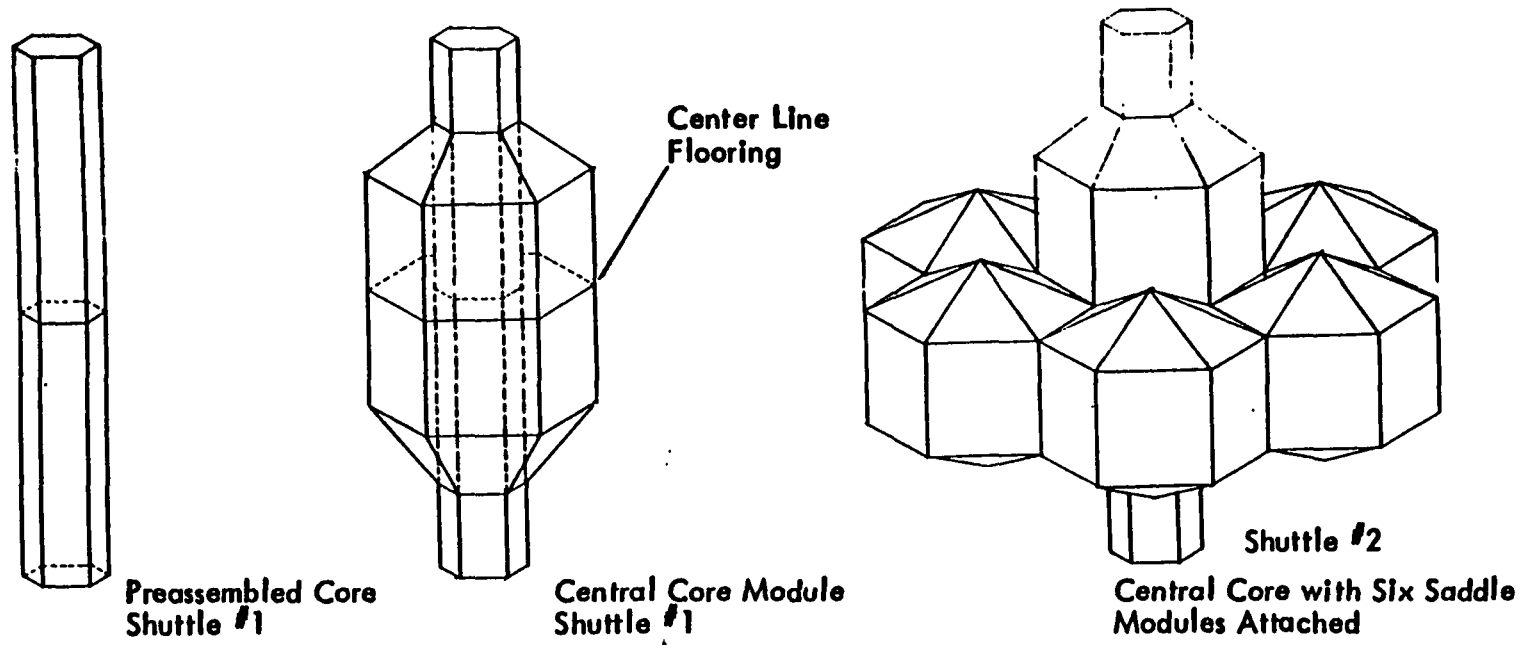
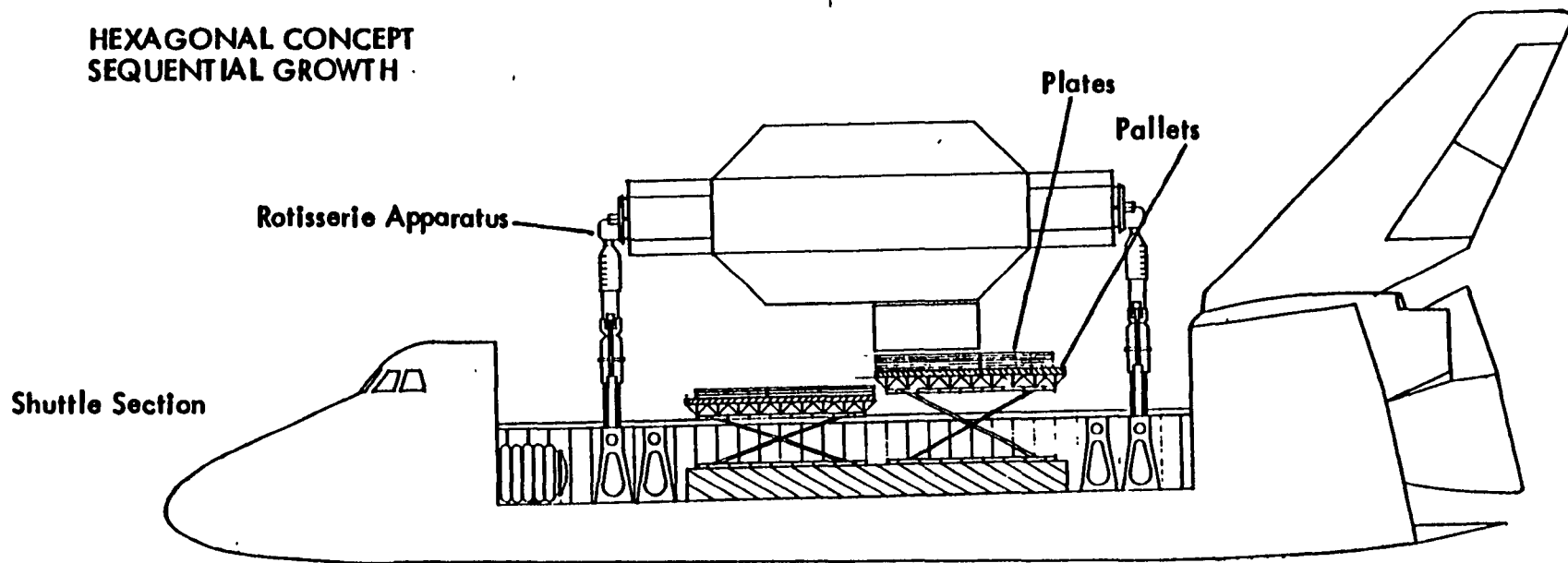


FIGURE 15



**HEXAGONAL CONCEPT
SEQUENTIAL GROWTH**



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FIGURE 16

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FIGURE 17

ELECTROREFINING PROCESS FOR LUNAR FREE METAL: TERRESTRIAL IMPLICATIONS AND APPLICATIONS, R. D. Waldron, Lunar and Planetary Institute, 3303 NASA Road 1, Houston, TX 77058

To be presented at the 35th NW/Fifth Biennial Rocky Mountain Joint Regional Meeting of the American Chemical Society, Symposium on "Materials Processing in Space."

Abstract

An electrochemical refining process is proposed for the separation and recovery of principal and trace elements from reduced metallic particles found in lunar soils. (The free metal content of lunar soils usually occurs in the 0.1 to 0.5 weight percent range and consists primarily of iron with minor amounts of nickel and cobalt and various trace elements. It is strongly ferromagnetic and readily separable from other soils constituents.) The proposed process involves anodic dissolution of the impure metal and cathodic deposition of pure iron in divided cells using aqueous chloride solutions as electrolytes. A second stage electrolysis is employed using an inert anode to oxidize a major fraction of the iron to the ferric state. The (impure) anolyte is batch equilibrated with a primary resin bed which is subsequently desorbed in the (pure) catholyte loop following an intermediate rinse elution to remove nickel and cobalt in a third (purification) loop. The purification steps are based on anion exchange separation of chloride complexes. All transfer operations and elutions are performed with elutants and distilled water to minimize reagent consumption and attrition. Important trace metals are removed by cementation or other methods. The proposed process is of primary importance in space industrialization to improve electrical and thermal conductivity of lunar metal and for nickel recovery which is otherwise unobtainable. Process variations will be discussed which are applicable to terrestrial scrap metal recovery. The potential importance of the lunar free metal resource to the earth's economy will be stressed.

LUNAR UTILIZATION

David R. Criswell

and

Robert D. Waldron

Lunar and Planetary Institute

Houston, Texas

LUNAR UTILIZATION

OUTLINE

- I. MOTIVATIONS FOR THE USE OF LUNAR RESOURCES
 - A. Historical Overview
 - B. Generalized Industries
 - C. Maturing Space Industries
- II. LUNAR RESOURCES
 - A. Lunar Literature
 - B. Global Properties
 - C. Lunar Mineralogy and Petrology
 - D. Average Chemical Compositions of the Regolith
- III. USES OF THE MOON
 - A. Whole Moon
 - B. Bulk Soil and Rocks
 - C. Products of Thermal and Chemical Processing

I. MOTIVATIONS FOR THE USE OF LUNAR RESOURCES

A. Historical Overview

Major motivations for the use of lunar materials are easily summarized: (1) the moon exists; (2) the moon is the largest source of matter near the earth; (3) we visited the moon; (4) we possess considerable general knowledge of the entire moon and lunar conditions and extremely precise knowledge of specific areas of the moon; and (5) devices and tools have been identified that can allow us to obtain material from the moon for large scale use in space at considerably lower costs than will ever be possible by bringing the material into space from the earth. Other chapters in this handbook deal with the economic advantages of obtaining and processing lunar materials and with the economic incentives to do so. Economic and social (human) systems will develop in space and become progressively less dependent on imports of materials from the earth for existence and growth. One can now visualize the general methods whereby solar energy collected on the moon and in space near the moon can be used to power electromagnetic catapults which can eject unlimited quantities of lunar soils and rocks into space to support industrial and general capital growth in cis-lunar space and beyond. This assurance is far more complete now than before the return of samples and geophysical data from the moon during the Apollo program. The energies of engineers and planners can be focused on the actual conditions to be encountered and be based on extremely extensive research and development bases created during the Apollo program (1.1). This will enable the rapid growth of cis-lunar industries to meet specific goals in space.

Prior to the first landing on the moon the National Aeronautics and Space Administration conducted a continuing set of yearly workshops on the planning of using the resources of the moon (1.2, 1.3, 1.4, 1.5 and 1.6). A major hope for the reduction of future space exploration was to find sources of materials

to use for propellants to operate spacecraft from the moon, to use in life-support systems, and for construction of habitats on the lunar surface in support of exploration and industry (1.7). These early efforts were concentrated on the advantages of further exploration of space to be gained from the use of lunar resources. As one example — a round-trip mission to Mars which would require an earth launched vehicle massing over 70,000 metric tons could be accomplished with a 750 metric ton vehicle which could proceed first from the earth to the moon, be refueled and then proceed to Mars. This example assumes a conventional hydrogen/oxygen propulsion system. As these early studies progressed a large range of topics were considered including synthesis of food stuffs, water extraction from lunar materials or deposits, surface mining, lunar gravity as a power source, fire hazards in oxygen atmospheres, drilling on the moon, use of lunar rocks and soils in cast basalt and ceramics and glasses, and electro-winning of oxygen from silicate rocks to name only a few. Extensive studies were conducted on the logistical support and equipment needed to support extensive lunar exploration in an expanded follow-on to the Apollo program (1.8). However, these studies did not result in the Apollo era implementation of the use of lunar resources. One reason was foreseen by G. W. Morganthaler (1.3, p. 5) as ". . . the best way to accelerate the project (use of the moon) out of the 'visionary' stage is to focus . . . on association of pay-off with other programs of national interest to make the project look like a tool to even the most conservative."

Work first reported in 1969 by P. E. Glaser (1.9) indicated the desirability of capturing solar power by means of solar cell arrays located in geosynchronous orbit and beaming the power to earth by means of microwaves. In this approach to the capture of solar energy the array would receive 6 to 15 times the flux of energy of a comparably sized terrestrial installation over the course of a year,

would operate in a less inclement environment and could be made of far less massive components thus allowing the implementation of operating systems at a fast pace and most importantly would consume only trivial quantities of terrestrial fuels in the installing and operation of the solar energy source over the projected 30 year life-time. Necessary operations in space would be orders of magnitude larger in scale than anything even envisioned prior to that time. An extremely large booster would have to be developed and operated on a regular schedule to achieve the necessary transfer of materials from the earth to space to create useful quantities of the space power stations (SPS) (1.10). At approximately the same time G. K. O'Neill began work on the feasibility of constructing extremely large habitations in space and concluded on the basis of the analyses of the lunar soils brought back during the Apollo program that the lunar materials were suitable for the construction of a large fraction of such habitats (1.11). Feasibility stemmed not simply from the distribution of chemical elements in the lunar soils but also from the identification of a means of ejecting large quantities of lunar materials off the moon by means of a linear electric motor (1.12). In this manner only solar power would be needed to acquire large quantities of materials in space for construction and the use of rockets and major propellant expenditures could be avoided. It was quickly realized that the lunar materials were satisfactory in chemical composition for the construction of 80 to 90% of a SPS (1.13; 1.14). In this manner not only could the scale of rocket missions off the earth be reduced by a factor of 10 to construct a series of SPS, but in addition the lunar materials could be used to build additional construction facilities in space — in effect bootstrap the creation of space industry. The rewards for this approach seem more than adequate because of the estimated need for over 700 billion dollars of new electrical generating capacity in the United States alone prior to the year 2020.

This is far larger than any estimate to date of the funds needed to create an SPS manufacturing from lunar materials.

Table 1.1 indicates one recent estimate of the mass of various elemental components versus lunar components (1.14). In this particular model the SPS is designed to supply approximately 10,000 Megawatts (i.e. 10 GW) of electric power at the output of a ground station. Total mass of the two versions are approximately the same at 98 and 118 thousand metric tons respectively. As importantly, the earth-based system would require that 35.4 kg of propellant and payload (consumables) be lifted from the earth for each kg of satellite placed in geosynchronous orbit (GEO), while the lunar resource model would require only 3.2 kg of propellant and payload launched from earth and 1.75kg from the moon (if a mass driver were employed) for each kilogram of satellite. These numbers are based on advanced shuttle derived launch vehicles. It is clearly possible to improve the base line SPS design to reduce this fraction even more. Even so 90% of the earth baseline SPS can be produced from lunar derived industrial feedstock. Estimates can be made of the total costs of creating the industrial infrastructure on the moon, in space and on earth to support the lunar materials approach. Assuming that no bootstrapping of production facilities is employed by the time 30 SPS units are produced the costs of deploying terrestrial units will equal the expense of creating the space facilities and operating the space facilities to manufacture 30 SPS units. There is a United States market for approximately 200 SPS units sized to produce 10 GW of power and a world market several times larger. The use of bootstrapping and SPS redesign to make optimal use of lunar materials should reduce this cross over point significantly.

B. Generalized Industries

Space power stations offer a lead-in example to a view of a broader usage of lunar materials by adjusting our mental image of what is possible in

space to a larger scale than hitherto envisioned. If we examine in detail the elemental chemical needs of an economy such as the United States' for the production of goods from non-renewable materials we find the facts shown in Table 1.2 (ref. 1.15). "Demandite" is an imaginary molecule that contains the mole fraction of all materials used in the United States in 1967. Note that fuels constitute the largest fraction of the "demandite" molecule. One major problem facing the modern industrial world is to find some source of energy to replace petroleum. Electricity produced by solar energy would do this. A new molecule of non-fuel, non-renewable elements (1.16) can now be defined (non-fuel demandite) by subtracting the fuel in Table 1.2 and introducing the fractions of the elements that composed the remaining substances in Table 1.3 (see columns 1 and 2). Surprisingly, 11 of these 16 elements can be obtained from the lunar soil with no more than a factor of 10 enhancement over their natural lunar concentrations. The other five elements comprise less than 10% (by weight) of the non-fuel demandite. What we see is that the moon offers a very large fraction of the elements with which our industry has experience in working and producing the broad range of goods that sustain our present style of life. However, it cannot be over emphasized that the style of process and production engineering will be far different in-space than on earth at the present time. From the very first there will be a strong emphasis on conservation of working fluids and reagents. They will be the precious elements, and vigorous technical development will go into devising reactions to minimize their loss. Over a period of time it may be reasonable to expect that space processing industries will introduce new industrial processing techniques to terrestrial practice which will drastically reduce the pollution effects from many major terrestrial industries. This would be an ideal spin-off from space to earth.

The cost of earth to space transportation will remain a significant factor in the cost of space manufacturing for many years. This can be seen in the

following manner (1.16). Consider columns (5) and (6) in Table 1.3. One kilogram of Apollo 15 soil will fractionate into 0.76 Kg of demandite and 0.24 Kg extra of oxygen and metals ("Excess" column). Assume the "Deficiency" of 0.24 Kg of demandite is supplied from earth. If the initial costs of acquiring the bulk lunar soil at an industrial plant in deep space is $X=20\$/\text{Kg}$, the cost of extracting the demandite fraction is $Y=.2\$/\text{Kg}$ (the same as metal extraction in the U.S.), and the cost of bulk transportation from earth to the industrial plant is $Z=1000\$/\text{Kg}$, then the unit cost of demandite composed of the extract from the bulk lunar soil and the terrestrial supplement will be

$$\begin{aligned} \text{eq(1)} \quad D(\$/\text{Kg}) &= [X \cdot (\text{Units Refined} - \text{Excess}) + Y \cdot (\text{Units Refined}) \\ &\quad + Z(\text{Deficiency})] \\ &= 240\$/\text{Kg} \text{ (for above example)} \end{aligned}$$

whereas the cost of the excess material will be

$$\text{eq(2)} \quad E(\$/\text{Kg}) = X + Y = 20.2\$/\text{Kg} \text{ (for above example)}$$

the cost of transporting and processing in space. Thus, the cost of the demandite is increased in this example by earth to deep space transportation costs. If by the year 2000 the lunar to space transport costs drop to $0.1\$/\text{Kg}$ and the earth to deep space costs drop to $40\$/\text{Kg}$ and the processing costs drop to $0.1\$/\text{Kg}$, then demandite (in this example) would cost $D \approx 9.78\$/\text{Kg}$ and the excess materials $E \approx 0.2\$/\text{Kg}$. Substitution of materials, searches for resources and lower earth/space transport costs must be given high priority.

This example hints that the concept of demandite applicable to mass throughput on the earth (Table 1.2) is not directly applicable to industry in space. Excess material in the terrestrial case is generally waste and discarded or dispersed. Figure 1 provides a more appropriate concept of "Space Demandite" and illustrates the fundamental differences between the terrestrial throughput economy and a developing space industry and habitation economy (1.17).

In space two new industrial functions must be conducted on a large scale — (1) creation of real estate (i.e. habitats and industrial regions) complete with lifestocks and, (2) provision of reaction mass for transportation. All long term human activity in space must be conducted inside massive shielding against solar and galactic cosmic rays. Approximately 4 Kg/cm^2 of matter (the composition does not matter to first order) must be present between people and deep space. In early habitats which contain only 1 to 100 km^3 of volume shielding will constitute the major mass fraction of bulk material extracted from the moon. Thus, one can imagine that all the bulk lunar material is refined (100% elemental separation) and the separates utilized to (1) complete the demandite deficiencies, (2) provide reaction mass and (3) be used as cosmic ray shielding and perhaps as refined material for pressure vessels. One proposal for the first space manufacturing facility is for it to be scaled to contain 6,500 people and have a finished product output of approximately 500,000 metric tons/year or 5 space power stations (SPS) a year. Refining the habitat shielding material would provide an early, short term source of the demandite deficiencies. Habitat shielding would constitute approximately $12.5 \cdot 10^6$ metric tons of bulk material provided from the moon over a 5 year period. Assume it is processed to remove the maximum amounts possible of the deficient elements (column 6 of Table 1.3). If this is done then we find that in order to convert one part in 3 of this refined material into terrestrial demandite (i.e., 5000,000 metric tons) we must export from earth 0.8 parts (40,000 metric tons of Cu, Zn, Pb, Cl, N, H and C) of the deficiency elements in column 6 of Table 1.3 to supplement the demandite molecule. Using the same values as in the previous example for transport and refining costs we find for this strategy of completely refining the bulk materials for the deficient elements that:

$$\begin{aligned}
 D(\$/\text{Kg}) &= (20\$/\text{Kg})(31-30.08) + 0.2\%/\text{Kg}(31) \\
 &\quad + (10^3\$/\text{Kg}) \cdot (0.08 \text{ Kg}) \\
 &\approx 104\$/\text{Kg}
 \end{aligned}$$

and as before the cost of excess materials

$$E(\$/\text{Kg}) = 20.2\$/\text{Kg}.$$

The effects of decreasing lunar (.1\$/Kg) and terrestrial launch costs (40\$/Kg) and processing costs (.1\$/Kg) result in demandite costs of $D = 6.30\$/\text{Kg}$ and refining costs and transport costs would be approximately the same.

C. Maturing Space Industries

Figure 1.2 provides a general view of the economy of the United States in 1972, and the potential for goods produced in space to find significant markets on earth or to contribute to the creation of economic loops in space similar to those on earth (1.18).

This histogram (derived by Robert and Leslie Ayres - 1.17) shows the total sales value in billions of dollars each year (vertical axis) versus the cost of producing the goods on a dollars per kilogram (kg) basis (horizontal axis). This was done by determining the value added in 230 Standard Industrial Categories (SIC) in 1972. Two general classes of SICs are included: those in which products are composed of elements that can be largely obtained from lunar materials and for which there may be advantages to working in space with either solar thermal or solar electrical power. The SICs include electrometallurgy, glass, ceramic, light and specialty metal working, and fabrication and electronics. These 64 SICs are indicated by the cross-hatched portions of the histogram.

The clear upper portion of each bar in the histogram included products that contain elements not readily available at the lunar landing sites, which may be available from a special class of asteroids which cross the orbit of the earth and are thought to be retrievable into orbit about the earth at initial costs

on the order of 20\$/kg.

There are 166 SICs in this group, including — pyrometallurgy, rolled or forged steel products, copper, zinc or lead products, industrial chemicals, plastics, textiles and concrete products. Also included are impure fabricated final products such as appliances and vehicles. Excluded are 239 sectors related to agriculture, forestry, food, animals, fossil fuels, asphalt, and non-fuel petroleum products and service industries. All goods included in this histogram had a total value in 1972 of \$202 billion. The goods in the cross-hatched portions of each box had a total value of \$58 billion.

The histogram is deceptive in one very serious way. There are many goods in missiles, electronics and aircraft SICs that have \$/kg values much higher than shown here. However, these products are included with other, cheaper products in the SIC to produce the lower average value.

If a new SIC for space power stations is eventually included in this graph, it will initially be located between 200 and 400\$/kg (far off the right edge) and have a value of \$50-100 billion a year. A new SIC for lunar mining would also be introduced at the right edge of the graph (approximately 20\$/kg) that would have an annual output value of \$2-4 billion (note point 1 in Figure 1.2).

The intrinsic cost (\$/kg) of lunar materials should drop radically as other markets that require large masses of materials are developed. As this happens, the cost in space of lunar materials should eventually approach the cost of ejecting them from the moon.

We noted that the lunar ejection cost could be a few cents per kilogram (.02/kg). This corresponds to point (2) in Figure 1.2 and implies that approximately 10-15 percent of the present SICs might eventually contain lunar components for use either terrestrially or in space. As a broader range of feedstock elements become available through asteroid resources, additional lunar

resources or substitution of materials, most of the SIC shown in Figure 2.1 could be penetrated by extraterrestrial materials.

However, this historical approach to possible market potential should not distract us from the example provided by the space power systems. New and exotic products and new standard industrial categories for space enterprises will develop, and the products can be made relatively inexpensive as we learn to obtain extraterrestrial raw materials at low unit costs approaching the cost of demandite (Table 1.2).

A drop of 1,000 to 1 in the cost of lunar materials, from 20\$/kg to 0.02\$/kg, may seem rather dramatic unless one realizes that the 380 kg lunar materials returned during the \$25 million Apollo program could be said to cost approximately \$66 million/kg. There is every reason to think basic cost reducing feedbacks made possible when mass production is used to meet the needs of mass markets can operate in space as they have on earth for 400 years. Learning curve experience will permit industry to continually drop unit prices.

Applying the demandite concept to space industry forces us to reexamine in detail the underpinnings of modern industrial societies (1.6). It is useful to reinterpret Table 1.1 (Terrestrial Demandite) for a space economy compatible with Figure 1.1.

CAPITAL (Long Duration Items)

Bedrock - Habitats, Transporters, Energy Collectors, Deposits for Momentum & Angular Momentum & Kinetic Energy & Thermal Inertia, Reserve Stocks, etc.

Life-stocks - Atmosphere, Water, Recycling biomass.

THROUGHPUT (Items Used Immediately)

Demandite - Items in habitats, export materials, recycle losses, etc.

Reaction Mass - Dependent on energy/unit ejected mass and power source mass/unit of energy produced for propulsion.

In this formulation we must view everything as a flow of matter driven by solar energy and organized directly or indirectly by human skill. The basic difference between bedrock, life-stocks and demandite is one of duration of usage of identifiable items or products. Bedrock and life-stock items should generally have a longer existence or period (T) of identity than that (t) of demandite items and reaction mass. The loss of materials in processing, recycling and as reaction mass probably places fundamental limits on the ratios of these four categories of mass. Determination of the limits would be very useful in defining the limits on space habitation. For example, a space community typified by a particular rate of demandite usage could be spread over a wider range of gravitation potential differences as the energy per unit mass of the rocket systems used to transport goods and raw materials increased. Or, conversely, the communities' throughput of demandite could increase. An especially interesting problem is to determine the maximum ratio of life-stock to bedrock mass and to the rates of flow of demandite and reaction mass. One must carefully review schemes for the chemical processing of lunar and asteroidal materials and the production of final products, especially bedrock and life-stocks to identify alternate production techniques which avoid the use of scarce elements. Also, refining strategies must be optimized to minimize total demandite costs in terms of terrestrial and non-terrestrial components. Earth to deep space transport costs should be continually decreased. High priority should be given to locating sources of the life-stocks and elements which are deficient in lunar materials. The asteroids, lunar polar regions and possibly material located at the L-4 and L-5 points can all be investigated.

Sources of early industrial operations in space do not depend on the creation of a "cheap" source of demandite. Economic profits from space solar power can be anticipated to be sufficiently great to pay for the transport from earth of the

necessary supplemental elements. In addition, the supply of certain elements (Ni, Fe, Cu, and Zn) from the asteroids to terrestrial markets may be economically attractive in the next decade. Application of the concepts of demandite, bedrock, life-stocks and reaction mass descriptions of space economies will aid in determining under what conditions a self-sufficient economy becomes possible in space.

The concept of demandite is useful not only in focusing attention on particular problems in preparing for space habitation/manufacturing, but also because it is clear that the answers to these questions will be extremely valuable in revising the terrestrial economy as the age of petroleum energy comes to an end. It may well be that the flow of innovative information back to earth on how to work with matter at all scales under a new set of conditions will be of far greater economic and cultural value than even the enormously valuable streams of solar energy which could be transmitted from space. Operations in space provide a defined and rigorous environment within which to create the gigantic test tubes necessary to develop complete control over the creation of abodes of life, industry and the next expanse advance in human culture.

Several major industrial, university and government sponsored workshops have focused on the exploration and exploitation of the moon in the post-Apollo era. NASA sponsored a major study by Rockwell, International, in the early 1970s of a long term lunar exploration effort supported in the general style of an expanded Apollo program (1.8). NASA summer workshops concentrating on the design of lunar bases (1.19) and initial space habitats were held in 1972 (Johnson Space Center, Houston, Texas,) and 1975 (Ames Research Center, Moffett Field, California, 1.20). Two subsequent summer studies also sponsored by NASA-Ames have concentrated on the creation of manufacturing facilities in space based on lunar materials (1.21) and also incorporating asteroidal materials (1.22). Three studies have been funded by NASA on use of lunar resources encompassing the mining and

chemical and thermal processing of lunar materials (Lunar and Planetary Institute, Houston, Texas, 1.17), the construction of space power stations from lunar materials (General Dynamics Corporation, San Diego, California, 1.14) and a study of the manufacturing, fabrication and assembly of components for a space power system from lunar derived feedstocks (Massachusetts Institute of Technology, Cambridge, Massachusetts, 1.23). Dr. K. A. Ehrlicke has presented extensive analyses of the benefits to be gained from use of lunar and other extraterrestrial materials (1.24). Lunar scientists made an early contribution to the identification of lunar research findings which could contribute to development of lunar resources at a special session of the Seventh Annual Lunar Science Conference (1.25). Proceedings of the three Princeton University/American Institute of Aeronautics and Astronautics conferences on space industrialization are invaluable overviews of the progress in this field (1.26 and 1.27). The most recent scientific assessment of the lunar and asteroidal resources was conducted at the University of California at San Diego in 1978 at a five day summer workshop which produced an excellent summary document (1.28).

The major overriding fact which is coming to the surface in all studies to date is that the moon is an accessible and usable resource by which to create a major industrial base in space. This is due not simply to the exploration conducted of the moon during the Apollo program but to the extremely large investment of funds in the development of space technology since 1950 (estimated to be in excess of 100 billion dollars) which has established the research and development base by which further exploration and exploitation of the moon can occur in a straightforward and planned manner. In addition, there has been an explosive growth in the competence on a technical level and in size of the commercial and industrial community to create, operate, and profit from extremely large engineering projects. This growth has been aided in part by the startling

advances in computers and their use. Thus, lunar operations which 10 years ago were major national challenges can now be mounted and operated by relatively small segments of industry if the correct approaches are used and if bootstrapping and the full range of technical ability of the nation's industries are employed. In the following section we will review the knowledge of the moon which has developed during and subsequent to the Apollo and Soviet Luna and Lunakhod missions. It is estimated that over 15,000 man years of research efforts have been expended on the various aspects lunar sample and geophysical research. In the third section consideration will be given to the range of products and processes that will be of interest in the early and later phases of industrial development of the moon.

II. LUNAR RESOURCES

A. Lunar Literature

An extremely extensive literature has come into existence since the start of the Apollo program on scientific investigations of the moon. Table 2.1 lists books and review papers which are of particular use in gaining an overview of the developments in these studies (1.28). The nine sets (to date) of the *Proceedings* of the Annual Lunar (and Planetary) Science Conferences are the backbone of the lunar literature and represent approximately 30,000 pages of referred and carefully cross-indexed papers. Major journal sources of literature are listed in Table 2.1.

In addition, the Lunar and Planetary Institute has produced over 20,000 pages of abstracts and proceedings of specialized conferences and maintains an extensive computerized bibliography of the lunar and planetary literature which can be accessed remotely by telephone/computer terminal linkage. Recently a *Handbook of Lunar Materials* (May 1978) was produced by the Lunar and Planetary Sciences Division of the Johnson Space Center (Houston, Texas 77058) to serve as an aid in engineering access to the lunar literature and direct access to the most pertinent features of the moon. This document is available on request from the Johnson Space Center (2.3). "Preliminary Science Reports" (Table 2.1) provide overviews of the six successful Apollo missions.

B. Global Properties

The moon is the only known natural satellite of the earth. General facts about the moon are given in Table 2.2. The moon revolves once around its own axis each time it completes an orbit about the earth. Thus, the moon always faces the same hemisphere toward the earth. The lunar day is 27.212 earth days in length or 653 hours from sunrise to sunrise. At the equator the temperature of

the lunar surface makes very large excursions from a predawn minimum of less than 100°K to a maximum in excess of 400°K . As one goes from the equator to the polar regions the temperatures decrease as the solar obliquity increases. Within a few degrees of the two poles there are craters which are never illuminated on the inside surfaces and therefore are extremely cold, less than 80°K . These craters may be repositories for water and other light gases and the more volatile elements which have been totally lost from the sunlit surfaces. The atmosphere of the moon is an extremely low pressure exposure in which the individual molecules collide only with the lunar surface or escape the moon and do not collide with each other. The surface pressure is greatest in the morning ($< 10^{-12}$ torr) and is far less at night.

Although the lunar surface is obviously pockmarked with craters resulting from the bombardment of the moon by meteorites over the past 3.6 billion years the moon at this point in time is extremely quiescent. It is possible to pick up at almost any point on the moon soil or rocks which have been sitting undisturbed on the moon for many 100 thousands to millions of years. The lunar surface is composed of soils and rocks referred to in combination as regolith, a term descriptive of the rubble making process which is believed to be the main way in which soil is produced as a result of the long term bombardment by meteorites. This soil or regolith is what dominates the visual appearance of the moon from earth. The soil is completely dry, extremely finely divided with an average grain size less than 50 micrometers, and extremely electrically resistive and an excellent thermal insulator at the top most surface.

The front side of the moon is divided into two distinct regions: the dark maria regions that are considered to be filled with volcanic extrusions and the highland areas which are bright (high albedo) and are mountainous. These features are readily apparent in Figure 2.1 as are the largest of the craters. Lunar

craters increase in number as smaller sizes are considered. These craters range in size from a few which are a major fraction of the radius of the moon down to microscopic pits which are only visible in electronmicroscope photographs of the surfaces of lunar grains and rocks.

The maria regions are topographically low, generally circular and consist of soils which are derived from mafic basalts of several different types. The bright highlands are on average approximately 1 km in altitude above the maria. Soils covering and composing the highlands consist of a mixture of mostly feldspar-rich (anorthositic) plutonic materials and minor amounts of an aluminum and trace element-rich basaltic material known as KREEP. KREEP is an acronym for potassium, phosphorus and rare earth elements (2.3). Analysis of returned samples has given detailed knowledge of the soils and rocks at nine landing sites on the earthward side of the moon (figure 2.1). Remote observations made from the instruments on board the last three Apollo missions and by means of telescopes from the earth have extended knowledge of the chemistry and mineralogy to most areas on the front side of the moon and in a belt approximately 20° wide around the backside of the moon. A basic reconnoitering of the moon has been completed for the equatorial regions. There is a vast body of detailed data on conditions in these regions for the development of engineering projects. Major discoveries which will enable even more extensive uses of the moon will certainly result from further exploration of the moon and by renewed surface explorations.

C. Lunar Mineralogy and Petrology

Figure 2.1 shows the location of the Apollo and Soviet landing sites from which samples have been returned and at which (Lunokhod 1 & 2) rover operations have been conducted remotely. Figure 2.2 is at the Apollo 15 site. Table 2.3A shows the range of the chemical compositions of the major minerals of the moon. The low and high titanium basalts are from maria regions (2.7).

The mineralogy of lunar materials is dominated by five minerals: pyroxenes, plagioclase feldspars, olivines, ilmenite, and spinel. Other minor minerals reported from lunar samples are also listed in Table 2.4. The major mineral chemistries are now distributed in more detail in the following paragraphs and Table 2.3B (2.3).

Pyroxenes. The basic chemistry of the pyroxenes can be represented by a mixing of the end member minerals: enstatite (MgSiO_3), wollastonite (CaSiO_3), and ferrosilite (FeSiO_3).^{*} These are usually abbreviated as En, Wo, and Fs, respectively. There are three structural forms of ortho-pyroxene, pigeonite (or low-calcium clinopyroxene), and augite (or high-calcium clinopyroxene), which are chemically differentiated by their CaSiO_3 content — orthopyroxene lowest and augite highest. All forms display a wide range of enstatite and ferrosilite contents. The minerals accept large amounts of Al (up to 12% Al_2O_3), Ti (up to 5% TiO_2), Mn (0.5% MnO), Cr (1.25% Cr_2O_3), and Na (0.2% Na_2O) into solid solution. An average chemistry cannot be easily defined.

Table 2.3B outlines the occurrence of pyroxene on the lunar surface. Pyroxenes are potential ores for silicon, calcium, magnesium, oxygen and possibly aluminum and iron. Based upon the occurrence shown in Table 2.3A & B mare basalts may be considered ores for lunar pyroxenes.

Olivine. Olivine is one of the dominant lunar minerals. It is a solid solution of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), with most compositions between Fo_{75} and Fo_{50} (75 to 50 percent forsterite). The mineral accepts limited amounts of Ca, Cr, Ti, and Al into solution. Table 2.3B outlines the occurrence of olivine on the moon and provides analyses of typical lunar olivines.

Olivine is a potential source of magnesium, iron, silicon and oxygen. Based upon the occurrence shown in Table 2.3B mare basalts may be considered ores for the mineral.

^{*}Compositions are often reported as mole percent of end member minerals, written as $\text{Wo}_2\text{En}_{80}\text{Fs}_{18}$, for example.

Feldspars. Lunar plagioclase feldspars are solid solutions of anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and albite ($\text{NaAlSi}_3\text{O}_8$), An and Ab, respectively. They can contain up to 2 mole % of orthoclase (KAlSi_3O_8). Plagioclase feldspar is one of the dominant groups of lunar minerals. Plagioclase occurs in all natural materials found on the lunar surface. Table 2.3B outlines the occurrence of plagioclase in lunar materials.

Most lunar feldspars have anorthite contents greater than An_{80} . The mineral anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) is a potential source of aluminum, silicate, silicon and oxygen, all of which are required for fabrication of structures in space. Based upon the known occurrence of plagioclase (see Table 2.3B), regions of light-matrix breccia may be considered potential ores for lunar plagioclase.

Ilmenite. Lunar ilmenites are mixtures of ilmenite (FeTiO_3) with small amounts of geikielite (MgTiO_3). They have a varied minor element chemistry. Ilmenite is among the minor lunar minerals, whose abundance is generally less than 2%. However, there are areas on the moon where ilmenite abundance surpasses 10%. Table 2.3B outlines the occurrence of ilmenite on the moon. The mineral ilmenite (FeTiO_3) is a potential source for iron, titanium and oxygen. Based upon the occurrence of ilmenite (see Table 2.3B), high-titanium mare basalts may be considered as potential ores for this mineral.

Spinels. Spinel minerals are complex mixtures of ulvospinel (Fe_2TiO_4), chromite (FeCr_2O_4), hercynite (FeAl_2O_4), picrochromite (MgCr_2O_4), spinel (MgAl_2O_4), and Mg_2TiO_4 . Their chemistries are complex and varied with substitutions of many minor and trace elements reported. See reference (2.3) for details on the physical properties of the various minerals taken from studies of analogy terrestrial or synthetic materials. The common rock types into which the various minerals assemble are named along the top of Table 2.3B. These rock types are now qualitatively discussed.

Mare Basalts. The mare basalts are igneous rocks thought to be originally derived from the interior of the Moon as liquids. Mare basalts can be divided into two major chemical groups based on titanium dioxide content: those that have $\text{TiO}_2 > \sim 9.0$ weight percent (primarily reported from the Apollo 11 and 17 sites), and those that have $\text{TiO}_2 < 5.0$ weight percent (see table 2.3). In addition to TiO_2 , there are significant differences in SiO_2 with the high titanium basalts (HTB) being 4 to 10 weight percent lower than the low titanium basalts (LTB). All the other oxides show significant overlap. The LTB's do generally have more MgO and FeO.

One advantage of this chemical grouping in addition to the obvious differences, is that these basalt types can be differentiated at a 1 km scale on the moon from earth-based spectral studies. Much of the nearside of the Moon has already been mapped with respect to distinguishing these two basalt units. The differences in the chemistry is quite logically reflected in significant differences in the modal mineralogy (based on volume percent of the various minerals present). The differences in titanium content is reflected in the much higher content of opaque minerals (ilmenite and armalcolite) in the HTB's. The differences in silica are evident in a corresponding decrease in the relative plagioclase and pyroxene content of the HTB's.

Texturally the HTB and LTB groups are not mutually exclusive. Both show variants from the vitrophyric basalts to coarse-grained ophitic basalts or fine- to medium-grained gabbros. In general the coarser grained the rock the more friable it is. Some of the most easily disaggregated rocks are the fine- to medium-grained gabbros. Residual glass and crystal shape appear to be the agents primarily responsible for the toughness of the rocks, and where the glass is lacking and the crystals equant to subequant, the rocks are more friable. Some specimens have micron to centimeter scale cavities (vugs and vesicles). The differences in

mineral compositions between the two basalt types are most significant except for the TiO_2 content of the opaques. The higher TiO_2 content in the HTB opaques reflects the presence of armalcolite which is not found in the LTB's.

Anorthositic Rocks. These rocks are composed almost wholly of plagioclase and are generally found in the highland areas although grains are present in samples of the mare soils also. Plagioclase is a sodium-calcium feldspar. Feldspar is a calcium, alkali, aluminum silicate. The three principal types are potassium feldspar ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$). The latter two form a solid solution series, plagioclase. The rocks are whitish in color and hard or competent.

Occasional coarse-grained rocks have been returned from the moon. The plagioclase in them is very rich in anorthite (90-97%), the olivine in forsterite (90%), and the pyroxenes are very magnesium-rich (EN/Fs > 9). The very plagioclase-rich specimens (15415 and 60025) are discussed in the section on breccias as cataclastic anorthosites.

Glass spheres are common in the lunar soils and interpreted to be pyroclastic in origin. Two peculiar concentrations of these have been found: the green glass (15426) and the orange glass (74220). Glass fragments have been reported which are very high SiO_2 and are granite like in chemical composition. It must be emphasized that these are rare (<1% by weight of material), but are ubiquitous in that some examples are found in almost every soil sample.

Breccias. The dominant process effecting the physical nature of the lunar surface is meteorite impact. The loose deposits generated by impacts constitute the regolith. Those deposits that have been lithified (turned into rock) by impact are called breccias.

Breccias display various physical and chemical properties. Physical properties are dependent upon the environment of the deposition while chemical properties

reflect the average composition of the surface struck by the meteorite.

Physical properties range from friable rocks with about one-third pore space to tough rocks with almost no pore space. Grain sizes may be "well sorted" or "poorly sorted." Pore space may consist of micrometer-sized cracks and gashes to millimeter or centimeter sized holes. Breccias may contain from zero to 50% glass.

Impacts are effective mixers of target materials and all deposits from a single impact have about the same composition. It is also true that all impacts in a given region have approximately the same target composition. Therefore, the breccias in the lunar highlands have compositions very similar to the lunar crust while the breccias in the mare plains have compositions similar to mare basalts.

Essentially every sample returned from the lunar highlands during the Apollo and Luna missions is a breccia. About one-third of the samples returned from the mare plains are breccias, the remainder being basalts.

Fragmental breccias are competent or semicompetent collections of soil grains which have been compressed or heated sufficiently to have some intergrain cohesion through processes like sintering or simply bulk compaction. These rocks may be very friable, like dry sand clods or may be very competent if sintering is well established. A nomenclature has evolved in the description of these breccias which appears to be textural, as in the terrestrial nomenclature, but in fact is a semi-empirical adaptation to the fact that both chemical and textural considerations are important in the naming of the various breccias. The nomenclature evolved very quickly over the early period of the Apollo program and serves as a common vocabulary to the research findings but is prone to differences from standard terrestrial terminology. It is well to note at this point, before the systematic descriptions, that all lunar samples, especially the breccias, are more-or less fractured. Each sample has through-going fractures that are commonly

branched. In some cases (e.g., the Apollo 14 breccias) these fractures are so abundant that the samples are dominated by the fractures and the debris of the fracture zones.

Crystalline-matrix breccias consist of a fine-grained, uniform-matrix with embedded mineral and rock clasts. The matrix consists of interlocking crystals of plagioclase feldspar, pyroxene, olivine and ilmenite with sizes ranging from 1 to 100 micrometers. The interlocking of crystals in the matrix bonds the total rock together. Most samples are tough with a low porosity (a few percent). Pore spaces vary from 0.1 millimeter to 10 centimeters and may be spherical or irregular cavities. Additional cavities, which are 5 to 50 micrometers in size and polygonal in shape, occur interstitial to the crystals in some regions of the matrix. Clasts range in size from 50 micrometers to tens of meters, and consist of abundant plagioclase with less abundant olivine and even less abundant pyroxene plus rocks.

Crystalline-matrix breccias are chemically equilibrated in that all crystals and grains of a given mineral in each sample have about the same composition. Thus, both matrix plagioclase and plagioclase clasts share the same composition in each sample, and that composition is different for different samples. Crystalline-matrix breccias occur only in the highlands, where they comprise about 50 percent of the samples returned.

Vitric-matrix breccias consist of an assemblage of mineral, glass and rock fragments bound together by grain-to-grain sintering and by smaller glass fragments acting as cement. Samples range from very friable to tough. These rocks are very porous; they commonly have bulk densities between 2.0 and 3.0. Polished surfaces display a network of micrometer sized fractures and irregular cavities whose abundance is an inverse function of the sample's density. The shapes of fragments is such that as the size decreases, the abundance increases. Detailed study of

size distribution for lunar materials has not been accomplished. Similar suites of terrestrial materials, however, follow a log-log law with a -2 to -3 slope (i.e. a decrease in size by a factor of ten would be accompanied by an increase in abundance by a factor of between 100 and 1000).

Compositions of included mineral and rock fragments is similar to the composition of analogous material in the surrounding regolith.

Vitric-matrix breccias may be considered as compacted and lithified regolith. There are no major chemical differences between local regolith and local vitric-matrix breccias. Vitric-matrix breccias have been referred to as soil breccias, regolith breccias, and glassy breccias. Vitric-matrix breccias even contain enriched abundances of solar-wind derived components such as the noble gases, carbon, nitrogen, and hydrogen.

Vitric-matrix breccias are abundant on the lunar surface. All breccias returned from the mare and about one-third of the breccias returned from the highlands are vitric-matrix breccias.

Light-matrix breccias are similar in texture and friability to vitric-matrix breccias except they lack glass fragments. They are but poorly-bonded aggregates of mineral and rock fragments that are cemented together by grain-to-grain sintering. Light-matrix breccias may be thought of as the glass-free, vitric-matrix breccias.

Light-matrix breccias occur within the lunar samples return from the Apollo 14 and 16 sites only. From various indirect data we may guess that light-matrix breccias may make up about 10 or 15 percent of the lunar highlands.

Cataclastic anorthosites are rare, crushed rocks consisting of 50 to 99 percent plagioclase feldspar. These samples are very friable. They consist of angular fragments of plagioclase, pyroxene and olivine, bound together by tiny amounts of glass or by grain to grain sintering. Fragment sizes vary from

about a micrometer to several centimeters and pore space ranges from 20 percent to essentially nil.

For the most part, minerals in these rocks are "pure" in that, plagioclase feldspar contains low amounts of iron and pyroxenes and olivines are Mg-rich and Fe-poor. Many of the plagioclase feldspars contain submicron rods and blebs of an opaque phase, probably Fe-metal or FeS. Approximately two-thirds of the cataclastic anorthosites returned by the Apollo program contain over 80 percent plagioclase. However, the fraction of samples with this abundance of plagioclase varies from site to site. Cataclastic anorthosites are rare at all landing sites. About 5 percent of the material returned from the highlands is in this category of material.

Granulitic breccias are rare, metamorphosed rocks which consist of a crystalline matrix and sparse mineral and rock clasts. These materials are tough, having virtually no porosity. The rocks are bound by the interlocking minerals of the matrix. The matrix consists of plagioclase feldspar and olivine and/or pyroxene in crystals on the order of 50 micrometers in some samples and 200 micrometers in others. Mineral compositions are the same for the matrix minerals as the minerals that appear as clasts. Granulitic breccias are rare on the lunar surface. Only five large rocks returned during the Apollo Program are granulitic breccias (four from Apollo 17 and one from Apollo 16), although rock clasts in other breccias and fragments in the regolith that are granulitic breccias have been found at all the landing sites. This suggests that granulitic breccias may be common at depths of a few kilometers throughout the highlands.

Soil. The surface of the maria is covered to a depth of 5 to 15 m by a fragmental soil (the regolith) produced by repeated impacts. The highlands, more heavily cratered, have a much deeper regolith. Most of the mare regolith is locally derived, but it contains a minor component of exotic fragments ballistically transported by impacts from distant areas. Vertical and horizontal mixing has

been more extensive in the highlands. A minor part, about 1 percent, of the soil is of meteoritic origin. Because of the absence of an atmosphere, the Moon's surface is directly exposed to the solar wind; consequently, the soil contains a small proportion of hydrogen and other light elements from the sun. Some degree of radiation damage is common to all surface samples (1.28).

The deepest direct depth samples of the moon are limited to the depth penetrated by the lunar drill on the Apollo 15, 16 and 17 missions. The total depth of penetration in each instance is approximately three meters. However, the meteoritic process believed to have produced the regolith has homogenized the soil in a given region. Thus, there is strong reason to believe that the many samples of soil taken in the Apollo missions of the surface materials are representative of the soil to the base of the regolith. In essence, the characterized soil is available in far larger quantities on the surface of the moon than one can readily envision using.

Surface soil has a bulk density the order of 1 g/cm^3 and increases rapidly with depth to 1.7 g/cm^3 at a depth of 30 to 60 cm. The mineral density of the soil is approximately 3.1 to 3.2 g/cm^3 . Naturally, there are variations in this profile. The soil around the lips of small craters tends to be very soft to a depth of tens of centimeters. Several of the mechanical properties of the soil are given in Table 2.5 (2.3).

Lunar soil generally appears as shades of grey except in the downsun direction when the soil can take on a light tan appearance. There are regions in which glass beads can give an orange (Apollo 17) or green appearance (seen from orbit). The volcanically produced glasses which produce these colors have been identified in soil samples. There is still some controversy over the exact cause of the darkness of the lunar soils which produce the dark appearance of the lunar mare. It is clear that an active process is involved which darkens the powder which composes the soil. Several processes including radiation damage,

sputtering and formation of different oxides are a few of the mechanisms mentioned to date.

The mean grain size of lunar soils ranges from 40 to 802 μm (Figure 2.3). Lunar soils are poorly to very poorly sorted, with sorting values (standard deviations) ranging from 1.99 to 3.73 ϕ , and many exhibit a bimodal grain size distribution. There is an inverse correlation between the mean grain size and sorting values (standard deviation), with the coarsest samples being the most poorly sorted. Weight percents in each grain size fraction are shown in Table 2.5 for the Apollo 11 soil 10084 which is a typical mare soil. About one-fourth of the soil is finer than 20 μm . Note also that 98% of the soil is finer than 1 cm. The soil is more like fine sand or powder than "terrestrial" soils. Most lunar soils have grain size characteristics consistent with those of debris from meteorite impacts. Exceptions include the black and orange "soils" collected at the Apollo 17 site, which are finer-grained ($M_z = 37.9$ and 40 μm) and better sorted ($\sigma_1 = 1.69$ and 1.57 ϕ). These samples have been interpreted as pyroclastic ejecta and not as soils. Lunar soils consist mostly of lithic and mineral debris derived by impact comminution of the underlying bedrock and glass particles formed by impact melting. Microscope identification of these particles shows that they can be grouped into several major categories generally similar to the rock types described earlier. It is generally thought that the exact character of the soil reflects not only the underlying source materials but also the effects of repeated reworking by meteorite bombardment. Both constructional (agglutination and brecciation) and destructional (comminution) processes operate. Several indices are used to interpret how long a soil has been worked: (a) quantity of gas derived solar wind implanted in the grains ($> 1\text{cc STP/gr}$); (b) mean grain size; and (c) the ratio of fine grained metallic iron (measured by ferro magnetic resonance) to FeO .

Agglutinates. Agglutinates were recognized immediately during the examination of Apollo 11 samples as an important soil component and as one of the keys to a genetic history of lunar soil. An agglutinate consists of comminuted lithic, mineral, and glass fragments bonded by glass droplets. The glass droplets generally are black to dark brown. Agglutinates contain fine-grained metallic iron formed by reduction of iron dissolved in the glass. The glass is vesicular, containing vesicles ranging from less than 1 μ m to several centimeters in diameter. The morphology of agglutinate grains ranges from simple irregular grains to more complex elongate, branching forms. Mineral and lithic clasts are randomly distributed throughout the agglutinate grains and on their surfaces.

Basalt fragments. Fragments of basalt are common at all mare sites. Basalt generally consists of plagioclase and pyroxene and may also have olivine, ilmenite and small amounts of other minerals. Basalts may be subdivided on the basis of composition (olivine bearing, etc.) or texture (equigranular, variolitic, etc.).

Breccia. Breccias are fragmental rocks created by impacts. They may be subdivided on the basis of composition (anorthositic, etc.) or textures (low grade or glassy, high grade or crystalline, melt matrix, etc.).

Mineral fragments. Constituent mineral fragments are liberated when lithic fragments are broken up by impacts. The most common mineral fragments in lunar soils are plagioclase feldspar and pyroxene. Olivine, ilmenite, and dozens of minor minerals may also be present.

Glass. In addition to agglutinates which are the major form of glass, other glass particles are present in the soil. Glass droplets, teardrops, and other regular shapes are generally present in small amounts (usually less than 1%). Blocky and vesicular glass are also found. Glass may be classified on the basis of shape, color, or chemical composition.

Relative amounts of each particle type. Table 2.6 a and b shows the relative amounts of the particle types in two typical soils, one from the mare region and one from the highland region of the Apollo 17 site. Data is shown for each of 10 size fractions. In general, lithic fragments are most common in the coarsest size fractions and mineral and glass fragments are most abundant in the finest size fractions. The grain size distribution for each size fraction is also shown.

Several other aspects of the soil are worthy of particular mention. The soil is completely dry. No grains or fragments have been found which now or in the past contained water in significant concentrations adequate to affect the collective physical properties of the soil. The soil is an exceptionally good electrical resistor to direct currents. At 0°C the resistivity is in excess of 10^{17} ohm-cm for a soil compaction similar to that at the lunar surface (2.8). In complete contradiction to expectations the extremely finely divided lunar soil is an extremely low loss conduit for seismic signals of less than 40 Hz in frequency. Very low attenuations are encountered and $Q \approx 3000$ seems consistent with the propagation and attenuation characteristics of the soil. As expected from pre-Apollo results the soil is an excellent thermal insulator with a thermal conductivity in the undisturbed state the order of $1 \cdot 10^{-4}$ W/cm-°K to a depth of 250cm (2.4).

Of particular importance to early utilization of the moon is the extent of native free iron grains in the highland and mare soils. These grains are very small, on the order of 100s of micrometers to a few hundred angstroms in diameter. A fraction can be extracted by magnetic separation techniques. Weight percentages of the order of 0.05% to 0.20% may be obtainable with only minor energy expenditures for soil excavation and processing and separation equipment of minimal complexity. In addition, the iron contains approximately 5% nickel and 0.2% cobalt (2.9).

D. Average Chemical Compositions of the Regolith

Table 2.7, taken from page 103 of (1.21), presents the average chemical composition of the regoliths of the eight landing sites on the moon (six in Apollo and two Luna). At some sites, the samples are distributed over areas of tens of square kilometers. Photogeologic studies as well as the chemical analyses of the soils suggest at least three major divisions of the lunar surface materials. These are large, circular mare basins, highlands, and ejecta around the mare basins. Numbers one and two are the most distinctive. Table 2.7 is compiled along these divisions. The homogeneity of the major soil collections within these divisions at a given landing site is remarkable. Orbital x-ray and gamma-ray spectrometers onboard the Apollo spacecraft extended these observations to approximately 20% of the equatorial lunar surface within 25° of the equator. Highlands are enriched in Al and Ca, whereas the mare are enriched in Fe, Cr, Mn, and Ti. Mare areas display significant variations in Ti content. Basin ejecta are intermediate in composition, except for a few elements such as K and P, which tend to be highest in the ejecta. Unsampled, but remotely observed highland areas on the far side appear to have a higher Al content than the Apollo 16 site.

The elements H, C, N, O and the noble gases occur in extremely low concentrations in lunar basalts and highland breccias. Lunar fine materials (soil and soil breccias), however contain appreciable concentrations of these elements (Table 2.8), which have been implanted by the solar wind. Most exposed mineral surfaces appear to saturate at approximately 10^{17} ions/cm², resulting in strong fractionations among concentrations of the gases relative to solar wind abundances. The solar-derived gases are present on grains located at depths of several meters.

Solar ions are implanted into exposed surfaces to depths of less than 0.2 μ m. Consequently, the largest concentrations of these elements are found in the finest grain sizes of lunar soils, which have the largest surface area to mass ratios.

These same surface layers experience considerable solid state damage, due to the amount of energy deposited by the -1 Kev/amu ions and occasional solar flare ions with Mev energies. Amorphous layers are commonly formed on grain surfaces and contribute to intergrain cohesion and aid sintering. A large fraction of the implanted gases are incorporated into the interiors of constructional particles, such as soil breccias and glass-welded agglutinates. This effect, and other factors such as the mineral dependent retentivity cause gas concentrations to correlate less than exactly with inverse grain diameter. Mature soils, with small mean grain diameters and a great fraction of constructional particles, contain several times the concentrations of solar-derived gases as do immature soils.

Concentrations of solar wind-derived elements among the most mature soils tend to be the same to within a factor of two. Differences in soil chemistry and mineralogy are less important than soil maturity in determining gas concentrations, with the exception that He and Ne are more readily retained in ilmenite (mare soils) and lost from plagioclase (highland soils). Helium is most concentrated in the $<2 \mu\text{m}$ size fraction of lunar soil ilmenite.

It is reasonable to expect that how energy electrostatic and magnetic separation techniques can be used to concentrate the smallest size fractions of the lunar soil and therefore the effective concentration of H, He and several of the volatile and siderophile elements at little cost. Calculations indicate that hydrogen concentrations of at least 10 to 20 times the bulk soil levels can be achieved with minimal energy expenditures and minimal machinery (Chapter 4, 1.17; p. 121-130, 1.27).

These elements H_2O , CO_2 , N_2 , Ar, Na, K S and C, may be partially or entirely driven from lunar material by heating. Most of the geochemical information on the easily volatilized elements within the lunar regolith was obtained by analyses of lunar soils.

Carbon abundances in lunar soils are greater than those found in lunar crystalline rocks. It has been shown that most of the carbon found in lunar soils derives from the solar wind, whereas carbon is indigenous to lunar rocks. Carbon abundances for lunar basalts range from 20 to 100 $\mu\text{gC/g}$ (Table 2.8). Lunar breccias typically contain carbon abundances intermediate to the soils and rocks.

Lunar crystalline rocks range in sulfur from 20 $\mu\text{gS/g}$ for anorthosites to 2800 $\mu\text{gS/g}$ for some lunar basalts. Lunar basalts are typically 5 to 10 times more enriched in sulfur than terrestrial basalts. In general sulfur content of soils are similar to the rock types which constitute the soil, and indicate that the solar wind and meteoritic components of sulfur in soils is minor.

Lunar materials are depleted in the volatile elements potassium and sodium as compared to terrestrial rocks. The lunar basalts range in sodium concentrations from 0.14 to 0.52 wt. % Na. No major differences in sodium abundances exist between mare materials and highland materials (Table 2.7). Lunar basalts range from 0.01 to 0.34 wt. % K with most crystalline materials containing 0.05 ± 0.03 wt.%K. In contrast to most terrestrial surface rocks, potassium is so low in concentration in lunar rocks as to constitute a minor or trace element and resembles the concentration levels in low-K oceanic tholeiites or in chondritic meteorites. Sodium is depleted in lunar materials relative to terrestrial basalts by a factor of about five.

The easily volatilized elements are lost from lunar samples over a wide temperature range which is a direct reflection as to the origin of these species. Lightly adsorbed species and contamination products (e.g. spacecraft exhausts) are generally removed from lunar soils at temperatures below 150°C . Solar wind-derived gases may be released from fines from 600°C to sample melting, with lighter gases releasing at lower temperatures. Solar wind derived species such as H_2O , H_2 , CH_4 , and a portion of the N_2 and CO are removed from lunar fines at

temperatures between 200^o and 900^oC. At temperatures near 900^oC chemical reactions and decompositions of mineral phases begin with the loss of S, CO, N₂, Na, Rb, K. Near the melting temperature of soils (1100-1259^oC) chemical reactions occur between various phases present with the evolution of reaction products CO, H₂S, SO₂, H₂, and CO₂. A summary of the gas evolution regions for various lunar materials is given in Figure 2.4.

Volatilization studies of lunar fines has shown that substantial quantities of carbon and sulfur are evolved in vacuum at temperatures as low as 750^oC. The alkali elements are lost from lunar fines at temperatures beginning around 1000^oC. The relative volatility of the alkali elements is Rb > K > Na for lunar materials. Loss of sodium does not occur readily until temperatures of 950^oC. Sulfur loss from lunar fines is substantial during vacuum pyrolysis. At temperatures of 1100^oC (below the melting temperature of most soil components) between 85 and 95% of the sulfur has been lost from lunar soils.

Several trace elements such as Zn, Cd, In, Hg, Pb, Ge, and the halogens, which generally occur in surface materials in concentrations of 10-0.001 ppm, also readily undergo volatilization and migration on the lunar surface due to heating and melting of soils by solar radiation and meteorite impact. As a result, these elements are often found in considerably higher concentrations in areas shadowed by large rocks and on grain surfaces of the finest grain sizes of soils.

The concentration of indigenous water in lunar basalts is vanishing small (<10 ppm) compared to terrestrial rocks and is generally difficult to distinguish from terrestrial contamination. Essentially all H₂O found in lunar soils has been formed by interaction of solar wind hydrogen with oxygen-bearing silicates. Pyrolysis of lunar materials have failed to release any organic compounds which could not be explained by contamination or as simple compounds formed from the solar wind. The upper limit of indigenous organics in lunar samples is about one part per billion.

III. USES OF THE MOON

A. Whole moon

The moon provides a place to stand. We have extensive experience in working on the moon with men during the Apollo program. The bulk of the moon eliminates cosmic radiation and meteorites from one half the celestial sphere for positions on the surface. The moon can be used to alter the trajectories of spacecraft approaching from the earth or from deep space. Both the trajectory and the velocity of a given object can be changed by these gravitational encounters (p. 209, 219 in 1.3). Velocity changes as large as 1.1 km/second can be achieved with respect to the earth and large changes in inclination with respect to the plane of the ecliptic can be accomplished with no propellant expenditures during the encounter. This method is applicable to the capture of asteroids into orbits about the earth (3.1 and 3.2). The moon is so large that no appreciable effects will be produced on the orbit of the moon about the earth. The earth can be observed from the earthward hemisphere of the moon. To a first approximation the earth is fixed in the lunar sky and in twenty-four hours all the earth's surface comes into view. On the far side of the moon the earth is never in view. This would be a good location for various types of astronomy, such as radio astronomy, in which terrestrially interfering effects can be eliminated (p. 39, 1.25).

Much lunar exploration remains to be done. There are clear scientific needs to survey the 80% of the lunar surface not observed during the Apollo program from orbit. Regions of particular interest are the craters in the polar regions which have not been exposed to sunlight for billions of years. There are great scientific needs to obtain many samples of the lunar interior to the maximum possible depth by means of major drilling operations. Scientists working on the moon could explore many aspects of lunar science which were only touched on in the Apollo program. Investigations which allow both greater detail of study and more

extensive observations both in time and over the geography of the lunar surface would be extremely useful and possible in the context of a permanent base on the moon. Eventually, as an economically productive installation grew on the moon there would be tourist traffic as there presently is to the Antarctic.

The surface of the moon is a sink for contaminants which functions more rapidly in some cases than does the ejection of materials into space about vehicles which are in turn in orbit about a planetary body. This is especially true for ionized atoms in the magnetosphere of the earth. The decay of radioactive ions from nuclear explosions in near earth space took many years to be lost from the inner regions of the Van Allen belts. Conversely, it is possible to create a tenuous atmosphere about the moon if great care is not taken in retaining all gaseous products from processing equipment in habitats and rockets (p. 77, 1.25). A major question which should be determined as early into manned operations on the moon as possible is the effects of one-sixth gravity on the human body (p. 34, 1.25). Hopefully, long term problems such as the loss of bone calcium in zero gravity will be less severe on the moon.

Early installations on the moon will be able to operate machinery and do a wide range of tasks which can be formulated and tested on earth prior to a return to the moon. However, early missions for a lunar base will certainly focus on developing uses for lunar materials which optimize the use of the materials as they are naturally found on the lunar surface with machinery which is especially productive for operations on the moon. In addition, there is considerable need to make the earliest possible use of lunar materials to produce the complete production facilities for the growth of lunar materials. This is due to the high cost of transporting machines, people or raw materials to the moon (approximately 2,000\$/kg). Creative use of our present knowledge of the moon combined with the enormous capabilities of modern technology should allow major reductions in

missions costs if some time is allowed for the creation of large production facilities from "seed" or bootstrapping installations.

B. Bulk Soil and rocks

It is comparatively easy to provide protection on the moon against cosmic radiation by simply burying people and sensitive machines approximately three meters beneath the lunar surface. In most areas excavating would be relatively easy. In addition, the soil of the moon is an extremely good thermal insulator. Approximately ten centimeters of the uncompacted soil will dampen out the diurnal heat pulse. Bulk soil can also be used to offset internal pressures such as on the inside of a buried habitat and thereby decrease the total stress on the structure. This may be of considerable importance in the design of structures with large interior volumes. Bulk lunar soil can be transported to space in the early phases of space operations and be used as reaction mass for mass driver reaction systems operating in interplanetary space. Fractions of the soil can be used in agriculture in closed environments to supplement the diets of base personnel.

It has long been obvious that solar energy can be used during the lunar day to provide electrical and thermal power. However, the provision of power during the lunar night has always presented a major problem. One possible way to store very large quantities of thermal energy which can then be made available for either thermal or electric use is to melt a large pool of several hundred cubic meters of lunar soil. The pool will form its own glass lined pit. The low thermal conductivity of the surrounding and supporting soil will hold heat loss to a minimum. Solar direct radiation employing very light weight mirrors can be used in the day to melt the soil. The pit would be covered by a highly reflective sheet steel foil to prevent radiation heat loss at night to space. The magma would be of low viscosity and the melting point would be 1000° and 1500°C depending on the exact lunar composition or fluxing additives in the melt. Heat would be extracted by gas flowing through highly refractory pipes submerged in the melt, then through

secondary heat exchange coils or directly to a turbine and radiator elements and then back to the lava pit.

It has been suggested that large scale lots of fusion materials could be manufactured on the moon through the use of simple breeder reactors, hybrid reactors (fusion breeders employing a fertile thorium blanket to produce U-235) or bomb breeder systems. In the latter the cheap neutrons produced during the detonation of thermonuclear devices are used as the neutron source for an "open-air" breeder; the bombs are simply detonated a few thousand meters above a distributed mass of depleted uranium. Certain problems exist but the location lack of air and lack of people on the moon are favorable factors (p. 45, 1.25).

Lunar mining as presently envisioned will more closely resemble terrestrial strip mining than excavations. Due to the highly fractured nature of the lunar soil the energetics are very low for the scooping of lunar materials. The low lunar gravity will permit the vehicles to carry very large payloads. It is probable that payloads more than six times greater per unit of vehicle than can be accommodated on earth will be feasible because the vehicle will be less stressed in supporting its own mass on the moon than it would be on earth. Very small, remotely controlled and semiautomated vehicles comparable to terrestrial backhoes or front-end loaders could accommodate the excavation of trenches for habitats, shops and industrial operations and also handle several tons a year of local excavation for materials processing operations (Carrier section III, 1.17; 131, 1.25; 63, 1.6; 161, 1.3). One novel aspect of soil transport on the moon deserves comment. Due to the lack of a lunar atmosphere and low lunar gravity it is possible that material can be thrown long distances to a small central collection point. Transport over tens of kilometers seems reasonable. The throwing process is more energy intensive than hauling, except for very deep pit mines, but would be quick, very flexible and minimize the need for rolling stock.

Work had been done on the use of explosions for excavation. Recent experimental and theoretical work on the cratering process is of direct relevance to explosive excavation (3.3).

Due to the finely divided nature of the lunar soils, the pristine condition of the surfaces of all the grains due to the lack of atmosphere and water and the low gravity on the moon there very likely will be a greater use of magnetic and electrostatic separation techniques. Many aspects of these separation techniques can be proven in the laboratory with small quantities of lunar samples. However, there is a need for the demonstration of the massive operations with equipment which could be placed on the lunar surface as part of early return missions (Inculet, section IV, 1.17). Crushing may increase the availability of some of the minerals and elements.

One component of the lunar soil which is of particular interest is the small weight fraction (approximately 10^{-4}) of free iron spheres which are generated by the reduction of ferric oxide by solar wind hydrogen implanted in the lunar soil grains and the residue of meteorites. This iron should be relatively easy to remove from the background soil by magnetic separation as part of a large scale excavation procedure. The iron can be used as the basis of an iron powder metallurgy (p. 73, 1.25) for the manufacture of equipment and bootstrapping of production without the need for more complicated chemical processing. Naturally, the iron would be very useful in magnetic systems and might find early use as an electrical conductor. It may be possible to find enriched quantities of the iron in association with localized regions of strong magnetic fields which can be located from lunar orbit.

It has been previously noted that there is present in the grains of the lunar soil a load of solar wind gases. The different minerals contain different concentrations of the various elements. Ilmenite is rich in solar wind hydrogen

and may be rather easy to extract from the lunar soil (3.4). If so, then soils which are especially rich in fine grains of ilmenite will be especially valuable for the hydrogen and chemically derived water which can be directly extracted without the need for separate chemical processing. Reasonably straight forward thermal processes are available to extract the hydrogen in the form of water from ilmenite (3.5, 3.6). Simple thermal processes can certainly be used to extract the other very valuable volatile gasses from the lunar soils. These include helium, nitrogen, carbon dioxide, sulfur dioxide and various forms of carbon. However, a rich field of investigation would center around less energy intensive chemical means by which to extract the volatiles and other elements from the extensively radiation damaged portions of the outer few hundred microns of the grains. Again, proposed systems can be checked out on earth with simulants of lunar soil and tiny samples of actual lunar sample if necessary.

C. Products of thermal and chemical processing

Table 3.1 summarizes the many general products which could be derived from the lunar soil in glass forming processes or from the chemical and oxide separates of the lunar soil.

The structural metals listed (Al, Fe, Mg, and Ti) will have to be alloyed in order to develop useful mechanical properties. Several elements (e.g. Si, Cr, Mn) used in forming commercial alloys of the structural metals are potentially recoverable from the moon. The natural iron on the moon also contains nickel and some cobalt. Finally, if enough carbon were recoverable from the trace amounts present on the moon (or brought from earth, or possibly obtained from a carbonaceous asteroid), and small amounts of other key alloying elements were imported from earth, one could produce many ferrous and non-ferrous alloys that are commonly used today.

In the case of steels, the more important alloying elements not readily available on the moon are C, Ni, Mo, W, V, and Nb (Cb). The physical properties of several commercial alloys containing these elements are generally similar to alloys in which such elements are absent but which instead contain lunar-indigenous elements. The properties including electrical conductivity magnetic characteristics, tensile strength, yield strength, hardness, and elongation are listed for both the pure metals and major alloys in Tables 3.2 through 3.10. Therefore, for use as structural metals in space, it is possible to produce alloys possessing a broad range of properties (as commonly required on earth) by alloying with carbon, lunar-indigenous elements, and/or minor amounts of lunar-deficient elements (LDE).

Several commercial aluminum alloys can be made from lunar-indigenous materials. However, higher strengths, approaching those of the strongest aluminum alloys made on earth, can only be obtained by alloying with small amounts of lunar-deficient elements, particularly Zn.

Only a few commercial alloys of magnesium and titanium can be formed solely from elements recoverable from the moon; but here again, as in the cases of steel and aluminum, significant improvements in properties can be obtained by alloying with minor amounts of lunar-deficient elements. The strongest magnesium alloys will require such lunar-deficient elements as Zn, while the strongest titanium alloys will need Mo.

It is evident that the structural metals to be manufactured in space will consist of alloys that are already in use, are well-characterized, and can furnish almost any desired property currently available. Nonmetallic materials similarly may be made solely from lunar sources, or modified with additions of lunar-deficient elements.

Product-mix options depend on the type of raw material used and the nature and quantities of finished products required for specific applications. A range of materials outputs can be made available by varying the mineral input and process conditions. The moon contains large quantities of a variety of minerals, so that the type of industry that might be attempted in space can be chosen after examining the various options available, rather than its being limited by any specific method or process for converting lunar material.

In building a large space manufacturing-facility via bootstrap operations:

1. Some materials almost certainly would have to be brought from earth.
2. The extent of additional structures that could be processed and manufactured in space from lunar materials would depend more critically on fabrication limitations than materials availability.
3. Versatility and properties would demand substantial use of steels, rather than aluminum or magnesium, as structural and magnetic metals and in tooling and manufacturing equipment.
4. Reprocessing and recycling carbon to form baked carbon and graphite products would be difficult in space. If possible, substitutes for such products would be highly desirable.

As one would expect from the anhydrous and refractory nature of the lunar surface the lunar materials they are definitely sources for a variety of glass and ceramic products. Useful glass and ceramic products can be derived from the native materials with only heating, from native fractions after beneficiation by magnetic, electric, physical or other means and from the chemically separated oxides and elements. Characteristics of several presently utilized glasses based on oxide combinations similar to those which could be produced from various oxides obtainable from the lunar surface are listed in Tables 3.11 and

3.12. The addition of even small fractions of elements from earth, the asteroids or from beneficiated lunar ores can have dramatic effects on the properties listed in these tables. Examples of the uses of cast basalts are presented in several works (p. 181, 1.3; 1.21). Sintered products can probably be obtained from the lunar soils. However, due to the low viscosity and relatively high melting point of most of the lunar materials considerable work with bulk quantities of the lunar soil may be necessary to develop sintering techniques which are sufficiently repeatable. One can anticipate the need for a higher level of control in the production of sintered products than glass or ceramic or cast basalts. Conversely, drills and tunneling devices which use very hot drill tips to melt through soil and rocks and leave a glass lined cavity may find extensive use on the moon to create facilities (3.10).

Products which are somewhat exotic by terrestrial standards may find considerable use and markets both in space and on earth due to the totally anhydrous nature of the lunar materials and the possibilities of maintaining purity levels of some elements in the lunar processing schemes which are not possible on earth. For instance, fiberglass produced in space or on the moon from lunar materials should be especially strong and resistant to cracking because of the complete lack of water. The glass can be coated with lunar derived metals and protected from hydration if earth use is planned. Optical fibers can be drawn from lunar derived glasses which are free of water molecules and therefore not given to internal degradations of optical properties over long periods of time. Production of lunar fibers is discussed by Ho and Sobon (3.7). A major technical challenge will be to provide binders and non-metallic coatings for glass and ceramic products. However, it does appear possible to produce a limited number of inorganic polymers and binders from a major fraction of lunar materials (3.8; 3.9). It should be noted that many of these products

will embody a major quantity of solar energy. If this product is shipped to earth the embodied energy represents an energy which was not derived from terrestrial sources and therefore not a drain on terrestrial resources.

As previously mentioned there may be very strong synergistic effects between the use of lunar materials and the transportation costs of space flight or other factors. Clearly, the refueling of rockets with lunar derived oxygen can greatly improve the payload capabilities of many space missions. It has been proposed that earth to orbit rockets could be refueled at suborbital velocities and altitudes by a tanker operating from earth orbit down to the rocket and thereby reduce by a factor of five or more the size of the rocket necessary to transport a given payload into orbit (p. 26, 1.25). Even greater economies can be possible for deep space missions and transportation to the moon (p. 93, 107 and 135 of 1.3; p. 23, 1.5). The use of life supporting oxygen derived from lunar materials is another obvious use (p. 187, 1.3).

In summary, the early use of lunar materials will allow by bootstrapping major reductions in the costs of developing lunar resources. In turn, continued and expanding use of lunar resources will make possible the economic development of cis-lunar space.

Acknowledgments

This work was performed in part at the Lunar and Planetary Institute which is operated by the Universities Space Research Association under contract number NAS 09-051-001 (mod. 24) from the National Aeronautics and Space Administration. This is Lunar and Planetary Institute contribution number 380.

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Table 1.1

LUNAR RESOURCE SPS MATERIAL REQUIREMENTS

		Original LRU Used for Concept Evaluation		Updated LRU Incl Nonrecoverable Processing Losses	
		Mass (T)	% Of Total	Mass (T)	% Of Total
Lunar material requirements	Silicon	31,649	32.2	34,829	29.5
	Native glass	20,093	20.4	34,685	29.3
	Oxygen	19,223	19.5	19,369	16.4
	Aluminum	11,925	12.1	12,275	10.4
	Iron	5,300	5.4	4,460	3.8
	Alloying elements	0	0	33	0
Total lunar material		88,190	89.6	105,651	89.4
Earth material requirements	Metals	2,316	2.4	2,840	2.4
	Graphite composite	0	0	0	0
	Various	7,874	8.0	9,651	8.2
Total earth material		10,190	10.4	12,491	10.6
Total SPS mass (T)		98,380	—	118,142	—
Percent of earth baseline SPS mass		100.9		121.1	

ORIGINAL FIGURES
OF POOR QUALITY

• Predicted mass of completed LRU SPS = 112,223 T

Table 1.2*

DEMANDITE

(a) Molecular composition

Use	Weight fraction	Components	Molecular fraction
Fuel	0.46	Hydrocarbon (CH ₂ to C ₆ H ₁₄)	0.8022
	Building	.45	Silica (SiO ₂)	.1115
Metals		.06	Calcium carbonate (CaCO ₃)
	Iron		.0110
	Aluminum		.0011
	(b)		.0008
Agriculture	.01	Magnesium	.0004
		(c)	.0004
		Nitrogen	.0076
		Phosphorus	.0008
Others	.02	Potassium	.0007
		Oxygen	.0053
		Sodium	.0053
		Chlorine	.0053
		Carbon	.0023

(b) Molecular properties

Parameter	Value
Average molecular weight	23.9
Average recovery energy, kJ/kg (kWh/kg)	15 (0.57)
Average unit cost, cents/kg	1.4
Total quantity used, Mg/yr	3 x 10 ⁹
Total value, \$	42 x 10 ⁹
Per capita mass consumption, Mg	15.4
Per capita energy consumption, MJ(kWh)	67 680 (18 800)
Per capita power consumption, kW	2.14

^aRepresents average nonrenewable resources used in the United States in 1968.

^bTotal of manganese, barium, chromium, fluorine, titanium, nickel, argon, tin, boron, bromine, and zirconium.

^cTotal of copper, zinc, and lead.

* Reference 1.15

Table 1.3

NONFUEL DEMANDITE COMPARED TO ELEMENTAL DISTRIBUTION FROM ONE MOON SITE

Element (1)	Weight Fractions				
	(2) Nonfuel demandite	(3) Apollo 15 mare (low titanium)	(4) Enhancement required ^a	(5) Bulk excess	(6) Soil (1 unit) deficiency
Silicon	0.2444	0.2158	1.13	-	0.0286
Oxygen	.4547	.4130	1.10	-	.0417
Iron	.0479	.1535	.31	0.1056	-
Aluminum	.0023	.0546	.042	.0525	-
Magnesium	.0017	.0681	.025	.0664	-
Copper, zinc, and lead	.0020	.000022	90.	-	.0020
(b)	.0030	.0189	.16	-	5.829
Calcium	.1417	.0696	2.0	-	.0721
Sodium	.0095	.0023	4.1	-	.0072
Sulfur	.0058	.0006	9.7	-	.0052
Potassium	.0021	.0008	2.6	-	.0013
Phosphorus	.0019	.0005	3.8	-	.0014
Chlorine	.0147	.0000076	1934.	-	.0147
Nitrogen	.0083	.00008	103.	-	.0085
Carbon	.0574	.000095	604.	-	.0565
Hydrogen ^c	.0025	.000070	350.	-	.0019
Total	0.9999	1.0000	-	(+) 0.241	(-) 0.241

^a Required to meet terrestrial demandite fraction.

^b Manganese, titanium, chromium, barium, fluorine, nickel, argon, tin, bromide, zirconium, and boron.

^c For use in plastics; does not include water.

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* Available from the Government Printing Office, Washington, D.C. 20402

Table 2.2

Global Properties

Total Mass (ref. 2.2)	7.353×10^{23} kg (0.0123 of earth)
Mean Density (ref. 2.1)	$3.343 (\pm .004)$ gm/cm ³
Mean Radius (ref. 2.1)	1738.09 km
C/MR^2 (ref. 2.3)	$0.392 (\pm 0.003)$
Surface gravity acceleration (ref. 2.3)	162 cm/sec ²
Central pressure (ref. 2.3)	42 kilobars
Seismic Energy Release (ref. 2.3)	$< 10^{15}$ ergs/hour (< 30 kilowatts)
Surface Heat Flux (ref. 2.3)	2μ W/cm ²
Range of Surface Temperatures	
At equatorial surface (ref. 2.5)	120-400 ⁰ K
At 150 cm depth 25 ⁰ N (ref. 2.4)	253 ⁰ K ($\pm 2^0$ K)
Surface area (ref. 2.2)	37.9×10^6 km ² (0.0743 of earth total)
Escape velocity (ref. 2.2)	2.37 km/sec (0.165 of earth—11.2 km/sec)
Semimajor axis (ref. 2.1)	384,400 km
Eccentricity (ref. 2.1)	0.055
Inclination (2.1)	18.5 to 28.5 ⁰
Total surface area visible from earth at some time (ref. 2.5)	59%
Synodical month - new to new moon (ref. 2.5)	29.530 588 2 ephem. days
Inclination of lunar equator	
to ecliptic (ref. 2.5)	1 ⁰ 32' 40"
to orbit (ref. 2.5)	6 ⁰ 41'

Table 2.2 Global Properties (Continued)

libration (ref. 2.5)	<u>in longitude</u>	<u>in latitude</u>
Physical - Displacement (selo) Period	$\pm 0.02^{\circ}$ 1 year	$\pm 0.04^{\circ}$ 6 years
Optical - Displacement (selo) Period	$\pm 7.6^{\circ}$ Approximately one sidereal year	$\pm 6.7^{\circ}$
Moon semidiameter at mean distance (ref. 2.5) geocentric	15' 32" .6	(0.259888° or 4.54591×10^{-3} radians)
topcentric, zenith	15' 48" .3	(0.2535° or 4.59894×10^{-3} radians)
Nodal month (node to node) (ref. 2.5)	27.212 220 days	
Period of moon's node (nutation period, retrograde)	18.61 tropical years	
Period of rotation of moon's perigee (direct)	8.85 years	
Moon's sidereal mean daily motion (ref. 2.5)	47 434" .889 871	- 0" .000 284T
Mean transit interval (ref. 2.5)	24 ^h 50 ^m .47	
Main periodic terms in the moon's motion (ref. 2.5)		
Principal elliptic term in longitude	22 639" sin g	
Principal elliptic term in latitude	18 461" sin u	
Evection	4 586" sin (2D - g)	
Variation	2 370" sin 2D	
Annual Inequality	-669" sin g'	
Parallactic inequality	-125" sin D	

where g = moon' mean anomalie

g' = sun' mean anomalie

D = moon's age

u = distance of mean moon from ascending node

Table 2.2 Global Properties (Continued)

Mean opposition magnitude, V_0 (ref. 2.1)	-13.0
Aphelion Distance (ref. 2.1)	$0.4055 \times 10^{+6}$ km
Perihelion Distance (ref. 2.1)	$0.3633 \times 10^{+6}$ km
Albedo (ref. 2.6)	
Average over front side	0.072
Range of albedo	0.03 to 0.15
Orbital velocity about the earth	1.03 km/sec

Table 2.3A*

Ranges of chemical compositions
for the major minerals

High-titanium basalts				
Modal abundance (Vol. %)	Pyroxene 42-60%	Olivine 0-10%	Plagioclase 15-33%	Opagues (mostly ilmenite) 10-34%
Component (Wt. %)				
SiO ₂	44.1-53.8	29.2-38.6	46.9-53.3	<1.0
Al ₂ O ₃	0.6- 6.0	-	28.9-34.5	0 - 2.0
TiO ₂	0.7- 6.0	-	-	52.1-74.0
Cr ₂ O ₃	0 - 0.7	0.1- 0.2	-	0.4- 2.2
FeO	8.1-45.8	25.4-28.8	0.3- 1.4	14.9-45.7
MnO	0 - 0.7	0.2- 0.3	-	<1.0
MgO	1.7-22.8	33.5-36.5	0 - 0.3	0.7- 8.6
CaO	3.7-20.7	0.2- 0.3	14.3-18.6	<1.0
Na ₂ O	0 - 0.2	-	0.7- 2.7	-
K ₂ O	-	-	0 - 0.4	-
Low-titanium basalts				
Modal abundance (Vol. %)	42-60%	0-36%	17-33%	1-11%
Component (Wt. %)				
SiO ₂	41.2-54.0	33.5-38.1	44.4-48.2	<1.0
Al ₂ O ₃	0.6-11.9	-	32.0-35.2	0.1- 1.2
TiO ₂	0.2- 3.0	-	-	50.7-53.9
Cr ₂ O ₃	0 - 1.5	0.3- 0.7	-	0.2- 0.8
FeO	13.1-45.5	21.1-47.2	0.4- 2.6	44.1-46.8
MnO	0 - 0.6	0.1- 0.4	-	0.3- 0.5
MgO	0.3-26.3	18.5-39.2	0.1- 1.2	0.1- 2.3
CaO	2.0-16.9	0 - 0.3	16.9-19.2	<1.0
Na ₂ O	0 - 0.1	-	0.4- 1.3	-
K ₂ O	-	-	0 - 0.3	-
Highlands rocks				
Modal abundance (Vol. %)	5-35%	0-35%	45-95%	0-5%
Component (Wt. %)				
SiO ₂	51.10-55.4	37.70-39.9	44.00-48.0	0 - 0.1
Al ₂ O ₃	1.00- 2.5	0 - 0.1	32.00-36.0	0.80-65.0
TiO ₂	0.45- 1.3	0 - 0.1	0.02- 0.03	0.40-53.0
Cr ₂ O ₃	0.30- 0.7	0 - 0.1	0 - 0.02	0.40- 4.0
FeO	8.20-24.0	13.40-27.3	0.18- 0.34	11.60-36.0
MgO	16.70-30.9	33.40-45.5	0 - 0.18	7.70-20.0
CaO	1.90-16.7	0.20- 0.3	19.00-20.0	0 - 0.6
Na ₂ O	-	-	0.20- 0.6	-
K ₂ O	-	-	0.03- 0.15	-

* Ref. 2.7

(CRYSTALLINE MATERIALS)

Type of Bulk Sample - Across		(Average Composition of Mare ¹ and Highland ² Minerals in Heavy Boxes — % Minerals in Box)								
Mineral Type	Maria Basalt	Anorthositic Rocks (Highlands)	Fragmental Breccias	Soils	Crystalline Breccias	Vitric Breccias	Light Matrix Breccias	KREEP BASALTS		
						Oxide	Mare	Highland		
Pyroxenes (*% of component) (Meta-silicate - M_2SiO_3) M=Ca, Fe, Mg	(40-65%)* Pyroxene is mostly Ca-rich in mare basalts. A few samples contain less pyroxene (as low as 30% in some cases and down to 5% in one vitrophyre).	(0-40%) Pyroxene in these rocks is mostly Ca-poor.	(5-30%) The quoted value is for mineral grains over 25 microns across.	(5-20%) The pyroxene composition and amount mimics the local rocks. Pyroxene is high-Ca in mare regions and low-Ca in highland regions.	(5-25%) Contain both high and low Ca pyroxenes.	←	47.84 ¹	53.53 ²	(50%) Low-Ca pyroxene. Extreme end member. KREEP is interstitial.	
Olivine (Ortho-silicate - M_2SiO_4) M=Fe, Mg	(0-35%) The olivine content is a function of the detailed chemistry of each mare lava flow.	(0-40%) Most anorthositic rocks contain only a few percent olivine. Rocks with up to 40% olivine are rare. One very rare rock contains 99% olivine.	(0-5%) Olivine content is a function of the local rocks. It is higher in regions where local rocks contain olivine.	(0-4%) The olivine content is a function of the local rocks.	(1-5%) Olivine in these rocks are usually clasts greater than 50 micrometers across.	←	37.36 ¹	37.66 ²	(0-5%)	
Feldspar ($MA_1_2Si_2O_8$ or $MA_1Si_3O_8$) M=Ca, Na	(15-35%) The plagioclase abundance is about the same in both high Ti and low Ti mare basalts.	(40-98%) Most anorthositic rocks contain over 75% plagioclase, anorthositic rocks with less than 70% plagioclase are rare. Anorthositic rocks are uncommon on the lunar surface and no deposit of anorthositic rocks is known at this time.	SiO_2 46.06 ¹ 46.67 ² TiO_2 0.15 0.02 Al_2O_3 33.71 33.51 FeO 0.68 0.25 MnO 0.01 — MgO 0.31 0.09 CaO 18.07 17.78 BaO — <0.01 Na_2O 0.67 1.51 K_2O 0.04 0.13	(10-60%) Soils mimic the local bedrock. Thus soils in mare regions contain little plagioclase whereas soils in highland regions contain more plagioclase.	(50-75%) These rocks are limited to the lunar highlands.	(15-50%) These rocks are very fine-grained. They are lithified soil and mimic the local soil composition.	(70-90%) These rocks are most abundant at the North Ray Crater locality at Apollo 16 site and at Apollo 14. They are poorly bound soil and are essentially glass free.	(50%) Plagioclase		
Ilmenite ($M_2Ti_2O_3$) M=Fe, Ti	(0-25%) Ilmenite abundance is a strong function of basalt type. High Ti basalts tend to contain over 15% ilmenite while low-Ti basalts tend to contain less than 10%. Vitrophyres of both high and low Ti contents contain less than 1%.	(trace) Almost no ilmenite occurs in these rocks.	(2-12%) These values are for ilmenite grains larger than 25 micrometers across. The ilmenite content of a breccia mimics the local terrain. In high-Ti mare regions the value is about 10%, in low-Ti mare regions it is about 4% and in the highlands it is about 1%.	(0.5-5%) The ilmenite content is a function of local rocks. It is high in regions where local rocks are low.	(1-2%) These rocks are limited to highland regions. The ilmenite is generally about one micrometer across.	←	Oxide	Mare	Highland	(Trace)
Free Metals	Fe - 100-75% Ni - .02-25% Co - .02- 3% P - .02- 7% S - .02- 4%	(trace)	(Similar to soil)	(0.01-0.5%) Finer grained in mare than highlands.	(Similar to soil)	(Similar to soil)	(Similar to soil)	(Similar to soil)	(Trace)	

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Table 2.4
LUNAR MINERALS .

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Major

Olivine $(\text{Mg,Fe})_2\text{SiO}_4$
Pyroxene $(\text{Ca,Mg,Fe})\text{SiO}_3$
Plagioclase Feldspars $(\text{Ca,Na})\text{Al}_2\text{Si}_2\text{O}_8$

Minor

Spinel $(\text{Fe,Mg,Al,Cr,Ti})\text{O}_4$
Armstrongite $(\text{Fe}_2\text{TiO}_5)$
Silica (quartz, tridymite, cristobalite) SiO_2
Iron Fe (variable amounts of Ni and Co)
Troilite FeS
Ilmenite FeTiO_3

Phosphates

Apatite* $\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl})_3$
Whitlockite* $\text{Ca}_9(\text{Mg,Fe})(\text{PO}_4)_7(\text{F,Cl})$

Zr mineral

Zircon* ZrSiO_4
Baddeleyite ZrO_2

Minor Silicates

Pyroxferroite $(\text{Fe,Mg,Ca})\text{SiO}_3$
Amphibole $(\text{Ca,Mg,Fe})(\text{Si,Al})_8\text{O}_{22}\text{F}$
Garnet (?)
Tranquillityite* $\text{Fe}_8\text{Zr}_2\text{Ti}_3\text{Si}_3\text{O}_4$

Minor Sulfides

Mackinawite $(\text{Fe,Ni})_9\text{S}_8$
Pentlandite $(\text{Fe,Ni})_9\text{S}_8$
Cubanite $(\text{CuFe}_2\text{S}_3)$
Chalcopyrite (CuFeS_2)
Sphalerite $(\text{Zn,Fe})\text{S}$

Table 2.5

AVERAGE MATERIAL PROPERTIES OF SURFICIAL LUNAR SOIL

Soil	G^a	Porosity	Void ratio	D_r^b	ϕ_{TR}^c	ϕ_{PL}^d
Consistency	N/cm^3	Percent	e^n	Percent	Degrees	Degrees
Soft	0.15	47	0.89	30	38	36
Firm	0.76 to 1.35	39 to 43	0.64 to 0.75	48 to 63	39.5 to 42	37 to 38.5

$^a G$ = Penetration resistance gradient.

$^b D_r$ = Relative density = $(e_{max} - e)/(e_{max} - e_{min})$, based on standard American Society for Testing Materials methods.

$^c \phi_{TR}$ = Angle of internal friction, based on triaxial compression tests.

$^d \phi_{TR}$ = Angle of internal friction, based on in-place plate shear tests.

Shear Strength Parameters: Cohesion = 1 KN/m^2

Friction angle = 35°

Modulus of subgrade reaction: $1000 \text{ KN/m}^2/\text{m}$ (nominal) factor of 10 variations both ways for 0.1 cm to 10 cm depressions.

Fluid conductivity: $< 1 \cdot 10^{-5} \text{ cm/sec}$

TYPICAL GRAIN SIZE DISTRIBUTION FOR "OLD" SOIL

10084,853

	Weight Percent	Cumulative Weight Percent
4 - 10 mm	1.67	1.67
2 - 4 mm	2.39	4.06
1 - 2 mm	3.20	7.26
0.5 - 1 mm	4.01	11.27
250 μm - 0.5 mm	7.72	18.99
150 - 250 μm	8.23	27.22
90 - 150 μm	11.51	38.72
75 - 90 μm	4.01	42.73
45 - 75 μm	12.40	55.14
20 - 45 μm	18.02	73.15
< 20 μm	26.85	100.00

Table 2.6A*

PETROGRAPHY OF A SERIES OF SIZE FRACTIONS FROM 71061,1: A TYPICAL APOLLO 17 MARE SOIL

Components*	Petrographic Description, vol. %						Visual Estimate in Lunar Receiving Laboratory				
	<20 μ m	20-45 μ m	45-75 μ m	75-90 μ m	90-150 μ m	150-250 μ m	250-500 μ m	0.5-1mm	1-2mm	2-4mm	4-10mm
Agglutinates	17.0	17.3	13.0	17.3	9.3	11.8	10.0	10.0			
Basalt, equigranular			9.0	15.0	19.6	30.9	51.5	65.0	100.0	100.0	100.0
Basalt, variolitic			0.6	1.6		3.4					
Breccia											
Low grade, brown			1.0	4.0	3.6	5.1	6.9				
Low grade, colorless			0.3	1.3	0.6			5.0			
Medium, high grade			1.0	1.3	1.6	2.8	1.5				
Anorthosite			...	...	0.3	...	...		
Cataclastic anorthosite			1.0	...	...	...	...
Norite			...	...	...	...	...
Gabbro			...	...	...	...	0.5	5.0			
SUBTOTAL	17.0	17.3	12.9	23.2	25.7	42.2	60.4	75.0	100.0	100.0	100.0
Plagioclase			16.3	7.0	17.3	9.0	8.5				
Clinopyroxene			21.3	26.3	21.0	17.4	10.8				
Orthopyroxene			...	...	...	...	...
Olivine			...	...	...	...	...
Ilmenite			6.0	3.3	4.6	3.3	2.3				
SUBTOTAL			43.6	36.6	42.9	30.3	21.6				
Glass											
Orange			7.6	5.0	6.3	4.5	0.8				
"Black"			18.7	10.6	9.6	5.1	6.1	5.0			
Colorless			1.0	1.0	1.3	...	1.5				
Brown			0.3	5.2	4.6	3.3	...				
Gray, "ropy"			0.7	0.6	...	1.7	...	10.0			
Other			2.0	...	...	1.0	...				
SUBTOTAL			30.3	22.4	21.8	15.6	8.4	15.0			
Total number of grains counted	300	161	300	300	300	178	130	20	100	?	?
Wt. % of total sample for each size fraction	17.98	12.21	8.39	3.0	8.66	7.04	7.08	3.44	6.15	6.74	10.16

Sample 71061,1 was taken from Station 1 on the mare surface. Agglutinate versus nonagglutinate grains were identified using a scanning electron microscope in the size ranges of <20 μ m and 20-45 μ m. The >10mm fraction of the sample made up 9.42% of the sample.

* The <20 μ m fraction is 83% nonagglutinate; the 20 to 45 μ m fraction is 82.7% nonagglutinate.

* Reference 2.8.

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Table 2.6B*

PETROGRAPHY OF A SERIES OF SIZE FRACTIONS OF 72441,7: A TYPICAL SOUTH MASSIF SOIL

Components*	Petrographic Observation, vol. %							Visual Estimate in Lunar Receiving Laboratory			
	<20 μ m	20-45 μ m	45-75 μ m	75-90 μ m	90-150 μ m	150-250 μ m	250-500 μ m [†]	1-2mm	2-4mm	4-10mm	>10mm
Agglutinates	21.0	50.0	39.3	45.5	41.7	54.6	30.5	20.0	25.0	25.0	
Basalt, equigranular			0.6	1.5	1.3	1.3	...				None
Basalt, variolitic			0.3	...	1.3	...	1.0				Present
Breccia											
Low grade, brown			9.3	6.6	9.3	10.7	9.4				
Low grade, colorless			2.7	2.3	6.3	0.7	6.3	80.0	74.0	75.0	
Medium high grade			22.7	29.0	19.3	20.0	30.5				
Anorthosite			...	...	1.0	...	...		1.0		
Cataclastic anorthosite			0.7	1.2	1.3	0.7	2.1				
Monite			...	...	0.7	0.7	1.0				
Gabbro			...	...	...	...	...
SUBTOTAL			36.3	40.6	40.5	34.1	50.3	80.0	75.0	75.0	
Plagioclase			10.7	1.2	6.7	3.3	7.3				
Clinopyroxene			6.0	3.9	3.0	2.7	2.1				
Orthopyroxene			1.0	...	3.3	...	...		
Olivine			...	1.2	0.7	...	2.1				
Ilmenite			...	...	0.3	...	...		
SUBTOTAL			17.7	6.3	14.0	6.0	11.5				
Glass											
Orange			0.3	1.2	0.3	...	...		
"Black"			1.3	1.5	0.3	...	1.0				
Colorless			1.0	1.5	1.3	...	...		
Brown			3.3	3.0	1.0	5.3	4.2				
Gray, "ropy"			...	...	0.3	...	1.0				
Other			...	...	0.3	0.7	1.0				
SUBTOTAL			5.9	7.2	3.5	6.0	7.2				
Total number of grains counted	300	162	249	259	300	150	95				
Wt. % of total sample for each size fraction	25.84	18.79	12.08	4.01	11.02	8.37	8.55	3.67	2.76	1.01	None

Sample 72441,7 was taken from Station 2 at the base of the South Massif and on the 'light mantle' deposit [from Heiken and McKay, 1974]. Agglutinate versus nonagglutinate grains were identified by using a scanning electron microscope in the size ranges <20 and 20-45 μ m.

* The <20 μ m fraction is 79.0% nonagglutinate; the 20-45 μ m fraction is 50.0% nonagglutinate.

[†] No visual estimate was made for the 500-1000 μ m fraction (wt. % = 3.91).

* Reference 2.8.

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Table 2.7

Compilation of average composition of lunar soils for 80 elements^a (1.21)

	Mare					Highland		Basin ejecta		
	High		Low		L-15	L-16	L-20	L-14	L-15	L-17
	A-11	A-17	A-12	L-11						
Al ₂ O ₃ %	3.73	13.97	13.77	0.32	15.31	27.18	23.07	17.41	17.54	25.30
CaO %	12.12	10.62	10.55	9.74	12.07	15.79	14.07	10.79	11.57	12.36
Cr ₂ O ₃ %	0.30	0.46	0.35	0.53	0.29	0.107	0.15	0.22	0.28	0.25
Fe ₂ O ₃ %	15.75	17.53	15.41	19.75	15.41	5.18	7.35	10.26	11.58	8.59
K ₂ O %	0.15	0.076	0.27	0.10	0.10	0.11	0.08	0.58	0.17	0.16
MgO %	8.17	9.62	9.91	11.29	8.79	5.34	9.25	9.47	17.41	10.29
MnO %	0.21	0.24	0.22	0.25	0.21	0.065	0.11	0.14	0.16	0.11
Na ₂ O %	0.44	0.35	0.43	0.31	0.36	0.47	0.35	0.70	0.42	0.41
P ₂ O ₅ %	0.12	0.07	0.31	0.11	0.14	0.12	0.11	0.50	0.16	0.14
SiO ₂ %	42.47	39.37	46.17	46.20	43.95	45.09	44.95	48.03	46.59	45.38
TiO ₂ %	7.67	9.12	3.07	2.16	3.53	0.56	0.49	1.70	1.22	1.52
Al %	7.29	5.30	7.25	5.46	3.21	14.38	12.20	9.21	9.28	10.30
Ca %	8.66	7.59	7.54	5.96	3.63	11.25	10.05	7.71	6.27	9.19
Cr %	0.21	0.31	0.24	0.36	0.20	0.07	0.10	0.15	0.19	0.18
Fe %	12.25	13.63	11.92	15.35	12.75	4.03	5.77	10.36	9.00	5.58
K %	0.12	0.063	0.22	0.08	0.08	0.09	0.066	0.46	0.14	0.13
Mg %	4.93	5.30	5.98	6.81	5.30	3.52	5.59	5.71	6.29	5.21
Mn %	0.16	0.19	0.17	0.19	0.16	0.050	0.085	0.11	0.12	0.085
Na %	0.33	0.25	0.36	0.25	0.27	0.35	0.26	0.52	0.31	0.30
O %	41.6	39.7	42.3	41.3	41.5	44.6	44.5	43.8	43.3	42.2
P %	0.05	0.03	0.14	0.05	0.06	0.05	0.05	0.22	0.07	0.06
S %	0.12	0.13	0.10	0.063	0.21	0.064	0.08	0.038	0.08	0.06
Si %	19.84	18.63	21.57	21.58	20.54	21.07	21.00	22.46	21.77	21.35
Ti %	4.50	5.55	1.84	1.29	2.11	0.34	0.29	1.02	0.79	0.97
Ag, ppm	9.0	9.3	62.0	50.0	95.0	9.6	16.2	17.5	56.0	6.5
Ar, ppm	1.0	1.2	0.3	0.7	-	1.2	-	1.0	-	-
As, ppm	0.32	-	0.092	0.010	0.41	0.14	0.23	0.066	-	-
Au, ppm	3.7	2.5	2.5	2.11	2.5	8.47	4.93	6.7	3.3	4.9
B, ppm	3.5	2.0	9.3	-	4.3	5.9	39.0	19.0	-	-
Ba, ppm	140	85.7	413	122.	215	127.3	89.6	767.5	279	190.
Be, ppm	2.0	-	5.0	1.31	2.2	1.2	-	5.5	2.3	-
Bi, ppm	1.5	7.7	1.5	0.36	4.9	1.8	2.7	1.7	0.17	-
Br, ppm	0.239	0.093	0.165	-	0.21	0.217	0.13	0.41	0.06	-
C, ppm	135	32	104	95	-	106.5	-	130	125	155
Cd, ppm	0.045	0.032	0.046	0.062	0.80	0.097	0.049	0.131	0.042	0.04
Ce, ppm	50.0	25.3	104.0	31.4	33.4	30.3	20.5	185.0	54.0	46.0
Cl, ppm	30.2	5.7	31.0	7.6	53.5	20.9	13.0	44.0	5.9	-
Co, ppm	32.0	35.0	43.0	54.4	37.0	25.3	40.5	35.8	42.0	33.0
Cs, ppm	0.18	0.30	0.30	0.23	0.95	0.11	0.11	0.53	0.19	0.18
Cu, ppm	11.5	11.0	10.3	3.2	31.0	3.25	19.0	11.1	7.9	6.4
Dy, ppm	20.2	12.2	24.5	8.6	10.9	6.2	5.0	39.0	13.6	11.0
Er, ppm	11.5	7.99	15.35	5.13	6.3	4.39	2.5	23.5	7.86	6.5
Eu, ppm	2.0	1.56	1.9	1.01	2.3	1.23	0.98	2.64	1.30	1.35
F, ppm	278	-	132	45.	242	72	37	219.	60.	-
Ga, ppm	4.3	7.5	4.3	4.43	4.4	4.5	3.7	6.8	3.5	4.7
Gd, ppm	16.3	11.4	25.7	8.1	9.8	6.7	1.06	34.8	11.74	10.07
Ge, ppm	1.0	0.193	0.32	0.17	1.44	0.76	0.46	0.70	0.42	-
H, ppm	51.0	59.5	45.0	63.6	-	56.0	-	79.6	52.0	98.0
He, ppm	60.0	36.0	10.0	8.0	-	6.0	-	8.0	-	-
Hf, ppm	8.9	7.3	12.7	5.2	4.75	3.9	2.9	22.2	7.6	5.5
Hg, ppm	0.015	-	0.023	-	-	0.004	-	-	-	-
Ho, ppm	5.4	-	5.3	1.7	2.5	1.50	0.88	7.8	3.3	-
I, ppm	-	2.0	-	-	-	5.6	12.0	-	35.0	-
Ir, ppm	-	2.4	90.0	3.4	35.6	31.0	19.0	89.0	7.5	3.4
Fr, ppm	7.8	5.4	5.5	3.1	9.7	12.4	9.5	12.4	9.3	8.3
La, ppm	17.3	7.32	38.3	11.3	11.5	11.7	7.5	69.4	24.0	16.9
Li, ppm	16.5	9.77	19.5	9.09	9.7	7.4	5.7	29.9	10.8	11.7
Lu, ppm	1.6	1.03	1.93	0.72	0.84	0.59	0.40	3.10	0.98	0.98
Mo, ppm	0.70	-	0.34	-	-	0.34	-	-	-	-
N, ppm	119	60	34	30	134	39	107	92	190	81
Nb, ppm	15.8	19.1	34.0	13.0	15.9	12.3	12.0	56.0	16.0	18.0
Nd, ppm	42.6	23.0	75.6	23.0	26.9	19.3	10.8	105.0	35.0	27.6
Ne, ppm	5.0	2.0	2.0	2.0	-	1.0	-	2.0	-	-
Ni, ppm	206	131	199	146	174	345.	208.	321	292.	286.
Os, ppm	14.0	-	6.0	1.79	30.0	22.0	-	-	-	-
Pb, ppm	2.9	0.80	4.8	1.033	6.0	2.58	1.15	10.02	2.5	1.922
Pd, ppm	21.0	-	9.7	6.2	-	24.0	-	50.0	-	-
Pr, ppm	7.7	-	10.1	3.3	-	4.97	-	23.0	-	-
Rb, ppm	3.0	1.2	7.23	2.70	1.35	2.48	1.55	15.25	5.0	4.21
Re, ppm	5.26	0.47	0.34	0.39	0.36	0.32	3.19	1.15	-	-
Rh, ppm	0.1	-	0.4	-	0.077	-	-	-	-	-
Ru, ppm	0.5	-	0.747	-	0.046	0.010	-	-	-	-
Sb, ppm	4.1	25.4	47.0	30.0	3.9	9.7	5.7	3.4	-	26.0
Sc, ppm	62.9	65.0	39.2	37.1	39.9	3.9	17.0	21.9	22.0	18.0
Se, ppm	0.39	0.27	0.30	0.18	0.39	0.24	0.20	0.331	-	0.23
Sm, ppm	11.7	8.0	20.3	5.85	8.3	5.38	3.39	30.9	9.6	8.1
Sr, ppm	0.7	-	0.3	-	1.7	0.22	0.3	-	-	-
Sr, ppm	193.0	166.0	128.9	104.2	234.0	168.0	140.3	183.3	152.0	150.0
Ta, ppm	1.5	-	1.58	0.55	1.4	0.50	0.50	4.1	1.35	0.97
Tb, ppm	3.3	2.63	4.07	1.4	1.5	1.07	0.30	5.4	4.2	1.72
Te, ppm	0.07	0.01	0.05	-	0.028	0.323	0.051	0.031	-	-
Th, ppm	2.24	0.32	6.53	1.75	1.07	1.37	1.44	13.5	4.15	3.01
Tl, ppm	2.1	1.4	2.0	0.94	1.6	7.7	6.2	22.0	2.4	-
Tm, ppm	1.5	-	2.02	-	0.73	0.57	0.41	3.9	-	-
U, ppm	1.37	0.26	1.61	0.483	0.300	0.52	0.45	3.43	3.99	0.90
V, ppm	66	123	110	191	73.5	25.5	38	49	84	52
V, ppm	0.24	0.14	0.74	0.31	-	3.31	-	1.9	-	0.52
Y, ppm	107	74	145.	47	48	39.3	49	242	73	64
Yb, ppm	10.5	7.48	13.7	4.53	5.59	3.56	2.40	22.7	7.3	6.15
Zn, ppm	23.0	49.0	5.3	12.3	25.0	24.0	34.1	23.0	14.5	29.0
Zr, ppm	331	236	503	175	302.	163.8	192	342	278	252

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^aMajor elements (>0.1%) are reported first as both the usual oxide notation and elements. Data compiled from the Data Base Compilation of the Lunar Sample Curator, NASA Johnson Space Center, Houston, Texas

Table 2.8

Table 4-2. Typical Solar-Wind Gas Concentrations of Lunar Fines

Site	cm ³ STP/g					ppm		
	He 10 ⁻²	Ne 10 ⁻⁴	Ar* 10 ⁻⁹	Kr 10 ⁻⁸	Xe 10 ⁻⁸	H	C	N
Apollo 11	11-25	22-33	4-5	28-66	8-37	50	142-226	102-153
Apollo 12	4-38	8-68	1.4-3.7	7-35	4-10	80	23-180	40-130
Apollo 14	5-9	10-18	2.9-5.3	16-42	5-17	70	42-186	80-164
Apollo 15	4-10	8-23	1.1-4.9	8-42	2-12	13-120	21-186	25-113
Apollo 16	0.6-5	2.6-15	1.5-7.2	8-60	4-24	10-79	31-280	30-155
Apollo 17	6-29	13-50	1.9-7.5	6-32	5-11	41-211	4-200	7-130
Luna 16	18	38	6.4	38	32		N.D.	134-2100
Luna 20	4	11	3.5	19	8		N.D.	80-800
Luna 24							N.D.	N.D.

*Excludes ⁴⁰Ar which is formed by radioactive decay of K.

N.D. = not determined.

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Table 3.1

USEFUL PRODUCTS FROM LUNAR SOURCES

Structural materials

Metals—steels, aluminum, magnesium, titanium

Reinforced metals—aluminum, magnesium
reinforced with silica, steel or alumina

Glasses, fused silica

Ceramics, alumina, magnesia, silica, compounds

Hydraulic cements (need water)

Thermal materials

Refractories plus chromia, titania, titanium silicide.

Same as ceramics above plus castables, ramming cements,
insulation, fiberglass, fibrous or powdered ceramics

Electrical materials

Conductors—aluminum, iron, resistance alloys (FeCrAl)

Electrodes—graphite, Fe_3O_4

Magnetic materials, iron alloys, magnetic ceramics

Insulation, glass, ceramics

Fibrous materials

Glass, silica (for apparel, paper, filters, etc.)

Plastics, elastomers and sealants

Soluble silicates, silicone resins (contain some C)

Adhesives and coatings

Anodized aluminum, magnesium, titanium,
electroplating (Cr)

Sputtered coatings, etc.

Lubricants, heat-transfer fluids

Sulfides, SO_2 , He

Industrial chemicals

Detergents, cleansers, solvents, acids, bases H_2SO_4 , H_3PO_4 ,
CaO, NaOH

Biosupport

Oxygen (breathing); 16/18 of water by mass

SiO_2 —soil component (includes many trace nutrients)

Constituent elements of life-forms. O, Ca, C, Fe, Mg, K,
P, N, Na, H and others

Table 3.2

ELECTRICAL CONDUCTIVITY OF PURE METALS

Element	Resistivity	Conductivity		Density	Mass Conductivity	
	10^8 (m)	10^{-8} (mho/m)	(%IACS)	10^{-3} d(kg/m ³)	10^{-3} (mho m ² /kg)	(%IACS)
Cu	1.6730	.5977	103.0	8.96	6.671	103.0
Ag	1.59	.6289	108.4	10.492	5.994	92.6
Al	2.6548	.3767	64.9	2.699	13.96	215.6
Mg	4.45	.2247	38.7	1.738	12.93	199.7
Na	4.9	.2041	35.2	.971	21.02	324.7
Fe	9.71	.1030	17.8	7.874	1.308	20.2
Cu(IACS)	1.7241	.5800	100.0	8.96	6.473	100.0

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Table 3.3

PROPERTIES OF WROUGHT ALUMINUM ALLOYS

Alloy	Composition					Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn* Hardness	Shear Strength (psi)	Fatigue Limit (psi)	Electrical Conductivity (% IACS)
	Al	Mn	Mg	Si	Cr							
1C	99.45+%					12-27,000	4-24,000	na	na	8-15,000	na	62
1060	99.60+%			.25		10-19,000	4-18,000	6-43	19-35	7-11,000	3-6,500	62
1100	99.0+%					13-24,000	5-22,000	5-45	23-44	9-13,000	5-9,000	57-59
3003		1.2%		.6M		16-29,000	6-27,000	4-40	28-55	11-16,000	7-10,000	40-50
5005			0.8%	.4M		18-29,000	6-28,000	4-30	28-51	11-16,000	na	52
5050			1.2%	.4M		21-32,000	8-29,000	6-24	36-63	15-20,000	12-14,000	50
5052			2.5%	.45M	0.25%	28-42,000	13-37,000	7-30	47-77	18-24,000	16-20,000	35
5056		0.1%	5.2%		0.1%	42-63,000	22-59,000	10-35	65-105	26-34,000	20-22,000	27-29
5083		0.7%	4.5%	.4M		42-46,000	21-33,000	16-22	na	na	23,000	29
5086		0.5%	4.0%	.4M		38-47,000	17-37,000	10-22	65-86	23-27,000	na	31
5154			3.5%	.45M	0.25%	35-48,000	17-39,000	10-27	58-80	22-28,000	17-21,000	32
5357		0.25%	1.0%	.12M		9-32,000	7-30,000	6-25	32-55	12-18,000	na	43
6063		0.1	0.7%	.4		13-42,000	7-39,000	9-22	25-95	10-27,000	8-10,000	50-58
6101			0.5%	.5%	0.03M	32,000	28,000	15	71	20,000	na	56
6151		0.2M	0.6%	1.0%	0.25M	48,000	43,000	17	100	32,000	11,000	42-54

*Dependent on temper; 1500 kg load, 10 mm ball

M = Maximum

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Table 3.3 (Continued)

PROPERTIES OF CAST ALUMINUM ALLOYS

Alloy	Composition						Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn* Hardness	Shear Strength (psi)	Fatigue Limit (psi)	Electrical Conductivity (% IACS)
	Zn	Cu	Mn	Mg	Si	Ti Cr							
A13					12.0%		35,000	na	3.5	na	na	na	31
43					5.0%		19-33,000	8-16,000	8-10	40-45	14-21,000	8-17,000	37-42
214				3.8%			25,000	12,000	9	50	20,000	7,000	35
220				10.0%			48,000	26,000	16	75	34,000	8,000	21
356				0.3%	7.0%	.2M	25-34,000	20-34,000	2-6	60-80	20-30,000	8-13,000	39-43
360				0.5%	9.5%		47,000	25,000	3	na	30,000	19,000	37
AlMag35			0.2	7.0%		.2	35-40,000	19-21,000	9-13				

HIGH STRENGTH COMMERCIAL ALLOYS

7075	5.5	1.5		2.5		.3	83-91,000	73-80,000	11	150	48,000	23,000	30
7178	6.8	2.0		2.7		.3	88-97,000	78-86,000	10-11				31

PROPERTIES OF PM ALLOYS

MA67	8.0	1.0		2.5		1.62Co	99,000						
MA87	6.5	1.6		2.42		.37Co		73,000					

*Dependent on temper; +500 kg load, 10 mm ball

Table 3.4

PROPERTIES OF CARBON AND LOW ALLOY STEELS

AISI No.	Composition					Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn Hardness
	C	Mn	Si	Cr	Other				
1020 HR	0.2	0.3				60,000	35,000	30	
CR						80,000	60,000	18	
1095 HT	1.0					108,000	97,000	10	
1340 HT	0.4	1.75	0.3			227,000	206,000		448
4140 HT	0.4	0.9	0.3	1.0	0.2 Mo	225,000	208,000	10	426
5140 HT	0.4	0.8	0.3	0.8		232,000	211,000	11	448
HSLA									
A 242						70,000 min	50,000 min	24 min	
(Cromasil)	0.2	1.2	0.7	0.5		90,000	60,000	20	
A 656			X		Al, Ti, V, N	95,000 min	80,000 min	12	
X70 (pipe)	0.23M	1.6M				82,000 min	70,000 min	14 min	
Molycorp	0.06	1.35			0.1 Nb, rare earth	85,100	71,100	38	

M = Maximum

Table 3.5

Properties of Medium Alloy Steels

AISI No.	Composition					Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn Hardness	Conductivity (% IACS)
	C	Mn	Si	Cr	Other					
501 stainless	0.1m	1.0M	1.0M	5.0		70-115,000	30-90,000	20-28	160-240	
4042	0.4	0.8	0.3		.25 Mo	231,000	210,000	12	448	
4340	0.4	0.7	0.3	0.8	1.8Ni, .25 Mo	250,000	230,000	9	484	
8640	0.4	0.9	0.3	0.6	0.5Ni, .2 Mo	240,000	220,000	10	472	
9260	0.6	0.9	2.0	0.3		132-355,000	67-330,000	14-15	27-64 RC	
Tool st. 6B	1.2	0.4	0.3	0.8	.3M V, .3M Mo 1-2.5 W				59-65 RC	
Electrical Steels										
M15 (Tr 58)	.07	4.0				63,000	50,000	4	65 RB	2.5-3.8
M5-8 (Or 60-80)	.01	3.0				60,000			65 RB	3.3-3.8

M = Maximum

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Table 3.6

Properties of High Alloy Steels

AISI No.	Composition					Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn Hardness	Conductivity (% IACS)
	C	Mn	Si	Cr	Other					
Stainless C										
410	.15	1.0M	1.0M	12.5	.5M Ni	75-115,000	40-80,000	23-30	150-212	
430	.12M	1.0M	1.0M	16.0		75-92,000	40- X,000	15-35	160-190	
440C	1.1	1.0	1.0	17.0	.75 Mo	110-265,000	65-250,000	2-12		
446	.35M	1.0M	1.0M	25.0	.25 Mo	85-135,000	55-105,000	25	180-200	
10D	.7	.3	.3	4.0	14W, 1-2V, .75M Mo				57-66 RC	
Kanthal A-1 (Heat, ox. resisting alloy)				22.0	5.5Al, .5 Co	92-121,000	64-92,000	12-20	200-260	1.2
Sendust			9-10	5.0Al						2.2

m = minimum

M = maximum

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Table 3.7

MECHANICAL PROPERTIES OF MAGNESIUM ALLOYS

Alloy	Type	Composition				Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Bhn Hardness	Shear Strength (psi)	Electrical Conductivity (% IACS)
		Al	Mn	Ca	Th/Zn						
AM100A	Cast	10.0%	0.1%			22-40,000	12-22,000	1-10	52-69	18-21,000	10-12
M1A	Wrought		1.2%	0.09%		33-37,000	18-26,000	7-17	42-54	16-18,000	34.5
A3A	Wrought	3.0%				36-42,000	22-32,000	15-21	46-73	19-23,000	
HM21A	Wrought		0.5%		0.2%Th	34,000	25,000	10		18,000	33-34.5
HM31A	Wrought		1.2%		0.3%Th	42,000	33,000	10		22,000	26
AZ81A	Cast	7.5%	0.15		0.7%Zn	40,000	12,000	15	55	21,000	12
AZ91C	Cast	9.0%	0.2		0.7%Zn	40,000	19,000	5	70		10-11.5
+500 kg load, 100 mm ball		"High Strength" Commercial Alloys									
ZK60	Wrought	8.5%	0.5%Zr		5.5%Zn	44-53,000	31-44,000	11-16	65-82	24-27,000	29-31
AZ80A	Wrought	8.5%			0.5%Zn	48-55,000	33-40,000	6-11	67-80	22-24,000	10.6

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Table 3.8

MECHANICAL PROPERTIES OF TITANIUM ALLOYS

Alloy	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Electrical Conductivity (% IACS)
99.2% Ti	58,000	40,000		—
99.0% Ti	90-110,000	75- 90,000	19-23	3.1-3.5
Ti-8M	140-160,000	130-155,000	14-22	1.9
Ti-4Al-4Mn	145-150,000	125-150,000	na	1.2
Ti-5Al-1.5Fe-1.4Cr-1.2Mo		160-185,000	15	1.0
"High Strength" Commercial Alloys				
Ti-4Al-3Mo-1V	200,000	175,000	4-7	
Ti-13V-11Cr-3Al	190-240,000	135-220,000	2-15	

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Table 3.9

MECHANICAL PROPERTIES OF PURE METALS

Metal	Tensile Strength (psi)	Yield Strength (psi)	Modulus of Elasticity (10 ⁶ psi)	Elongation (%)	Bhn* Hardness	Conductivity (% IACS)†
Aluminum (99.996%)	6,900-16,300	1,800-15,400	9.99	55-49	17-27	64.9
Iron (99.9+%)	35,000-40,000	10,000-20,000	28.50	30-60	82-100	17.8
Magnesium (99.98%) (excluding very weak sand casting)	24,000-30,000	10,000-20,000	6.50	2-15	35-47	28.7
Titanium (99.9%)	34,000	20,000	15.50	54	25 RC	4.1

*500 kg load, 10 mm ball

na-data not available

†international annealed copper standard ($\sigma = .58 \times 10^6$ mho/cm @20°C)

RB = Rockwell B

RC = Rockwell C

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Table 3.10

PROPERTIES OF MAGNETIC MATERIALS

Soft Materials

Type	Induction (Tesla)		Field (Oersted (Amp/m))			Permeability		Curie Temp.	Resistivity
	B _{max}	B _{rem}	H _c	(@1T)	Core Loss (W/lb) 60 cps .014" @1.5T	Initial	Max.	°C	Ω cm
M15	1.95	.5	.25	(19.9)	1.46	1,300	2-11,000	730	45-69 x 10 ⁻⁶
M8	2.01	.66-.86	.05-.1	(4-8)	.8	2,500	55-60,000	740	45-52 x 10 ⁻⁶
M5					.5				
Sen'ust (Mg,Mn)Fe ₂ O ₄	1.0		.035			30,000	120,000	500	81 x 10 ⁻⁶
S1,S3,R1	.16-.2		.6-2.5	(47.7-199)		40-50(1Mc)	350-1800	265	
4373A			.3	(23.9)		1,000		170	
Fe ₃ O ₄	.6					70		585	10 ⁻²
γ-Fe ₂ O ₃	.52							675	
MnO·xAl ₂ O ₃ }									
(1-x)Fe ₂ O ₃						Useful @10 ⁹ cps			
5A,B1-2	.1-.145							140-180	10 ⁵ - 10 ⁷

Table 3.10 (Continued)

PROPERTIES OF MAGNETIC MATERIALS

Hard Materials

<u>Type</u>	<u>Induction (Tesla)</u>			H_c	H_d	$(BH)_{max}$	<u>(Gauss-Oersted)</u>	<u>Curie Temp.</u>	<u>Resistivity</u>
	B_{max}	B_{rem}	B_d				/ (Tesla-Amp/m)	$^{\circ}C$	$\Omega \text{ cm}$
$M0 \cdot 6Fe_2O_3$ oriented	.48	.385	.192	2,200(175,000)	1,820(144,800)	3.5×10^6	(27,850)	450	10^4
M=Ba, Sr, (Ca-Ba-Sr)								450	
$M0 \cdot 2FeO \cdot$ } $8Fe_2O_3$.48								

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Table 3.11

COMPOSITION OF COMMERCIAL GLASSES

Application Code No.	Composition (wt %)							
	SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	B ₂ O ₃	Other
1720	62.0	17.0	8.0	7.0	1.0		5.0	
1723 } electric	57.0	15.0	10.0	7.0			5.0	
6720 } general/	60.0	10.0	5.0		9.0	2.0	1.0	
6810 } lighting	56.0	10.0	4.0		7.0	1.0	1.0	3.0 PbO
7900	98.0	0.3					3.0	
7913 } high temperature	96.5	0.5					3.0	
7940	99.9							
9606 radome	56.0	20.0		15.0				9.0 TiO ₂
G-20 lab ware	75.7	5.1	1.3		6.2	1.2	6.9	3.6 BaO
E-fiber electric	54.0	14.0	17.5	4.5			10.0	
C-fiber chemical	65.0	4.0	14.0	3.0	8.0	0.5	5.5	
S-fiber high strength	65.0	25.0		10.0				

Table 3.12

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Glass code ^a	Thermal shock resistance, °C ^c for annealed plates 6 in. x 6 in.			Reference temp., °C for various viscosities (Poise)			
	1/8 in. thickness	1/4 in. thickness	1/2 in. thickness	Strain Point	Annealing Point	Softening Point	Working Point
				10 ^{14.5}	10 ¹³	10 ^{7.65}	10 ⁶
0010	(65)	(50)	(35)	395	435	625	985
0080	(65)	(50)	(35)	470	510	695	1005
0120	(65)	(50)	(35)	395	435	630	980
1720	(135)	(115)	(75)	670	715	915	1190
1723	(125)	(100)	(70)	670	710	910	1175
1990	(45)	(35)	(25)	330	360	500	755
2405	(135)	(115)	(75)	500	530	770	1085
2475	(65)	(50)	(35)	440	480	690	1040
3320	(145)	(110)	(80)	500	540	780	1155
6720	(70)	(60)	(40)	510	550	775	1010
6750	(65)	(50)	(35)	445	485	670	1040
6810	(85)	(70)	(45)	490	530	770	1010
7040				450	490	700	1080
7050	(125)	(100)	(70)	460	500	705	1025
7052	(125)	(100)	(70)	435	480	710	1115
7056				470	510	720	1045
7070	(180)	(150)	(100)	455	495		1070
7250	(160)	(130)	(90)	490	540	780	1190
7570				340	365	440	560
7720	(160)	(130)	(90)	485	525	755	1140
7740	(180)	(150)	(100)	515	565	820	1245
7760	(160)	(130)	(90)	480	525	780	1210
7900	(1250)	(1000)	(750)	820	910	1500	
7913				890	1020	1530	
7940	(1250)	(1000)	(750)	990	1050	1580	
8160	(65)	(50)	(35)	395	435	630	975
8161				400	435	600	850
8363				300	315	380	460
8871	(55)	(45)	(35)	350	385	525	785
8910				405	445	650	1010
9506						1350	
9700	(150)	(120)	(80)	520	565	805	1200
9741	(150)	(120)	(80)	410	450	705	
G-20				524	569	794	1190
N51a				540	580	795	1175
X4					520	710	
E glass ^e						830	
T glass ^e						715	
C glass ^e						750	
SF glass ^e						675	
S glass ^e							

^e Bulk Working Properties

FIGURE CAPTIONS

1.1 Demandite will be used in a similar manner in space as on the earth following the replacement on earth of hydrocarbon fuels. However, space industries will have a far greater incentive to conserve working fluids or recycle mass than on earth in the various industrial processes due to the launch expense of obtaining and replacing initial stores from earth. In this figure the lower case letters correspond to the total extraterrestrial and terrestrial mass in kilograms extracted (m' , m , d_e), processed (d_s , d), lost (l), or exported (e_p , e_o , e_e) from a space industry from the start of the use of extraterrestrial materials. The mass flow of personnel to and from space is given by p and p' respectively. The dots over the small letters indicate the flow rates of these masses. Initially capital investment in the creation of space industry will be approximately proportional to the mass of machines, materials, and people which must be transported into space [C_e (Kg), p (Kg), p' (Kg)] due to the high cost of earth to orbit transportation compared to earth surface or in-space transportation. Thus there is tremendous incentive to reduce the initial integral launch mass. As space industry matures its overall efficiency and economic return will be determined in part by the efficiency with which recycling can be accomplished. The coefficients c_p (Kg/kg) and c_r (kg/kg) are respectively for life support and recycled process fluids in industrial operations. These coefficients specify the kilograms of materials which must be brought from earth to process one kilogram of extraterrestrial material at a given stage of process on make-up of loss from one kilogram of life support material. These coefficients must be

FIGURE CAPTIONS (continued)

much less than unity. In the production phase it is important to minimize the need for demandite make-up mass from earth [d_e (kg/kg)] and capital equipment sent from earth [c_e (kg/sec)] from earth. The coefficients (kg/kg) specify how many kilograms of new terrestrial material must be introduced per kilogram of processed or constructed terrestrial facilities or goods output. This ratio changes with time. The large letters refer to the value added (M' , M , P , E_e , E_s), by processing or combining terrestrial and extraterrestrial materials ($D = D_s + D_e$) or to the value of input capital flow (C_e) on a dollars/kilogram (\$/kg) basis.

Figure 1.2 Histogram of the total sales value in billions of dollars (vertical axis) versus the average value in dollars per kilogram (horizontal axis) of goods produced in 230 Standard Industrial Categories of the United States economy in 1972.

Figure 2.3 Cumulative grain size distribution for lunar soils. Most soils lie within the envelope. Two particularly coarse soils are also shown. (NASA photo S-76-30404.)

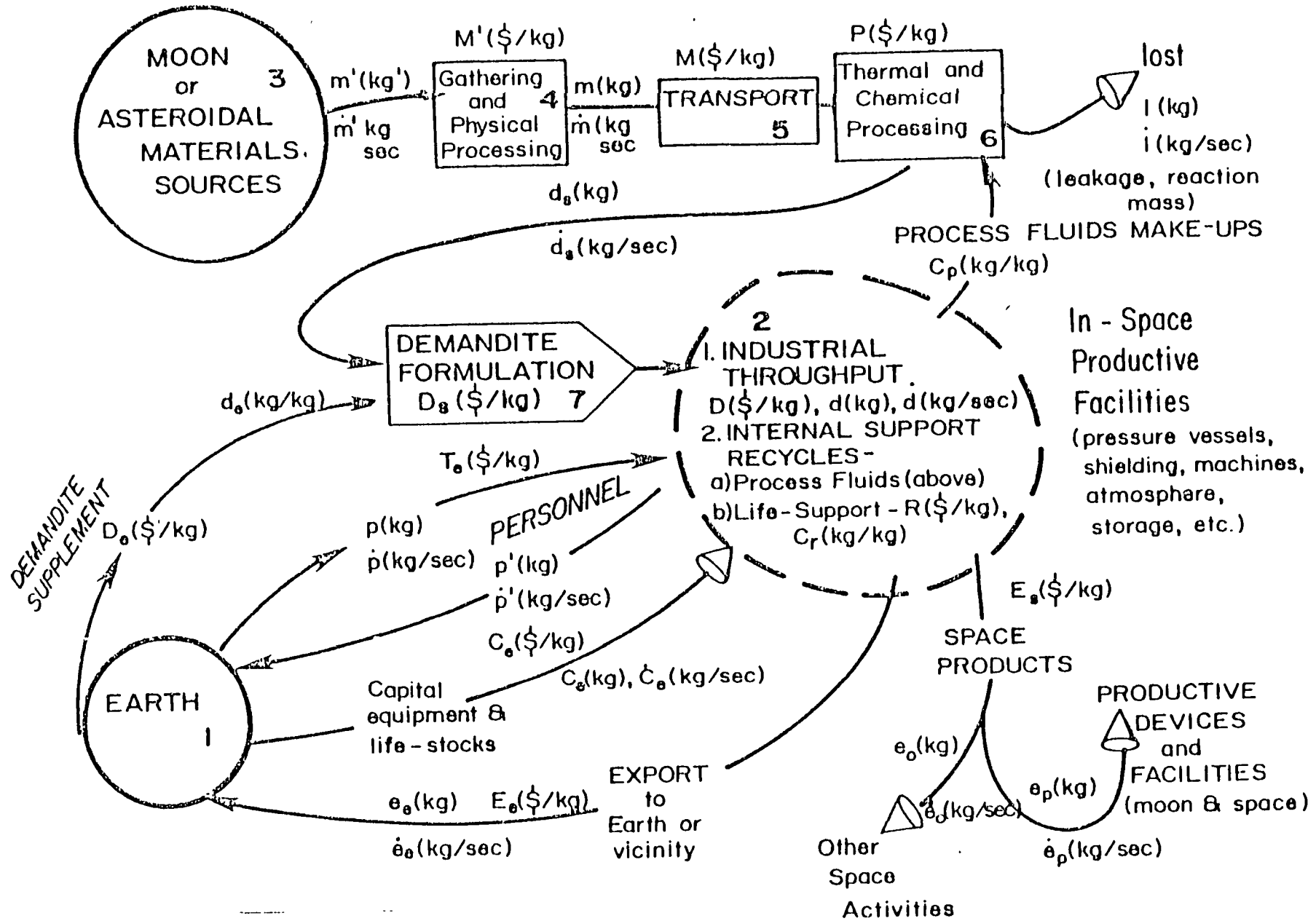
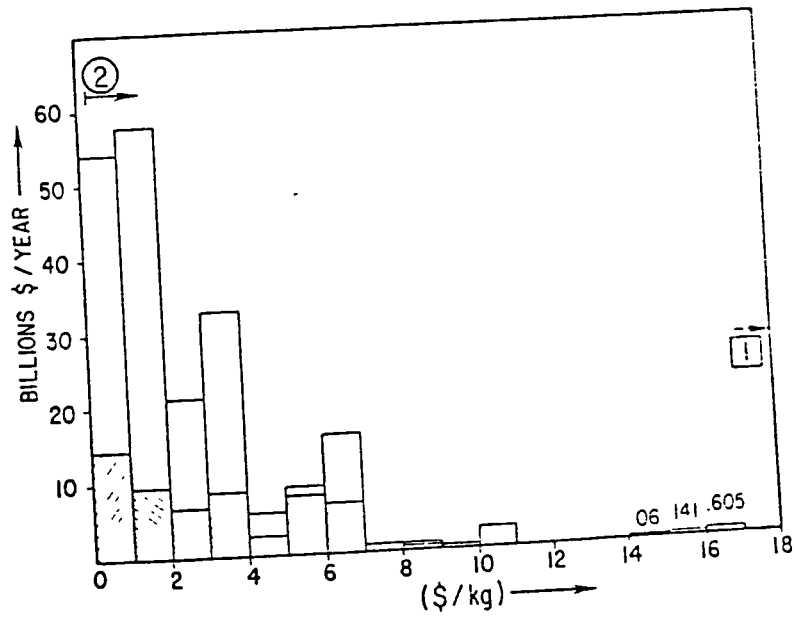


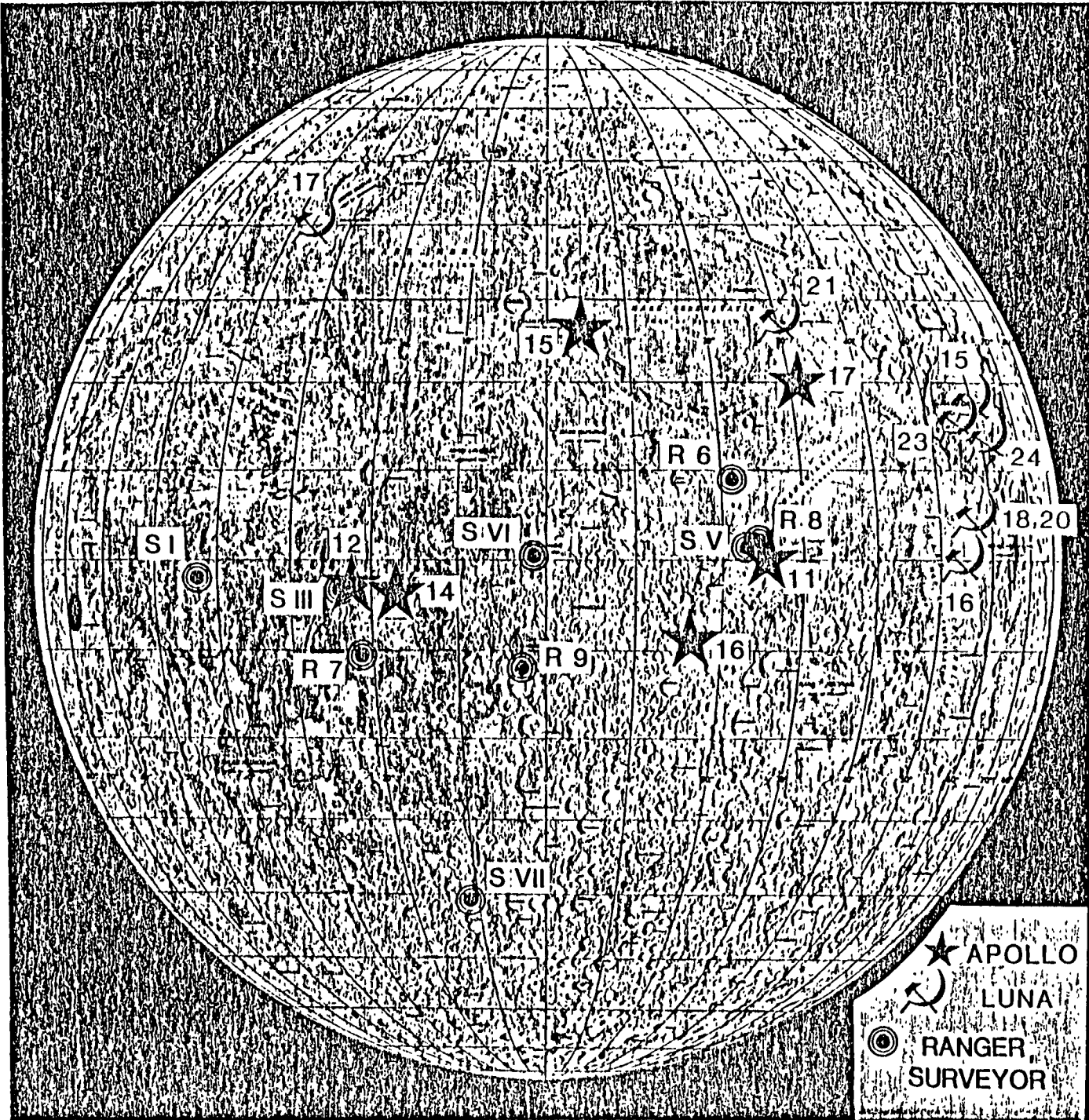
Figure 1.1

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Figure 1.2
Potential of Goods Produced in Space



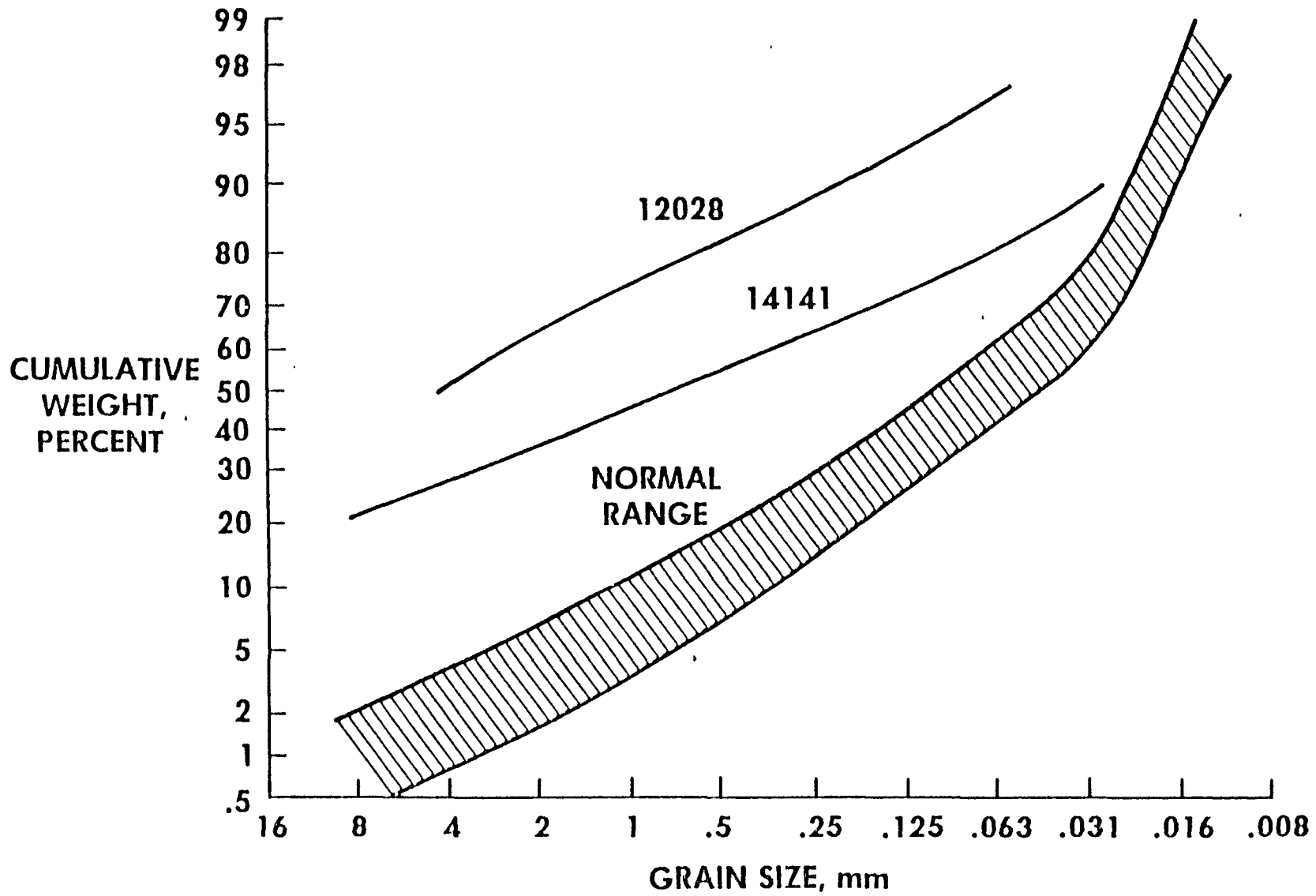


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Figure 2.2 APOLLO 15 SURFACE

GRAIN SIZE DISTRIBUTION IN LUNAR SOIL



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Figure 2.3

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GAS EVOLUTION REGIONS (HEATING UNDER VACUUM)

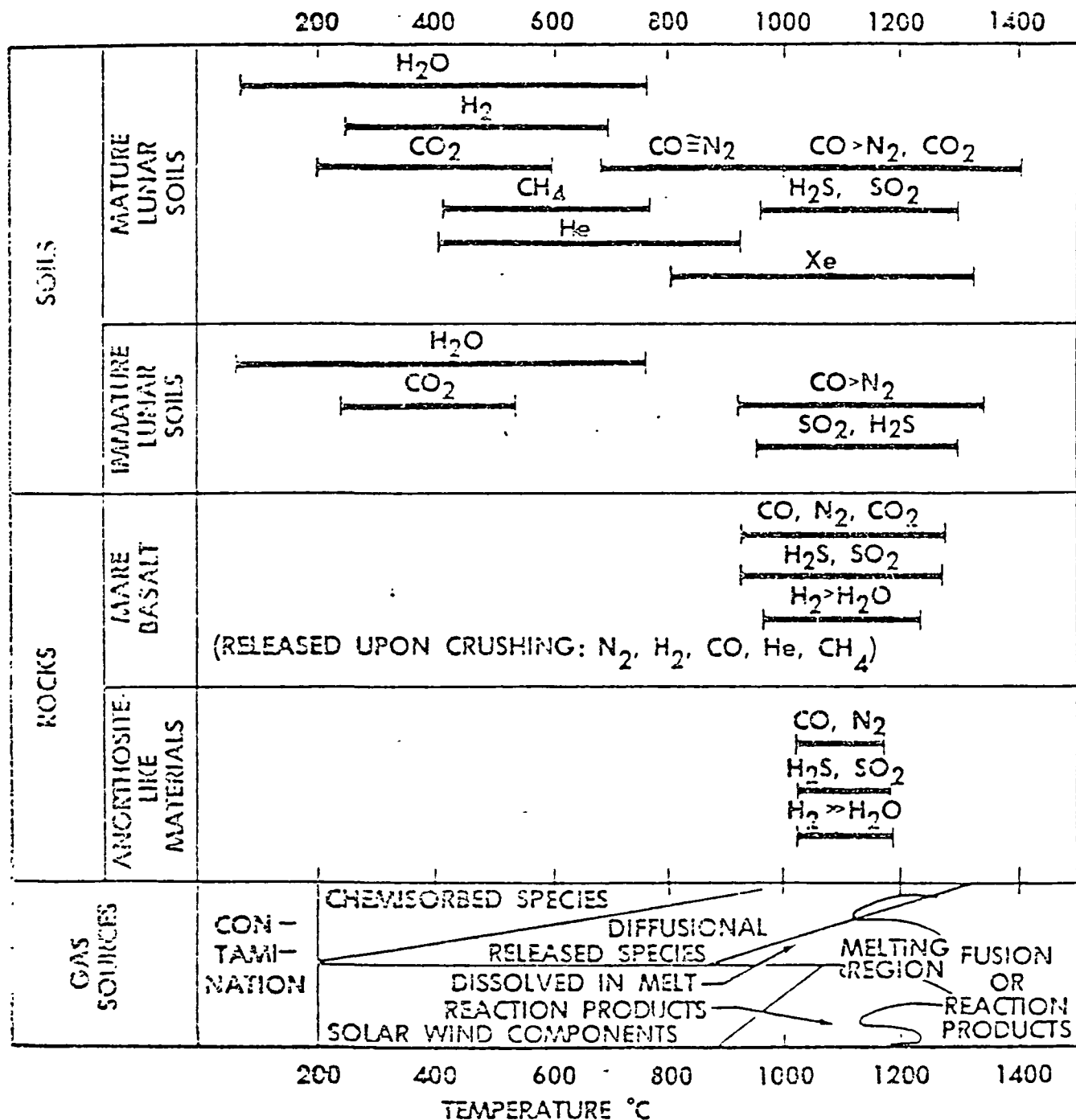


Figure 2.4 Summary of gas evolution regions for lunar materials.

MATERIALS PROCESSING IN SPACE

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"SPACE INDUSTRIALIZATION"

Editor

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CRC PRESS, INC.

1980

MATERIALS PROCESSING IN SPACE

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Industrial activity involving processing of material resources into tangible products has hitherto been confined to regions close to the surface of the earth. With the demonstrable capability to transport and support humans in space orbits and the lunar surface established, it is logical to assume that industrial activity involving material products will eventually extend to various extra-terrestrial locations. The cost effectiveness of such extraterrestrial industry will depend on technology development in such areas as transportation systems, mining and beneficiation, materials processing, manufacturing and fabrication, and assembly, maintenance and life support.

Classification

We may classify various industrial operations according to location into 4 regions: earth, near earth orbit, far space, and lunar surface. Eventually extensions to other planets such as Mars may become important. The sequence of operations necessary to convert raw materials into useful products may be conducted entirely in one of the specified regions, or materials or semifinished goods may be transferred from one region to another at various stages. Some possible optional routes are shown in Figure 1.

We shall limit our discussion to operations falling within the PROCESSING-REFINING steps for all locations except the earth. We shall exclude from PROCESSING-REFINING those steps comprising mining or gathering of raw materials and physical beneficiation by magnetic, electrostatic, thermal or combined treatments designed to beneficiate or upgrade raw materials by selective separations. We shall also exclude those post-refining steps primarily concerned with changes in particle size, state of aggregation, geometrical arrangement or

macro- or micro-shapes of materials assemblies which we shall regard as manufacturing operations. We shall also exclude those volumetric or surface treatments performed on partially or completely shaped components such as heat treatment, surface hardening, plating, anodizing or other coating operations, regardless of whether or not chemical modifications result.

Materials processing in space will thus be restricted to operations required to separate desired components from various grades of raw or physically beneficiated input ores, semi-purified feedstocks, or process scrap and convert and/or refine them to elements, alloys or compounds suitable for subsequent manufacture into finished goods or consumables.

Development of Options

Of the various alternative materials flow routes shown in Fig. 1, four options have been studied in some detail to determine technical and economic feasibility. These are:

1. EARTH (mining/beneficiation and/or partial processing) - SPACE
(processing and/or partial manufacturing) - EARTH (balance + use)
2. EARTH (mining/beneficiation and/or partial processing) - SPACE
(balance + use)
3. LUNAR (mining/beneficiation and/or partial processing) - SPACE
(processing and/or partial manufacturing) - EARTH (balance + use)
4. LUNAR (mining/beneficiation and/or partial processing) - SPACE
(balance + use)

These options have process characteristics summarized in the following table:

TABLE I
CHARACTERISTICS OF MATERIALS PROCESSING OPTIONS

Option	Transportation Costs	Element Constraints	Market Size	Competitive Costs
1	high	none	large	poor
2	high	none	small	fair
3	low	lunar recov. elements + small addns.	large	fair
4	low	lunar recov. elements + small addns.	small	excellent

In point of time we may expect option 4 to become cost effective first followed by options 2 and 3 for limited product areas and finally by option 1 in highly specialized technologies.

Options 1 and 3 must compete with industrial activity completely confined to earth. To overcome the adverse transportation costs we must achieve substantial economies in PROCESSING-REFINING or MANUFACTURING in comparison with earth plant practice. This is only likely to occur as a result of the unique properties of the space environment. Of these, the most important is expected to be extended duration of low or zero gravity processing and, to a lesser extent, unlimited volume vacuum processing with vanishing moisture or oxidation problems.

Option 2 must compete with option 4 or a sequence involving EARTH (mining/beneficiation, processing and/or partial manufacture - SPACE (balance + use). In this case, option 4 may be expected to display a transportation cost advantage, but the alternate earth starting route traditionally used for space projects has little or no difference in transportation costs from option 2, and the competitive edge will depend on PROCESSING-REFINING and MANUFACTURING efficiencies. Here again, we may expect that option 2 will be cost effective when substantial economies in PROCESSING-REFINING can be achieved as a result of unique features of the space environment.

MATERIALS PROCESS SELECTION

The nature, complexity, and criteria for selection of materials processing and refining systems may be expected to be substantially different for space processing of earth-derived vs. lunar or space-derived materials. In this context, we shall consider scrap materials already in space as space-derived materials, regardless of original source, since their transportation costs would be similar to other space-derived materials.

For the former, the specific output (output mass rate per unit plant mass), energy efficiency, requirements for reagent recycling and element constraints are of little or no importance and a given (specialty) plant may perform a single or small number of operations to produce a small quantity or specific rate of very high specific value product (\$/kg).

Materials processing plants for lunar or asteroidal materials on the other hand will probably be complex, high specific output plants similar to basic industries on earth, and in which efficient recycling of reagents containing lunar deficient elements must be practiced to avoid excessive mass rates for reagent replacement. After a mature level of space industrialization occurs, a variety of special processing facilities for small output, high specific value products may be established.

The Availability of Materials from Space

Table II shows the composition of the major constituents of the mare and highlands regions of the moon [1]. Meteoritic bombardment has tended to homogenize the distribution of minerals in these two regions to great depths. There are no aqueous processes operating on the moon to concentrate minerals or elements. Thus we expect to work with the dust and surface rocks of the moon, rather than look for deep veins of minerals. Table III presents compositional information

derived from remote observation of the surfaces of major asteroids [2,3]. It is evident that the chemical/metallurgical industry in space will be substantially different from that on earth, due to scarcity of key elements such as H, C, Na, Cl, etc. One may also recover gaseous constituents from the atmospheres of earth or other planets.

In common with industry on earth, one may anticipate commercial use of both native lunar mineral products (raw or beneficiated) and processed or refined materials (metals, oxides, etc.) for various applications, with price-performance criteria determining use patterns. Native lunar soils may be sintered or fused to obtain a variety of ceramic, cast basalt, and dark-glass products. Free iron may also be recoverable by magnetic methods from lunar soil.

Table IV shows elements that are potentially recoverable from the moon. (The designations "major," "minor," and "trace" are ours.) The light trace-elements are mostly due to solar wind bombardment of the lunar surface. Alpha radiation, due to radioactive decay, is responsible for some helium, while impacts of carbonaceous meteorites are responsible for some of the carbon that is present.

The major elements can be recovered using hydrochemical, pyrochemical, electrochemical or physical processes. This can be performed in orbit or on the moon. The chemical plant would also have to be responsible for the recycling of nonlunar materials. The minor elements could either be co-recovered from the major-element processing or be obtained by separate means. In the latter case, the processing could only be performed on the moon, as it would be uneconomical to ship large quantities of soil into space solely for the purpose of obtaining minor constituents.

While the overall abundances of many of the trace elements on the moon do not greatly differ from those on earth, the absence of known concentrated

deposits (ore bodies) of such elements makes prospects for their efficient recovery rather dim. Of course, one may still bring critical materials from the earth in modest amounts. Also, note that the major lunar elements constitute the preponderant mass of mineral elements used in earth industry (excepting air, water and fuels).

The selection of chemical or physical processes to convert raw or beneficiated lunar or asteroidal ore (or, alternatively, specialty earth materials) to desired elemental and compound materials suitable for further industrial processing involves many of the same factors of cost, raw material availability, transportation, environmental and personnel hazards, etc., which influence selection and design of earth-based plants, although the criteria are weighed differently. In addition, the unique constraints and opportunities of the space environment must be considered in selection of suitable processes. One must establish criteria to compute figures of merit for alternative processes to allow selection of an optimum process route. Once the process route is chosen, the process can be analyzed in terms of the individual unit operations which can then be sized using conventional engineering procedures. The resulting preliminary design can then be compared with other process routes (or with earth-based processing and launch-to-orbit alternatives) to establish systems performance of the various options.

Criteria for Process Evaluation

The prime consideration for evaluation of space processing and manufacturing systems must center on cost effectiveness in producing structures, functional hardware and supplies in orbital or lunar surface locations vs. earth-based processing and launch into orbit. In such comparisons, especially for lunar materials processing, it is essential that functional substitutions be considered since some items such as organics, fiber-reinforced resins, beryllium products,

copper, silver, refractory and precious metals, plus materials with appreciable water content would be difficult to produce from lunar materials. Fortunately, acceptable substitutes exist for any of those substances which would be needed in substantial amounts.

The cost in orbit of earth manufactured products may be taken as the earth market price plus the cost of orbital lift. The latter is anticipated to be in the range of \$654/kg using space shuttle technology.* Several estimates of the cost of launching lunar materials into orbit have been given. It seems safe to conclude that regardless of ultimate technological advances, the cost per unit payload of lunar orbital launch is likely to remain at 10% or less of the cost of earth orbital launch given a sufficient mass requirement.

Regardless of the materials processing and manufacturing systems chosen, it is unrealistic to anticipate that the value added per conversion step of high specific output processes will be comparable or lower in cost than similar operations on the earth. Exceptions may occur for operations uniquely dependent on the space environment. On the other hand, it is fully reasonable to anticipate that the cost of such operations should not exceed ten times their equivalent cost on earth. To meet such a limit, it is essential that the mass of capital equipment, expendables, reagent inventory, and support facilities which must be launched from earth should be far exceeded by the annual output mass of such high rate operations. Analysis to date of the materials processing portion of such operations shows that this requirement is readily met.

The total "earth supplied equivalent mass" (ESEM) per unit mass output chargeable to the materials processing portion of an industrial facility must be property defined to permit inter-comparison between alternative processing systems.

* NASA Report NSC-12973 Solar Power Satellite Concept Evaluation (July 1977)

Mass derived from lunar sources should be separately assessed as "lunar supplied equivalent mass" (LSEM) which would include input materials in inventory and in the process loop. It seems preferable to charge the output mass inventory to the manufacturing operation except possibly for output materials used captively for plant operations.

Mass for necessary support services may originate jointly from earth supplied and lunar supplied material. Rather than attempt to break down such items, it may be preferable to assign probable cost figures to such support operations.

Output mass must be clearly defined in terms of products and primary needs. A large mass output of slag-like materials which may only be useful for radiation shielding should perhaps not be listed as a primary output product in computing plant mass requirements per unit "output" mass.

In addition to mass considerations, other criteria of importance in process evaluation include process reliability, manpower requirements for operation and maintenance, potential hazards to on-site personnel, adaptability to process scrap materials, and ease of repair in case of malfunction. In the latter case, corrosion of parts which can only be replaced from earth supply is far more serious than corrosion of lunar derived parts.

Original cost of chemical process equipment per unit mass is expected to be dwarfed by orbital lift costs in all but a few special cases and thus would be of minor importance. If replacement items for many of these units could be fabricated from lunar materials, this would offer the opportunity for cost reduction in growth or replacement in space industrial operations.

Process Constraints

A successful orbital or lunar surface materials processing plant must operate with several constraints which rarely concern industrial plants operating on earth. These include:

1. Lack of virtually inexhaustible supplies of air and water.
2. Lack of unlimited heat sinks offered by (1).
3. Lack of unlimited fuel supplies; coal, oil, electric, gas, etc.
4. Lack of inexhaustible oxidizing and reducing agents.
5. Lack of expendable acids and bases (except CaO).
6. Lack of key chemicals: ammonia, salt, chlorine, caustic, soda ash, carbon dioxide, sulfuric and phosphoric acids, carbon and graphite and organics.
7. Lack of ordinary solvents.
8. Lack of unlimited inertia in foundations (except on moon).
9. Lack of support vendors.

These constraints do not prevent use of these reagents, supplies or services, but make it essential that for high rate processes, ordinarily expendable materials must be recycled to original form with a minimal attrition or loss (preferably below 1% per cycle).

This requirement has a corollary in that the output or material leaving the high mass rate plant must be a separation and/or recombination of the chemical elements present in the feedstock. Since the only non-metallic elements present in significant quantities from various lunar raw materials are silicon and oxygen, the output streams must be necessarily limited to elements, alloys, silicides and oxides.

For the major mineral constituents of lunar rock and soil; pyroxenes, feldspars and olivine, the compositions are silicates which may be described as addition compounds of metal oxides and silica. Conceptually the processing of such materials may be broken down into separation of the constituent oxides (including silica) followed by reduction of that portion of the metallic oxides and silica desired to obtain structural metals and oxygen (or higher oxides,

e.g., Fe_2O_3). For ilmenite, FeTiO_3 , the same steps are necessary except that no silica is involved.

Despite the compositional constraints imposed by lunar source materials, a surprising variety of industrial materials could be supplied. Table V shows a list of useful products, with examples of what could be made at a space manufacturing-facility, primarily from lunar materials. Although not listed, water would be made from oxygen obtained from lunar materials and hydrogen brought from earth. (Hydrogen is also a trace element on the moon, but even though its weight abundance may typically range between 50-100 ppm, its atomic abundance may be 1% that of silicon. If extractable, this hydrogen could be used to produce the water needed to replace that lost in process recycling — since no recycling process is 100% efficient.)

The structural metals listed in Table VI (Al, Fe, Mg, and Ti) will have to be alloyed in order to develop useful mechanical properties. Table I shows that several elements (e.g., Si, Cr, Mn) used in forming commercial alloys of the structural metals are potentially recoverable from the moon. In addition, there is "neutral" iron on the moon that also contains nickel and some cobalt, which could possibly be recovered. Finally, if enough carbon were recoverable from the trace amounts present on the moon (or brought from earth, or possibly obtained from a carbonaceous asteroid), and small amounts of other key alloying elements were imported from earth, one could produce many ferrous and non-ferrous alloys that are commonly used today.

In the case of steels, the more important alloying elements not readily available on the moon are C, Ni, Mo, W, V, and Nb (Cb). The physical properties of several commercial alloys containing these elements are generally similar to alloys in which such elements are absent but which instead contain lunar-indigenous elements. (The properties compared included tensile strength, yield strength, hardness, and elongation.) Therefore, for use as structural metals in

space, it is possible to produce alloys possessing a broad range of properties (as commonly required on earth) by alloying with carbon, lunar-indigenous elements, and/or minor amounts of lunar-deficient elements (LDE).

Several commercial aluminum alloys can be made from lunar-indigenous materials. However, higher strengths, approaching those of the strongest aluminum alloys made on earth, can only be obtained by alloying with small amounts of lunar-deficient elements, particularly Zn.

Only a few commercial alloys of magnesium and titanium can be formed solely from elements recoverable from the moon; but here again, as in the cases of steel and aluminum, significant improvements in properties can be obtained by alloying with minor amounts of lunar-deficient elements. The strongest magnesium alloys will require such lunar-deficient elements as Zn, while the strongest titanium alloys will need Mo.

It is evident that the structural metals to be manufactured in space will consist of alloys that are already in use, are well-characterized, and can furnish almost any desired property currently available. Nonmetallic materials similarly may be made solely from lunar sources, or modified with additions or lunar-deficient elements.

GENERAL CLASSIFICATION OF MATERIALS PROCESSING SYSTEMS

In an attempt to review and discover practical materials processing systems for lunar or other materials, it seemed worthwhile to attempt a general method of classifying such systems. Although the number of possible process variables is extremely large, especially in composition of one or several reagents, there are certain features in common which distinguish methods of separating constituent components from relatively non-volatile solid compounds and mixtures. These separation methods and operating temperatures are more important in determining the character and nature of the processing plant than the specific reagents involved.

To separate one or more constituents from a high melting point solid with negligible vapor pressure at ordinary temperatures, one must create conditions to allow the desired constituent to gain a reasonable mobility or diffusibility (M/D) on a micro- or atomic-scale to permit it to react or migrate so that separation may be effected. (In this context, we shall not consider grinding or dispersion techniques which merely serve to reduce particle size or permit transport of solid phases by slurries or fluidization techniques). Figure 2 shows a classification of mobility/diffusibility routes in which the output streams are designated as V (vapor), L (liquid), or F (fluid = V or L). [The intermediate output of the chemical solid-solid reaction is labeled C*, which designates a solid state reaction the solid output of which is rerouted through the system to some other mobilizing step.]

Once a mobile (liquid or vapor) phase is available, a separation from other mobile constituents and residues (which we shall define as residual solid material of negligible vapor pressure) may be accomplished by one of the routes shown on Fig. 3. (The residues if present may be recycled to the mobility/diffusibility (M/D) system.) The separation steps are designated by P (physical), S (semi-physical), C (chemical) or EC (electrochemical).

In many cases, the mobilizing and separating operations may take place simultaneously or in the same apparatus. Recycling of chemical reagents may follow the same general outline, although in many cases the volatility or fluidity of the reagents may already be established.

Flow Chart Analysis

To further expand the analysis, one may separate an entire chemical or materials processing system into a network (flow chart) of steps or segments, each one of which may be characterized by one or more input streams and one or more output streams. If we denote by (I, O) the number of input and output

streams, a (1,1) segment represents either a materials mover such as a pipe, pump, conveyor, etc., or a stream heater, cooler, grinder, crusher, or physical treatment unit. A flow chart is the representation of such a network in which the (1,1) segment representing flow lines are usually drawn as simple lines. Any segment representing flow lines are usually drawn as simple lines. Any segment with two or more outputs must of necessity incorporate some phase separation function except for special cases based on differential concentration of a single phase as, for example, with gaseous diffusion units. We may also distinguish between physical segments and chemical (reactor) segments according to whether lack of or presence of a chemical reaction occurs in such steps. Finally, we may note that a mobility/diffusibility step is only required when solids with little or negligible vapor pressure must be treated to permit extraction or flow of a desired constituent and when surface reactivity of the grain is expected to be too slow.

If reasonably pure output products are desired (e.g., 99% purity), it is clear that for processing a typical lunar soil (Table II), the seven major elements will require at least six separation steps (assuming (n,2) steps) if all these elements are desired either in reduced or oxide form. Even if one is only interested in recovering oxygen, silicon, aluminum and iron in commercially pure form, it would appear that at least four separation steps would be required. In addition, extra separation steps may be anticipated for recycling of necessary reagents.

The enormous number of process variations possible may be realized when one considers that even if a single separation process for each of the 22 categories shown in Fig. 3 was considered for each of the six separations above, one would have more than 113 million combinations (22^6) of separation segments to consider. The 13 classes of M/D steps would further increase the number of possible process variations.

The complete network or flow diagram must contain steps necessary to recycle all reagents not derivable from lunar soils. A detailed mass balance chart should also include mass replacements for electrode attrition, wear or corrosion of containers, etc. These latter considerations in many cases may require a greater mass replacement rate than reagent recycle loops with readily achievable efficiencies.

In order to narrow the field of promising materials processing systems and limit the cost and scope of development effort expended in analysis and improvement of parallel processes, it is imperative that a method of rating comparable processes be established based on realistic evaluation of anticipated performance and realistic assessment of technological risks involved.

General Survey or Overview of Processing Methods

For the M/D sections, the physical options have an advantage over the other routes in not requiring reagents or solvents. On the other hand, either very high temperatures and/or low pressures or high energy excitation is necessary to vaporize or fluidize silicate rock. Vapor pressures below about 0.1 Torr so restrict materials transfer rates that they are seldom of process interest for high volume production. In systems at very high temperatures, thermal losses at low pressures are apt to be excessive relative to mass transfer rates.

Neutral* solvent systems (L2) would normally be employed rather than fusion (L1) if a substantial reduction in melting point or operating temperature is possible. There would be little incentive to use a neutral solvent at operating temperatures near the melting point of the feed material. Reactive* solvents (L3-6) can operate from at or below room temperature up to high

* A neutral solvent is defined as one from which the original material may be recrystallized (in principle) in a substantially equivalent form to its original state. Reactive solvents produce chemical alteration of one or more constituents of the solute.

temperatures, but the latter would probably not be useful for the same reasons as with neutral solvents. All of the chemical systems listed here are considered to operate below the melting point of the feed material. For higher temperature chemical operations, the feedstock is presumed to have melted (L1) and the chemical reaction is treated in the separation section.

For the separation section, the physical and semi-physical options involve well recognized phase and homogeneous separations. The diffusion routes (P1 and P7) are often not too highly selective at useful concentrations and are generally employed only when no alternative phase separation is practical or convenient. The two phase scrubbers and absorbers (S_1 , S_2 , C_2 , S_3) are often useful at low to intermediate temperatures but are apt to present severe materials problems at elevated temperatures.

General Observations Concerning Chemical Conversions

The previous classification does not separately group steps to produce free elements or other reduction products. These do not differ materially from other chemical steps and require the same types of separation procedures. Metals reductions at temperatures above their melting points are generally self-separating due to the common immiscibility of molten metals with non-metals, slags or fused salts. (This is not true in all cases, however.) However, the separation of constituent elements of alloys is generally difficult.

Solvent systems may be subdivided into aqueous (L_3 , L_4) and non-aqueous classes. In the former, the water solubility in acid and near neutral solutions of metallic compounds is of general interest. We may note that most metallic nitrates, chlorides, perchlorates, fluoborates and fluosilicates are water soluble, while there is some limited solubility of fluorides and sulfates for some of the metals. Most of the remaining common anions form insoluble salts with all but the alkali metals. Nitrate, perchlorate and fluoborate compounds

present stability or availability problems that render them less attractive than the other salts for general separation and reduction operations.

In basic solution, only the silica, titania, and alumina fractions are likely to have sufficient solubility to be of interest, and these constituents are often rendered insoluble in the presence of polyvalent metallic ions such as Ca^{++} , Mg^{++} , etc. Recycling of base (NaOH) is somewhat more difficult than for acids due to lower volatility.

Most metal chlorides are readily vaporized, while fluorides are much less volatile. Both are easily reduced by active metals or electrochemical action. Sulfides are also potential candidates for metals reduction, but many have very high melting points.

Reduction Processes

Reduction processes may be expected to differ in significant aspects depending on the element being recovered. The principal routes may be divided into direct (electrochemical reduction) methods and indirect (pyrochemical) methods — however, the latter would generally require electrochemical regeneration of the reducing agent. For processing on the lunar surface, it may be practical to use neutral iron as a reductant with ferrous or ferric oxide as spent product without attempting to recycle the iron. Such open cycle use of reductants, which is commonplace on earth, would be prohibitive in orbit due to high launch costs even from the moon.

Direct electrodeposition processes may be conducted in a variety of electrolytes, but only a small fraction of lunar metallic content may be deposited from aqueous solution. Of the major and minor lunar elements, only Fe, Mn, and Cr are normally platable from aqueous solutions [4], although Na, K, Ca, and Mg could probably be recovered by using a mercury cathode. Aluminum might be recovered with ternary liquid metal alloy cathodes, but its solubility in mercury appears to be too low for practical operation.

All of the metals are recoverable by electrodeposition from various non-aqueous electrolytes, principally fused salts, but these processes pose a number of corrosion and anode durability problems, depending chiefly on the temperature of operation. Electrodeposition from electrolytes containing two or more of the reducible elements may also present formidable purification problems.

It would be highly desirable to generate oxygen at the anode instead of chlorine or other product, since reconversion of the chlorine to chlorides and evolution of oxygen in some recycle step would involve another oxidation-reduction reaction. Electrolysis of fused silicates, carbonates, hydroxides, or oxides, or such compounds dissolved in molten fluorides can generate oxygen, but for such processes conducted above 400-500°C, the resistance of potential anode materials deteriorates rapidly. For example, in commercial aluminum production, the use of graphite anodes results in virtually complete conversion of the oxygen to carbon monoxide and dioxide at temperatures between 950 and 1000°C [5]. Despite considerable work in this field, no satisfactory durable anode has been developed for this application.

One may, of course, recycle the oxides of carbon to oxygen and graphite, but this is not an easy operation, and the fabrication of graphite electrodes is a very slow and mass intensive process and should be avoided if at all possible.

Fortunately, satisfactory electrodes with very long service lives have been developed for oxygen evolution from aqueous solutions and from fused alkali hydroxides operating near 300°C. Electrolysis in this latter system was pioneered by Hamilton Y. Castner who developed a process for sodium production nearly a century ago [6]. The Castner cell was subsequently superseded for sodium production, and aluminum production from sodium was discontinued, but a modification of this method appears to offer many advantages for an extraterrestrial reduction process.

This process would generate the required number of reduction equivalents of sodium plus oxygen, and the sodium would be used for indirect (pyrochemical reduction) of silicon and the structural metals. Reduction of magnesium halides with sodium would not proceed to completion under normal circumstances, but magnesium oxide may be reduced with silicon which can be formed by sodium reduction.

Summary of Chemical Conversions

The difficulties attendant upon separation and/or direct reduction of constituents of complex oxides and silicates prompts one to examine various classes of compounds which can be generated by treatment of the oxide materials by various reagents. From the previous discussions on aqueous solvent systems, one might wish to consider nitrates, chlorides, perchlorates, fluoborates, fluosilicates, fluorides and sulfates. Sulfides, carbonates, phosphates and (to a limited extent) carbonyls might also be usefully employed in certain phases of materials processing loops. Nitrates and perchlorates present potential difficulties due to their instabilities toward severe thermal or oxidation-reduction conditions and to the difficulties in resynthesizing such reagents. Fluoborates seem to offer few advantages in comparison with fluosilicates and require makeup of another lunar deficient element. Sulfates, carbonates and phosphates seem to present limited capabilities in general solubility/separation operations but might be useful in specific separations.

Ammonia/ammonium salt chemistry has a unique advantage in that pyrolysis of ammonium compounds can usefully purify a number of the major and minor lunar elements as readily convertible compounds. The stability of ammonium ion or ammonia is not as great as halides toward severe oxidation or thermal exposure, but it is better than nitrates or perchlorates and regeneration is fairly easy in comparison with these compounds.

Sizing

In the absence of reliable kinetic data, it is difficult to estimate the size and mass of process equipment which will be required to obtain unit output from any proposed processes. However it is possible to list certain features that should probably be avoided or minimized if possible for high specific output plants. These include:

1. Steps that require long completion times.
2. Steps in which the input material is present in low concentration.
3. Mass transport of volatiles at very low pressures.
4. Phase separations from viscous suspensions.
5. Reactions with low percent conversion per pass.
6. Reactions involving handling or storage of large volumes of gas.
7. Reactions involving large transfers of heat to or from single phase fluids, especially gases, using heat exchangers.
8. Processes which reject large amounts of process heat at low temperatures (below 200-300°C).
9. Processes for which suitable structural materials do not offer reasonable service lives.

CHEMICAL PLANT DESIGN

Some factors that must be considered in designing a chemical (MATERIALS PROCESSING/REFINING) plant in space are shown in Table VI. The specific problems or opportunities created by these factors are expected to differ materially for high specific output plants (for conversion of LUNAR/SPACE raw materials) than for specialty plants (for conversion of EARTH materials which will usually be partially refined).

I. (High Specific Output Plants for Conversion of Space-Derived Materials)

General Considerations

A chemical plant for extraterrestrial materials processing may be expected to utilize equipment very similar to that employed in earth-based plants. Because of the importance of minimal mass, most apparatus initially brought from earth will be constructed of materials of high specific strength (strength/weight ratio) perhaps using thin linings of corrosion resistant materials (e.g., even gold). Later equipment made from lunar materials would not require extraordinary strength/weight ratio materials. Special consideration may also be required to be compatible with the special space environmental factors encountered during transport, assembly and operation. These include unlimited vacuum sink, adjustable level of artificial gravity (except on lunar surface) and provision for radiative dissipation of process heat loads.

Space Environmental Factors

(Vacuum)

The vacuum sink availability for space processing facilities may be useful for several types of operations either in orbit or on the lunar surface. The most generally useful would be the ability to use refractories and structural materials which are normally sensitive to oxidation at higher temperatures than would otherwise be possible except inside vacuum furnaces. Thus, ordinary steels could be used for retorts in metals reductions, and such materials as titanium and refractory metals, carbon and carbides, boron nitride and other non-oxide refractories could be used for structural and insulation purposes without danger of excessive oxidation. This should permit improved multilayer radiation shield insulations for extremely high temperature processes. Sublimational effects may limit the utility of such systems for certain applications, however.

The use of space vacuum as a separation technique may have very limited application, since the escape of volatiles except for very limited amounts of oxygen or water vapor could rarely be tolerated.

It would appear desirable to locate most of the processing facilities in a large container with an atmosphere and temperature compatible with human activity. This would permit easier inspection, maintenance and operation of the system and thus greater productivity.

(Gravity)

The reduced gravitational attraction for lunar based plants or adjustable centrifugal forces for simulated gravity in orbital plants will allow some mass savings in support structures for process equipment. It seems likely that most of the chemical unit operations would not operate satisfactorily under conditions of weightlessness, since all mass transfer operations except for introduction of gases into a vessel would be unnecessarily complicated by absence of a gravitational effect. Storage tanks or reactors of fixed volume for solids, liquids or slurries would be difficult to load or unload and such operations as filtration, distillation, countercurrent extraction, etc., would be rendered difficult if not impossible.

The most likely uses for weightless processing would be for heating corrosive reaction masses by radiation or induction using gas jet or electromagnetic repulsion to prevent contact with the walls of a chamber and, after removing volatile products, byproducts or impurities if present, allowing the reaction mass to cool in place or in a "drift tube" zone until it could be handled.

(Heat Sink)

The unavailability of massive external air or water heat sinks makes management of process waste heat especially important. All major heat rejection loads will ultimately have to be transferred to space radiators for final disposition. In addition, the poor heat transfer characteristics of vapor heat exchange devices makes such elements heavy and undesirable. This leads to the

general conclusion that to raise or lower the temperature of a gas stream it will be preferable to adiabatically compress or expand the stream rather than use wall or tube type heat exchangers. Similarly, in distillation operations it will be advantageous to use a suitable temperature by adiabatic compression. The mass penalty for additional pumping power will usually be far lower than other alternatives for disposition or transfer or process heat.*

Unavoidable low or medium temperature heat loads, such as from electrolytic cells may require heat pumping to higher temperatures to avoid excessive space radiator masses. A simplified analysis indicates that below some temperature determined by mass:power ratios of space power systems and mass:area ratios of space radiators, it becomes desirable to heat pumps all heat rejection leads to such base line temperatures which fall in the range 500-600°K based on satellite hardware masses of current design. Similarly, refrigeration equipment for liquefaction of cryogenics should have heat rejection temperatures at the same level.

Reagent and Equipment Mass

For solution processes, the mass of the solvent system will generally exceed the mass of lunar input material except where solutions of over 50% by weight are practical. A more typical level may be about 5-10% by weight of solute. Furthermore, not all of the solute may be transferred per pass when the various separation or extraction steps are performed, so the ratio of solvent to "active solute" mass is normally much greater than unity.

Fortunately, for aqueous solutions, most of the solvent mass need not be transported from the earth, since the oxygen content which represents 88.8% of the mass of water, is derivable from lunar materials. Even the hydrogen content

*See e.g. "Heat Transfer," A. J. Chapman, MacMillan (1960)

may be extracted in sufficient quantities to largely or entirely replace the content lost in residual moisture content of plant products.

One may inquire as to the relative magnitude of equipment and reagent mass for the various units needed for a chemical processing plant. Specifically, one would like to know whether the vessels, tanks, pipes and other items of process equipment weigh more or less than their contents. A simple analysis shows that for most cases of equipment which contain 10% or more material in condensed phases, the contents may be expected to far outweigh the container, while for gases the container will invariably outweigh the contents and furthermore, in this case, the ratio of container to content mass is practically independent of pressure.

This finding reiterates the undesirability of processes which require storage or handling of large volumes of gas. In addition, for processes operating primarily in condensed phases, the mass of the processing operation, apart from power and radiator facilities, will probably be dominated by the masses of reagents involved, which in turn will depend on reaction and process times for the individual steps. In the analyses which follow, we shall estimate both total reagent masses and net (earth based) reagent masses for some of the process steps of the HF acid leach process.

It shall be convenient in the subsequent analyses to define three mass ratio terms; R_m , R'_m and r_m which are respectively the ratios of the mass of vessel contents, net mass (LDE)* of vessel contents, and mass of container to the equivalent input mass of lunar ore contained in the respective vessel or process apparatus. These ratios multiplied by actual process times yield equivalent process times which will be used in a later section to estimate plant mass and volume (sizing).

* Lunar Deficient Elements - All elements except the 13 major and minor lunar elements.

Unit Operations

The unit operations required to perform the processing steps required for conversion of raw materials into industrial feedstocks are those generally familiar to the chemical engineering profession. These may be grouped into the following classes:

1. Materials handling; storage, conveying, pumping, compression, mixing, stirring, extruding, grinding, metering, etc.
2. Phase separation: distillation, filtration, extraction, drying, defoaming, precipitation, crystallization, sedimentation, centrifugation, etc.
3. Energy, heating and refrigeration; generation of process power and transfer of heat into or out of reactors and other processors.
4. Reactors; solid-solid, solid-liquid, solid-gas, liquid-liquid, liquid-gas, and tri or polyphase systems.

(Materials Handling)

Except for storage, these operations are not expected to require substantial masses. Most material can pass through a materials handling step with velocities of .01 - 1 meter/sec or even higher so such units would rarely have to handle more than a few minutes throughput of the operation. Fine grinding using a ball mill or equivalent may be somewhat slower, but is not expected to be necessary for processing of lunar soils. Entrainment of liquids or dust in gas flows may become a problem in lunar gravity or low artificial gravity, but inertial gas- or hydro-cyclones or other devices may be used to suppress carryover.

(Phase Separation)

The actual physical separation of different phases is usually limited by pressure or inertial considerations such as foaming or entrainment in distillation columns or sedimentation velocities in centrifugal filters or sedimentation centrifuges, although the material process time may be limited by heat transfer

rates, growth rates of crystallites or precipitates, etc. Because of the recycle nature of the various materials flow loops, it may be more desirable to shorten process times even at the expense of recycling larger than normal fractions of intermediate flow streams to reduce masses of intermediate stages. However, at the exit stages of the plant, it is important to limit loss of reagents, especially those containing lunar deficient elements (LDE), so it is necessary to attempt to carry those steps nearly to completion.

As an example we may consider drying of non-metallic output streams. For many cases in which industrial drying of solids is practiced, the observed drying rate or rate of weight loss is initially nearly constant, but below a certain moisture content, the rate drops and often becomes nearly proportional to the "excess residual water content" or content in excess of the equilibrium level corresponding to the local temperature and pressure [7]. For such a dependence, drying would continue at a progressively slower rate for an infinitely long time and never reach constant weight. For a practical process, the operation must be terminated at some reasonable time or residual moisture content. It may be readily shown that an optimum drying time or moisture content can be evaluated in terms of the minimized total mass of drying equipment and replacement mass to supply hydrogen for water lost.

(Process Energy, Heating and Refrigeration)

Process energy requirements may be satisfied by primary electrical or solar thermal sources, or indirectly using steam or other working fluid or by exchange with other process flow streams. For processes in which solar thermal energy is possible, one may anticipate a substantial mass reduction for equivalent power levels. (Mass reductions by factors of 30 or more may be possible by substituting solar thermal for solar electric power.)

The coupling of thermal energy into powdered solids is often a troublesome task, and can rarely be done efficiently by radiation. One would normally prefer to heat such material by exchange with recirculating gases heated in an adjacent unit by contact with structures heated by a solar furnace, electric arc, resistance or induction sources. In certain cases, it may be possible to heat the powdered solids by high frequency dielectric or microwave energy.

In heat exchange in which gas flow in one or both streams plays a part, one would like to operate at very high velocities or Reynold's numbers since the heat transfer coefficients in turbulent flow are roughly proportional to the 0.8 power of velocity or Reynold's number [8]. Heat transfer involving fluids in boiling or condensing flow are much higher than when no phase change is involved, so when liquids must be heated it is advantageous to operate under conditions of solution pressure and heater temperature to produce nucleate boiling at the interface when vapor pressures permit such operating modes.

Refrigeration or cooling operations may be required for process steps or for collecting, separating and storing non-condensable gases. Oxygen storage and hydrogen storage will probably represent the largest power and equipment requirements. Liquefaction of these gases would greatly reduce masses of the storage vessels required to handle these materials. By sub-cooling down to the triple point or lower, even further weight reductions are possible.

(Reactors)

The design of reactors is usually dictated by the heat balance requirements (endothermic or exothermic) and whether internal or external heating or cooling are required. Internally heated or cooled systems can usually be designed in large tubular, cylindrical or spherical vessels, while external heat transfer usually requires a large surface area and at least one short dimension (ca 0.2 to 0.5 m). Electrolytic cells usually require a low anode-cathode separation

(ca 0.1 m or less) to avoid excessive power losses, but the cell may contain multiple anodes and cathodes and thus attain considerable minimum dimensions. Heat rejection requirements usually limit the size of electrolytic cells, however.

It is somewhat remarkable that the mass output of a diverse range of chemical reactors per unit volume per unit time in sizes that span over five orders of magnitude are nearly constant lying close to 1 lb/ft³ hr in English units or about 16 kg/m³ hr. Figure 4 shows a graph of several reactors from blast furnaces and cement kilns at the large end to electrolytic cells and magnesium and zinc retorts with volumes below .05 m³*. This chart can be used to predict or verify the size of reactors for lunar materials processing steps estimated in the absence of commercial or pilot plant qualifying data.

Corrosion attack on reactor structures or general thermophysical deterioration may be expected to some degree in all high temperature processes, except where cold wall systems are used. This reality may present the greatest deterrent to use of very high temperatures in materials processing steps. The use of valves, pumps, filters, materials handling and other equipment and the containment of pressures becomes exceedingly difficult at temperatures above 1500°C. Reliability of operations may be adversely affected, and maintenance requirements excessive if many operations are carried out at such temperatures. In contrast, suitable apparatus and materials have been developed for handling almost any substance present in water solutions or steam-based systems.

General Sizing Considerations

The size of chemical reactors and other process equipment is generally controlled by one or more of three factors; reaction kinetics, heat transfer limitations (surface area) or momentum limitations in which the inertial effects of mass movement may cause foaming, entrainment or turbid dispersion of multiphase systems. The reaction rates in heterogeneous systems are often diffusion

*Data compiled from Ref. 15 and other sources.

limited, but the use of fine particles and high turbulence can increase throughputs in gas-liquid and gas-solid systems. For reactions involving crystal or precipitate growth, only the degree of supersaturation or control of nucleation can markedly affect the process rate. The rates of most chemical reactions can be increased by raising the temperature, but the equilibrium constant or conversion fraction may be adversely affected for some cases. This may also require higher pressure apparatus which will then require more massive reaction vessels.

The engineering characterization of any proposed process may be identified by parameters defined below. The sizing (volume) of equipment for any segment may be expressed as:

$$V = \frac{\dot{Q}_i \ell}{\rho_i v_i} = \frac{\dot{Q}}{\rho_i} t$$

where \dot{Q}_i is the mass flow rate of component i (kg/sec), ℓ is a characteristic length (meter) of flow path in apparatus, ρ_i is the partial density of component i (kg/m^3), v_i is a characteristic velocity of the i th component (m/sec), and t is the process time (sec). Parameter values characteristic of commercial process equipment may be derived from apparatus specifications. This will permit sizing estimates for specific processes not presently in commercial or pilot plant service.

The equipment and reagent masses corresponding to the process volumes can be derived using the mass ratio terms and equivalent times previously defined. The equivalent times represent the times required for passage of equivalent lunar input material (mass) equal to the mass of the specific vessel, equipment or reagent contents for the process step in question. Summation of the appropriate equivalent times therefore yields the total time required for the passage of

sufficient input raw-material to equal the gross or net reagent masses or the structural masses for the processing system. Additional equivalent times may be derived to account for masses required for mechanical and thermal power sources; for distribution equipment, motors, pumps, compressors; for heat-transfer equipment, space radiator facilities; and for other necessary support functions.

II. (Specialty Plants for Conversion of Earth-derived Materials)

As previously outlined, materials processing of earth-derived materials will probably be restricted to materials used in fabrication of high specific value products, and then probably only where the unique properties of the space environment permit substantial improvements in efficiency or capability in comparison with processing on the earth's surface. (Scrap in space reprocessing systems, regardless of the source of the scrap have been excluded from this category as previously noted.)

The design factors previously listed apply also to the specialty plants, but many of the comments regarding practical limitations need no longer apply. Thus while the special space environmental factors are more apt to be obstacles rather than advantages for high specific output plants, they must provide some unique opportunity to prepare materials with purities or compositions either impossible to achieve in an earth based plant or whose cost of production on earth would exceed the space processing cost by at least the transportation penalty.

The following table lists some possible classes of operations which could be performed more readily in the space environment.

TABLE VII

OPPORTUNITIES AFFORDED BY SPACE ENVIRONMENTAL FACTORS

- I. VACUUM
 - A. Processes requiring large structures in vacuum
 - B. Processes requiring multiple vacuum to atmosphere transitions
 - C. Processes requiring slow degassing or desorption (heat sensitive drying, freeze drying) and thus large volume vacuum storage or inventory
 - D. Processes requiring extensive electron beam processing
 - E. Processes requiring air sensitive refractories
- II. LOW OR ZERO GRAVITY
 - A. Containerless processing
 - 1. Metals
 - 2. Semiconductors
 - 3. Insulators
 - B. Processes favored by suppression of convection
 - 1. VHT (very high temperature) processes with inert gas fill
 - 2. Controlled solidification
 - a. single phase, single crystal or polycrystalline materials
 - b. directional solidification
 - c. zone refining
 - d. multiphase solidification (alloys with unique dispersions)
 - C. Processes for preparing materials with controlled gradient properties (mechanical, thermal, electromagnetic) etc.
- III. LOW TEMPERATURES
 - A. Processes requiring long duration cryogenic cooling and thus large volume cryogenic storage or inventory

The best prospects for specialty processing would involve materials of high specific value such as precious metals, gemstones, rare isotopes and some very high temperature materials. In addition, some organic compounds of biological interest such as enzymes, hormones or compounds of pharmaceutical interest may be candidates.

Some of the materials processes which have been proposed for space facilities have included: growth and purification of semiconductor crystals, growth of metallic and gemstone crystals, preparation of ultrapure glasses for optical fiber waveguides, preparation of high performance rare earth-cobalt magnetic materials, and preparation of biochemicals by electrophoresis [9].

(Containerless Processing)

Levitation or confinement of hot matter without a physical boundary has generally been restricted to small masses for research purposes on earth [10], although confinement of plasmas has been the subject of intense development for fusion power systems [11]. It is relatively simple to levitate small masses of electrically conducting fluids (molten metals) against earth gravity, and methods have been proposed which would allow levitation of any desired mass [12]. The suspension is normally achieved by the reaction forces between induced electrical currents in the fluid and external currents. This produces a heating effect in addition to the lifting force, the ratio of which can be adjusted to some extent by varying the frequency or geometry of the alternating field, but it can not be made arbitrarily small. In residual force fields below about 10^{-3} earth gravities, the heating effect can be reduced to almost any desired value without danger of the fluid contacting external apparatus. Thus one may perform various cooling cycles which would be impossible for fluids on earth. In addition, other methods of suspension using weaker forces can be considered such as electrostatic suspension, acoustic standing waves, photon beams, gas or vapor stream momentum, and the magnetic induction method can be extended to poorly

conducting fluids such as semiconductors, molten glasses and refractories, etc. (Most refractory insulators have high enough loss currents in the molten phase to permit suspension in orbital apparatus.)

SPECIFIC PROCESSES FOR LUNAR-DERIVED MATERIALS

Electrolysis of Molten Silicates

Limited investigations of direct electrolysis of molten silicates of compositions similar to lunar basalts have been performed [13]. The high melting points and viscosities of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the "reagentless" advantage of the direct electrolysis route and requires consideration of extraction and recycling of fluxing reagents.

The chief objections or problems awaiting solution are the corrosion or durability of anodes used for oxygen recovery and the purification and separation of cathodic reduction products which are likely to consist of iron-aluminum-silicon alloys plus minor amounts of additional impurities.

Carbothermic/Silicothermic Reduction Process

One of the first serious attempts to define a process option was performed by Phinney et al. [14] at the 1976 NASA-Ames Summer Study, in which silicothermic and carbothermic reduction of bulk lunar soil was discussed. After crushing the raw material, and magnetically separating the ferrous from the non-ferrous fractions, reduction could commence. Silicon will reduce iron at 1300°C, as shown by Equation 1:



The products can be separated by centrifugation.

The iron-free silicates would be reduced by carbon at 2300°C, as shown by Equations 2-5:



By this process, it would be expected that aluminum and silicon form a melt, while the other reduced metals, including the major impurities Ti, Mn, and Cr, would be removed as vapors. However, the reaction chemistry is much more complicated. At 2300°C, condensed compounds, such as SiC, Al₄C₃, and Al₄O₄C are present, along with gases such as Al₂O, SiO, Al, and Si. The equilibrium pressures of Al₂O and Al are so high, that liquid aluminum cannot be formed at pressures near one atmosphere. Perhaps the greatest defect of the carbothermic reduction process is that although the winning of aluminum on earth via carbothermic reduction has been attempted for many years, no practical process for producing purified aluminum by this method has proven satisfactory [15].

Carbo-Chlorination Process

At the 1977 NASA-Ames Summer Study, Rao et al. [16] decided quite early that carbothermic reduction would probably be impractical for space processing. They opted for carbochlorination of lunar anorthite, CaAl₂Si₂O₈, and lunar ilmenite, FeTiO₃, which could be beneficiated from lunar soil [17]. The desired products are aluminum, iron, silicon (or silica), and titanium. The basic reactions involved in this process are shown in Table VIII. Reaction (1) represents the carbo-chlorination of anorthite, run at 700°C. Electrolysis of AlCl₃ would yield aluminum, while hydrolysis of SiCl₄ would give silica, or *reduction of it would produce silicon*. Reactions (13)-(17) show the basic scheme involved in carbochlorination of ilmenite. At 800°C the iron in ilmenite

is selectively chlorinated [18] as was shown by Reaction (13). Rao and co-workers felt that a fluidized bed process would achieve the best results.

They also discussed methods for obtaining magnesium and oxygen from non-terrestrial materials. They would extract magnesium from olivine (forsterite, Mg_2SiO_4) via silicothermic reduction at $1200^\circ C$, as shown by Reaction (18). Reactions (8), (19), and (20) describe reactions on the effluent CO from carbochlorination, so that conversions can be performed on the resultant CO, CO_2 and H_2O products, in order to produce oxygen. A basic flow chart for the process including carbon and oxygen recovery is shown in Figures 5a and b.

Subsequent studies have indicated that carbochlorination would create a major problem of plant size. The recycling of chlorine and carbon would require facilities much larger than the basic processing plant. One of the major advantages of carbochlorination was that it would require only a minimum of hydrometallurgical operations. Water would be needed, however, for hydrolysis, chlorine regeneration and possibly a coolant for the system. In order to minimize the size of the heat rejection radiators, large amounts of heat energy would have to be raised (heat pumped) to about $280^\circ C$, to achieve a mass efficient system.

These results led us to believe that processes which rejected less heat at low temperatures and making use of hydrometallurgical operations would tend to be more useful options for space processing.

NaOH Basic Leach Process

A review of the literature [19-22] indicates that anorthite can be decomposed with NaOH in an autoclave, and subsequent treatment of those products with more base can eventually yield alumina and calcium silicate; the latter could be used to make glass or hydrolyzed to yield lime and silica. The reactions involved

in this process are given in Table IX. For both basic and acidic leaching, sodium present in lunar soil can probably make up for any sodium lost during recycling. In this process, calcium impurities in the recycled NaOH would not present a problem as base, and not pure NaOH, is needed. A flow diagram for this process is shown in Figure 6.

HF Acid Leach Process

This process uses low temperature hydrochemical (hydrometallurgical) steps to separate the silica content of the lunar raw material from the other metallic oxides by conversion to fluorides and fluosilicates followed by vaporization of the silica as SiF_4 , and separation of the calcium and the structural metals (Al, Fe, Mg, Ti) by a variety of solution, precipitation, ion exchange, or electrolytic steps. Generalized process equations are given in Table X. Iron may easily be recovered from solutions by electrowinning, but the remaining metals except Mg are preferably recovered by sodium reduction of the corresponding fluorides, fluosilicates or fluoaluminates. Magnesium may be made by silicon reduction of MgO .

Sodium for the metals and silicon reduction can be conveniently obtained by a slight modification of the Castner cell which at one time was the major commercial method for producing sodium. The Castner cell uses the electrolysis of molten NaOH to produce Na, O_2 and H_2 . For lunar operations, the hydrogen is an undesirable by-product which can be largely eliminated by using a diaphragm cell and vacuum drying the anolyte to remove the water formed by discharge of OH^- ions.

Metal oxides and silica are obtained, where desired, by hydrolysis of the corresponding fluorides or fluosilicates with steam (or with NH_3 if desired for SiO_2) or by ion exchange (or permeation) methods. Detailed analyses of the options available for these separations remain to be completed.

A pictorial flow diagram for the HF acid leach process is shown in Figure 7.

Of the processes studied to date, the HF acid-leach one appears to have the best potential for minimal operating mass, ease of element separations to high purity, flexibility, and favorable energy and heat-rejection requirements.

A number of details and options remain to be investigated. Many of these specific process steps can be fully defined by straightforward experiments.

Separation of the fluoro compounds of the metallic elements by solubilities of fluorides or fluosilicates as a function of pH and F:Si ratio – with or without additional ion-exchange or electrolytic steps – will require extended literature searches and laboratory investigations. Pyrolytic and hydrolytic behavior of fluorides, fluosilicates and fluotitanates will also require additional research.

Despite these informational gaps, nearly all of the proposed operating steps have been studied on a laboratory scale, and about 75% of the steps have been conducted on a pilot or commercial scale under equivalent or comparable conditions.

(Thermochemistry)

The heat transfer requirements of the HF acid leach process may be derived from existing thermochemical data for the compounds present in the process equations. These may be used to prepare the ΔH vs T map shown in Fig. 8. In this figure the enthalpy changes involved in water transfer – distillation and condensation – have been omitted. The electrolysis heat load represents only the ohmic heat loss of the process step.

The total input power requirement is projected to total 4100 KWH/metric ton. For the plant sizing analysis, this was increased to 7130 KWH/metric ton to allow for various losses.

(Plant Sizing)

The techniques of plant sizing and mass estimation developed in the preceding discussion were applied to the HF acid leach process. The results are shown in Table XI. By summing the equivalent times for containers, net

masses of lunar deficient elements and extra inventory and equipment, one obtains a total equivalent time of 81 hrs. If one uses gross instead of net reagent mass, the total becomes 155 hrs. In either event, the plant should be able to process more lunar ore than its total mass each week, or on an annual basis it could supply more than 50 times the earth lift mass of the plant.

(Reagent Replacement Mass)

The principal lunar deficient elements used in the HF acid leach process are H, F, Na and optionally N. (Sodium is probably not a serious consideration since it is a minor lunar element and frequently occurs at levels exceeding 2.5% of the total metallic equivalents in feldspar fractions from mare soils.) These recycling elements will occur principally as chemically or physically combined water or hydroxyl ion (H) or fluoride ion (F) and as ammonia or ammonium ion (N).

The hydrogen and nitrogen content of vacuum dried, calcined refractory oxides or other compounds can be reduced to almost any desired level given sufficient time and temperature at low pressure although mass efficient operation may not be served by drying to less than 0.1% as discussed earlier. If we assume a conservative residual content of 0.5% H₂O and 0.1% NH₃ for the non-metallic output streams and zero for these impurities in metal outputs, the ratios of reagent replacement mass:input mass for H and N may be expected to fall in the ranges $3.7 - 7.4 \times 10^{-4}$ and $4.1 - 8.2 \times 10^{-4}$ depend on amount of reduced products. The moisture content or dew point of oxygen can be held to insignificant levels.

The residual fluorine level will occur principally as residue from steam hydrolysis of refractory fluorides, and cannot be baked out in a practical manner. Analytical studies [23] suggest that the fluorine content of pyrohydrolyzed fluorides can be reduced to 0.25 to 0.5% without undue extension of the process. Vacuum cycling may possibly lead to lower residual levels. We may anticipate F replacement mass:input mass ratios in the range of $1 - 2 \times 10^{-3}$ and possibly lower with improved vacuum desorption.

Total reagent replacement mass:input mass can probably be held below one part in 300 with further improvements likely. At this rate, the reagent replacement mass requirement would equal the initial net plant mass in 3 to 6 years. It may be noted that replacement mass need not be supplied in elemental, toxic or hazardous forms.

(Plant Scaling)

The mass and volume of the processing facility are expected to scale almost linearly with annual throughput. Minimum practical installations may range as low as 1 kg/hr (7-8 metric ton/yr). At a very small scale, the mass:throughput and power:throughput ratios may be expected to increase — perhaps by as much as a factor of two.

The concept of the bootstrap growth of processing capacity can increase the annual output mass:net plant mass ratio by an amount limited by the reagent requirements for lunar deficient elements. For the HF acid leach process, the LDE net reagent mass represents 28% of the net plant mass, so the annual output:net plant mass ratio could be nearly quadrupled by expanding equipment capacity using lunar materials. Even greater increases may result from process revisions or modifications of operating cycles which can reduce the equivalent times required for LDE reagents.

Acknowledgment

The Lunar and Planetary Institute is operated by the Universities Space Research Association under Contract No. NSR 09-051-001 with the National Aeronautics and Space Administration. This paper is LPI Contribution No. XXX.

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TABLE II
RANGES OF CHEMICAL COMPOSITIONS FOR THE MAJOR MINERALS

High-titanium basalts				
Modal abundance (Vol. %)	Pyroxene 42-60%	Olivine 0-10%	Plagioclase 15-33%	Opagues (mostly ilmenite) 10-34%
Component (Wt. %)				
SiO ₂	44.1-53.8	29.2-38.6	46.9-53.3	< 1.0
Al ₂ O ₃	0.6- 6.0	-	28.9-34.5	0 - 2.0
TiO ₂	0.7- 6.0	-	-	52.1-74.0
Cr ₂ O ₃	0 - 0.7	0.1- 0.2	-	0.4- 2.2
FeO	8.1-45.8	25.4-28.8	0.3- 1.4	14.9-45.7
MnO	0 - 0.7	0.2- 0.3	-	< 1.0
MgO	1.7-22.8	33.5-36.5	0 - 0.3	0.7- 8.6
CaO	3.7-20.7	0.2- 0.3	14.3-18.6	< 1.0
Na ₂ O	0 - 0.2	-	0.7- 2.7	-
K ₂ O	-	-	0 - 0.4	-
Low-titanium basalts				
Modal abundance (Vol. %)	42-60%	0-36%	17-33%	1-11%
Component (Wt. %)				
SiO ₂	41.2-54.0	33.5-38.1	44.4-48.2	< 1.0
Al ₂ O ₃	0.6-11.9	-	32.0-35.2	0.1- 1.2
TiO ₂	0.2- 3.0	-	-	50.7-53.9
Cr ₂ O ₃	0 - 1.5	0.3- 0.7	-	0.2- 0.8
FeO	13.1-45.5	21.1-47.2	0.4- 2.6	44.1-46.8
MnO	0 - 0.6	0.1- 0.4	-	0.3- 0.5
MgO	0.3-26.3	18.5-39.2	0.1- 1.2	0.1- 2.3
CaO	2.0-16.9	0 - 0.3	16.9-19.2	< 1.0
Na ₂ O	0 - 0.1	-	0.4- 1.3	-
K ₂ O	-	-	0 - 0.3	-
Highlands rocks				
Modal abundance (Vol. %)	5-35%	0-35%	45-95%	0-5%
Component (Wt. %)				
SiO ₂	51.10-55.4	37.70-39.9	44.00-48.0	0 - 0.1
Al ₂ O ₃	1.00- 2.5	0 - 0.1	32.00-36.0	0.80-65.0
TiO ₂	0.45- 1.3	0 - 0.1	0.02- 0.03	0.40-53.0
Cr ₂ O ₃	0.30- 0.7	0 - 0.1	0 - 0.02	0.40- 4.0
FeO	8.20-24.0	13.40-27.3	0.18- 0.34	11.60-36.0
MgO	16.70-30.9	33.40-45.5	0 - 0.18	7.70-20.0
CaO	1.90-16.7	0.20- 0.3	19.00-20.0	0 - 0.6
Na ₂ O	-	-	0.20- 0.6	-
K ₂ O	-	-	0.03- 0.15	-

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TABLE III
ASTEROID SURFACE MATERIALS:
CHARACTERIZATIONS [3]

<u>Asteroid</u>	<u>Mineral Assemblage*</u>
Hebe	NiFe > Cpx
Iris	NiFe, Ol, Px
Flora	NiFe > Cpx
Metis	NiFe, (Sil (E))
Hygeia	Phy, Opx (C)
Parthenope	NiFe, (Sil (E))
Irene	NiFe, Px
Eunomia	NiFe - (Ol) > Px
Psyche	NiFe, Sil (E)
Thetis	NiFe, Cpx
Melpomene	Sil (O), Opx (C)
Fortuna	Phy, Opx (C)
Phocaea	NiFe, Px, Cpx
Euterpe	NiFe, Px, Cpx
Bellona	Sil (O), Poq (C)
Europa	Phy, Opx (C)
Concordia	Phy, Opx (C)
Ausonia	NiFe, Px
Eurynome	NiFe - Cpx
Sappho	Sil (O), Poq (C)
Alkmene	Sil (O), Opx (C)
Io	Sil (O), Opx (M)
Thisbe	Sil ()), Opx (C)
Siwa	NiFe, Sil (E)
Dembowska	Ol, (NiFe)

*Mineral assemblage of asteroid surface material: NiFe (nickel-iron metal); Ol (olivine); Px (pyroxene, generally low-calcium orthopyroxene); Cpx (clinopyroxene, calcic pyroxene); Sil (O) (mafic silicate, most probably olivine); Sil (E) (spectrally neutral silicate, most probably iron-free pyroxene, enstatite); Phy (phyllosilicate, layer lattice silicate, meteoritic clay mineral, generally hydrated, unleached with abundant subequal Fe²⁺ and Fe³⁺ cations); Opx (C) (opaque phase, most probably magnetite or related opaque oxide).

Mathematical symbols (">", greater than; ">>", much greater than; "=", approximately equal) are used to indicate relative abundance of mineral phases. In cases where abundance is undetermined, order is most abundant to least abundant.

TABLE IV

POTENTIAL AVAILABILITY OF LUNAR ELEMENTS

Major elements $\geq 1\%$ lunar
O, Si, Al, Ca, Fe, Mg, Ti

Minor elements 0.1 - 1%
Cr, Mn, Na, K, S, P

Trace elements $< 0.1\%$
H, He, C, N plus all others

(Beneficiation may permit concentrating some trace elements into minor or higher range.)

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TABLE V

USEFUL PRODUCTS DERIVABLE PRIMARILY FROM LUNAR SOURCES

STRUCTURAL MATERIALS

Metals

Steels, aluminum, magnesium, titanium and alloys

Reinforced Metals

Metals above reinforced with silica, steel, alumina or titanium silicide

Glasses

Calcium, magnesium, aluminum, or titanium silicates, fused silica, foamed glasses

Ceramics

Alumina, magnesia, silica, complex oxides, fused basalts

Hydraulic Cements

(Need water)

THERMAL AND SPECIALTY MATERIALS

Refractory and Hard Materials

Ceramics above plus chromia, titania, titanium silicides

Abrasives

Alumina, garnets, silicon carbide, titanium carbide (limited by C)

Insulation

Ceramics above plus fiberglass, fibrous or powdered ceramics

ELECTRICAL MATERIALS

Conductors

Aluminum, magnesium, iron, resistance alloys (FeCrAl), silicon

Electrodes

Fe_3O_4 , TiO, graphite (limited by C)

Magnetic Materials

Iron alloys, magnetic ceramics (ferrites, magnetoplumbites)

Electrical Insulation

See glasses, ceramics and thermal insulation

FIBROUS MATERIALS

Glass, silica, synthetic mineral wool

For apparel, paper, filters, etc.

PLASTICS AND ELASTOMERS

Silicone resins (limited by C)

SEALANTS, ADHESIVES AND COATINGS

Soluble silicates

Anodized coatings

Electroplating

Chromium, etc.

Sputtered or vacuum deposited coatings

LUBRICANTS, HEAT TRANSFER FLUIDS

Sulfides, graphite (limited by C)

SO₂, He

INDUSTRIAL CHEMICALS

Detergents, cleansers, solvents, acids, bases

H₂SO₄, H₃PO₄, CaO, NaOH

BIOSUPPORT

Oxygen (breathing), 16/18 of water by mass

SiO₂ - soil component (including trace nutrients)

Bioelements O, Ca, C, Fe, Mg, K, P, N, Na, H others

TABLE VI
CHEMICAL PLANT DESIGN

- I. SELECTION OF PROCESS OPTIONS
- II. SPECIAL SPACE ENVIRONMENTAL FACTORS
 - A. Gravity (natural or artificial)
 - B. Vacuum
 - C. Heat rejection
 - D. Recycling of nonlunar indigenous materials
- III. DESCRIPTION OF UNIT OPERATIONS
 - A. Materials handling
 - B. Phase separations
 - C. Heat exchange
 - D. Reactors
 - E. Energy requirements
 - F. Heat rejection requirements
- IV. SIZING FACTORS
 - A. Kinetics limited
 - B. Heat transfer limited
 - C. Momentum limited

TABLE VIII
CARBO-CHLORINATION PROCESS EQUATIONS

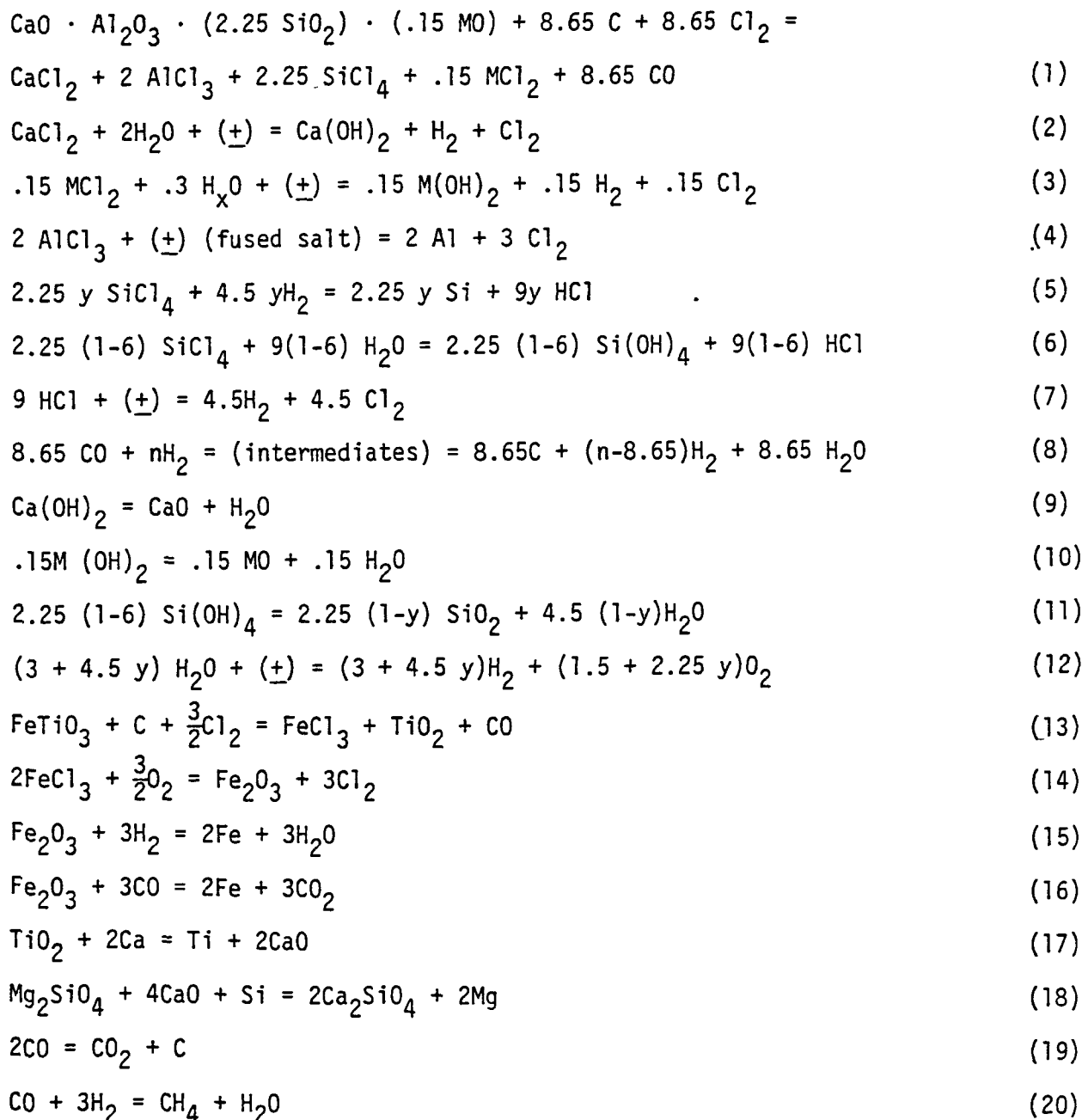


TABLE IX

NaOH BASIC LEACH PROCESS EQUATIONS

1. $2(\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2) + 6 \text{NaOH} + 2 \text{H}_2\text{O} \xrightarrow[\text{autoclave}]{300^\circ\text{C}}$
 $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 + \text{Na}_2\text{O} \cdot 2 \text{CaO} \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O} + \text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O}$
2. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O} + 2 \text{NaOH} + 2 \text{CaO} + 2 \text{H}_2\text{O}$
 $\xrightarrow[\text{slurry}]{220^\circ\text{C}} \text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3 \text{H}_2\text{O} + \text{Na}_2\text{O} \cdot 2 \text{CaO} \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O}$
3. $\text{Na}_2\text{O} \cdot 2 \text{CaO} \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O} \xrightarrow{95^\circ\text{C}} 2 (\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}) + 2 \text{NaOH}$
4. $\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O} + 2 \text{H}_2\text{O} \rightleftharpoons \text{Ca}(\text{OH})_2 + \text{Si}(\text{OH})_4$
5. $3 \text{H}_2\text{O} + \text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 + \text{CO}_2 \xrightarrow{25^\circ\text{C}} 2 \text{Al}(\text{OH})_3 + \text{Na}_2\text{CO}_3$
6. $2 \text{Al}(\text{OH})_3 \xrightarrow[\text{calciner}]{1100^\circ\text{C}} \text{Al}_2\text{O}_3 + 3 \text{H}_2\text{O}$
7. $\text{Na}_2\text{CO}_3 + \text{CaO} + \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \text{CaCO}_3\downarrow$
8. $\text{CO}_3 = 2 \text{R}^*\text{OH} \rightarrow \text{R}_2^*\text{CO}_3 + 2 \text{OH}^-$
- 9a. $\text{CO}_3 = \rightarrow \text{CO}_2\uparrow + 1/2 \text{O}_2\uparrow + 2 \text{e}$
- 9b. $\text{Na}^+ + \text{H}_2\text{O} + \text{e} \rightarrow \text{Na}^+ + \text{OH}^- + 2/1 \text{A}_2\uparrow$
10. $\text{CaCO}_3 \xrightarrow[\Delta]{} \text{CaO} + \text{CO}_2$
11. $\text{R}_2^*\text{CO}_3 + 2 \text{HX} \rightarrow 2 \text{R}^*\text{X} + \text{CO}_2\uparrow + \text{H}_2\text{O}$
12. $2 \text{R}^*\text{X} + \text{CaO} + \text{H}_2\text{O} \rightleftharpoons \text{CaX}_2 + 2 \text{R}^*\text{OH}$

R* = ion exchange resin

TABLE X
HF ACID LEACH PROCESS EQUATIONS

1. $xMO \cdot SiO_2 + (4 + 2x) HF = xMF_2 + SiF_4 (aq) + (2 + x) H_2O$
- 1'. $xMO \cdot SiO_2 + (5 + 2x) HF = xMF_2 + HSiF_5 (aq) + (2 + x) H_2O$
2. $SiF_4 (aq) + nH_2O = SiF_4 (v) + nH_2O(v)$
- 2'. $HSiF_5 (aq) + nH_2O = SiF_4 (v) + HF (aq) + nH_2O(v)$
3. $(1-y) [SiF_4 (v) + 4H_2O = Si(OH)_4 + 4 HF]$
- 3a. $(1-y) [SiF_4 (v) + 2H_2O = SiO_2 + 4HF]$
4. $(1-y'z) [xMF_2 + H_2O = xMO + 2xHF]$
5. $y [SiF_4 + 4Na = Si + 4NaF]$
6. $y' [xMF_2 + 2xNa = xM + 2xNaF]$
7. $z [xMF_2 + xSiF_4 (aq) = xMSiF_6 (aq)]$
8. $z [xMSiF_6 (aq) + xH_2O + \text{electrical energy} = (x/2)O_2 + xM + xH_2SiF_6]$
- 8a. $z [xMSiF_6 (aq) + M'SO_3R^* = xM'SiF_6(aq) + xMSO_3R^*]$
9. $mNaF + mR^*OH = mNaOH + mR^*F$
- 9a. $mNaF + (m/2) Ca(OH)_2 = mNaOH + (m/w) CaF_2$
10. $mNaOH + \text{electrical energy} = mNa + (m/2)O_2 + (m/2)H_2O$
11. $(1-y) [Si(OH)_4 = SiO_2 + 2H_2O]$

R* = ion-exchange
m = 4y + 2xy'

TABLE XI

EQUIPMENT AND REAGENT MASSES - PROCESS AND EQUIVALENT TIMES

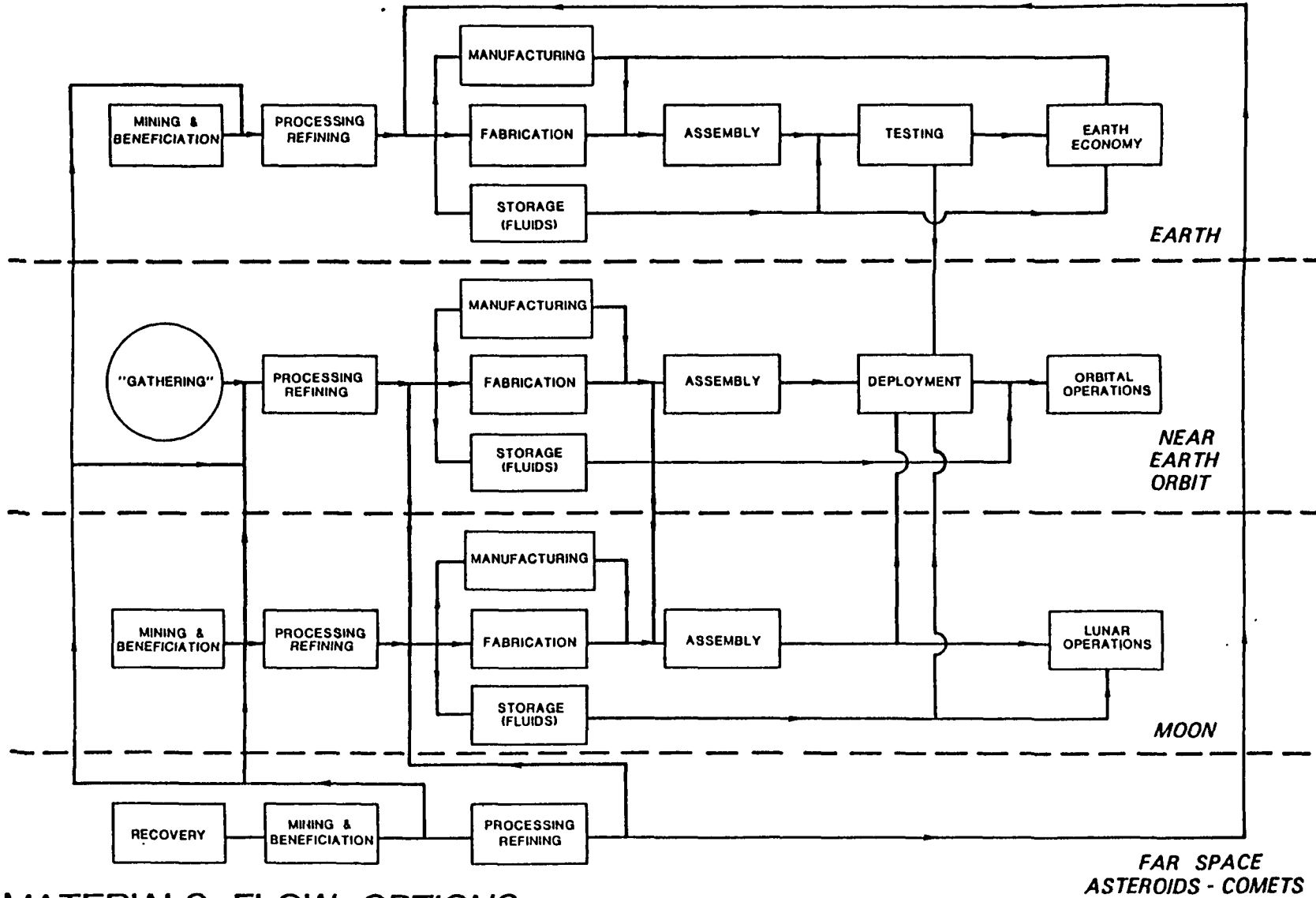
Step	t	R_m	r_m	R'_m	$h_1=tR_m$	$h_2=tr_m$	$h_3=tR'_m$
	Process Time(hr)	Contents Equiv. input	Mass Ratios Container Equiv. input	Net contents(LDE) Equiv. input	Equivalent Times* (hr) Contents	Container	Net(LDE)contents
Acid Leach	.5	22.2	.48	7.95	11.1	.24	3.97
Sedim.centrifuge/ Distill	.0167	22.2	28.8	7.95	.371	.48	.133
Hydrolyze	.5	44.9	.96	14.7	22.5	.48	7.36
Sedim. Centrif.	.0167	44.9	42.6	14.7	.75	.71	.207
Distill/Condense	.00278	7.06	86.4	2.14	.0196	.24	.006
Distill(1/2)	.00278	22.5	86.4	7.36	.0625	.24	.020
Hydrolyze/dry	3.0	3.0	.55	.728	9.0	1.66	2.18
Distill	.00278	7.63	86.4	1.36	.021	.24	.004
Electrolysis	27.5	1.45	.173	.036	40.05	4.75	1.0
Metals reduction	3.0	1.76	.48	.7	5.28	1.43	2.1
Regeneration(est)	.5	5.0	.48	.7	2.5	.24	.35
Misc.	.5	1.0	.4	1.0	.5	.2	.5
Subtotal	35.54				92.15	10.91	17.83

EXTRA MASS

(metric tons @ 4.21 ton/hr input)

equiv. time (hr)

Reagent Inventory	20	4.7
Compressors	10	2.4
Heat Exchangers	10	2.4
Pipes, Valves	5	1.2
Electrical	6	1.4
Structural & Misc.	25	5.94
Radiators (20 MW)	24	5.7
Elec. Power (30 MW)	120	28.5
Subtotal	220	52.24



MATERIALS FLOW OPTIONS

Figure 1.

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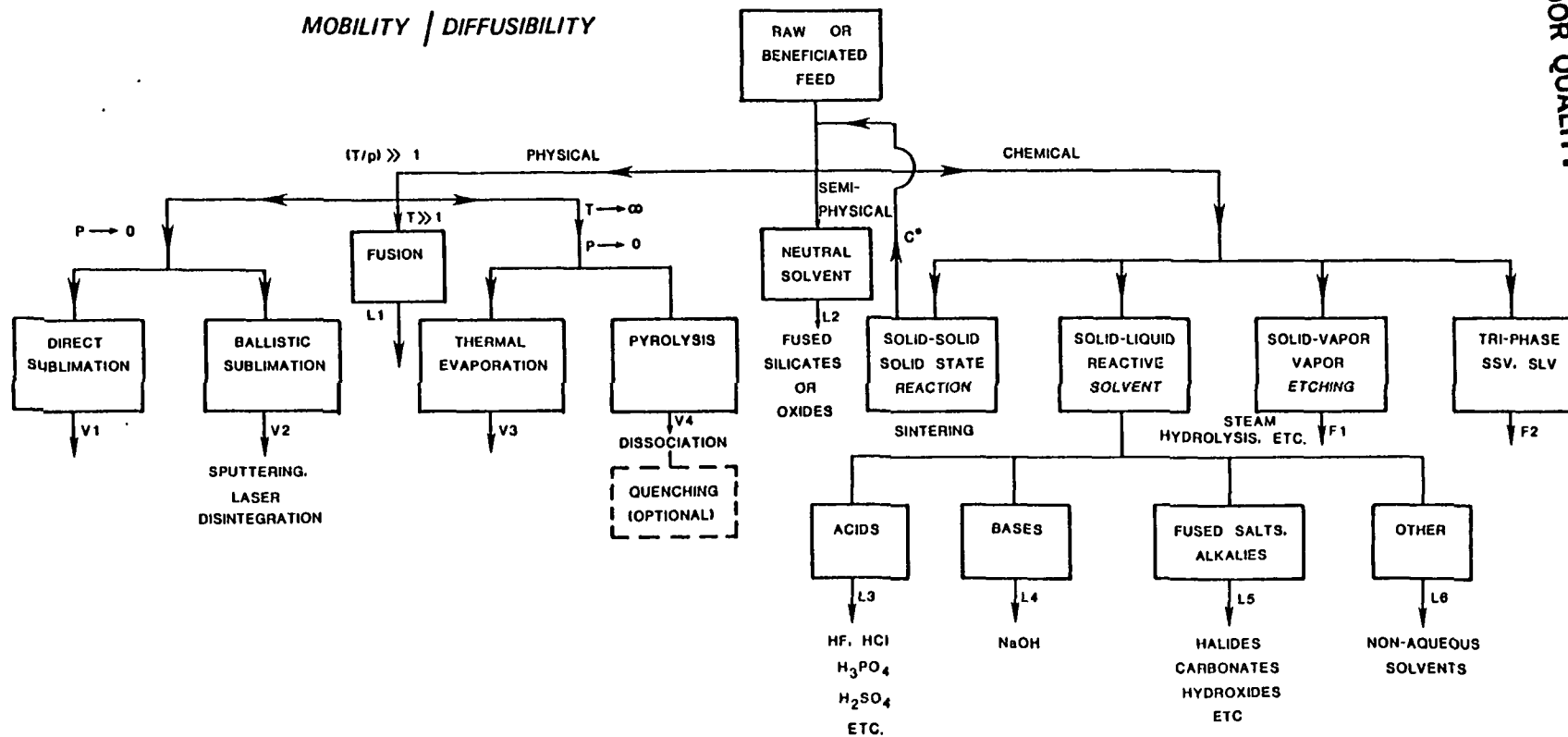


Figure 2.

SEPARATION

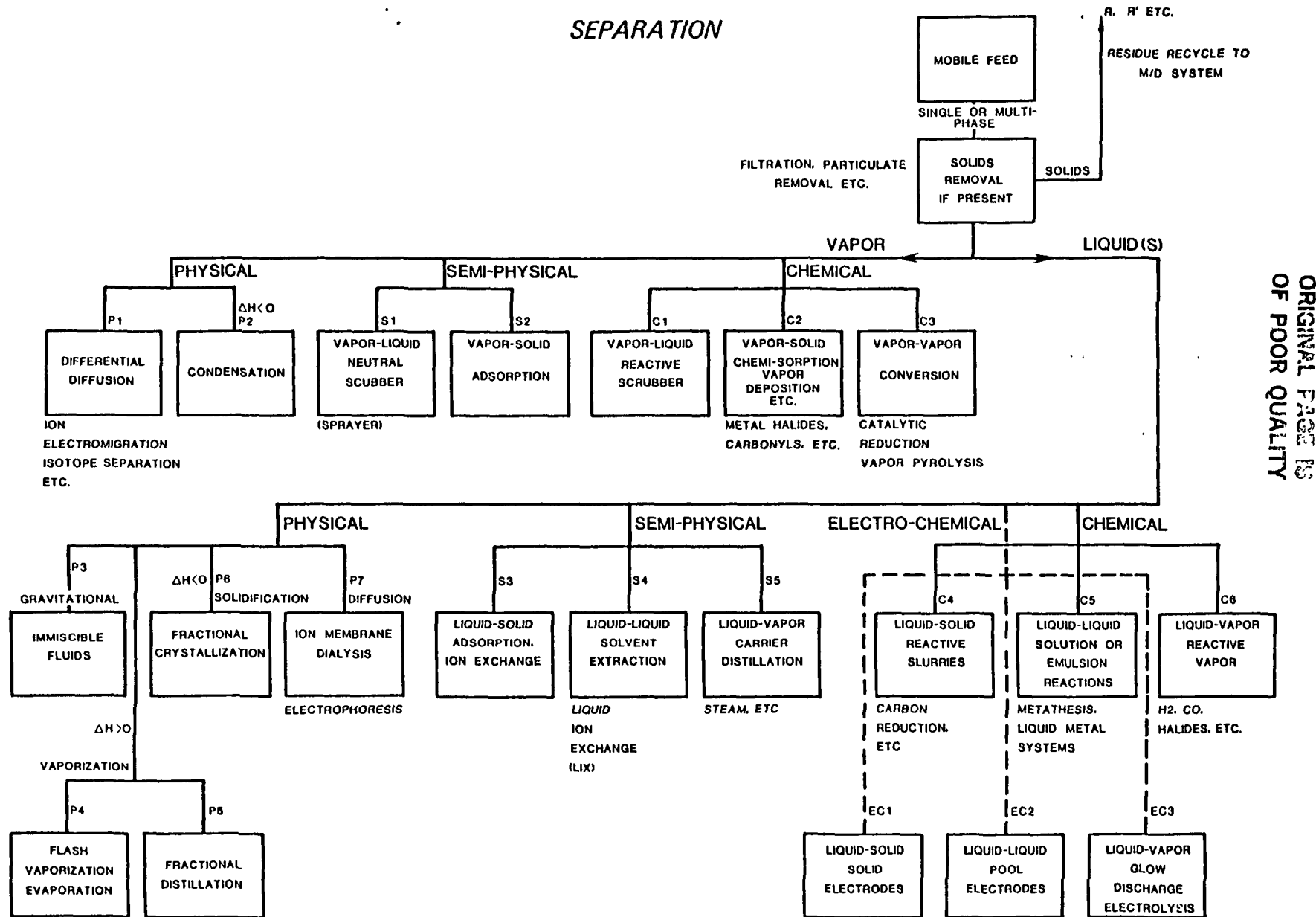


Figure 3.

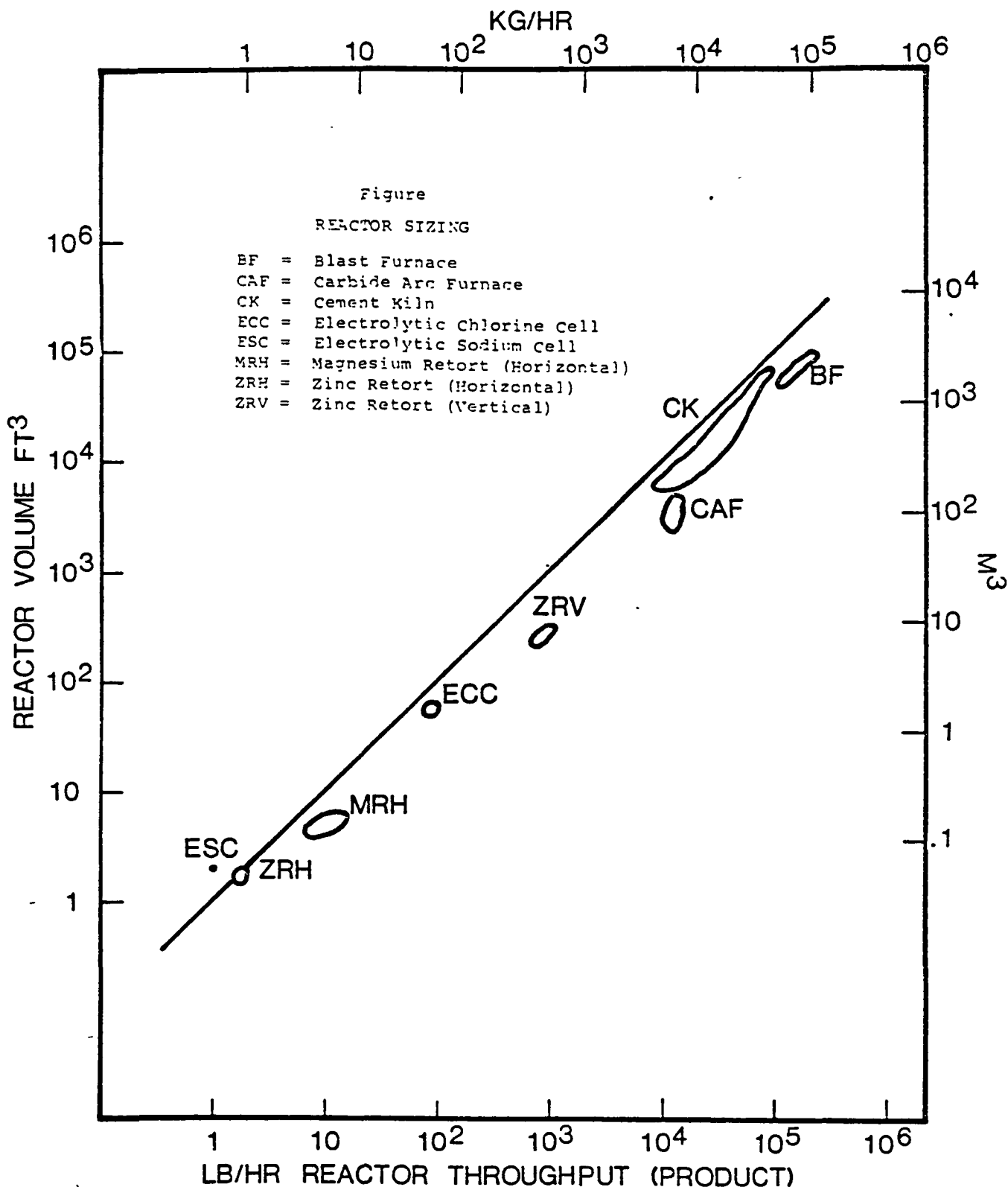
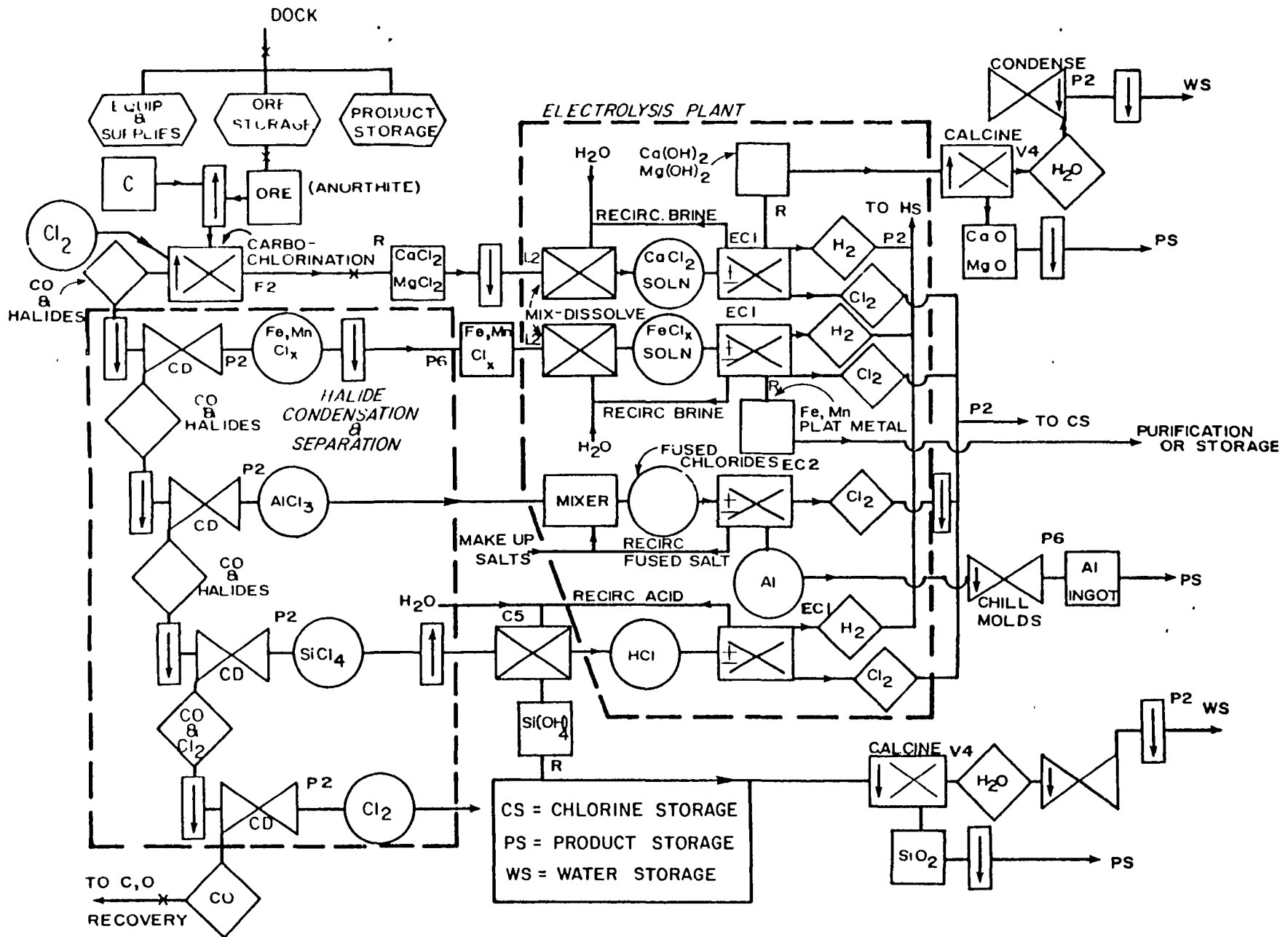


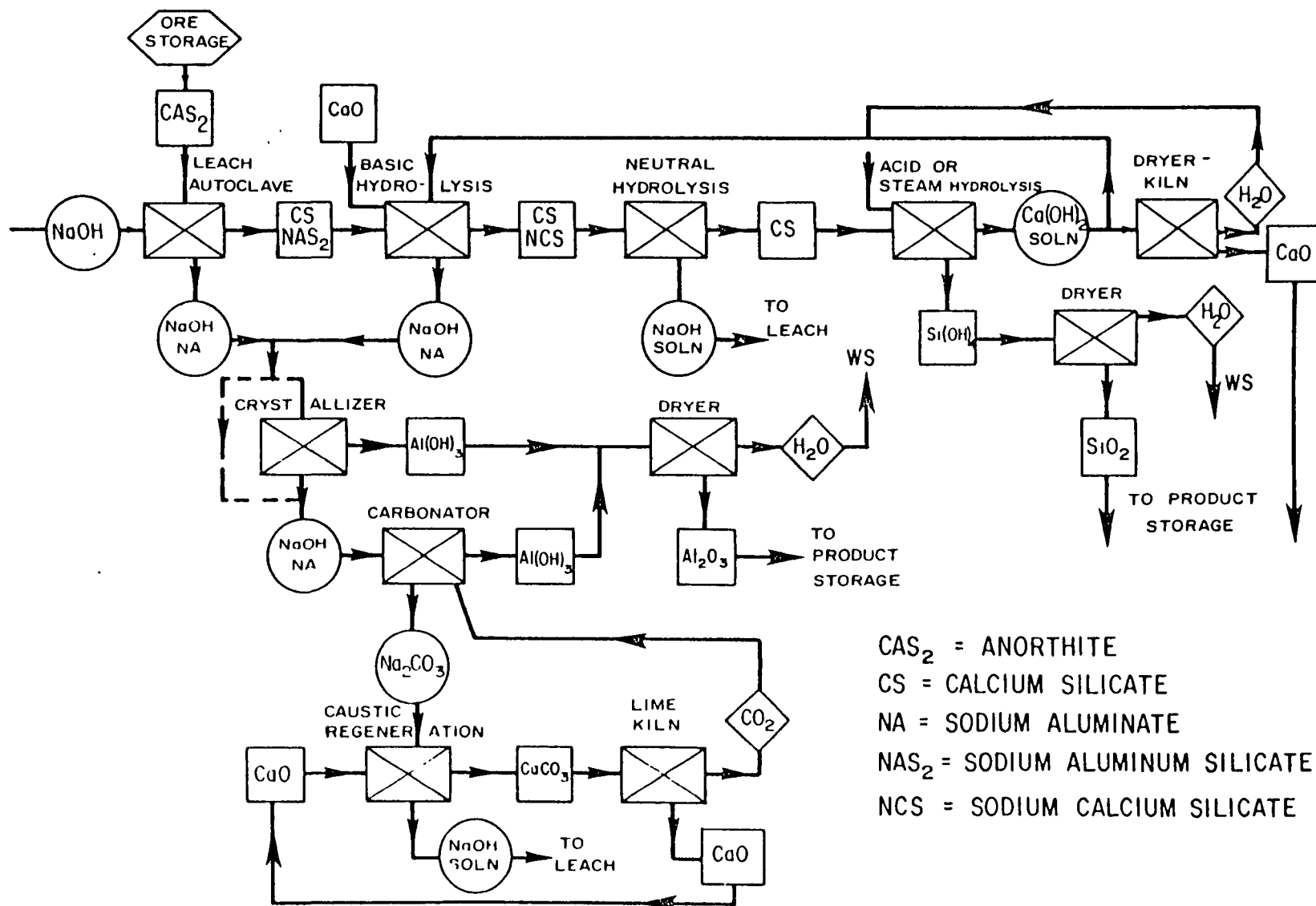
Figure 4



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Figure 5a.

SEPARATION



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Figure 6.

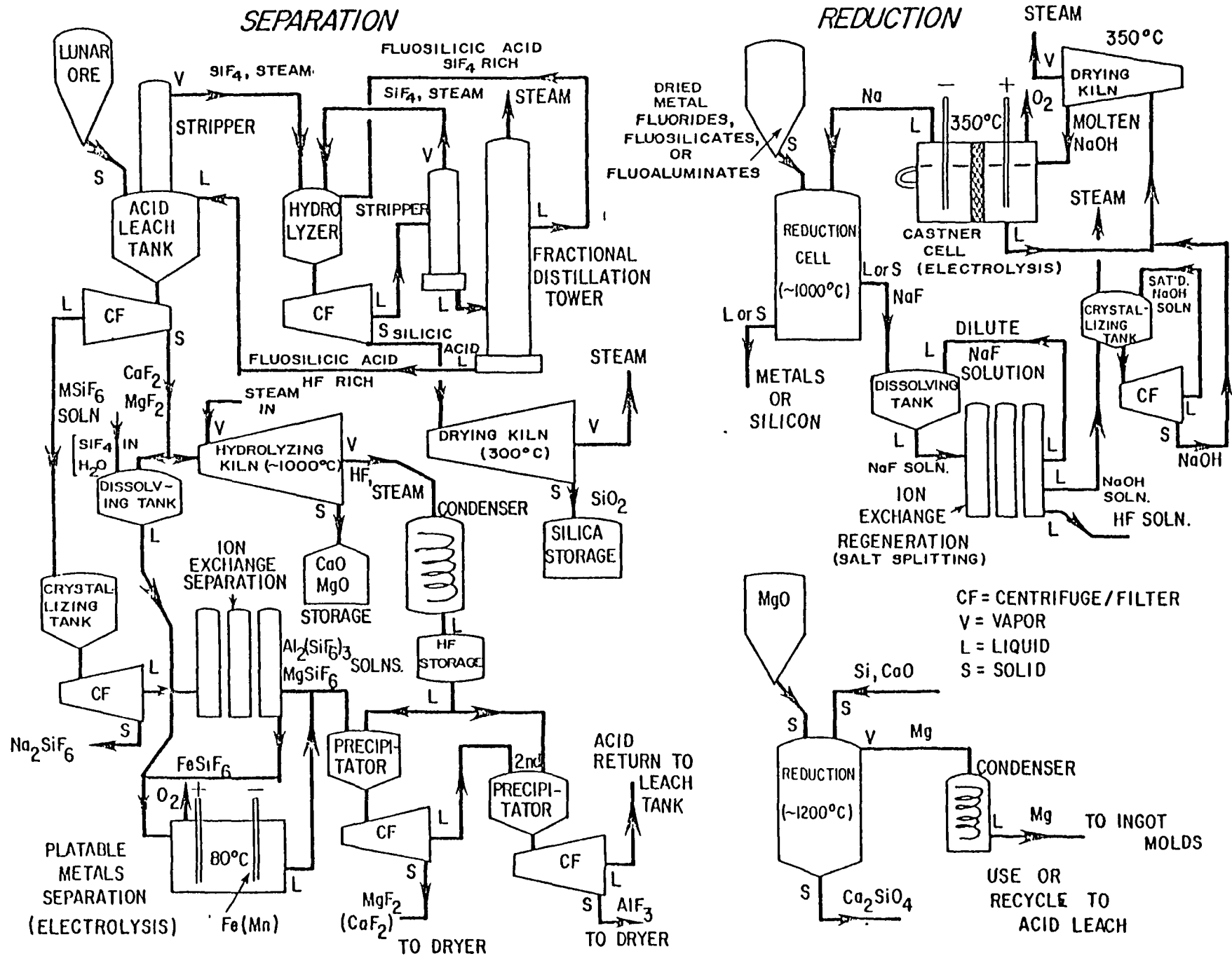


Figure 7.

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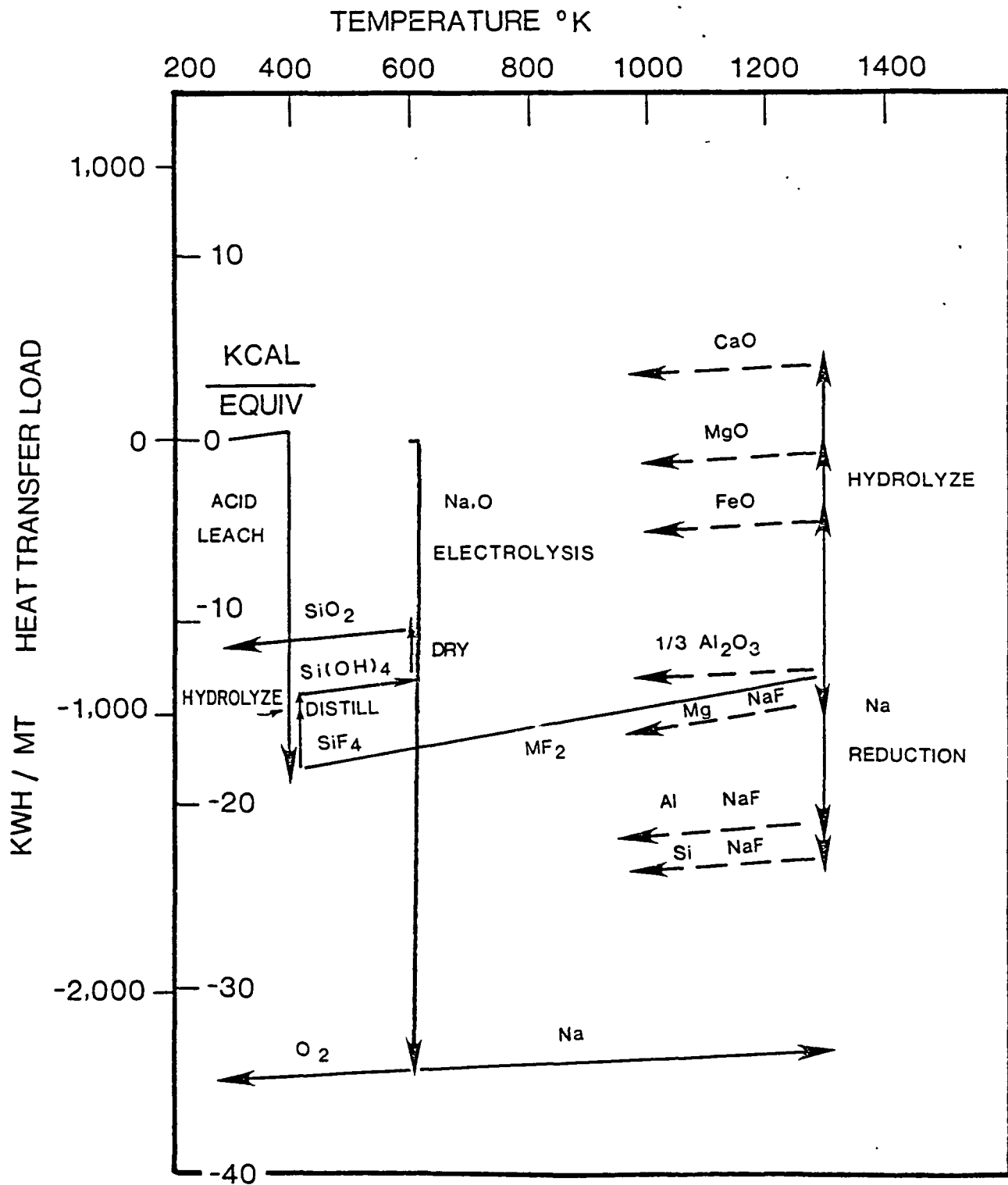


Figure 8.

NASA-JSC