



National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center

Houston, Texas 77058

30 September 1978

(NASA-CR-158870) EXTRATERRESTRIAL MATERIALS
PROCESSING AND CONSTRUCTION Final Report
(Lunar and Planetary Inst.) 476 p
HC A21/MF A01

N79-29204

CSSL 22A

Unclas
G3/12 31645

EXTRATERRESTRIAL MATERIALS
PROCESSING AND
CONSTRUCTION

FINAL REPORT

NSR 09-051-001 Mod. No. 24

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30 September 1978

OBJECTIVES AND RECOMMENDATIONS

Present day space operations support the service segments of the national and world economies. Astounding advances have been made over the past twenty years in the development of space tools for observation, communication and exploration. Major advances are forthcoming which will be characterized in part by a widening and increasing occurrence of direct connections between terrestrial individuals and space hardware. However, an economy capable of directed original growth in potency must be self-sufficient. It must be supported by the more fundamental materials economy. The creation of materials economies is the industrial revolution which has a 400 year history. Keys to the development of a materials economy are the availability of matter to be worked, energy to do the work and skill to use energy to mold matter to new uses and combinations. Development of a space materials economy or true space industrialization is strongly inhibited by the extremely high costs of obtaining matter from earth with which to work in space. Solar energy is clearly available to do work in space. The moon, and possibly certain asteroids, are primary sources of raw materials for large scale use in space.

Space systems have been proposed in detail which can provide large quantities of lunar and eventually asteroidal materials at low unit costs (\$/kg) for industrial use in cis-lunar space.

In this study we examine the application of available terrestrial skills to the gathering of lunar materials and the processing of raw lunar materials into industrial feed stock. We find that much terrestrial technology can be transferred to

the gathering of lunar materials and the processing of raw lunar materials into industrial feed stock. We find that much terrestrial technology can be transferred to industrial operations in space. Immediate development of plans and operations to make use of lunar materials in the 1980's in space is appropriate and feasible from the standpoint of gathering lunar surface materials and processing them in space. Planning for and the creating of a materials industrial economy in space can be initiated now. Major immediate objectives, which appear achievable, are to decrease the complexity of the physical systems and the capital expenditures needed to establish the first space industries. Space industrialization is technically feasible.

Our challenge is to craftily employ the skills available to us in our university, industrial/commercial and government organizations to create the initial materials economy in cis-lunar space for a minimum investment and in a minimum time. Now is the time to exploit the accomplishments resulting from this nation's 100 billion dollar investment in space, one fourth of that in lunar operations to produce a viable materials economy in the cis-lunar space.

CONTENTS

OBJECTIVES AND RECOMMENDATIONS	<i>i</i>
CONTENTS	<i>iii</i>
STUDY PERSONNEL	<i>x</i>
CHAPTER I. EXECUTIVE OVERVIEW	I-1
A. INTRODUCTION	I-1
B. THE MOON AS A SOURCE OF INDUSTRIAL MATERIALS	I-5
C. SCHEMATIC OVERVIEW OF SPACE INDUSTRIALIZATION	I-9
D. SPACE POWER STATIONS AND MATERIALS PROCESSING SCALES	I-12
E. CHEMICAL PROCESSING	I-21
F. LUNAR STRIP MINING	I-26
G. BENEFICIATION OF LUNAR SOILS	I-27
H. LUNAR GLASS AND CERAMIC PRODUCTS	I-29
I. MATERIAL GOODS AND THEIR INTRINSIC VALUE (\$/kg), MASS AND ENERGY OF PRODUCTION	I-30
J. DIRECTIONS FOR RESEARCH AND DEVELOPMENT	I-34
REFERENCES	I-52
TABLES	I-55
FIGURES	I-65
CHAPTER II. PROCESSING OF LUNAR & ASTEROIDAL MATERIALS	II-1
INTRODUCTION, BACKGROUND	II-1
PART ONE - METHODOLOGY	II-3
A. GENERAL CONSIDERATIONS	II-3

CONTENTS - continued

Potential Availability	II-3
Recovery Potential	II-5
Derivable Products	II-8
Product Mix Options	II-9
Bootstrap Operational Capabilities	II-10
B. MATERIALS PROCESS SELECTION	II-11
Introduction	II-11
Criteria for Process Evaluation	II-12
Process Constraints	II-15
C. GENERAL CLASSIFICATION OF MATERIALS PROCESSING SYSTEMS	II-16
Flow Chart Analysis	II-17
General Survey or Overview of Processing Methods	II-19
General Observations Concerning Chemical Conversions	II-20
Classification of Previously Proposed Processes	II-22
Assessment of Prior Methods	II-22
Solution Processes for Chemical Separations	II-23
Reduction Processes	II-24
D. CHEMICAL PLANT DESIGN	II-28
General Considerations	II-28
Space Environment Factors	II-29
Reagent and Equipment Mass	II-31
Unit Operations	II-33
General Sizing Considerations	II-38
PART TWO - SPECIFIC PROCESSES	II-40
E. ANHYDROUS PROCESSES	II-40
INTRODUCTION	II-40

CONTENTS - continued

1. Carbochlorination	II-40
2. Electrolysis of Molten Silicates	II-43
F. HYDROCHEMICAL (AQUEOUS) PROCESSES	II-43
1. HF Acid Leach Process	II-44
2. HCL Acid Leach Process	II-47
3. NaOH Basic Leach Process	II-51
G. SYNOPTIC COMPARISONS OF PROPOSED PROCESSING SYSTEMS	II-53
H. SOME PERSPECTIVES IN THE MINING/ BENEFICIATION/MATERIALS PROCESSING/ REFINING PHASES OF SPACE INDUSTRIALIZATION	II-54
PART THREE - TECHNOLOGY DEVELOPMENT	
	II-58
INTRODUCTION	II-58
I. TIME, COST & SCALE OF TECHNOLOGY DEMONSTRATION PROGRAMS	II-60
J. INFORMATION REQUIREMENTS FOR MANAGEMENT DECISIONS IN THE IMPLEMENTATION OF SPACE PROCESSING TECHNOLOGY	II-62
K. PROCESS SELECTION AND QUALIFICATION	II-64
L. DETAILED RECOMMENDATIONS	II-68
M. TECHNOLOGY INTERACTION STUDIES	II-76
REFERENCES	II-80
TABLES	II-83
FIGURES	II-100
APPENDICES	II-134
(A) MASS HEAT TRANSFER CONSIDERATIONS IN LOW PRESSURE DISTILLATIONS	II-134
(B) ELECTRODEPOSITION OF ACTIVE METALS AS AMALGAMS	II-136

CONTENTS - continued

(C)	MINIMIZATION OF POWER PLUS SPACE RADIATOR MASS BY HEAT PUMPING	II-138
(D)	COMPARISON OF CONTAINER AND CONTENT WEIGHTS OF SPHERICAL AND CYLINDRICAL VESSELS	II-140
(E)	ANALYSIS OF OPTIMUM MASS FOR DRYING PROCEDURES	II-142
(F)	PROJECTED MASSES FOR SPACE ELECTRIC AND THERMAL POWER AND RADIATORS	II-144
(G)	ENGINEERING DESIGN PARAMETERS	II-146
(H)	CARBOCHLORINATION PROCESS ENGINEERING DATA	II-148
(I)	HF ACID LEACH PROCESS ENGINEERING DATA	II-157
(J)	MATERIALS SPECIFICATIONS	II-176
CHAPTER III. LUNAR STRIP MINING ANALYSIS		III-1
	SUMMARY	III-1
A.	INTRODUCTION	III-1
B.	MINING PLAN	III-3
1.	Mining Rate	III-3
2.	Mine Geometry	III-4
3.	Early Year of Mine	III-4
C.	NUMBER OF HAULERS AND EXCAVATORS	III-5
1.	General Expression	III-5
2.	Discussion of Factors	III-5
3.	Complete Expression	III-16
4.	Number of Haulers Required	III-16
5.	Hauler-Excavator Match	III-19
6.	Spare Vehicles and Spare Parts	III-20
7.	Summary of Mining Equipment	III-20

CONTENTS - continued

D.	MASS OF MINING EQUIPMENT	III-20
1.	Mass of Haulers	III-20
2.	Mass of Front-End Loader	III-21
3.	Cumulative Mass of Mining Equipment	III-22
E.	ENERGY REQUIRED FOR MINING SYSTEM	III-22
1.	Hauler Transport	III-22
2.	Ballistic Transport	III-24
F.	PERSONNEL	III-25
1.	Lunar-Based Personnel	III-25
2.	Automatic Haulers	III-26
3.	Remote-Controlled Front-End Loader	III-27
G.	ADDITIONAL STUDIES	III-27
H.	REFERENCES	III-30
I.	TABLES	III-31
J.	FIGURES	III-40
CHAPTER IV.	BENEFICIATION OF LUNAR SOILS	IV-1
	SUMMARY	IV-1
A.	GENERAL	IV-1
B.	PRINCIPLES OF ELECTROSTATIC SEPARATION	IV-3
C.	A LOOK AT THE EXPECTED LUNAR MINERAL BENEFICIATION TO BE CARRIED OUT ON THE MOON SURFACE	IV-9
D.	KEY STUDIES NECESSARY FOR A DEFINITIVE EVALUATION OF THE APPLICABILITY OF ELECTROSTATIC SEPARATION TO LUNAR SOILS	IV-17
E.	CONCEPTUAL DESIGN FOR AN EXPERIMENTAL APPARATUS TO STUDY THE ELECTROSTATIC SEPARATION OF THE LUNAR SOILS	IV-20

CONTENTS - continued

F.	CONCEPTUAL DESIGN OF A LUNAR FACILITY FOR PRODUCING 1 MEGATON OF BENEFICIATED ORE PER YEAR	IV-22
G.	CONCLUSIONS	IV-25
H.	REFERENCES	IV-28
I.	TABLES	IV-32
J.	FIGURES	IV-35
K.	APPENDICES	IV-50
	(A) Patents	IV-50
	(B) Tribo and Traveling Fields	IV-62
	(C) Forces on Charges Particles	IV-64
CHAPTER V.	LUNAR GLASS AND CERAMIC PRODUCTS	V-1
A.	INTRODUCTION	V-1
B.	LUNAR MATERIALS OF IMPORTANCE AS GLASS AND CERAMIC PRODUCTS	V-1
	1. Lunar Soil as Found	V-2
	2. Anorthite from Purified Plagioclase	V-3
	3. Silica from Silicon Oxidation	V-4
	4. Alumina and Magnesia	V-5
C.	PROCESSING OF LUNAR MATERIALS - GENERAL CONSIDERATIONS	V-5
D.	SOME SPECIFIC EXAMPLES OF PROCESSING COMMON GLASS AND CERAMICS IN SPACE AND ON THE MOON	V-8
	1. Production of Glass Windows in Space	V-8
	2. Production of Glass Wool in Space or on the moon	V-9
	3. Production of Refractories on the Moon	V-9

CONTENTS - continued

E. SPECIAL "GLASSES" BASED ON HIGH VACUUM AND/OR ZERO GRAVITY	V-10	
F. CONCLUSIONS AND RECOMMENDATIONS	V-11	
G. REFERENCES	V-12	
H. TABLES	V-13	
I. FIGURES		
CHAPTER VI. INTRINSIC VALUE (\$/KG), TOTAL MASS (KG) AND PRODUCTION ENERGY OF SELECTED GOODS		I-1
A. BACKGROUND	VI-1	
B. SELECTION CRITERIA	VI-5	
C. METHODOLOGY	VI-11	
D. TABULAR RESULTS DESCRIBED	VI-18	
E. REFERENCES	VI-23	
TABLES	VI-25	
FIGURE	VI-52	

STUDY PERSONNEL

Dr. David R. Criswell - is the principal investigator on the "Extraterrestrial Materials Processing and Construction Program." He is the Associate Scientist with the Lunar and Planetary Institute which is operated by the Universities Space Research Association. He has been with the Institute since 1970 and has conducted 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 Research Association (1976-1977) which conducted the review of all proposals for experiments to fly onboard the development missions 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.

Dr. Robert D. Waldron - is a research scientist with the Lunar and Planetary Institute and is 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 post-doctorial 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.

Dr. Thomas E. Erstfeld - is currently a Senior Scientist with the Systems and Services Division of Lockheed Electronics Company, Inc. in Houston, Texas. He was with the Lunar and Planetary Institute in 1977 and 1978 and worked on the development of ion exchange processes for the processing of lunar soils. He received his Bachelor of Science degree in 1973 from Gannon College and the Doctor of Philosophy in

chemistry from Brown University in 1977. He is a member of the American Chemical Society.

Dr. W. David Carrier, III - is with Bromwell Engineering of Lakeland, Florida, and previously with Woodward Clyde Consultants (San Francisco), Bechtel, Inc. (San Francisco) and the Johnson Space Center. His work at the Johnson Space Center was concerned with development of sampling devices and research strategies for gaining an understanding of the properties of the lunar soil from the standpoint of civil engineering applications. He has extensive experience in the analysis of civil engineering projects concerned with large scale excavation and extensive experience with the development of lunar research during the Apollo program. He was a recipient of the Norman Medal of the American Society of Civil Engineers in 1972 for his work on the Apollo-11 investigations of the properties of the lunar soil. He received the Bachelor of Science, Master of Science and Doctor of Philosophy in Civil Engineering from the Massachusetts Institute of Technology in 1965, 1966 and 1969 respectively. Dr. Carrier was a consultant to this program and provided the majority of the analysis for chapter III.

Professor Ion I. Inculet - is the Chairman of the Electrical Engineering Group of the faculty of Engineering Science at the University of Western Ontario, London, Ontario. He has extensive industrial experience in design and development

engineering and as director of projects related to electric motors, high frequency generators, instrumentation and control systems. He has carried out fundamental research at the University of Western Ontario on various aspects of electrostatics engineering related to contact charging, corona phenomena and electrostatic painting, fine particle separation in fluidized beds, and pesticide applications in orchards and field crops. Professor Inculet received his Bachelor of Science in 1944 from Laval University of Quebec. He has over 50 publications, holds four patents on electrostatic processes and is an active member in five scientific and professional societies. He was elected a Fellow of the Institute of Electrical and Electronic Engineers in 1978.

Professor John D. Mackenzie - 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. He provided the majority of the work on chapter V as a consultant to the program.

Dr. Robert U. Ayres - is president of the Variflex Corporation in Washington, D.C. Dr. Ayres is a physicist with a strong working background in economics and is extremely active in exploring the application of physical theory to the understanding of economic concepts. He received a Bachelor of Science in Mathematics from the University of Chicago in 1954, his Masters of Science in physics from the University of Maryland in 1956 and the Doctorate of Philosophy in physics from the University of London in 1958. He has authored several books on physical economics, contributed to professional journals in economics and is a member of the AAAS, American Economic Association, Society of Automotive Engineers, World Futures Studies Federation, and other professional groups. He consults extensively on environmental problems with several analysis groups in the Washington area, particularly Resources for the Future, Inc.

I. EXECUTIVE OVERVIEW

A. INTRODUCTION

Incorporation of extraterrestrial materials into large space structures and products for the materials and service^{1,2} industries requires the introduction of two new planning elements into the development of the overall space system which are different from the complete supply of all materials from earth. These new elements are: (1) acquisition of the raw materials from the moon, earth approaching asteroids or other materials sources and (2) the physical and/or chemical processing of the materials into forms suitable for the utilization by downstream industries. Table I presents seven qualitative arguments for the use of extraterrestrial materials.

In this investigation we have focused on the utilization of material from the moon because the characteristics of soils, rocks and data returned during the Apollo program have been examined in great detail (>15,000 man years of research). An extensive, well indexed and reviewed literature exists from which specific engineering approaches and problems can be accurately defined for the acquisition and processing of the soils.³ In addition, over 1,500,000 man-years of well documented technical effort was accumulated during the Apollo, Skylab, Apollo-Soyuz, and Space Shuttle programs with respect to creating and operating extensive manned activities in earth orbit, cis-lunar space and on the lunar surface.

Earth approaching asteroids will at some point in the future be an important source of industrial material for use in space. One can expect to obtain a greater range of materials from a number of asteroids than can be obtained from the low latitude lunar soils.^{3,4,5} However, we do not know in detail the bulk mineralogy or chemical composition by indirect observations of any of the asteroids. Detailed systems planning and analysis for asteroid use is more challenging pending direct analysis. It is not unreasonable that early return to the vicinity of the earth of large quantities of asteroidal materials may constitute a portion of the early exploratory phase. Immediate utilization of asteroidal mass for radiation protection, reaction mass or other direct functions can occur on return. Thereafter chemical processing schemes can be brought into operation.

The "Extraterrestrial Materials Processing and Construction" program has focused on the following major tasks:

- (1) Review the available literature on lunar soils and rocks and identify one or more chemical processes by which the major oxides and chemical elements can be extracted. A critical review was also conducted on previously proposed processing schemes and their limitations and advantages were identified.

- (2) Applicability of terrestrial knowledge of glass and ceramic production technology to the production of lunar glasses and ceramics was investigated.
- (3) Gathering of the soil on the lunar surface by means of excavation equipment was studied in terms of terrestrial experience with strip mining operations on earth.
- (4) The application of electrostatic beneficiation techniques was examined for use on the moon to minimize the quantity of materials requiring surface transport and to optimize the stream of raw materials to be transported off the moon for subsequent industrial use.
- (5) The Standard Industrial Categories (SIC's) of the United States' economy were examined for 1967 and 1972 to determine which SIC's contained items producible in large part or partially from lunar materials. The average intrinsic cost (\$/kg) of all the products in each SIC was calculated. The total energy of production of each SIC (billions kilowatt hours) was determined. The study provides the first qualitative feel for which terrestrial industries initially might be adaptable to operate in space due to considerations of available raw materials, intrinsic product value (\$/kg) and sector energy consumption.

Major results of the studies are summarized in Table II and are described in the following pages. The study did not consider the various means which have been proposed to eject material from the lunar surface into space or the fabrication of goods from the chemically processed industrial feedstock except for suggestions of a few interesting potential products. Attention was given to the possible alloys that could be produced from lunar materials and from lunar materials combined with minor or trace alloy elements from earth. Finally, specific recommendations are made for experiments and theoretical investigations which would provide key information for the planning of baseline or reference systems for the chemical processing of lunar soil. Development plans to achieve those systems early in the shuttle era are presented. The results of these studies are in preparation for publication in the scientific, engineering and business literature.^{6,7,8,9}

We will examine in the remainder of this executive summary why the moon constitutes not only a suitable reservoir of raw materials for the construction of space power systems (SPS) but why it is also well suited to meet many of the major materials needs of a general industrial economy. Specific chemical processing systems selected for further study as appropriate to the space environment will be discussed and it will be pointed out that the development time of one or more of these as a

space system scaled to the prototype industrial level can be readily accomplished in the early 1980's. Such prototype systems can satisfy the materials needs of initial large space projects in the late 1980's and early 1990's by processing of lunar materials. Results of the studies on glass production, lunar strip mining and electrostatic beneficiation and technology transfers to space will be reviewed. We will examine the various Standard Industrial Categories to determine which contain input materials and operations appropriate to space. Finally, the recommendations for near and midterm studies to identify and develop specific physical, thermal and chemical processing systems will be presented. It is very likely that the time and expense needed for the development of the initial materials processing systems will be very reasonable by the standards of aerospace hardware development. This is due in part to the small scale of the materials handling requirements of the early large space systems which are comparable to the prototype level in terrestrial industry and in part to the considerable industrial experience available for the production of similar processing operations.

B. THE MOON AS A SOURCE OF INDUSTRIAL MATERIALS

Dry and dusty, the moon appears to be an unlikely place from which to extract the basic elements necessary to build either specialized structures in space or a generalized space economy. However, surface appearances are deceiving and the basic elemental requirements of present terrestrial industry are not generally appreciated. Terrestrial industry consumes

a wide range of elements in producing the outputs which make industrial societies possible. Demandite is a conceptual or synthetic molecule which is composed of the weight fractions of the major elements consumed by industry (Figure I-1). Table I-3 gives one estimate of the weight fraction of materials used in the United States' economy in 1968.¹⁰ Notice that by weight 40% of the molecule is fuel for the industrial and transportation industries. Space demandite must differ radically from this distribution because solar electricity must replace hydrocarbons as the source of energy. This is similar to what must happen eventually on the earth either for reasons of depletion of the hydrocarbon reserves or possibly due to carbon dioxide contamination of the atmosphere.¹¹ Approximately 45-52% is used as building materials for roads, dams, building and so on. Table II-4 (column 3) gives the weight fraction distribution of elements in the demandite molecule if the fraction of the hydrogen and carbon used as petroleum is subtracted but the fraction (2%) used for plastics is retained. Notice that oxygen, silicon and calcium mostly in the form of calcium carbonate (CaCO_3) and silica (SiO_2) are the most common elements. Metals constitute 5.7% of the molecule, agriculturally related elements 1%, and chemical processing elements 3%. In column 4 we see the weight distribution of elements in the Apollo 15 soils. What is immediately apparent is that most of these economically significant elements (O, Si, Ca, Fe, Al, Mg and Ti) can be extracted from the lunar soil with no more than a factor of two enhancement in concentration. The metals are especially

abundant. Elements requiring especially large enhancements constitute approximately .03% of the demandite weight fraction (C, Mn, N, Cl, and H) whereas elements requiring a factor of 2.1 to 10 enhancement (K, P, Na, and Ca) constitute 8% of the demandite weight fraction. Such enhancements are possible so virtually all the non-fuel demandite can be acquired from lunar soils sampled to date. It must be emphasized that these are the elements used in the production of new goods and process elements and not the elements which are continuously recycled in industry and agriculture such as those in water and air (hydrogen, nitrogen and carbon).

Industry in space (Figure I-2) will certainly require a different mix of chemical inputs. It is likely that fiberglass and glass will replace concrete and stone as dominant components in building materials for large structures. Lunar soil is an ideal source of raw materials for such structures. The availability of solar thermal and electric energy will minimize the processing costs in space of glass and fiberglass composites. Extractive industry in space must continually design for increasing closure against loss of the various process fluids. The economic pressures will be far stronger for process closure due to costs of replacing lost fluids than in terrestrial industry due to environmental and economic pressures. Research and development of space industries will have many direct applications to terrestrial industrial practices and could assist in drastically reducing the production of waste products in terrestrial industries by introducing new practices. In addition, the elements which

are most abundant on the earth such as iron, aluminum, silicon, magnesium and titanium will be developed to perform an increasing number of industrial roles due to higher costs of less available elements. Thus, space industries can be expected to introduce new products and procedures to terrestrial industry of the exact character that will be needed in the future to circumvent the effects of depletion of key minor element resources. It is also foreseeable that the glasses, ceramics, and metals produced in space may find markets on the earth not simply due to possible lower costs but due to the elimination of the need to provide process energy on the earth to extract and refine the materials. In this manner a fraction of processing energy can be made available for other purposes of higher social desirability. Approximately 20% of the gross energy content of fuels is consumed in bringing the energy to the market place. This fraction is rising steadily as less accessible or more polluting energy sources are exploited. In the United States more than 20% of the energy is expended in processing metals (8%), chemicals and allied products (8%), petroleum refining (4%) and production of non-metallics (2%).¹² These fractions could eventually double as more materials are extracted from minimal grade stocks on earth.¹⁰ Thus, power may be effectively transported to the earth at some future time, in large quantities, in the form of the processing energy of refined industrial feed stocks from extraterrestrial materials.

C. SCHEMATIC OVERVIEW OF SPACE INDUSTRIALIZATION - GROWTH AND PRODUCTION

Figure I-2 is directly relevant to understanding the goals of the "Extraterrestrial Materials Processing and Construction" program. In this diagram are identified the major functional activities and where they occur, major mass accumulations and flow rates, capital and through-put expenditures and critical recycle loops for the grow and steady state phases of a space industry. Definitions of the various letters are stated in the caption to figure I-2.

Major efforts have been directed in this study toward understanding the chemical processing techniques that are applicable to space operations which would occupy box (6) in figure I-2. We have examined previous schemes proposed for bulk chemical processing techniques, identified new processes and adaptations, estimated plant masses and efficiencies for one particular design and explicitly considered the quantities of materials which must be supplied for plant construction and operation in the first and subsequent bootstrapped plants.

One consulting effort was directed toward the suitability of lunar soils to the production of glass and ceramics (Box 6). A second, the physical beneficiation of lunar soils into ore concentrates by electrostatic separation devices (Box 4) was considered because it may allow a low cost and low power means to tailor the input of raw material into the transportation system to the needs of the final industrial processes which are dominant at a given time. Physical processing might occur on

the moon prior to material ejection into space or/and in space at the industrial center.

A third consulting effort focused on the scale of strip mining activity on the moon which is required to support a mass flow off the moon of 30,000 MT*/yr to 1,000,000 MT/yr in terms of type of equipment needed, mining conditions, buildup of equipment with time, power needs versus time and the type and number of personnel needed. The mining study relates to the activities in box (4) and on the moon (3).

The fourth report was a survey of industrial output on earth in terms of the intrinsic value of goods produced (\$/kg) and the total energy consumption of these goods (Billions Kw-Hr). The study was organized by Standard Industrial Categories as a general guide to the types of industries which could be expected to evolve in space, the intrinsic value-added by such industries (\$/kg) and in the longer view to provide a guide as to what large space industries might penetrate the terrestrial market place.

Several general observations concerning figure 2 are worth making. The coefficients d_e (demandite make-up from earth), C_p (processing fluids make-up) and C_r (make-up loss of life-support materials) should be minimized both in the start up and steady operating phases of space industry. The loss of material (1 & 1) should be minimized. The mix of material M' should be adjusted to minimize transport requirements and processing requirements. The demandite formulation can be expected to change with time as different space products are emphasized and

* MT = metric tons

as experience allows the development of more material substitutions. It is not unreasonable to expect $d_e < 0.05$ to 0.01 to be achievable. As the population in space increases there will evolve habitable structures in which material used for radiation protection will also be used for structural support of the internal atmosphere and other loads. Very likely a fiberglass-metal composite will be evolved to provide this combined function and will provide multi-story internal walls (floors) for large habitats. Attention should be given at an early stage to the construction of such units and the recovery of the minor and trace element inventory from the raw lunar materials which would be used for the wall or hull construction. Finally, the volume and number of distinct regions of space over which industrial operations are performed should be minimized in the early phases.

It has been estimated that lunar soil [M' (\$/kg)] can be obtained in the early phases of space industrialization for as low as 15 to 30 \$/kg.^{13,14} With time, this cost should drop to a small multiple of the cost of the electric power used to eject material from the moon. As an example: If power could be acquired in space at 25 mills/kw-hr the minimum ejection cost would be approximately 0.02 \$/kg which is considerably less than the cost of most terrestrial refined materials and finished goods and considerably less than the expected turn of the century earth launch costs of 15-30 \$/kg. However, in the earliest stages of industrialization the space products can have intrinsic values between 20 and 200 \$/kg to cover the cost of lunar

material acquisition and processing and capital investments and still be less than the cost of launching the materials from earth.

It appears on the basis of our chemical processing studies that process fluids make-ups $C_p \leq 0.005$ can be achieved for anorthosite processing. This study and previous studies^{15,16} indicate that $C_e(\text{kg}) \leq 3 \cdot 10^3$ tons must be placed in low earth orbit to implace a supply base on the lunar surface which can eject $\dot{m}_k = 3 \cdot 10^4$ tons/year of lunar soil into space initially and grow to an annual ejection rate of $\dot{m}_k = 10^6$ tons/year in five years.

D. SPACE POWER STATIONS AND MATERIALS PROCESSING SCALES

Space solar power stations appear to be ideal candidates for initial products because of their expected high intrinsic value (200 to 400 \$/kg, E_e in figure I-2) 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.¹⁷ With redesign this fraction might be increased somewhat and more importantly the fabrication processes might be substantially simplified. An area of considerable possible advancement is the replacement of the basis photovoltaic cell with photoelectric emission devices which appear to be extremely easy to produce in space from lunar materials and ideally suited to space operation in a radiation environment.^{18,19,20}

Using the terrestrially baselined SPS models, the principal materials input requirements from the moon appear to be easily met and are given in table V for a 87,800 MT SPS with a projected 10 gigawatt ground output.¹⁷ Assuming production of one SPS per year for the first few units the output processing rates of lunar materials are 56,000 MT/yr for silica glass, 15,000 MT/yr for pure silicon, 12,000 MT/yr for aluminum, and 5,000 MT/yr for iron. Earth import of 440 MT would be required. The qualitatively significant point is that these processing quantities are more comparable to the production capacities of terrestrial prototype plants rather than to the capacities of large scale industrial plants. Other reductions in the mass of highly refined components can be anticipated as systems designed to make best use of lunar materials and the space environment are considered.

It is important to pursue the subject of the SPS as a candidate for construction in space because it provides a dramatic model by which to appreciate the power of lunar utilization for establishing space industry of a qualitatively significant nature in a reasonable period of time with near term technology. Figure I-3 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. 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 metric tons. 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.

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 MT or the same as one SPS. We see that the SPS is an extremely efficient mechanism for the collection of and conversion of solar energy.

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. The sophisticated components have a total mass of approximately 4,500 MT and occupy a volume of equivalent mass of concrete of 10 by 10 by 9 meters. The mass of ground antenna supports is large and corresponds to 20% 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.

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 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 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.^{21,22} 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.¹⁰

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 a overall mass of the order of 8,000,000 MT including foundations, radiation shield, reactors, generators, and ancillary equipment.

A coal fired plant composed of 20 units of 0.1 GW output would have a mass the order of 2,000,000 MT 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 MT of coal each year. Thus, one 10 GW coal station must transport the mass equivalent of Grand Coulee Dam each year.

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 figure I-3. 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.²² 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 very heavy lift launch vehicles (PHVLLC) to transport 100,000 MT to low earth orbit is indicated in figure I-3 as effluent from Grand Coulee Dam. The effluent could form of a slug of water 10 meters deep by 300 meters wide by 660 meters long. Theoretical designs are available of boosters which are scaled to accomodate this quantity of liquid propellant usage over the course of 250 flights. Other booster designs utilize hydrocarbons and liquid oxygen and have an effluent mass approximately four times as great. 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 1,100 MT or 790 MT in the first stage and 360 MT in the second stage with a payload to orbit of 390 MT. Half of the fuel in each flight would be to boost the inert mass of the second stage into orbit.

If hydrogen and oxygen were burned stoichiometrically the moon and used to eject with 60% efficiency 100,000 MT into space by means of an electromagnetic mass driver then only 27,800 MT of water would be produced which corresponds to 1.4% of the terrestrial water effluent or a stream flow in figure I-3 of 10 meters deep by 300 meters wide by only 9.3 meters rather than 660 meters in the terrestrial example. 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 70, 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.

The magnitude of equipment which must be employed on the moon and in space in the gathering and processing of lunar material are explored in figures I-4 and I-5. As was suggested in the discussion of figure I-2 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. Figures I-4 and I-5 are based on systems designs which embrace that approach. The first (I-4) depicts the assembly of an initial lunar supply base. The rationale and design of the base was developed during the 1977 summer study on space industrialization conducted at the NASA Ames Research Center.²⁴ Initial mass on the moon of the base would be approximately 800 metric tons. Approximately 4000 metric tons of landers, fuels and payload would have to be ejected from low earth orbit to the moon to land the base. It would begin ejecting 30,000 metric tons/year of bulk lunar soil and grow in launch capacity to 600,000 metric tons/year over a 5 year period. 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. Shown in figure I-4 is an excavation of a few meters depth 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. In the first two years a backhoe of the type shown here with a mass of less than 25 tons could accommodate the excavation rates of 30,000 to 60,000 metric tons per year with only 3 to 6 sorties each terrestrial day. It would be available for other operations the

remainder of the day. 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. An extensive analysis of the build-up of the mining machines is presented in chapter III. Under nominal conditions with electrostatic 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.

Figure I-5 is an artist's conception of a prototype plant to process anorthosite. It incorporated the design requirements appropriate to space operation and at the same time utilizes much available processing technology. Anorthosite is a very common mineral in the lunar highlands and an excellent source of aluminum, silicon, silica, oxygen, and other minor elements. The chemical plant shown in this drawing in low earth orbit, passing over Galveston Bay at sunrise was scaled to process 30,000 metric tons of anorthosite (90% pure) each year. A 30 megawatt 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 63 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 immediately minimizes the amount of material which must be shipped from earth to start production. Space radiators to eject process heat from the plant are the large flat objects above the oxide separator and electrolysis units. Make up of fluorine (3 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 utilized 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. In one scenario of industrial development this soil could be a large portion of the initial soil ejected from the moon and returned to the earth by the mass driver reaction engine originally used to transport the lunar base to low lunar orbit.

A rather surprising result of this study which evolved this particular processing design is the low mass of the space unit. Only ten to fifteen 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 ten to fifteen 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 should be usable to fabricate additional tanks and plants. If so, the amount of material necessary to be transported from earth to build successive plants of equal capacity might drop from 290 metric tons to 100 metric tons or less. Three to four processing units of this design could provide most of the refined feedstock for the manufacturing of one 10Gw SPS per year. Naturally, there would be many other possible applications for the refined feedstocks. Smaller units can be deployed by one shuttle.

E. CHEMICAL PROCESSING

Chapter II deals primarily with the scientific and engineering considerations involved in processing of extraterrestrial raw materials into refined materials suitable for industrial feedstocks. The focus is on processing of lunar materials. The economics of such activities are briefly considered.

The implementation of an industrial capability in space will be limited by three types of constraints: 1) Raw materials availabilities, 2) Process selection, design and operational limitations, and 3) Development of technologies necessary to establish the processing and manufacturing facilities and support continued operations. The first two groups are discussed in Part One of this chapter while the last is treated in Part Three. Part Two

gives an extended discussion of specific processes for materials conversion and refinement.

In Part One (I), the compositions of the major mineral fractions of lunar soil which may be considered potential feedstocks for chemical processing plants are described. Seven major elements are identified — aluminum, calcium, iron, magnesium, oxygen, silicon and titanium — which are widely distributed and available in concentrations above 1% by weight. Six additional (minor) elements — chromium, manganese, phosphorus, potassium, sodium and sulfur — generally occur in the 0.1 to 1% range.

The absence of easily recoverable light elements such as hydrogen, carbon, nitrogen, chlorine and such metals as copper, zinc, lead, etc. imposes restrictions on the diversity of output products of processing and manufacturing plants and, additionally, on the manner of use of many chemical reagents used expendably on earth. Nevertheless, a surprising diversity of useful product can be made solely or predominately from lunar materials (Table VI) and a broad range of chemical reagents may be employed by careful recycling of all substances containing significant (over 1%) amounts of lunar deficient elements. Such recycling operations appear to be readily accomplished for the processes studied to date.

Process selection will be governed primarily by the mass of equipment, reagents, power and heat rejection facilities required to obtain a given output rate and the design and operational constraints set by the space environment — vacuum, low gravity, radiation, radiant heat rejection, etc. The reagent mass

requirements are, in turn, dependent on either lunar availability or successful recycling efficiencies. The major changes from earth plant practice would be the management of air, water, fuel and waste heat. Most plant operations could be conducted in pressurized containers with artificial atmospheres appropriate to the processing conditions and simulated (centrifugal) or lunar gravity. Water is also expected to be used in a number of plant operations.

A general method is presented of classifying potential processing methods based on the nature of process steps to release or mobilize desired elements or constituents of raw materials and to separate phases or fractions of given process streams. While some exotic processes based on physical or semiphysical rather than chemical methods are possible and, as such, may not require reagents in the usual sense, it appears that practical engineering considerations and difficulties with purifying product streams would make such schemes less attractive and of higher technological risk than more conventional chemical routes.

General principles of chemical plant design are discussed in section D. It is shown that the normal operations of materials handling, phase separations and heating and cooling of process streams can be expected to operate in substantially the same manner as for earth plants provided a centrifugal gravity is supplied for orbital operations. Ultimate heat rejection by space radiators will generally be required, and for low temperature waste heat it may be desirable to heat pump such loads to 250 — 300°C to minimize radiator masses. Sizes and masses of chemical reactors

require kinetic (rate) data which may be unavailable for some proposed process steps, but correlations between volume and throughput for analogous industrial reactors allows one to estimate reactor sizes.

Part Two (II) discusses specific processes and treats in varying level of detail five prior and presently proposed processes for conversion of lunar ores into industrial feedstocks. A sixth process, carbo-silico thermic reduction, is also included in a section which compares the respective processes in regard to a number of features including maximum processing temperatures, power, product purity, process complexity, technological risk and key problems.

Of the candidate processes studied, the HF acid leach process appears to have the best potential for minimal operating mass, ease of element separations in high purity, and favorable energy and heat rejection requirements. It would be premature to rule out any of the other processes without formulating a valid rating method for comparing current or new candidate processes. However, the HF process is certainly useful for the immediate development of baseline engineering models. The HF process uses several steps which have been successfully employed on a commercial scale on earth, but which are no longer used due to competitive cost factors of alternate routes. Such (obsolete) processes may be the most desirable methods of performing a number of essential steps in an overall processing system. A pictorial flow chart for the HF acid leach process is shown in Fig. 1 - 6 which is the basis for the space processing plant shown in figure I-5.

Technology development is discussed in Part Three (III). It is evident that materials processing is but one link in a space industrialization activity which will also require transportation systems, mining and beneficiation, manufacturing and fabrication facilities and assembly, maintenance and life support systems. It appears that the development costs of the transportation technology will dominate the technology development programs, but advances in this area may be separately funded from other mission requirements and, in the long run, appear inevitable.

The development of chemical processing technology can be conducted for the most part on earth by using synthetic lunar samples made from earth rocks and chemicals. In particular, no additional lunar sample retrieval missions seem necessary to develop the process steps appropriate to low-latitude lunar soils. In addition there does not appear to be any critical size of processing or pilot plant necessary to demonstrate reliable operation in orbit. For example, a single space shuttle payload could contain all of the operating elements of a typical processing system which could be tested in sequence. A similar small system could be operated on the moon in the first stages of buildup of a lunar materials supply base and either reduce costs or increase the capabilities of such a base in comparison to providing all building materials from earth.

A series of detailed recommendations is presented for process chemistry development (of the HF acid leach process) and supportive technologies which will be required for almost any chemical process adopted. A limited discussion of the interactive

studies between processing technology development and development activities in transportation, mining and manufacturing phases of space industrialization is also given.

F. LUNAR STRIP MINING

Chapter III contains a detailed parametric analysis of the types, number, total mass, and power of excavation equipment necessary to initiate surface strip mining of 30,000 tons per year of undifferentiated lunar soil and expand the mining rate to 3,000,000 tons per year by the fifth year of operation. A result of great importance is that the mining operation, even at maturity, is rather small by terrestrial standards.

The introduction of electrostatic or other non-fluid techniques for beneficiation of the raw ore at the excavation site is a qualitatively significant option. If only the most useful fraction of soil need be transported to the launching area then only a very small fleet of vehicles is necessary for an operation specifically configured for the mining of anorthite. A single front-end loader (mass of approximately 25 tons) can accommodate the excavation and hauling needs for the first two years with or without at-mine beneficiation. However, by year five a nominal fleet of twenty-four ten-ton haulers would be required to excavate 3,000,000 tons per year of ore and waste 2 km from mine to launcher and return the 80% waste to the mine. With beneficiation only five ten-ton haulers would be required. Cumulative mass of excavation equipment to the moon by the end of year five would be approximately 80 tons with or 150 tons without beneficiation at the mine site. The nominal annual energy requirements would be 67 MW-Hr* or 390 MW-Hr

* MW-Hr = megawatt-hours.

respectively by the end of year five. The mining of anorthite can be taken as the large scale limit of lunar mining operations to provide 1 megaton/year of a selected ore. To provide 1 megaton a year of bulk soil requires less equipment.

Surprisingly, one can anticipate a very high level of automatic and remote control of the excavation and haulage operations with essentially no manned involvement on the moon but with remote control by terrestrial operators. It is reasonable to assume that maintenance of the excavation fleet can be provided by one person. By six to eight years into the mining operation the total mass of spare parts delivered to the moon would exceed the mass of complete haulers imported. Several specific studies should be conducted to provide tighter definition of the constraints and burdens the mining operation will place on the overall payload which must be delivered to the moon.

G. BENEFICIATION OF LUNAR SOILS

Chapter IV details the application of electrostatic techniques to the beneficiation of lunar soils. This technique appears to offer an ideal means of concentrating particular size ranges and mineral types from bulk lunar soil. Surfaces of lunar grains are pristine, uncontaminated by the effects of humidity, and therefore should preserve their characteristic surface electrical conductivity and electronic work function which are the key materials factors that permit differential separation of grains by electrical forces. Grain temperature is the main external variable which controls conductivity and

work function in the lunar environment. Temperatures of interest are readily attainable in the lunar environment by use of light sources, heated or cooled base plates, time of excavation and excavation depth. In addition, the low lunar gravity will allow greater displacement of charged grains due to an external electric field, which in turn can be ten times more intense in lunar vacuum than on earth. Finally, evidence does exist that electrostatically driven motion of lunar dust operates naturally on the lunar surface. If applicable, the electrostatic operations should permit low power and low mass machines to beneficiate ore. A conceptual design consistent with terrestrial designs, is presented for a lunar unit to process 30,000 tons per year of material which would require 7 KW power, mass approximately 20 tons and be 12 m long, 6 m high and 3 m wide including excavation equipment and tracks. Pertinent patent literature on terrestrial electrostatic devices is included.

Experimental evidence as to the minimal efficiency of electrostatic beneficiation can be obtained by non-destructive experiments with available lunar soil samples. Very high priority should be given to such experiments, not simply for industrial data but also for the use of the separation technique to make possible unique experiments in lunar sample research.

One uniquely interesting technology identified in this study was the use of traveling-electric-fields (TEF) to charge and move dust grains. In one embodiment of this device parallel wires are imbedded across the short dimension of a long plastic

sheet. A two or three phase voltage pattern is rippled along the imbedded wires, thereby producing a traveling electric field over the plastic sheet. Charged dust laying on the sheet will be physically moved with the field down the sheet. Triboelectricity occurs on grain impacts so all dust is quickly charged and transported. This low power device could be built into the surface of space suits and be used to clean them of lunar dust prior to entering an air lock.

H. LUNAR GLASSES AND CERAMIC PRODUCTS

Chapter V confirms the commonly held assumption that glass and ceramic articles could be made from lunar soils. This has now been shown to be fact as a result of limited confirmatory experiments in the Materials Sciences Department at UCLA. Glass and ceramic has been made from oxide mixtures identical to those characteristic of the Apollo 11 (mare, high titanium), Apollo 12 (mare, low titanium) and Apollo 16 (highland) soils. A photograph of glass and fiberglass produced from the Apollo 12 mixture is presented in figure V-1. The Apollo 11 and 12 synthetic samples melted at 1350°C and were very easily made into glass. The Apollo 16 mixture melted at 1500°C and also readily formed glass on cooling. Specific components of lunar soil, such as anorthosite, will also be valuable for forming specialty products such as clear glass. Thus, glass and ceramic production can benefit from mineral separation devices as well as the availability of refined silica and silicon fractions of the lunar soil.

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 laboratory experiments to establish general procedures for the production of a wide range of glass and ceramic products. These early terrestrial experiments can establish the needed key experiments to be performed early in zero-gravity to allow final design of lunar and space production equipment.

This report surveys general conditions and procedures for the production of clear window glass, refractory and chemically inert containers, fiberglass wool, and light pipe fibers. 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. Special notice is taken of the use of solar energy and the possibility of glass production by sintering of amorphous powders

I. MATERIAL GOODS AND THEIR INTRINSIC VALUE (\$/kg), MASS AND ENERGY OF PRODUCTION

Chapter VI explores in a unique manner a theme which has been repeated many times in the preceding material. That is that the cost of raw materials plays a basic role in the type of economic activities and products which can be pursued in space. We have chosen to explore this theme by examining the

economy of the United States in 1967 and 1972, years for which appropriate data exists. We determined total value, total mass and total energy consumed in the production of goods which could be made from lunar materials with very little additional terrestrial materials and whose production could use solar energy to advantage (more likely goods). The study was extended to also examine goods which might be made in space from lunar materials and with solar energy but which could require significant importation from earth of make-up mass, might be bulky products which would pose some problems in downshipping to the earth or that might require major changes in processing procedures from present terrestrial practices. These were termed less likely goods. Excluded from the analysis were goods and processes which require petroleum, non-lunar chemicals or agricultural products. It was found that 64 Standard Industrial Categories in the United States economy could be considered to be compatible with space manufacturing using lunar materials (more likely) and that 166 categories could be adaptable to the less likely category. There were 239 SIC groups excluded from the study.

A second interpretation can also be made of the results of this analysis. It provides a listing of the productive categories of the United States economy which can provide major immediate technological assistance and guidance to a space program based on a source of inexpensive lunar materials. In effect this listing guides one in seeking out industrial competence to assist in transferring capabilities from the earth to space.

The full listings are presented and explained in chapter VI. The more likely class contains electronic devices, electrochemistry and related processes, ceramic and glass products, many types of machines, non-ferrous metals and other items. Many items in the less likely category have been found on reinspection following more work in the processing areas to be more adaptable to space production than first thought. Figure I-7 provides one manner of examining these results. This is a histogram of the more likely (cross hatched bars) and less likely (clear bars) on the basis of a \$/kg index. We have taken the average price of all goods in each of the 230 SIC's examined and divided by the materials inputs to those goods that are actually embodied in the final goods. The histogram is the total sales value of goods in a given price interval which is 1\$/kg wide versus the average price per kilogram in each such SIC. The goods in all SIC's shown here had a total shipped or sales value of more than 410 billion dollars (104 billion \$ for the more likely and 310 billion \$ for the less likely). Total mass and energy consumption of the more and less likely goods were 65 and 1,577 billion kilograms and 384 and 1,400 billion kilowatt-hours respectively. It should be noted that 384 billion kilowatt-hours corresponds to the total annual output of 4.4 power stations rated at 10Gw each. Thus, energy embodied in space products and delivered to the earth in effect can liberate some fraction of terrestrially produced power for other uses. These figures apply to 1972.

We see in the histogram that most goods sell for less than 10\$/kg. The figure is deficient in one critical aspect in that

there are significant quantities of specialized goods in some of the SIC's which sell for significantly more than the SIC average used here but they are not specifically accounted for or displayed here. If space power stations are eventually included in this graph, they will initially be located between 200 and 400 \$/kg (far off the right edge) and have an annual value to 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, and have an annual output value of two to four billion dollars [note point (1) in Figure I-7].

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. We noted at the first of this chapter that the lunar ejection cost could be the order of a few cents per kilogram ($\approx .02$ \$/kg). This corresponds to point (2) in Figure I-7 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's shown in Figure I-7 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, that terrestrial-type products can be produced for

use in space more cheaply than sending them from earth, and that the products can be relatively inexpensive as we learn to obtain extraterrestrial raw materials at low unit costs approaching the average cost ($\approx 0.01\$/\text{kg}$) of non-fuel Demandite (Table III).

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 of lunar samples 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.

J. DIRECTIONS FOR RESEARCH AND DEVELOPMENT

It is completely clear that space industrialization can evolve a materials economy based on lunar and eventually asteroidal materials sources. The pertinent question at this time is - How small in costs and size can the initial systems be made and still grow at a sufficiently rapid rate to produce meaningful production in space in reasonable periods of time? This question has not previously been asked. The answer should not depend on the existence of one particular product, for example space power stations, but should encompass the summed values of a wide range of products, services, systems and as importantly new possibilities and capabilities which would be impossible in the context of terrestrially originated programs. We recommend a three level program of identification/synthesis, analysis, and carefully directed experimentation which will insure the rapid development

of our knowledge of the investments required and the potential payoffs for a materials space economy based on lunar materials.

The IDENTIFICATION/SYNTHESIS program would identify possibilities for major reductions in scale of proposed approaches toward space industrialization based on lunar materials. Approaches for the acquisition and utilization of lunar materials would be proposed and synthesized into a general program leading to the development of an extraterrestrial materials economy in space. The program would generate an overall scenario for the program complete with estimated costs, growth profiles and possible products.

The ANALYSIS program would consist of a series of separate efforts at university, private and government facilities requested or selected by the IDENTIFICATION/SYNTHESIS group. These efforts would consist of detailed studies of specific problems or models for equipment, systems and/or possibly economic growth models. The ANALYSIS program would be very suitable for small contracts to university researchers.

The EXPERIMENTAL program would also consist of numerous small research efforts at university, private and government facilities. Specific devices, process experiments and simulations which would provide definite confirmation of the initial (or minimum scale) capabilities for early use of lunar materials or special devices for reducing the costs of initial space exploitation would be developed. These efforts would bring to light both unexpected difficulties or opportunities for the generation of industry and goods in space. Again, the program and experiments envisioned

would make excellent use of the diverse abilities and interests of the university research community.

The total program would profit by being a highly visible activity. The status of achievement toward reducing the cost of initial space industrialization could be continually updated as additional concepts and information are obtained. This status should be continually communicated to all workers and interested parties.

An exceeding wide range of talents, the majority outside of the present aerospace community, would have to be organized. The group should be interfaced in an almost real-time manner so that the synergistic effects resulting from bringing together very diverse capabilities and possible solutions to problems would be quickly recognized. It is very important in reading the recommendations of specific workshops, studies and experiments in the following sections to consider them as examples of activities which should be pursued primarily because they provide one real pathway for the reduction of the initial costs of space industrialization. However, these possibilities must represent only the first steps in what should be done. The real key is to bring together many talents and stimulate the presentations of new concepts, analyses, models, experimental data and projections in a continual atmosphere of checking against physical reality and improvements of the overall initial industrial system.

It is suggested, as one possible approach, that the IDENTIFICATION /SYNTHESES program consist of a staff of 10 scientists, engineers and economists who would be responsible for the

administration and documentation of the overall program. The administrative group would support the operation of a multi-unit panel which would meet four to six times a year for several days. There would be approximately 30 members on the panel. Appointments would be on a rotating basis with staggered terms. The administrative group and the panel would establish one or more reference plans for the initial approaches to space/lunar exploitation and would request NASA to accept proposals on specific technical problems (analyses and experiments) the panel identified.

The reference plans would be circulated to all proposers and to the widest possible general audience prior to selection of proposals. The reference plan itself would be open to continuous critical review from all quarters and would be constantly updated at the frequent meetings of the panel. Proposals would be selected on four month cycles and would generally be tailored in funding level and duration for the accomplishment of the specific task rather than for a specific period of time such as one year.

The administrative group would constantly document the activities of the panel, provide listings of ongoing experiments, print the abstracts of all meritorious proposals submitted to the panel for consideration, whether or not funded, and maintain at least one systems model of the space industrialization scheme considered most feasible by the panel at that time. These activities would be documented by monthly newsletters to all participants and at costs to anyone requesting the information. The system would be completely open with no proprietary information.

All participants would be invited to attend at least one major annual meeting for direct interactions. It is to be expected that special work-shops would also be held as necessary either at the main location of the panel or at locations necessary to minimize costs. All results of funded efforts would be required to be published in the open literature and an extremely comprehensive indexing service would be maintained of the literature generated and referenced. This would be the objective of drawing in the expertise of the widest possible range of human capabilities for consideration and to establish a wide spread literature which could be readily accessed throughout the world both in a planned fashion and so an arbitrary reader could be expected to encounter reference to the space industrialization program in his general reading. In the following subsections we will consider specific topics for these three categories as we presently perceive the research needs with regard to gathering materials on the lunar surface and the processing in space or on the moon of the various soil fractions.

IDENTIFICATION/SYNTHESIS

1. Organization of an administrative panel to construct a reference model for a low cost program of space industrialization. The group would request and recommend for funding original research proposals for requested and newly identified research problems of both an analytic and experimental nature. The group would constantly update the reference model, would make available as expeditiously as possible the new and revised models

and study results, would organize and conduct workshops on key topics, and communicate the program achievements to a wide audience.

2. Development of a flexible model for the economic growth of systems in space in terms of quantities which could be provided by most experienced workers in a given field of production or development.
3. Identification of non-aerospace technologies which should be examined in greater depth for application to cis-lunar industrialization.
4. Identification of specific technical advances which could greatly reduce the cost or expand the development of cis-lunar industrialization.
5. Identification of products which could be made in space from lunar materials with or without the addition of terrestrial materials and would have use in space or on the earth and estimate the possible net value of these products as a function of raw and processed materials costs.

In the following recommendations of specific analytical and experimental studies we have concentrated on the areas of materials gathering on the moon and physical, thermal and chemical processing on the moon or in space which are consistent with the general thrust of investigation in this report. We have indicated the number of man years believed to be required for various studies and the priority we attach to the importance of the various tasks as either enabling a major qualitative advance in the development

of space industrialization or in more fully defining particular processes suggested in this study.

ANALYSES/MODELS [priority (1 highest, 4 lowest), man-years]

1. (1,2) Development of computer models for the generation of electricity and power on the lunar surface utilizing to the maximum extent in-situ resources with minimum complexity of required machinery on the moon should be pursued. One possible approach is the use of photoemission for power generation by creating simple diode circuits in trenches in the lunar surface. It is possible that unlimited power might be provided during daylight hours by this approach at a very early point in the start of operations. Much data is available from solar power station research which is applicable to lunar and space processing.
2. (2,2) There is a clear need for solar furnaces operating on the moon or in space to provide process heat. Most solar furnaces designs to date have been for applications where modest or zero mass flows through the focal plane have been required. Configurations to permit optical coupling and accommodate materials flows, insulation, regenerative heating, and a rotating focus for heating materials in a centrifugal force field should be studied. Of particular concern are vignetting problems in reflector designs. This may favor transmission optics in some cases such as at high volume production.
3. (3,1/2) Conceptual analysis must be done on space radiator systems scaled to reject process heat. General features of space heat radiators have been extensively studied

in connection with previous proposed heat engine power systems. Process heat rejection may more commonly be necessary in to 200 - 300⁰C range. Characteristics of practical radiator systems for this temperature range should be studied including use of steam and acid solutions as working fluids. Particular points to consider would be identification of various working fluids of different temperatures and materials compatibility requirements, study of operations under low or zero gravity or centrifugal force fields. Potential freeze up conditions for various systems should be examined.

4. (4,1/2) Conceptual designs for heat pumps should be explored for the pumping up of heat loads to the 300⁰C range for rejection to space. The selection of working fluids, thermodynamic cycles and construction materials necessary for input temperatures down to cryogenic for the liquefaction of oxygen and/or hydrogen should be investigated.
5. (2,1) Orbital processing plants will be required to conduct a number of unit operations normally conducted in a gravitationally driven flow or separation process. These unit operations must be redesigned to operate in a rotating environment where significant changes of the local acceleration vector may occur in time and over the flow path. Analyses of these centrifugal counter current processes should include the short term variations in magnitude and direction of the local acceleration.

The conceptual design studies are necessary to identify potential problem areas.

6. (4,1/2) Batch processing, quasi-continuous processing or interruptions of fully continuous process lines will generate linear and angular momentum surges on equipment, solar optics alignment and possibly affect machine and human performance. An analysis should be conducted predicting the magnitude, effects and design considerations of such surges for several process plant designs. Systems to buffer these process surges should be indentified. There will be similar need to buffer changes in the volume of process gases and liquids in the event of process interruptions.
7. (3,1) Adoption of modular designs for creation of matching capacity of various segments of particular processing systems can improve reliability of overall operations through redundant or parallel modules providing they can be valved off in case of malfunction. There should be a systematic analysis of unit processes to determine adaptability to modular design including effects of operating temperature, insulation requirements, heat transfer requirements, materials compatibility and formability of construction materials. Paralleling can increase mass and maintenance for a plant and should not be used indiscriminately. In particular, units operating at very high temperatures or requiring excessive amounts of insulation or brittle materials of construction

may be poorly suited to modular design. Identification of tubular or other units which can be lengthened and for which flow rates can be varied without compromising performance should be begun. Processes which can only effectively be increased in capacity by increases in cross sectional area of units should be identified.

8. (3,1/2) Information should be gathered from industry sources to estimate the production scrap rates versus potential unit costs to determine the present and probable attainable rejection fractions for various operations in manufacturing, fabrication, and assembly. Studies of the advantages or disadvantages of recycling such scraps versus simple disposal and replacement with additional raw materials supplied from feedstock should be attempted.
9. (3,1/2) Identification of expendable materials and in particular high volume requirements such as washing, rinsing, etching or other systems commonly associated with various manufacturing operations should be started to determine regeneration or replacement needs for such steps. Estimates should be made of the composition and quantity of reagents, lubricants, detergents and normally expendable supplies required by manufacturing options.
10. (4,1/2) Estimates of the type and quantity of abrasives, hard tool materials and other refractories used in manufacturing operations should be developed. Potential methods of separation of abrasive grains from metallic

chips should be undertaken to facilitate recycling if indicated. Refractory recycling should also be considered.

11. (1,1) An extensive survey should be conducted of all the possible electric, magnetic and physical systems which could be used in the non-fluid separation of lunar minerals. Analyses should be conducted where appropriate to consider the effect of operating the processes in space over a range of gravitational accelerations and on the moon. The ability to efficiently separate scarce lunar minerals such as spinels, ilmenite or troilite by virtue of non-fluid means may make recovery of certain minor or trace elements practical which would not otherwise be possible.
12. (3,1) A detailed survey should be conducted of information available from NASA, DOE and DOT on possible power storage systems for excavators and other mobile equipment at the lunar base and for reserve power during lunar night or emergency periods.
13. (1,2) Continuing studies should be supported of initial and long term lunar mining with a focus on equipment, either traditional or non-traditional, which would serve to minimize requirements in the lunar environment for power, mass and complexity and maximize reliability, remote or automatic operation and productivity. Special attention may be required for dust contamination.

Experiments are necessary to establish the exact parameters of several stages of the process schemes proposed in this study and to confirm the overall feasibility of the electrostatic processing technique to lunar soils. These experiments are of a very small scale and are suitable to university or other laboratories on the basis of limited, directed contracts. Broader ranging studies are necessary to begin to appreciate in detail the possibilities for in-situ power supplies for solar electricity and what can be done directly with lunar glasses and ceramics. Many other experiments of this general directed nature will be identified as the program progresses. However, no element of the program need be seen as open ended because of the end goal which is to find a low cost means to establish material industrial operation in space in a reasonable time frame. There will be a clear point of diminishing returns for the initial efforts. Specific experiments identified in this study follow. Most of the expenses of these studies will be associated with direct labor rather than apparatus.

EXPERIMENTS

1. (1,1) Solubility data is needed to fill information gaps and verify previous results on solution chemistry of elements in the HF-H₂SiF₆ system. This information is necessary to improve efficiency of separation of various elements, removal and recovery of minor elements and permit more detailed sizing calculations for systems. Solubility (saturation) data review and determination

should be conducted for fluorides and fluosilicates of Al^{+++} , Ca^{++} , Fe^{++} , Mg^{++} and also the minor elements Na^+ , Mn^{++} , and Cr^{+++} as a function of F:Si ratio, pH and temperature including identification of equilibrium crystalline phases.

2. (4,1/2) Solubility (saturation) data should be reviewed and determined for the fluorides and fluotitanates of Al^{+++} , Ca^{++} , Fe^{++} , Mg^{++} and also minor elements Na^+ , Mn^{++} and Cr^{+++} as a function of F:Ti ratio, pH and temperature including composition of equilibrium crystalline phases. Data for these systems are required for titanium recovery and desirable for materials processing for oxygen production in excess of other solid materials requirements.
3. (2,2) A comparative study of the reduction of simple and complex fluorides of Si, Al, and Ti should be conducted. Si, Al and Ti can be produced by sodium reduction of their simple fluorides or by reduction of their Na or K fluosilicates, fluoaluminates (cryolites) or fluotitanates. These alternative routes can offer greatly changed volatilities, melting points, etc. which may make the reductions more convenient and influence corrosion or containment problems and materials separations.
4. (3,1) Comparative studies of the hydrolysis of simple and complex fluorides (fluoaluminates and fluotitanates) should be conducted. Analytical studies of steam hydrolysis have shown marked dependence of rates on melting points

and chemical nature of hydrolytic products. For example hydrolysis of NaF is rendered much simpler if combined in the form of Na_3AlF_6 in the presence of excess alumina. Also hydrolysis of CaF_2 and MgF_2 is facilitated in combination with lower melting fluoride solutions or complex compounds.

5. (3,1) There should be a review of pyrolysis data and experimental determinations where indicated for Na, K and NH_4 fluosilicates and fluotitanates. Dissociation vapor pressures of Na and K fluosilicates and fluotitanates are important for process engineering if reductions of these materials are used. Dissociation of NH_4 fluoro-compounds, especially if it proceeds via NH_3 and acid salts, offers useful routes to regeneration of acids and bases from salts and also a valuable method of purifying silicon and titanium compounds.
6. (1,1) Ion exchange data should be reviewed and determinations performed for fluorides and fluosilicates of H^+ , Al^{+++} , Ca^{++} , Fe^{++} , Mg^{++} and the minor elements Na^+ , Mn^{++} , and Cr^{+++} and for NH_4^+ for cation and anion exchange resins and anion and cation permeable membranes. Ion exchange behavior of fluoro ion species of solutions of major and minor lunar elements is needed to optimize separation processes to recover simple fluorides for reduction or to recover hydroxides for conversion to oxides. This latter separation cannot normally be done directly from fluosilicate solution because of hydrolysis of the fluosilicate solution. If this can be done

efficiently with ion exchange techniques this will permit easier recovery of oxides than by separation of corresponding fluorides followed by steam hydrolysis.

7. (4,1) Amalgam chemistry and electrochemistry investigations of Na, Ca and Mg systems offer a potential route to reactive metals that is possibly much easier than high temperature reductions. The possible processes should be identified and analyzed in terms of space systems. (See Section II, appendix B.)
8. (2,1/2) Anhydrous leaching of silicates with NH_4FHF offers the possibility of a process option which would greatly reduce the amount of water transported in distillation operations to separate SiF_4 and HF from leach and hydrolysis solutions.
9. (1,2) Development of photoelectric power supplies should be pursued in parallel with theoretical investigations of design and emplacement of such systems on the lunar surface.
10. (2,2) A comprehensive set of experiments on the non-fluid separation of lunar and synthetic mineral grains should be conducted to provide input data to mining and processing studies.
11. (1,4) A wide range of experiments should be conducted on the production of glasses and ceramics for tests of fundamental characteristics and into sample products. Some of the tests should be conducted in vacuum and in zero gravity as soon as the space shuttle is available

for experiments. Portions of the tests should be directed to obtaining information necessary for the design of production processes in space and on the moon.

12. (1,2) The development of a wide range of soil simulants should be started immediately to supply well characterized materials for processing studies.

Work underway and to be done in the October, 1978, through September, 1979, time frame is directed toward the publication of the results to date in the open literature, continuation of development of one reference design of a space processing system and organization of two workshops. Articles have been or will be published shortly in the Journal of Contemporary Business (Commercial Prospects for Extraterrestrial Materials — reference 6), Chemical Engineering (Manufacturing in Space and the Role of the Chemical Engineer — reference 7) and the Proceedings of the 5th Conference on Static Electrification at St. Catherines College, Oxford (Electrostatic Beneficiation of Ores on the Moon Surface — reference 9). A paper based on the analysis of lunar strip mining is being prepared and will be submitted for publication early in 1979.

Work at the Institute will concentrate on a continuation of the definition of a reference model for one chemical processing approach. We will continue development of prioritized technology readiness plans extending in scope from terrestrial experiments to space and lunar experiments, and prototype facilities. We will complete a flow sheet for the acid-leaching (HF) process proposed to reduce anorthosite to its constituent oxides. This flow sheet

will be useful in engineering studies of prototype plants and as a comparison for other potential processes. It would be expedient for one of the NASA field centers to conduct a summer engineering design program on the conversion of this flow sheet into an engineering specification for a lunar and/or space processing plant complete with cost and development estimates for a range of plant sizes. Possible variations of the basic process flow will be explored, such as replacing a Na-reduction step with a electrolysis operation. Finally, an attempt will be made to identify exotic compounds which are not presently used terrestrially due to environmental factors or hazards (example — use of calcium as electric wire) but might be of potential use in space.

Two workshops are being organized dealing with the production of glass and ceramic products from lunar materials and the application of electrochemistry techniques to the electrical separation of lunar materials into the constituent elements. Professor J. Mackenzie has agreed to chair and assist in organizing the glass and ceramic workshop. This meeting will be held in the early part of 1979. Professor N. Hackerman of Rice University has assisted in promoting interest on the part of the Electrochemical Society of America in organizing a jointly sponsored workshop with the Lunar and Planetary Institute on the direct electrochemical separation of lunar materials. A proceedings of the workshop is anticipated and the workshop is planned for the spring of 1979. The interest shown by high level professionals in a wide range of disciplines toward the development of specific technologies for large processes is direct and powerful evidence of the reasonableness of the expectation that many aspects of terrestrial technology can

be transferred to industrial operation in space and on the lunar surface. Lower costs of materials and greatly expanded capabilities in space can directly result from the deliberate planning and application of the available terrestrial technologies of industrial materials production to the development of lunar materials as the early basis for cis-lunar industries.

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Table I

QUALITATIVE MOTIVATIONS FOR THE USE OF
LUNAR AND ASTEROIDAL MATERIALS

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1. The unit cost (\$/kg) of lunar materials acquired in space should be significantly less than the shipping rate of terrestrial materials to low earth orbit or to deep space. This is because the lunar escape energy is 5% of that of the earth and the moon has no atmosphere. Therefore it is possible to directly eject material from the lunar surface into space by means of electromagnetic launchers. The electromagnetic launchers are embodied as systems which are much less massive and require less energy (propellant) than terrestrial rockets over the lifetimes of the two systems.
 2. It is possible to immediately begin detailed planning and development of lunar supply operations and research on processing of lunar materials due to the vast knowledge that has been acquired on the lunar materials and manned operations on the moon during the Apollo missions and by post-Apollo research.
 3. If the bulk of the materials for large space structures and their operations are obtainable from the moon terrestrial launch operations can be specialized for the transport to space of people, materials not available from extraterrestrial sources, and high technology production and control machinery rather than bulk cargo. This will permit the use of smaller mature launch systems, maximize the use of the space shuttle systems for the

Table I - (continued)

- remainder of the century and minimize concerns of the environmental impacts of terrestrial launches.
4. Growth of the large scale industry in space will not be limited by one major engineering system (large boosters for earth surface to orbit) but will have at least three separate and distinct materials supply sources — the earth, the moon and earth approaching asteroids. The rate of materials extraction from the extraterrestrial sources can be expanded in large part by devices made in space, thus progressively decoupling the cost of further growth from the expense of terrestrial launch operations over time.
 5. Considerable expertise exists outside of the aerospace community which can be applied to industrial scale operations in space for the supply of services to the earth and the generation of economic systems for use exclusively in space. The key is to reduce the cost of material inputs to resemble more closely materials costs in the terrestrial market place. As this occurs the costs of all space operations are not dominated by the single factor of transportation expense to orbit.
 6. Techniques and devices developed in the context of a space system for the processing of large tonnages of materials and goods will result in the much wider application of aerospace developments to terrestrial industrial practices than the far more specialized developments of earlier manned and unmanned space programs.

Table I - (continued)

7. Increasing the range of participants in the planning and operations of large space programs will inevitably result in an increasing rate of discovery of new and profitable applications for growth of industry into space. The possibilities for future exploitation and exploration will be considerably enriched by an expanded base of in-space operations. This is probably the only way the economic reach of space industries can be extended past the service segment of the national and world economies.

Table II

SIGNIFICANT RESULTS OF THE "EXTRATERRESTRIAL
MATERIALS PROCESSING AND CONSTRUCTION" PROGRAM

1. An initial scale of materials usage in a large space structures program such as the proposed space power satellites ($4 \cdot 10^4$ to 10^5 tons per year) is consistent with the industrial prototype scale of chemical processing operations (possibly with parallel units). Development of such processing units is normally expected to require three to eight years to complete rather than 12 to 18 years as is common in large scale terrestrial industries which process far larger inputs of materials (10^5 to 10^7 tons per year) in the intensely competitive terrestrial economy.
 2. Mature industrial installations in the terrestrial economy must be refined in design to allow extremely accurate knowledge of the final costs of products over a wide range of competitive conditions including labor, materials, financing and markets. Often success or failure will depend on small differences between rather similar technical approaches to the same products. In space the initial competition will be against the cost of launching bulk or semifinished goods from earth (> 200 \$/kg). It seems reasonable to expect the unit costs of various processes to be only a few times higher in space than for similar operations on the earth even in the initial stages of operations (≥ 1 \$/kg). Learning curve experience acquired in space operations will steadily enhance the attractiveness of lunar feedstocks in competition with terrestrial supplies.
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Table II - (continued)

3. Three chemical processes have been identified for the chemical separation of all the principal lunar minerals into the major oxides and into their major elements. These processes utilize low temperature and low pressure aqueous leaching in either hydrogen fluoride, hydrogen chloride or sodium hydroxide. Electrochemical techniques are used for metals separations. These processes appear to be compatible with operations in a space environment although artificial gravity is required in several of the process steps.
4. All steps in the hydrogen fluoride process are either based directly on systems used commercially for similar process steps or are based on common laboratory practices. A set of small-scale experimental and analytical projects are described which can be done in university or industrial laboratories. The experiments will provide knowledge necessary to immediately proceed to the design of a prototype processing unit based on the hydrogen fluoride option. The unit could be used for production tests on the earth and for very early in-space processing tests in the space shuttle.
5. There is minimum or no need for additional exploration at low lunar latitudes to confirm the existence of usable sources of the most common lunar minerals as dependable sources of the major elements (oxygen, silicon, aluminum, iron, calcium, magnesium, and titanium). It will be extremely profitable to survey the remaining lunar surface from orbit to locate concentrations of minor elements and volatiles in order to

Table II - (continued)

enrich the inventory of lunar elements available for exploitation. It will be useful to have high resolution topographic maps of possible mining sites.

6. Glasses, fibreglasses and ceramics have been produced from oxide mixtures identical to major mare (iron rich) and highland (aluminum rich) soils sampled at the various Apollo landing sites. Mixtures of major lunar soils, soil separates and elemental separates can provide ingredients for an extensive suite of glasses and ceramics for a wide range of structural, processing, optical and other uses. Glass and ceramic production can be fully explored with terrestrial simulants of lunar materials. Vacuum production of the test articles should receive special attention. Unique glass products produced from lunar soils may be one of the first commercially attractive products for terrestrial use.
7. Lunar mining operations have been studied by means of parametric models based on terrestrial experience with strip mine operations. The initial operations are extremely small by terrestrial standards. Even the materials handling required to construct 5 to 10 space power stations each year (90,000 tons per station) is small by terrestrial standards if electrostatic or magnetic separation techniques can be used at the mining site to minimize haulage. Current terrestrial practices are consistent with a highly automated mining system where most of the human involvement is in machine maintenance and remote monitoring rather than direct operations.

Table II - (continued)

8. Electrostatic separation techniques appear to be directly applicable to the tailoring of raw lunar soil with small, low power devices to select only the mineral fractions which are most appropriate in elemental content to the immediate needs of the space industrial complex. Device developments can be done with very small quantities of lunar soil. However, it is likely that a prototype device for lunar processing should be tested and operated on an unmanned rover early in final site verification operations.
9. A survey of the Standard Industrial Categories (SIC's) of the United States reveals that the major materials inputs to 64 of these categories is consistent with a lunar supply source and/or can take advantage of solar thermal/electrical power in processing and fabrication. Goods in these 1972 categories had an output value of 58 billion dollars. These SIC's included electrometallurgy, glass, ceramics, light and specialty metal workings and fabrication and electronics. These SIC's represented not simply possible product ranges for space manufacturing but more importantly in the early stages of space industrialization a vast source of technical expertise which can be focused on creating space industries. In addition, the process energy of these products was over 380 Billion kilowatt - hours in 1972. Import from space of such products also imports to the biosphere this space processing energy which could be a significant fraction of the total energy of the nation.

Table III

Non-renewable resources must be extracted from the earth, sea, and air and processed into a form which can be used by industry. "Demandite" is an imaginary molecule which contains the weight fractions of all the various materials used in the United States in 1968. The properties of Demandite are summarized below. Notice that fuels constitute the largest fraction of the Demandite molecule.

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
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		- 1.14 KwtHr/Kg

Reference (10)

Table IV

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 out the fuel in Table III and introducing the fractions of the elements which compose the remaining substances in Table III (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 non-fuel Demandite (columns 4 and 5).

(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	.2158	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		.9999	.9980	

(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 (10)

Table V

SUBSTITUTE LUNAR MATERIALS ¹⁷

Rank	SPS Application	Earth Baseline Material	Earth Baseline Material Mass (T)	Recommended Lunar Substitute Material	Equivalent Lunar Material Mass (T)	Earth Alloy Material Mass (T)
a	Protovoltaic 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 & mach	515	0
n	Solar cell inter-connects	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
			87,800T	TOTAL	88,190T	440T

FIGURES (CHAPTER I)

- I-1. Schematic of the flow of matter from the sources on and in the earth to the final products and losses. Wealth, personal freedom, and the overall adaptability/complexity of the industrial societies appears to be determined by how efficient these industrial activities are and on how much technology and science can reduce the degree of human involvement necessary for direct operation of industry. All this activity takes place in the biosphere (natural recycling system driven by solar energy) and on the bedrock provided by the surface of the planet. Demandite represents the average distribution of elements used to form the products of civilization.¹⁰
- I-2. 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

FIGURES (CHAPTER I) continued

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 (Kg/kg) and c_p (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 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.

FIGURES (CHAPTER I) continued.

- I-3. Artist sketch, to scale, of the Grand Coulee Dam in the state of Washington. The small volume of mass on the upper left hand portion is the volume of an SPS compressed to the density of concrete (5 T/m^3). The small volume on the lower right hand side is the volume of the active electronics necessary in the ground rectenna to receive 10 gigawatts of power from the SPS and convert it to a form suitable for transmission to terrestrial users. Grand Coulee will produce 9.2 gigawatts of electrical power on completion of installation of full generator capacity.
- I-4. This is an artist's concept of one particular design of a lunar base specialized for the long-term supply of minimally processed lunar soil to a collection point in space. The view is from a few hundred meters above the landing pad to the southwest of the main complex. The base is composed of four converted shuttle tanks in the middle foreground of the picture, a small mining area in the lower right, a photovoltaic power supply in the middle left and electromagnetic launching device for soil units stretching from the center to the upper right. This view is of the second lunar day of base emplacement.²⁴
- I-5. This is one possible concept of a chemical plant in low earth orbit which is configured to process approximately 30,000 tons/year of lunar soil. Ten to 15 space shuttle missions would be required to deploy the plant in low earth orbit. It is described in the text. The gold octagonal solar array

FIGURES (CHAPTER I) continued

dominates the picture. It supplies power to operate an electrolytic separation unit in the background. In the foreground, behind the solar mirror is the oxide separation unit in which all the common lunar minerals can be separated by wet chemistry processes for further chemical and electrolytic processing. Plant mass is less than 300 tons including processing fluids which must be brought from earth. Notice the small bag of lunar soil entering the loading chute. The bag of soil is to scale for a 2,000 ton unit of lunar soil sufficient to operate the plant for 25 to 30 days. In the foreground is a shuttle hydrogen tank reconfigured to provide a zero gravity workshop. In the background is a rotating habitat for the 20 man crew necessary during the proof testing phase of the prototype plant. The oxide separation and electrolysis units are also rotated to provide controlled gravity for the chemical processing. The long black objects extending from the processing units are radiators for the rejection of waste heat. The plant is shown coming into sunlight just over Galveston Bay. Four of these units could supply the industrial feedstock to build one SPS/year.

- I-6. Pictorial flow diagram for HF acid leach process. The separation section (left) shows the steps where the raw or beneficiated lunar ore is dissolved in hydrofluoric acid and the silica and metallic oxide fractions into fluorides or fluosilicates and are separated by distillation, precipitation, ion exchange or other methods. The portions of the fluoro compounds needed

FIGURES (CHAPTER I) continued.

to supply the elemental (reduced) products are transferred to the reduction section (right) while the remainder are hydrolyzed with steam (or acids) to recover HF and regenerate silica and metal oxides.

The reduction operations for silicon and aluminum use metallic sodium, produced by electrolysis of fused sodium hydroxide to reduce the corresponding fluoro compounds to free elements plus sodium fluoride. The sodium fluoride is decomposed to HF and NaOH by ion exchange, hydrolysis or electrolytic means. Magnesium metal (and calcium if required) are produced by reducing their oxides with silicon (or aluminum).

I-7. 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.

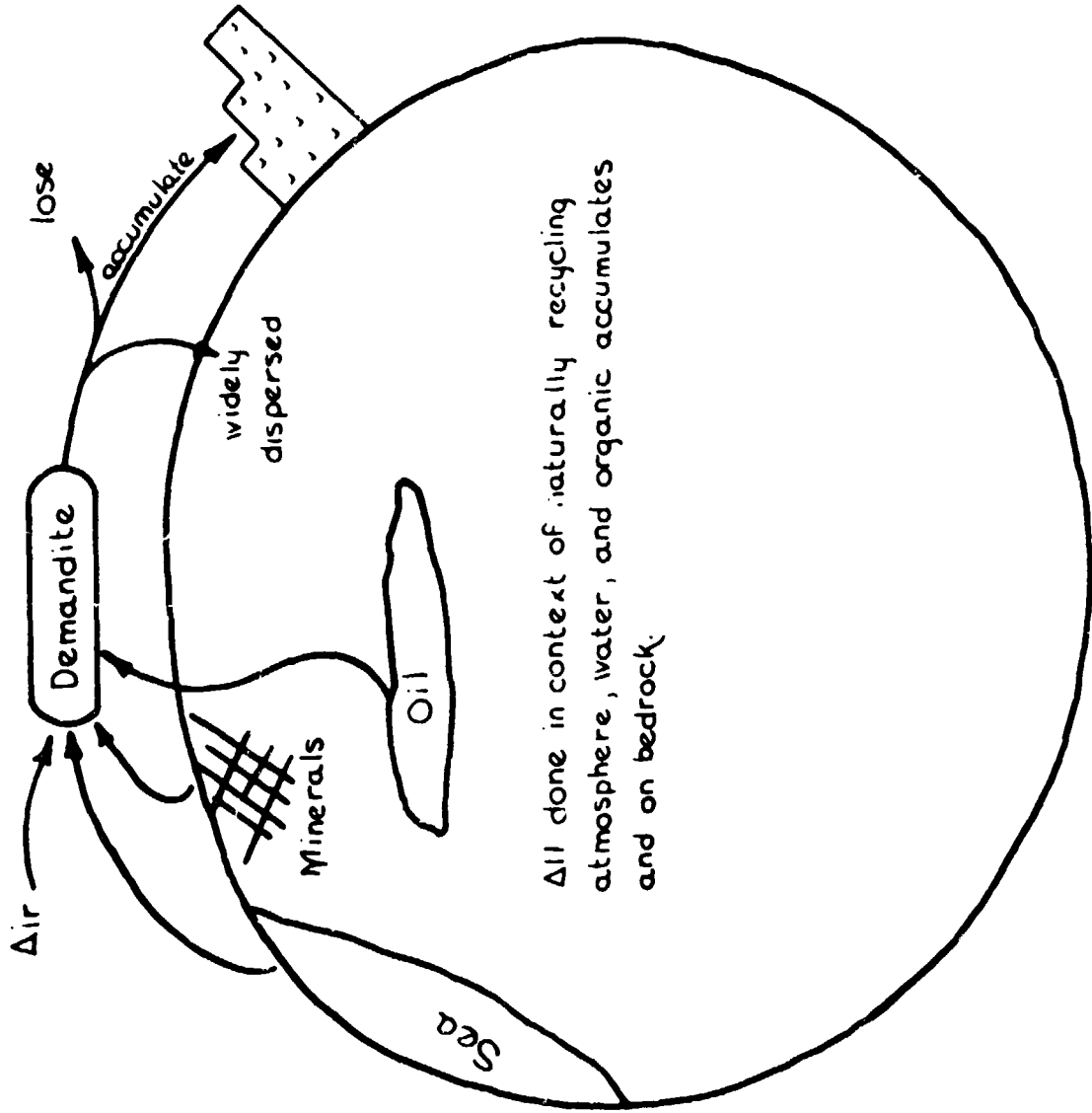


Figure I - 1

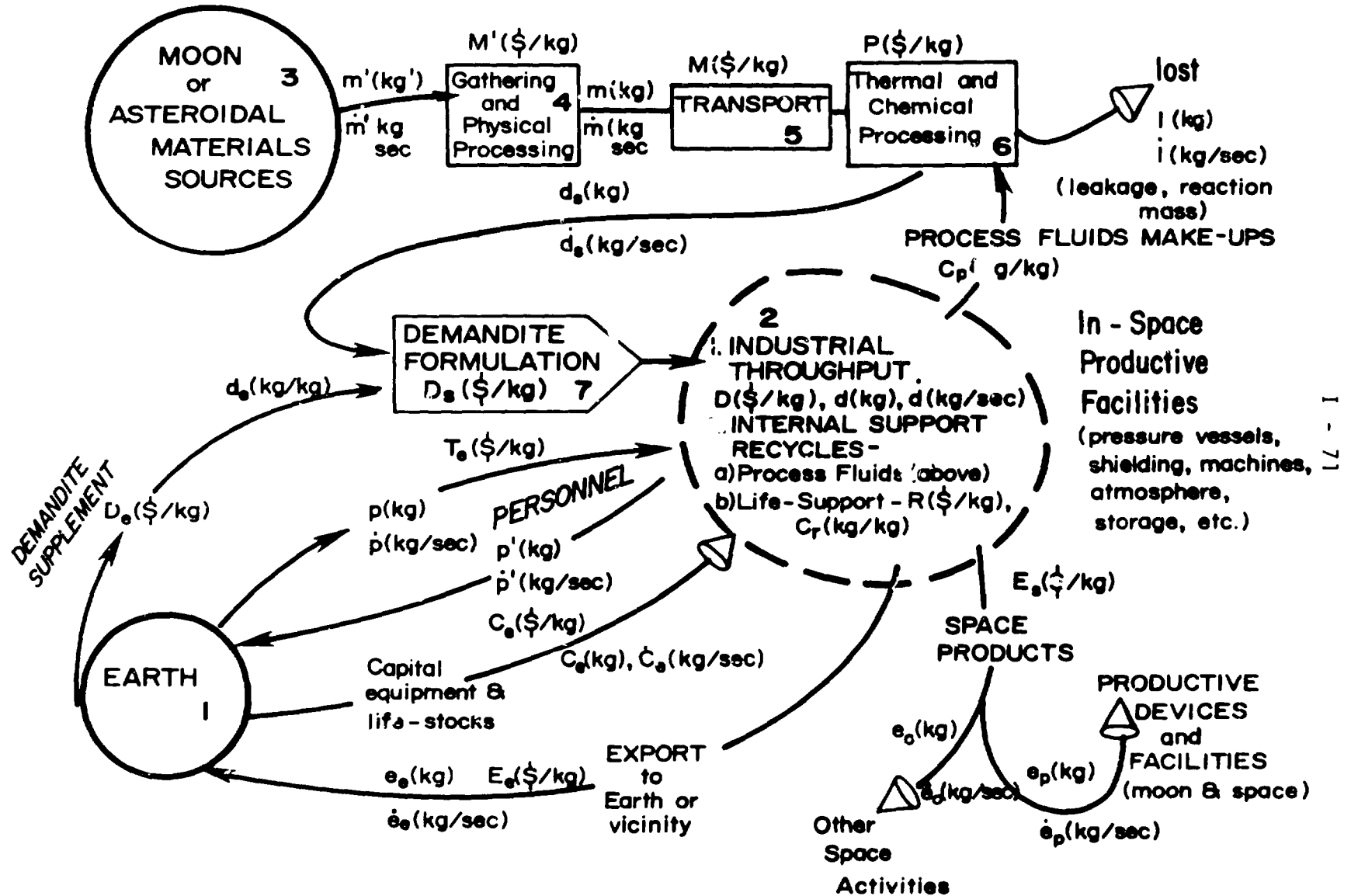
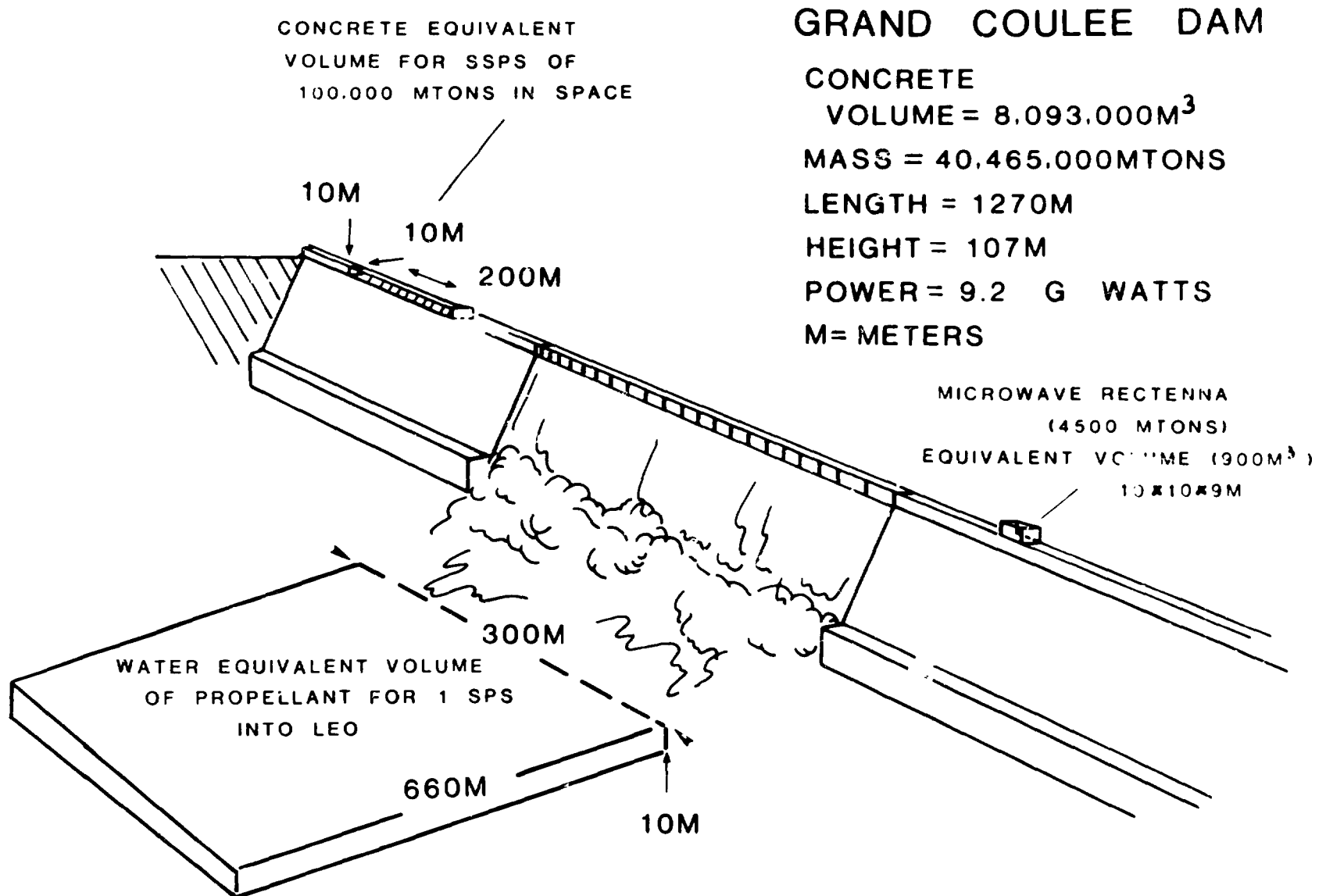


Figure I - 2



I - 72

Figure I - 3



Figure I - 4

IS PRETTY POOR QUALITY ORIGINAL

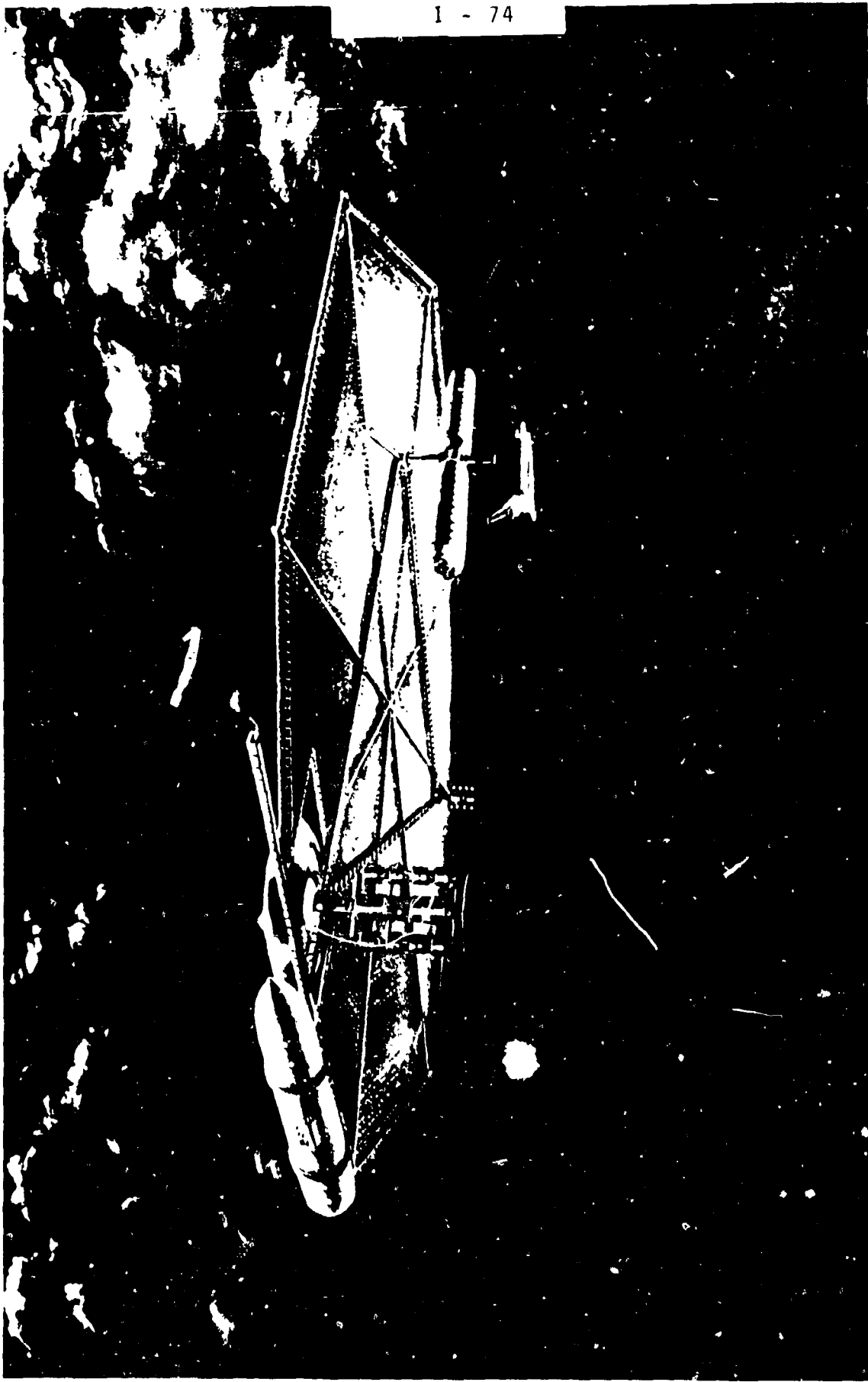


Figure I - 5

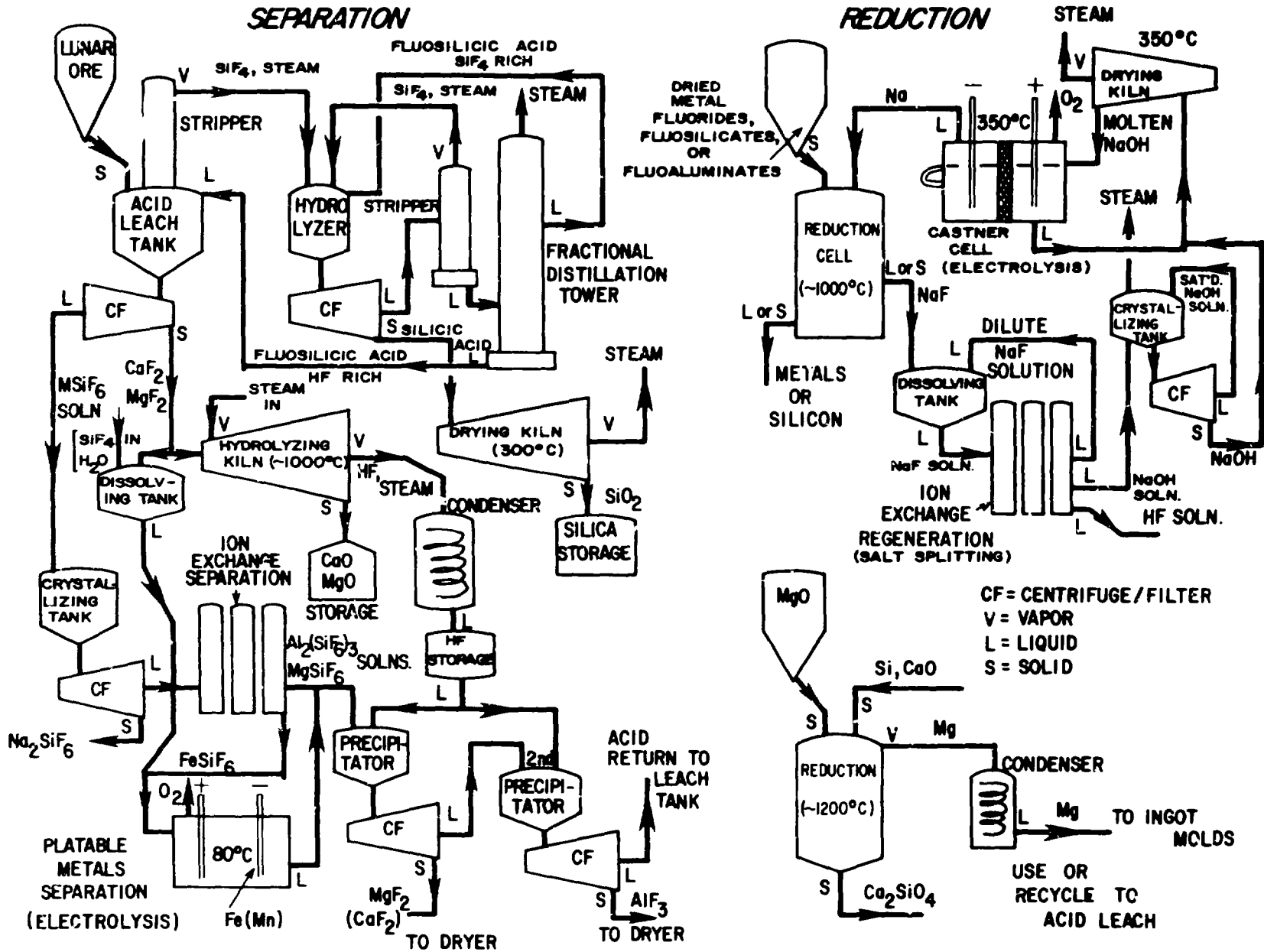


Figure I - 6

I - 75

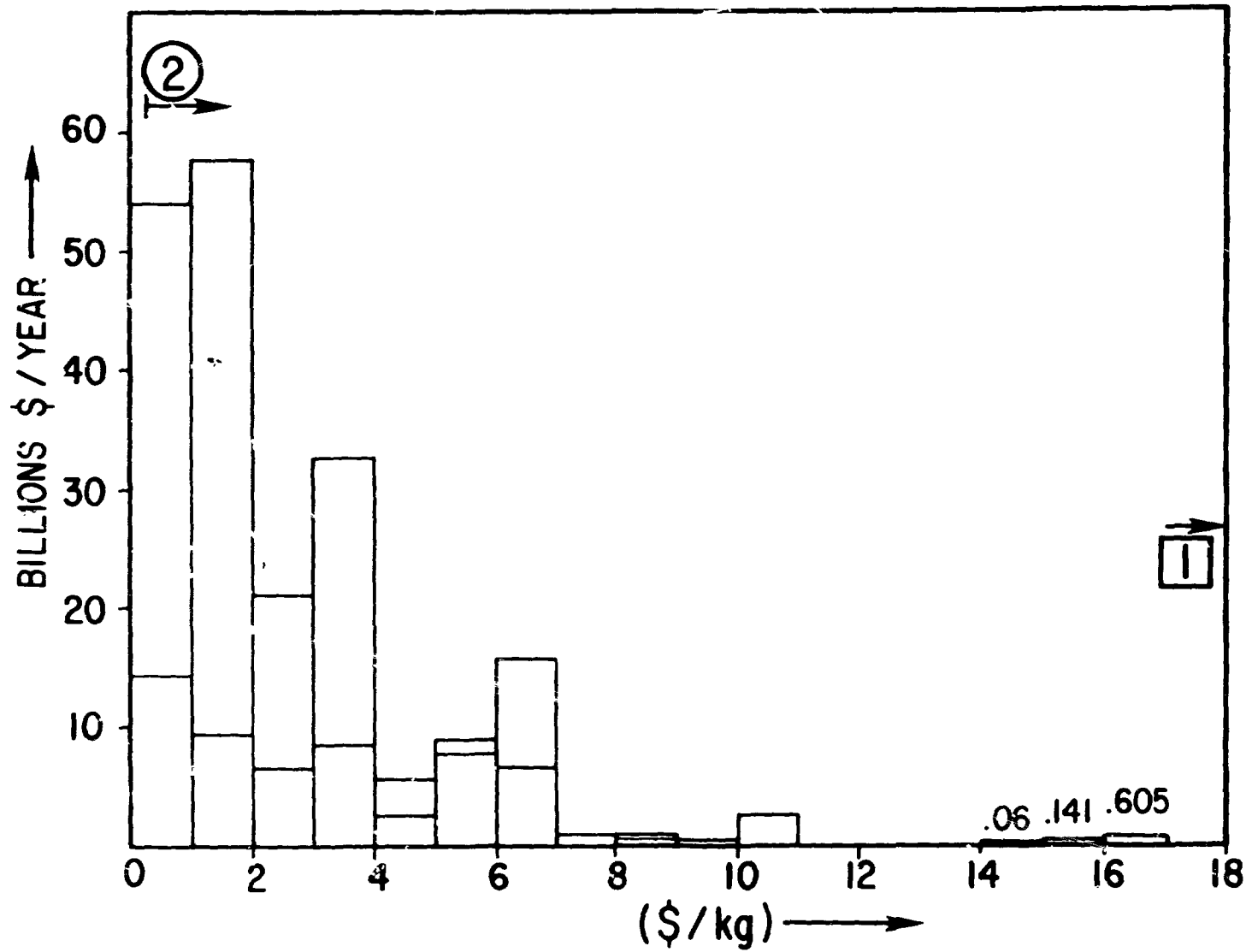


Figure I - 7

II. PROCESSING OF LUNAR AND ASTEROIDAL MATERIALS

(Separation, Conversion and Refinement)

Introduction

This report will deal with the general and specific requirements of materials processing plants designed to convert raw or beneficiated lunar soil or rock (or, alternatively, asteroidal material) into industrial material feedstocks useful for manufacturing operations in orbital or lunar locations. Generation of major materials requirements for space operations from lunar or asteroidal sources can greatly reduce transportation costs associated with launch of equivalent payloads from earth due to more favorable energy and power considerations from the former sources.

Background

The concept of industrialization of space including manufacturing of raw materials and finished products has been explored by a number of prior investigators¹⁻³. Recent work has included sessions at the 1976 and 1977 NASA/Ames Summer Study Programs. These sessions investigated specific chemical processes for conversion of lunar materials into silica, silicon, aluminum, iron, magnesium, titanium and oxygen using carbothermic or carbochlorination reactions to separate and/or reduce the constituents found in lunar silicate or ilmenite minerals.

In the present study was undertaken to investigate the carbochlorination process in greater detail and perform a preliminary engineering analysis of the mass, power and operational

requirements needed to perform such operations in orbital or lunar locations. At the same time, a reconsideration of some of the available options in mining, processing and manufacturing operations starting with non-terrestrial sources and including alternative chemical or physical routes to separate and recover constituents from lunar or asteroidal materials was begun which led to the detailed study and analysis of a hydrochemical process for treating silicate or ilmenite ores.

Much of the prior study effort was geared to a scenario in which the lunar base activity was restricted primarily to mining, beneficiation, packaging and launch support for further processing in orbit. Refinement and manufacturing would be conducted in orbit in which critical materials or components not readily producible from lunar feedstocks or manufacturable in orbit would be lifted from earth along with operating manpower. The primary mission orientation dictating the desired output materials from space processing and manufacturing facilities was the Space Satellite Power System (SSPS) concept which has been the subject of in-depth engineering investigations. While the present study is basically compatible or consistent with this scenario, it is by no means restricted to such considerations, and the revised process can be examined in a more general framework of space industrialization which would address the following four questions:

1. What can be mined and recovered on the moon or in orbit more economically than supplied from the earth?
2. What useful products can be derived from said materials?
3. What product mix options are available?

4. Can a bootstrap operation be established with a minimum requirement for earth source structures, equipment or expendable supplies? (Specifically, could the materials and processing capability be established to construct additional processing and manufacturing facilities to increase production from the output of initial processing and manufacturing units supplemented by a minimal earth-lift involvement?)

PART ONE — METHODOLOGY

A. GENERAL CONSIDERATIONS

In common with industry on earth, one 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 consumption patterns. The physical processing requirements for the unconverted mineral products will be treated in other sections of this report and will not be considered further in this discussion.

Potential Availability

Restricting ourselves at this point to lunar raw materials, we shall discuss the potential availability of individual elements from raw or beneficiated lunar soil and/or rock sources. Results of remote and direct sampling techniques have shown a remarkable constancy of composition of lunar rock and soil samples,⁴ but with some characteristic differences between highland and mare areas and individual sampling sites. Extensive analytical work has established that six elements invariably occur at levels

above 1% by weight: O, Si, Al, Ca, Fe and Mg, while a seventh, Ti, occurs above that level in mare samples, but averages about 0.5% in highland sources.⁵ These seven elements are considered the major lunar elements and are potentially recoverable from a variety of input ore sources.

An additional six elements we shall classify as minor elements which generally occur at levels between 0.1 and 1% by weight.⁵ These are: Cr, Mn, Na, K, S and P. These elements are not present at levels which might justify primary chemical recovery methods, but they would be expected to accumulate during the processing of significant quantities of the primary elements and if recovered, could provide alloying elements for metals or makeup chemicals for processing reagents such as NaOH, KOH, H₂SO₄, H₃PO₄ and SO₂, etc.

The remaining elements normally occur at levels below 0.5% by weight and we classify them as trace elements. They would not normally be recoverable in sufficient quantities to merit additional processing facilities except in special cases. However, four of the light elements, H, He, C and N, are of special interest because of their potential importance as chemical intermediates and because they could be recovered by outgassing of lunar soil as well as during chemical solution processes used for major element recovery. The atomic abundance of H may typically amount to 1% of the silicon content even though the weight ratio of H to SiO₂ is typically 1:(4,00 - 10,000). This may be sufficient to replace H loss due to residual moisture in plant product after drying operations.

In addition to the chemically bound iron in the minerals,

there is a measurable content of reduced (neutral) iron present as small particles in the lunar soil. While this constituent would be considered a "trace" material based on abundance, the potential ease of recovery by magnetic methods plus elimination of subsequent energy intensive stages attendant to reduction of ferrous iron may make recovery of neutral iron an attractive alternative to recovery of chemically combined iron for structural metal requirements.

Recovery Potential

(Major Elements)

Separation and recovery of the seven major elements in elemental form or as their oxides may be achieved by any of the major processing routes: hydrochemical, pyrochemical, electrochemical or combined processes, such as are used for similar operations on earth-based plants. The principal distinguishing requirement for a successful non-terrestrial process is that all reagents, catalysts or other substances employed in the process which might be lost or converted to different compounds would have to be recycled to original form unless their mass conversion rate amounted to a small fraction of the production rate of the principal products. A practical limit might be at about the 1% level. These processes may be conducted either on the lunar surface or in orbit. An orbital location would permit some unit operations to be conducted in a gravity-free environment if desired, but materials handling problems seem to make such steps less attractive. An exception might be for processes in which corrosion effects have proven severe and in which levitation of process streams would be possible.

(Minor Elements)

Recovery or disposal of the minor elements would be necessary since they will pass through the process stream in sufficient quantities that their consumption of reagents could not be ignored. Of these six elements, the alkali metals, Na and K, tend to occur primarily in the feldspar fraction of lunar minerals while the manganese is found in nearly constant proportion to iron (ca. 1:30) and thus tends to concentrate in pyroxenes and ilmenite fractions. The three remaining elements, Cr, S and P tend to concentrate in the scarce mineral fractions spinel, troilite and whitlockite respectively.

The alkali metals will normally remain in solution in most leaching-solvent systems and can be recovered by crystallization or ion exchange. The metals, Mn and Cr would be valuable alloying constituents for ferrous metallurgy and could be recovered by electrodeposition, ion exchange or chemical precipitation. The S and P content could be recovered by an ion exchange or chemical precipitation.

Any large scale requirement for the minor elements would necessitate chemical processing on the lunar surface since it would be impractical to transport large masses of material to recover a small percentage of the weight of the ore. An exception to this rule may be possible if very efficient ore beneficiation of scarce mineral phases can be performed by physical methods such as electrostatic separation in conjunction with mining operations.

(Trace Elements)

Recovery of trace elements except for the light trace elements,

H, He, C and N, would rarely be useful unless they would be readily separable on equipment designed for major element separation processes as for example, from an ion exchange column. The abundances of precious and soft metals are so low as to make recovery operations uneconomical. The non-metals present storage and purification problems while transition metals such as Cu, Ni, Co would require substantial post-recovery processing to convert to useful forms.

Some recovery at a later state of trace elements may eventually prove practical if the slag or refuse output of the major element processes can be partially segregated or differentiated. Thus, if a fraction of the slag output can be substantially enriched in heavy metal content or in individual elements, these can be later reworked if they are separately stored upon exit from the plant.

The light trace elements would largely appear as volatiles released upon dissolving or heating the material processed in major element recovery. Partial oxidation would generate additional carbon oxides. These gases could be separated from condensable vapors and retained for process make up or special uses.

Extraction of additional amounts of the light trace elements with possible additional elements which could form volatile species in the presence of reducing or oxidizing gases may prove practical on the lunar surface, especially if a commitment to handle large quantities of lunar soil is made as would be required in the extraction of neutral iron. The heating of large quantities of lunar soil to approximately 1000°C for the extraction of light

element volatiles would require substantial energy consumption per unit output, but even without thermal recovery, the energy requirement would be low in comparison with chemical methods of extraction. For example, using a mean heat capacity of lunar rock of 0.2, a ΔT of 1000°C would require about 200 cal/g. Since the equivalent weight of lunar silicate minerals generally falls in the range of 15 - 20 g, the sensible heat per equivalent would only amount to 3 - 4 Kcal/gram equivalent which is much lower than most chemical processing energy requirements. If we assume a nominal recoverable light element content of 300 PPM (H = 75, He = 20, C = 100, N = 100, Bal = 5) the thermal energy requirement per unit mass of light elements (m_{LE}) becomes:

$$\frac{\Delta H}{m_{LE}} = 200 \times \frac{10^6}{300} = 667 \text{ Kcal/g.}$$

If one includes S which would be recoverable and would normally occur at about 1000 PPM, the thermal requirement $\Delta H/m_{VE} = 154$ Kcal/g where m_{VE} is the mass of volatile elements (light elements plus sulfur). These energy requirements are very high when viewed by normal thermochemical standards, but probably offer the only practical way to recover large quantities of these trace elements from lunar sources. However, substantial reduction in energy requirements would be possible by regenerative heat exchange between degassed and input feed streams.

Derivable Products

The elements listed above can furnish raw materials for a variety of useful products necessary for various industrial operations. Table I shows some classes of materials requirements

for processing plant and manufacturing operations which could be partially or completely met from lunar derived materials.

Not all of these requirements would necessarily prove more economical to satisfy from lunar source materials and space processing and manufacturing as opposed to supply from earth, but their availability should promote further study of practical feasibility of various options.

Product Mix Options

The relative quantities of various output streams from a lunar materials processing plant can be selected within constraints established by various raw or beneficiated feedstocks to obtain plant design optimized for desired end applications. In addition, for a given processing plant, some flexibility in output is possible by alteration of input feed, although in such cases, the output of various sections of the plant may not be well matched, and some process steps may have to operate at substantially less than rated capacity.

The principal variables include the relative requirements for silica and silicon products, structural metals, refractories and oxygen. In terms of plant processing requirements, the most important considerations are ratios of reduced to oxidized products and gas (oxygen) to solids ratios. The principal consideration in oxygen requirement is whether or not a sizeable need for propellant oxygen is established. If it is, the oxygen requirement could far outstrip the need for reduced products (structural metals and silicon), but it would still be necessary to produce metals as a surplus by-product. This output imbalance could be avoided if reactive metals such as calcium or magnesium

could be utilized as fuel in advanced propulsion systems.

If only limited demand for propellant oxygen materializes, it is likely that oxygen released by reduction of structural metal requirements would exceed all other needs for oxygen. In such a case, it may be necessary to discard some oxygen since storage is more difficult than for the solid products.

Table II shows some product mix option considerations applicable to lunar materials processing. Figure 1 and Table III show the range of individual major metals content as a function of silica content for principal mineral species potentially available as inputs for processing plants.

Bootstrap Operational Capabilities

The most important questions regarding the establishment of industrial activity in space or on the moon apart from general utilitarian and economic considerations involve the capability of initial processing and manufacturing facilities to support and sustain a flexible course of expansion and diversification to fulfill future requirements of various types. It appears clear that some special requirements in any case would have to be supplied from earth, but it also appears likely that the major fraction of materials and fabricated items could be processed without the use of earth based materials or facilities.

To support general expansion and diversification activity, there are certain common capability requirements which are independent of particular mission activity. Thus, the materials processing activity should be able to produce products which could be fabricated into essentially similar processing plants to permit expansion of output. The manufacturing capability

should be able to fabricate these additional processing plants as well as similar and diversified manufacturing facilities. In addition, the plants should be able to produce solar power systems to support their own operations as well as habitation and biosupport systems including agricultural activities.

It appears that the materials processing section of such an industrial complex could produce most of the ferrous and non-ferrous metals requirements, glass, refractories, insulation, electrical and magnetic materials likely to be needed in chemical, manufacturing and power plants for use in space. The economic feasibility of overall industrial development may depend more critically on efficiency and flexibility of space manufacturing and fabrication than on materials processing. Certainly the analysis of cost-effectiveness of various potential routes to space industrialization will require considerable additional study.

B. MATERIALS PROCESS SELECTION

Introduction

The selection of chemical or physical processes to convert raw or beneficiated lunar ore 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 locations vs 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 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

*NASA Report JSC-12973 Solar Power Satellite Concept Evaluation (July 1977)

remain at 10% or less of the cost of earth orbital launch given a sufficient mass requirement.

Regardless of lunar materials processing and manufacturing systems chosen, it is unrealistic to anticipate that the value added per conversion step will be comparable or lower in cost than similar operations on the earth. 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 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 properly defined to permit inter-comparison between alternative processing systems. It would appear logical to charge the mass of electrical and solar thermal power facilities necessary for the operation of the plant plus the mass of any space radiators necessary for heat rejection from plant operations or the corresponding fraction of common power or radiator facilities. The mass of capital equipment should be amortized over its useful lifetime and an "equivalent mass interest rate" assessed since the mass is originally translated into lift cost. Replacement or expendable mass consumption is expected to be a consequence of reagent loss plus lubricants and items subject to progressive wear or deterioration.

Mass derived from lunar sources should be separately assessed as "lunar supplied equivalent mass" (LSEM) which would include input material 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 material 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

reductions in growth or replacement in space industrial operations.

Process Constraints

A successful orbital or lunar 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 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 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 or oxygen (or higher oxides, e.g., Fe_2O_3). For ilmenite, FeTiO_3 , the same steps are necessary except that no silica is involved.

C. 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 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 takes place 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 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 (2^{26}) 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 system 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. Appendix A gives an analysis of the ratio of thermal losses to materials transport in low pressure, high temperature systems.

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 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

*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.

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.

Classification of Previously Proposed Processes

Prior studies had examined processes based on melting silicate rocks or soil followed by chemical reduction^{1a} (carbothermic and silicothermic reduction) or electrochemical reduction (electrolysis).⁶ Another proposed route involved conversion of silicates to chlorides using carbon and chlorine followed by separation and/or reduction.⁷ Acid and basic leach processes were also studied in previous reports under this contract. These materials processing systems for lunar materials may be classified in accordance with the above method using a shorthand notation of the M/D section and the separation section as follows:

Carbothermic reduction (See Fig. 4)	L1, C4; C0 recycle C2 or C3
Carbochlorination	F2, plus P2, P6 and/or P5; Reduction P2, EC2 and C6, etc.
Electrolysis of	
Molten Silicates	L1, EC1 or 2 plus additional separations
HF Acid Leach	L3, plus P2, C1, and (P7, S3, and/or C5, EC1); RF1, R'V4, etc.
Basic Leach	L4, plus C5 and RF1, etc.

The complete process including all recycle and regeneration steps can be described by such a notation if all solids separated are given an R designation and all fluids requiring additional processing are given an F designation. These notations are included on several of the flow charts appearing in this report.

Assessment of Prior Methods

The carbochlorination process was studied in greater detail in the initial phases of this contract study and these results

appear in a later section. Analysis of this route revealed that the facilities and power required to recycle the chlorine and carbon from such reactions overshadowed the plant facility needed for formation of chlorides and hydrolysis or reduction of the initial separation products.

As a result of that study, it became apparent that it would be far preferable to perform the chemical separation of constituent oxide components by processes which did not require oxidation or reduction of the input material or reagents. This arises since the energies of reduction of the principle oxides of lunar silicates exceed 50 Kcal/gram equivalent compared to 5 - 10 Kcal/equiv. for most solution processes, and further that the oxidation-reduction steps must invariably be reversed in an electrolysis step which tend to be slow and thus impose substantial mass penalties.

Solution Processes for Chemical Separations

A number of solution processes routes were examined for possible use in lunar materials separations. These included:

(Low temperature, aqueous)

1. Acid leach
2. Alkaline leach

(Medium temperature, nonaqueous)

3. Caustic fusion
4. Carbonate fusion

(Medium temperature, high pressure)

5. Steam leaching

(High temperature)

6. Lime sinter

A comparative model for rates of solution of silicate rocks and glasses in various solvents may be drawn from data on chemical reactivity of fused silica shown in Table IV. These results indicate HF is the most rapid solvent for silica of the low temperature (aqueous) reagents. Process 6 involves the addition of excess lime to lunar silicates with firing to produce "lunar cement" phases; i.e., mixtures of C_3S , C_2S , C_3A , etc. These phases may be hydrated and acid leached or hydrolyzed for separation. The hydration and hydrolysis reactions also tend to be sluggish except under autoclave conditions.

The preceding considerations plus kinetic expectations led the author to select a HF acid leach route for the M/D and subsequent separation steps for in-depth evaluation. This process is an adaption of one previously studied for extraction of industrial feedstocks from coal ash.

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 reaction 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,^{8a} although Na, K, Ca, and Mg could probably be recovered by using a mercury cathode (see Appendix B). 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.^{8b} 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 production of sodium that "made possible the world's first truly commercial process of making aluminum"^{8c} nearly a century ago. 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 extra-terrestrial 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.

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.

Figures 5 - 8 show the free energies of formation per two gram-equivalents for oxides, fluorides, chlorides and sulfides vs. temperature. In general, elements farther down on such charts form more stable compounds than elements high on the charts and thus are capable of reducing the latter compounds. One notes that sodium and potassium are more effective reductants in the halide and sulfide systems than in the oxide system.

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, from the experience obtained during the course of this investigation, it is possible to list certain features that should probably be avoided or minimized if possible. 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.

D. CHEMICAL PLANT DESIGN

General Considerations

A chemical plant for extra-terrestrial 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 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. Appendix C gives a simplified analysis which 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. Similarly, refrigeration equipment for liquifaction 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
*See e.g. "Heat Transfer", A. J. Chapman, MacMillan (1960)

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 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 weight more or less than their contents. Appendix D gives a simple analysis which shows that for most cases of equipment which contains 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. Each process step is characterized by a process time, $t = \ell/v_i$, and the products tR_m , tR'_m and tr_m having the dimensions of time (hr) represent 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 tR or tr products then yields the total times required for the passage of sufficient input raw material to equal the gross or net reagent masses or structural masses for the processing system. Additional equivalent times may be derived to account for masses required for mechanical and thermal power sources and distribution equipment, motors, pumps, compressors heat transfer equipment, space radiator facilities and other necessary support functions.

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.

*Lunar Deficient Elements — All elements except the 13 major and minor lunar elements.

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. Heating and refrigeration; generation 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 illustration of the basic problem which might be common to any processes using water as an intermediate rinse or reagent, we may discuss drying of non-metallic output streams. Most finely divided metallic oxide or silica solids have an adsorbed or chemisorbed water content which can be removed by application of heat, time and pressure differential. 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.⁹ 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. In Appendix E we show that the optimum 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.

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 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. Appendix F gives some approximate values for masses of solar electric, solar thermal and space radiator power structures estimated from studies developed for SSPS systems.¹⁰ It is seen that 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.¹¹ 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 $1 \text{ lb/ft}^3 \text{ hr}$ in English units or about $16 \text{ kg/m}^3 \text{ hr}$. Figure 9 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 0.5 m^3 *. This chart can be used to predict or verify the size of reactors for lunar materials processing steps estimated in the absence of pilot plant qualifying data.

Corrosion attack on reactor structures or general thermo-physical 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

*Data compiled from Ref. 24 and other sources.

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 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 as shown in Appendix G. 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/m³), v_i is a characteristic velocity of the i th component (m/sec), and t is the process time (sec).

It may be extremely useful to calculate typical size data for all of the general classes of M/D and separation procedures likely to be encountered in lunar materials processing steps as an aid to selecting promising options for such steps.

For any proposed process step that has not been tried even

in an earth based pilot plant, it will probably be necessary to conduct pilot plant tests using simulated ore to verify projected reaction rates, before any real confidence can be obtained in plant sizing and output calculations. In the absence of such tests, it is highly probable that the capacities of individual processing units will be mismatched and some of the plant will be operating well below rated capacity to avoid accumulation at the output limiting steps. Such mismatches would in no way reflect on the ability of the individual units or the entire processing plant to perform their designated functions.

PART TWO — SPECIFIC PROCESSES

E. ANHYDROUS PROCESSES

Introduction

The analytical phase of the present contract led to a semi-detailed study of the engineering requirements of the carbochlorination process and an in-depth study of the HF acid leach process. Limited studies of the alkaline leach and HCl acid leach (ion exchange) process were also completed.

E1. CARBOCHLORINATION

As previously mentioned, a carbochlorination method of treating lunar feldspars was proposed in earlier studies for obtaining silicon, silica and aluminum from lunar sources.⁷ Full details of the necessary recycling steps were not developed in the previous studies. The process was based on the conversion of lunar silicates to silicon and metal halides which were separated on the basis of volatility and melting point differences prior to secondary processing. The halides were then either reduced

pyrochemically or electrochemically or hydrolyzed to hydroxides and/or oxides.

The first requirement in the analysis of a processing system is the development of provisional process equations for all reactions including the recycling of reagents. For this purpose we need an empirical equation for the input raw material. Previous studies of the mining and beneficiation of lunar ores¹² had established the composition of a hypothetical lunar feedstock prepared from lunar highland soil beneficiated to consist of 90 wt. % Plagioclase (feldspar) and 10% residue. This is shown in Table V with the corresponding molar content per 100 g concentrate. Rationalizing this composition to unit molar content of CaO leads to an approximate empirical formula of $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2.25 \text{SiO}_2 \cdot .15 \text{MO}$ where $\text{M} = 2/3 \text{Mg}$ and $1/3 \text{Fe}$ with a "molecular weight" of 300.5. The remaining minor and trace elements bring the total molecular weight to 303.1 and result in an equivalent weight of 17.52.

The basic process route chosen involves carbochlorination of the ore to form chlorides of the elements plus carbon monoxide. The aluminum chloride is electrolyzed to form aluminum plus chlorine, a fraction of the silicon chloride is reduced with hydrogen to elemental silicon plus HCl. The remaining chlorides are hydrolyzed to form hydroxides plus HCl with the latter being electrolyzed to regenerate hydrogen and chlorine.

The hydroxides are calcined to recover oxides and water. The carbon monoxide is processed by one, or more of several routes including hydrogenation (which is in commercial use) followed by cracking or pyrolysis, or absorption (in alkali)

followed by electrolytic reduction in fused salts. Finally, any excess water generated in the process will be electrolyzed to form hydrogen and oxygen. The hydrolysis of the calcium chloride can be conveniently combined with the regeneration of chlorine in an electrohydrolysis step analogous to that used in the chloralkali industry.

The principal difference between electrolysis of sodium chloride and calcium chloride using diaphragm cells is the greatly reduced solubility of calcium hydroxide which would form a slurry which would simplify removal from the catholyte. The returning electrolyte would require a slight acidification along with replacement of CaCl_2 content.

The preceding can be summarized by the equations in Table VI.

Equations 8 and 12 are subject to revision if electrochemical reduction of carbon oxides is employed.

Minor modifications to the preceding equations might include electrodeposition of Fe and Mn instead of hydrolysis and hydrogen evolution from transition metal chloride solutions and reduction of silicon and/or magnesium by sodium or calcium which could be obtained by electrolysis of fused chlorides or hydroxides.

A provisional flow chart for the process is given in Figures 10 and 11:

An engineering analysis of the principal power and plant sizing requirements is given in Appendix H. The principal power requirement involves the regeneration of chlorine (Eqns. 2, 3, 4 and 7). For an annual input capacity corresponding to a proposed mature space industrial operation of 399,000 metric tons, this

would require a chlorine manufacturing facility larger than any existing plant presently in operation.

E2. ELECTROLYSIS OF MOLTEN SILICATES

Limited investigations of direct electrolysis of molten silicates of compositions similar to lunar basalts have been performed.⁶ 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.

F. HYDROCHEMICAL (AQUEOUS) PROCESSES

Lunar rocks and soils may be converted to various mixtures of soluble and insoluble compounds upon treatment with various mineral acids or bases. Of the possible acidic reagents, only HF, HCl or mixtures of the two offer reasonable prospects for practical operation based on component solubilities, volatility (for recycling), thermal stability, and prospective rates of solution. In this last aspect, HCl may prove to be seriously deficient unless autoclave conditions are employed. HF offers a combined advantage of aggressive attack upon silicates with the convenient separation of silica content as a vapor molecule SiF_4 .

These considerations led to examination of two acid leach

processes; the first based on HF and the second based on HCl with the latter relying heavily on ion exchange techniques for separation of constituent components. A basic leaching process using NaOH was also studied. The reduction steps for the aqueous leach processes may be selected for optimum performance for each element being recovered.

F1. HF ACID LEACH PROCESS

General Discussion

This section will cover a low temperature solution process to separate the silica and metal oxide contents of the raw material for subsequent processing. In contrast to the carbonylation process, there is no requirement for oxidation or reduction in the separation reactions for for chemical regeneration of reagents.

The new process is based on the solution chemistry of silicon fluorides and uses the volatility of SiF_4 to separate it from the other fluorides. We shall review several features of the solution chemistry of SiF_4 to explain the process constraints inherent in the method.

In addition to the concentration parameters, there are two factors of importance in specifying the equilibria in fluosilicate-fluoride solutions — these are the molar F:Si ratio and the pH. Pure fluosilicic acid, H_2SiF_6 has a F:Si ratio of 6 and is a strong acid. Over most concentrations, additional silica will dissolve until a ratio F:Si of approximately 5 is reached.¹³ If one neutralizes a high ratio acid with free HF (F:Si = 7-8 or more), the fluosilicate ion will not hydrolyze until the pH rises above 8, while for F:Si approximately 5-6, hydrolysis will begin at a pH of 4 or 5.

Distillation of fluosilicic acid solutions will yield various proportions of SiF_4 , HF and H_2O . Condensation of these vapors for compositions with F:Si ratios below 5 will produce hydrolysis and precipitate free hydrated silica. Hydrolysis may also be conducted at elevated temperatures in the vapor phase.^{14,15}

The metallic oxide content of the original silicate will be converted to fluorides or fluosilicates depending on F:Si ratios. The fluosilicates are almost uniformly water soluble and may be separated or purified by ion exchange or crystallization techniques. The fluorides of sodium and potassium are water soluble. The remaining fluorides may be removed from solution and hydrolyzed with steam or reduced with sodium or other reagents. The fluorides or fluosilicates of the platable metals may be electrolyzed to deposit free metal and oxygen and those of the active metals may be reduced using mercury or other liquid metal cathodes as mentioned earlier.

A reduction facility to generate oxygen and an indirect reductant (sodium) to permit production of silicon and structural metals is proposed based on a modification of the Castner cell. In the original Castner cell, electrolysis of fused NaOH generates sodium and hydrogen at the cathode and oxygen at the anode. The hydrogen is formed due to build-up of water in the system upon discharge of OH^- ions. By using a diaphragm cell and withdrawing anolyte, the major fraction of the water could be removed and the cell would yield primarily sodium and oxygen. This would lower the electrical energy per equivalent of sodium and avoid the problem of handling large quantities of hydrogen.

The sodium would be used to reduce the SiF_4 and metal

fluorides to silicon and free metal. Magnesium fluoride is not easily reduced, but magnesium could be obtained by hydrolyzing MgF_2 to MgO and reducing the latter compound with Si.

The process with the various options is adaptable to several of the potential lunar minerals or concentrates including feldspars, pyroxenes, olivines and even non-silicates such as ilmenite and spinels. Thus, TiF_4 (Subl. Pt., $284^\circ C$) has sufficient volatility to be readily separated from other metallic fluorides, and the chemistry of fluotitanates $MTiF_6$ parallels that of the fluosilicates.) To develop the process equations, we shall use a generic silicate empirical formula of the form: $xMO \cdot SiO_2$ where $x = 0$ for silica, 1 for metasilicates (pyroxenes) and 2 for orthosilicates (olivine) or "pseudoorthosilicates" (anorthite). In this formula, M is considered divalent, so 1 aluminum atom would correspond to $x = 1.5$ and 1 alkali metal atom would correspond to $x = 0.5$. For the previous empirical formula for plagioclase concentrate, there are 8.3 metal equivalents to 9 silica equivalents so $x = 1.84$.

The process equations are summarized in Table VII and flow chart is shown in Figs. 12a and 12b. A pictorial flow diagram is given in Fig. 13.

Discussion of Process Steps

The solution and liquid-vapor equilibria of the system: SiF_4 -HF- H_2O are shown in Fig. 14 which is replotted in mole fraction scale based on data of prior investigators.^{16, a & b} Compositions below the $HSiF_5$ - H_2O join are not single phase but will hydrolyze to precipitate $Si(OH)_4$. Acids of compositions along this line will be designated SSA (silica saturated acid). The vapor

composition in equilibrium with such solutions contains almost no HF, but almost any ratio of SiF_4 to H_2O can be vaporized from SSA's of 80-100 mole % H_2O . (Although no data is currently available, if phases along the SSA line with low water content were prepared, one would expect almost no H_2O content in the vapor, but mixtures of HF and SiF_4 .) Since SiF_4 and H_2O plus other fluorides are the reaction products of equation 1, the first two may be evaporated from the solution and the last separated by filtration or crystallization which lends itself to a quasi-continuous process (Equations 1 + 2).

Equations 3 and 3A represent hydrolysis of SiF_4 in liquid and vapor phase respectively, while equation 4 represents hydrolysis of the metal fluorides. Equations 5 and 6 represent reduction reactions to produce silicon or metals. Equation 7 indicates the conversion of fluorides to fluosilicates which may be optionally selected to increase solubility for electrolysis (Eqn. 8), or ion exchange separation (Eqn. 8A). The sodium fluoride generated in the reduction reactions is converted to sodium hydroxide by ion exchange (Eqn. 9) or with $\text{Ca}(\text{OH})_2$ (Eqn. 9A).

Sodium for the reduction reaction is generated electrochemically as shown by equation 10. Finally, equation 11 represents the drying of the precipitated silica. Further process details and engineering analysis of power and sizing requirements are given in Appendix I.

F2. HCl ACID LEACH PROCESS

This process is based on the separation of Al, Ca, Fe, and Mg as soluble chlorides from Si and Ti which are insoluble in acid chloride solutions due to complete hydrolysis of their

chlorides in the presence of aqueous solutions. The soluble chlorides may be separated into individual components by a combination of cation exchange and anion exchange steps and/or electrochemical or other chemical methods. The separated components are then converted to hydroxides or directly to oxides by various pyrolysis or hydrolysis steps or alternatively are reduced to metals and oxygen or chlorine depending on the starting material for the reduction step. Generalized forms of the process equations are listed in Table VIII. Reduction may be accomplished by most of the methods previously described. The process can be used with chlorides derived from plagioclase, pyroxenes or olivine.

In the first step (Eqn. 1), the rocks are decomposed with HCl. The rate of attack of silicate rocks, soils or glasses by HCl solutions is the critical factor governing practicality of HCl leach methods of processing. Silica is precipitated as a hydrous suspension, and the metals become dissolved as metal chlorides. Iron may be oxidized to Fe^{3+} for ion exchange separation or plated out by electrolysis. Filtration or centrifugation will separate silica from the other species.

Aluminum and iron can be separated from calcium and magnesium using an anion resin such as Dowex 2 loaded with a complexing ion such as citrate.¹⁷ Eluting with water will remove Ca and Mg, and Al and Fe will be removed with 1 M HCl (Eqn. 2).

Aluminum can be separated from iron using anion resins (e.g., Dowex 1 in sulfate form).¹⁸ Al is eluted with 0.01 M H_2SO_4 , and Fe is removed with 0.1 M H_2SO_4 . Upon evaporation $Al_2(SO_4)_3$ and $Fe_2(SO_4)_3$ can be ignited to obtain Al_2O_3 and Fe_2O_3 , respectively,

with SO_3 and SO_2 (which can be oxidized to SO_3) as other products. The SO_3 can be used to make more H_2SO_4 . Aluminum can be produced in a cryolite electrolytic cell; Fe_2O_3 can be reduced with hydrogen.

Calcium can be separated from magnesium by using a cation resin such as Dowex 50 (H)¹⁹ followed by elution of Mg with 1.05 M HCl, while Ca is eluted with 2 M HCl (Eqn. 3). The CaCl_2 solution can be electrolyzed to recover chlorine, hydrogen, and $\text{Ca}(\text{OH})_2$ and after dehydration of the resulting hydroxide, CaO can be used in glass manufacturing. The MgCl_2 can be dried and used in a Dow cell to recover magnesium and chlorine.

It may be possible to separate all four ions directly with further development of improved solution processes (and/or resins).

Ion Exchange Engineering Considerations

For operations in space, a fixed-bed column seems to be the most practical. Industrial columns range in size from a few cm in diameter to over 6 meters (20 ft) with multiple-column-bed heights of over 30 m (100 ft.), as used in rare earth separations. Figure 15a illustrates a diagram of a typical fixed-bed column, and Figure 15b shows a diagram of a control system.

The ion exchange resins, which provide the mechanism for replacing one ion by another, generally consist of addition or condensation polymers to which a wide variety of functional groups can be added. These organic polymers would probably be made on Earth and shipped into space, since raw materials for making the polymers are scarce and the synthesis methods are complex. This disadvantage is not serious, however, since the exchange resin has a typical lifetime of a few years and replacement needs would

be low.

Regenerated solutions would have to be recycled. In order to avoid large holding tanks of dilute regenerant solution, proportioning valves can be used. In such a system the concentrated regenerants are pumped and automatically proportioned to water and directed on the beds at prefixed concentration.

In systems such as this, two tanks of each resin must be provided. While one column is being used for separation, the other one would be in the process of being regenerated.

The tanks and the piping (both internal and external) must be made corrosion resistant. This is usually achieved by making the vessels of stainless steel or aluminum and then coating them with plastic paint, plastics, or rubber. Naturally the conditions under which the network will be subjected will determine which alloy-coating combination to use.

Ion exchange operations can be performed manually, automatically or in various degrees of those two extremes.

Process Sizing

In industrial ion exchange processes, the maximum flow rate is approximately .0045 volumes solution per volume resin per second. (2 gal/ft³/min.) For a processing plant with a throughput of 30,000 MT/yr or 239,320 equiv./hr., the first separation described (Al and Fe from Ca and Mg) would require a minimum of 10 m³ (356 ft³) resin in order that maximum flow rate would not be exceeded (assuming 1 M solutions). Elution would require 28.4 m³ (7500 gal.) of solution. Separation of Al from Fe would require at least 10 m³ of resin and 4.8 m³ (1275 gal.) of solution for washing. Finally, separation of Ca from Mg would need at least

10 m³ of resin and 10.7 m³ (2825 gal.) of solution for eluting. These size estimates are based on treating 60,000 moles/hr of MCl_2 (60 m³/hr @ 1 M solution) with resin of nominal capacity of 2,000 equiv./m³. A resin bed of 10 m³ would thus contain 5,000 moles (10,000 equivalents) at 50% of saturation and would require 12 loading and unloading cycles per hour at this fractional loading.

F3. NaOH BASIC LEACH PROCESS

Basic leaching provides a process in which amphoteric oxides SiO_2 , Al_2O_3 and TiO_2 may be rendered water soluble and separable from other metallic oxides such as CaO , MgO and FeO . The presence of these polyvalent metals, however, introduces complications to the separations (in comparison with sodium) since they generally combine with silica to form insoluble silicates. Addition of stoichiometric or excess amounts of CaO would normally displace Mg and Fe from the silicate compounds and the calcium silicates may be decomposed by hydrolysis with acid solutions or steam or by displacement with sodium carbonate.

Dissolved sodium silicates or aluminates may be separated by controlled neutralization with $Al(OH)_3$ precipitating at higher pH than $Si(OH)_4$. Alumina may also be separated from alkaline solutions by controlled crystallization based on temperature dependence of solubility as in the Bayer process.

Mixtures of $Si(OH)_4$, metal silicates and $M(OH)_2$ precipitates may be separated by acidification which redissolves all components except the silica gel.

The initial leach step may be conducted with various levels of water content including anhydrous conditions and at temperatures

from ambient up to 900°C or higher. Water-based systems at elevated temperatures must be pressurized. The choice of leaching conditions will depend primarily on reaching acceptable rates for the process.

Based on published analytical studies by Rakhimov, Ponomarev and Ni²⁰, we have selected a first process step involving decomposition of anorthite with base in an autoclave at 300°C (Eqn. 1 of Table IX). The ternary silicate compounds are generally water insoluble but may be converted to calcium silicates plus water soluble compounds by further treatment. Thus, Shpigun, Sazhin, Fedorenko, and Shor²¹ reported that by forming a slurry of $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O}$ with water in presence of stoichiometric amounts of CaO and NaOH, $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3 \text{H}_2\text{O}$ and $\text{Na}_2\text{O} \cdot 2 \text{CaO} \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O}$ would be formed at 200°C (Eqn. 22). Ni, Ponomarev, and co-workers²² reported that treating $\text{Na}_2\text{O} \cdot 2 \text{CaO} \cdot 2 \text{SiO}_2 \cdot \text{H}_2\text{O}$ in a water bath at 95°C will decompose it to NaOH and $\text{CaO} \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$ (Eqn. 3). Following these operations the solution contains $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3$, $\text{CaO} \cdot \text{SiO}_2$, and NaOH. The $\text{CaO} \cdot \text{SiO}_2$ will be insoluble, whereas the $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3$ and NaOH remain dissolved. If some $\text{CaO} \cdot \text{Al}_2\text{O}_3$ were precipitated, addition of Na_2CO_3 would redissolve the alumina content. Silica can then be recovered by hydrolyzing the $\text{CaO} \cdot \text{SiO}_2$ with acid or steam (Eqn. 4).

Angstadt and Bell²³ described in a patent the precipitation of $\text{Al}(\text{OH})_3$ by passing CO_2 through 3 - 4 molar solutions of $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3$ (Eqn. 5). After separation, the filtrate contains only Na_2CO_3 . Calcining the $\text{Al}(\text{OH})_3$ at 1100 - 1200°C will produce water and alumina (Eqn. 5). The alumina can be stored with no

tie-up of necessary reagents, and aluminum can be produced from it, when it is needed.

It is thus theoretically possible to recover the reagents used in the preceding steps. Na_2CO_3 can be reconverted to NaOH by one of several processes: 1) treatment with lime (Eqn. 7), 2) conversion by anion exchange resin (Eqn. 8), or 3) electrolysis using ion permeable membranes (Eqns. 9a and b). Regeneration reactions are given by Equations 10-12. A flow chart is given in Fig. 16.

The eventual practicality of the basic leach process will probably depend on kinetics of solution, separation and hydrolysis steps as well as recycle efficiencies of the caustic solutions. It seems probable that the silica obtained will contain minor amounts of alumina and titania, but this may not be an important consideration if post refining steps are used. The process should operate satisfactorily with anorthite, but would require some modifications if used with pyroxenes or olivine since the presence of Mg and Fe would complicate hydrolysis of silicates.

Any of the reduction processes previously described as applicable to the reduction of oxides or halides may be used in conjunction with the basic leach separation steps.

G. SYNOPTIC COMPARISONS OF PROPOSED PROCESSING SYSTEMS

As previously discussed, the establishment of ratings or comparative figures of merit between various materials processing systems involves many factors characteristic of the processing systems themselves as well as their interaction with the other technologies involved in space industrialization which, in turn, will depend on specific applications characteristic of various

mission requirements. While there has been little discussion and no consensus on how to establish a useful scale for rating such systems, it would nevertheless appear useful to briefly survey the general characteristics, electrical and thermal energy requirements, technological risks and key problems facing the process routes previously studied.

Table X summarizes the principal features of the six generic processes previously proposed for transforming lunar materials. It would be premature to select or discard any of the above processes based on the analyses performed to date, but it seems likely that when a satisfactory rating system is adopted, the carbothermic/silicothermic and carbochlorination processes will be less favorably rated than some of the remaining contenders.

H. SOME PERSPECTIVES IN THE MINING/BENEFICIATION/MATERIALS PROCESSING/ REFINING PHASES OF SPACE INDUSTRIALIZATION

The materials processing systems proposed to date represent a small sampling of the enormous number of feasible processes for conversion of lunar materials. While there seems little doubt that any of these routes is technically feasible and would represent a practical materials processing system (if no other methods existed), nonetheless one would prefer some systematic method for prescreening potential processing systems to aid in selection of promising new routes as well as in optimizing or modifying previously studied or new systems.

One may perform rough sizing estimates for various physical and semiphysical M/D and separation operations from physical principles and engineering experience on earth-based processing

plants. For chemical conversions (reactors), experimental kinetic data is generally required, but correlations between reactor throughput and volume previously discussed may furnish rough but plausible minimum values.

In comparing various processes, it is worth noting that it is the total mass, power, simplicity, etc., needed for all steps necessary to reach a required degree of purity that are the meaningful quantities needed for objective comparisons.

The refining of the materials output streams of a processing plant has somewhat arbitrarily been grouped with the chemical conversion steps in the "materials processing" box of the industrialization sequence (Fig. 17), even though the outputs may require further refinement in manufacturing as, for example, with semiconductor grade silicon. It might be preferable, in principle, to consider separately all refining operations, but since these steps are intimately related to the method of primary processing and furthermore are subject to changing demands with technological evolution, it is probably wiser to group with the materials processing section all refining steps necessary to reach a level of purity satisfactory as input for manufacturing operations as customarily practiced on earth and indeed, to define specifications appropriate to specific materials products.

To analyze the technological options in the stages prior to manufacturing, we may utilize the flow chart shown in Fig. 18 which shows a chemically expanded "black box" processing stage. In this approximation the lunar soil is considered as a mixture of its seven major elements: O, Si, Al, Fe, Mg, Ti and Ca (which account for 99+% of its mass). The beneficiating stage which is useful

but probably not mandatory unless neutral iron recovery is needed or substantial demands occur for Ti or minor elements is conceptually shown as yielding six output streams — anorthite (feldspar), pyroxene, olivine, ilmenite, iron and gangue or slag with the last either rejected or converted to dark glass or ceramic products. We shall not discuss the mining operations except to note that the soil mining techniques are not expected to differ in any material way for any of the various options in beneficiation or processing except for beneficiating equipment installed on mobile mining apparatus.

The materials processing options, in effect, constitute various engineering solutions to the contents of the "black box" representing the materials processing steps.

One should not underestimate the importance of the scrap recycle loops (or mass flow) nor fail to note that these extend into the manufacturing, fabrication, assembly, and operational phases, of space activity. Even in an efficient manufacturing operation, the total mass of scrap generated may constitute and significant fraction if not actually exceed the mass of the acceptable product(s). The ability and efficiency of the materials processing operations to handle such scrap may have a vital bearing on the practicality of the whole industrial effort.

Similarly, the manufacturing and assembly operations may consume substantial quantities of reagents, cleaners, fluxes and other supplies normally expendable in earth operations. The ability and efficiency of the materials processing operations to regenerate such supplies may be of major importance.

Although representing an oversimplification, one may basically

consider the high temperature reduction methods as processes in which reduction is first performed followed by purification (or separation) of constituents from a mixed alloy, while the hydro-chemical processes perform the separation prior to the reduction(s).

Experience here on earth suggests that the latter method is almost always preferred, although it does not necessarily follow that this will also be true under lunar or orbital conditions. Metallurgical practice has shown that while it is often relatively simple to remove minor amounts of reactive metallic ingredients from more noble metals, the inverse is rarely possible except where large differences in volatility exists. Thus gold, silver, copper, lead and other soft metals are often purified by oxidation or conversion of more reactive impurities, but aluminum, titanium and similar metals are very difficult to purify from alloy form. The reduction product of high temperature reduction of undifferentiated or physically beneficiated lunar soil will likely be an iron-silicon-aluminum alloy with possible additional magnesium, calcium and titanium. Even if the latter materials were absent, the separation of iron from silicon and the latter from aluminum would be technically challenging. If silicon were readily removable from aluminum, the aluminum industry would probably be radically changed and clay would form the raw material of choice. In addition iron forms intermetallic compounds with both silicon and aluminum which renders separation extremely difficult.

Many of the difficulties ascribed to the carbothermic reduction process proposed earlier^{1a} apply also to the direct electrolysis

process. In the former route, one is additionally faced with the problem of recycling the carbon monoxide to carbon and oxygen, while with the latter, the durability of possible anode materials remains to be established. The aluminum-iron-silicon separation problem is treated in the following reference^{24a}. . .

An extended discussion of materials output capabilities and their dependence on composition specification is given in Appendix J.

PART THREE — TECHNOLOGY DEVELOPMENT

Introduction

The enactment of any directed activity in space, whether scientific, industrial, service, or military, requires a sequence of conceptual planning, engineering, design, acquisition of raw or semi-finished materials and supplies, processing and fabrication, assembly, testing, transportation (including launch and orbital injection and transfers), deployment and operation(s) (Fig. 19). Until the present time, the acquisition of materials and supplies has been from a variety of commercial sources and vendors with little or no assembly or deployment in space involved except for solar panels, antennae, etc.

With an increasing level of space activity forecast for a variety of missions, it becomes advantageous to examine potential alternative sources and sequences of materials acquisition, mining, processing, fabrication or manufacturing and assembly with necessary transportation requirements for planning various space programs which will become active in the 1980's and 1990's.

The development of an "assured" or demonstrated technology to effectively process lunar or other space derived materials to a variety of useful products will permit rational selection of cost-effective routes to various mission assignments. It may in some instances offer the only truly cost or environmentally acceptable method of deploying large masses of structures in earth orbit. Figure 20 shows some options available for sources and sequences to supply the mass and device requirements of future space missions.

The establishment of non-terrestrial materials sources for major portions of future space activities will require the establishment or development of several distinct technologies (Fig. 21) including:

A. Transportation

Lunar launching of large cumulative masses of raw or beneficiated ores and/or refined or finished materials.

B. Mining and Beneficiation

Extraction, sizing and beneficiating lunar or other soils or rocks.

C. Materials Processing

Conversion of raw or beneficiated ores and recycled scrap to structural metals and non-metals, oxygen and propellants.

D. Manufacturing and Fabrication

Conversion of refined materials to useful devices.

E. Assembly and maintenance

Erection of large structures and performance of maintenance, repair and replacement activities for other operations.

The early embodiments of steps A through E into hardware and systems will be governed initially by the traditional goals of predetermined missions (e.g., a particular large structure). However, with time each step will be enriched into many diverse physical operations to support the broader needs of a growing "in-space" economy just as has occurred on earth.

I. TIME, COST AND SCALE OF TECHNOLOGY DEMONSTRATION PROGRAMS

The transportation class represents technology which has no direct analogue in the industrial experience of earth-bound commerce but the remaining classes will consist of functional steps which have the majority of features closely related to similar activities on earth. Many of the mining, processing and manufacturing procedures used on earth can be adapted with little or no change from earth plant operations. Such procedures can be proof-tested on earth in a short lead time at low cost, especially for procedures which will be conducted inside pressurized vessels with a simulated centrifugal gravity. Some of the chemical process steps will invariably differ from those which have been previously conducted in pilot plants or on a commercial scale. For these steps, some sequence of development paralleling those involved in the introduction of new process technology in the chemical or metallurgical industries will be required. However, the customary lead time from lab scale to bench test to sub-pilot,

pilot plant and commercial production which would customarily require from five to 15 years may not be required for space processors. Space processing plants may be more typically in a throughput range characteristic of terrestrial pilot plants.

A major factor in extending the time period required on earth to proceed from the pilot plant to full scale facilities is the necessity of developing cost projections accurate to within 5 - 10% before committing major capital outlays to the design of full scale facilities. Such overriding competitive factors in the marketplace on earth will not exist in the early stages of space ventures where the competition will consist of earth manufacture vs. one or more space manufacturing options. In view of such considerations, a characteristic lead time for "space qualifying" a new chemical process from laboratory scale to pilot plant may be expected to range from about three to seven years with substantially shorter times required to qualify processes that have already been tested on earth on at least a pilot plant scale.

Order of magnitude costs for chemical process R & D programs can be estimated from capital costs experience for a variety of inorganic and organic chemical processes. Typical plant capacities for major chemicals would amount to 10^5 short tons per year with capital costs of \$25 to \$600 per ton per year²⁵. R & D costs may be expected to be less than 20% of the above figures for processes requiring no major advancement of the state-of-the-art. This would indicate an approximate \$12 million

R & D limit per major process segment.^{*} Since the space processing facility must of necessity recycle the lunar deficient elements used as reagents or solvents, it will consist of several "forward" and "reverse" process segments or steps to effectively close the various recycle loops.

Annual and cumulative cash flows for space processing may be expected to show the same general trends as for terrestrial plants (Fig. 22). Positive cash flows may have to be stated in equivalent "values" or credits for the products generated.²⁶

It would appear likely that the R & D necessary to sufficiently develop the necessary materials transport technology will dominate the overall costs of utilization technology for non-terrestrial materials.

J. INFORMATION REQUIREMENTS FOR MANAGEMENT DECISIONS IN THE IMPLEMENTATION OF SPACE PROCESSING TECHNOLOGY.

In the overall development of an industrial capability in space using non-terrestrial resources, efficient management will require long range planning combined with adequate periodic or semi-continuous review and modification based on progress and

* Projects whose estimated development costs would exceed 20-25% of the capital cost of a commercial scale plant are generally screened carefully before receiving management approval. Projects for completely new products without direct competition may occasionally warrant higher development costs. New processes for existing products may also justify higher development costs, but the risk due to competitive forces is higher. Finally, processes involving minor modifications of existing processes would not normally require excessive development costs, but if they were anticipated, such projects would rarely be approved.

information developed during the program. The information can be classified as external if derived from other technologies (such as transportation and manufacturing) or internal if required and derived (or retrieved) principally for the processing operations. There will be a considerable interaction between the various technologies, since the economic practicality of space industrial operations will be critically dependent on transportation costs, and the transportation requirements will depend on the efficiency of reagent recycling in processing. Similarly the efficiency of many potential manufacturing operations may be extremely sensitive to specifications or impurity levels in the refined output of the processors.

Because of the lead time required to implement pilot plant testing of various chemical processing stages of an overall plant design, it is important to develop information at the earliest time possible concerning various alternative routes to process lunar ores. The information required would be that necessary to establish "figures of merit" for the various options. These would include mass per unit throughput, power requirements, heat rejection requirements, unit labor requirements, reagent replacement mass requirements (recycle efficiency), versatility, and some attempt to quantify corrosion, safety, product purity, and output flexibility of the alternative routes. The extent of "new technology" required (defined as steps for which no comparable pilot or sub-pilot scale experience on earth is available) will influence development time and costs and reliability or uncertainty of the corresponding operations and should be considered in process evaluation. In these regards, one of the first objectives of workshops or

conferences assembled with representatives from industry and the space agencies to advance space industrialization should be to develop interim or permanent guidelines to permit calculation of figures of merit for such processing systems.

While the studies performed to date have outlined one or more feasible processing routes for conversion of lunar ores to industrial feedstocks, it would be prudent to broaden the level of options by examination of additional proposals from a more diverse group of chemical and metallurgical process specialists. These could then be subjected to the criteria established for rating such options to permit an initial screening to concentrate additional work to the most promising routes.

K. PROCESS SELECTION AND QUALIFICATION

The sequence of steps necessary to space qualify all of the individual operations required for a complete space materials processing plant (which demands a quasi-closed loop materials flow for all elements not readily derived from lunar sources) are summarized in Fig. 23.

A candidate process can only be evaluated when a complete mass flow and heat (energy) flow chart or balance sheet has been prepared. Unfortunately some of the information required such as percent conversion of reaction steps, reaction rates, and efficiencies of phase separations may not be available before laboratory testing programs are implemented. In the absence of such data, preliminary analysis of candidate processes can be made under three types of estimates: (1) probable values, (2) worst case values, or (3) parametric values. Under all of the preceding assumptions, a computer systems analysis could be performed to estimate required

sizing, energy, and heat rejection requirements for a candidate process and in the parametric cases to determine the sensitivity of such features as equipment and reagent masses, to reaction rates and separation efficiencies of individual steps. Such analyses can serve to identify critical information needed to make a rational selection between various candidate processes.

It may be possible to reject certain candidate processes if the sizing and energy requirements based on probable reaction rates is less favorable than the worst case estimate for an alternative process. Reaction rate estimates can often be made using data from chemically similar operations, so identification of such data sources should have an early priority in the systems analysis study. For steps in which no similarity data is available, an initial laboratory program should be implemented to obtain the necessary data. For the HF acid leach process, the greatest deficiencies in lab data would appear to lie in the solution chemistry of fluorides and fluosilicates, primarily in solubilities as a function of acidity, fluoride and fluosilicate ion concentration, and temperature. In addition, for precipitations, the rough rates of crystallite growth or time necessary to achieve filterability or sedimentation and for ion exchange resins or membranes, the diffusion rates and selectivities for fluoride and fluosilicate solutes will be needed for probable value estimates.

The accuracy of estimates for candidate processes in which few if any of the process steps have similar analogues in commercial or pilot plant experience in the chemical processing industry will of necessity be low unless some fairly extensive laboratory testing is conducted to fill in information gaps. In

the absence of some overriding incentive to pursue such a process, it may not be worth the time and cost to generate the needed information to permit a more refined sizing and energy estimate for such totally new processing routes.

Following a parametric analysis of sizing and energy requirements, sufficient laboratory data must be generated to permit the application of figure of merit criteria for process selection. Once a process is selected, the individual process steps will follow a sequence of lab-scale qualified, sub-pilot or pilot scale qualified, simulated space environment qualified, and orbital qualified steps to achieve the desired level of reliability and confidence in the proper functioning in space. Depending on the amount of equivalent or similar commercial or pilot plant experience, it may be possible to omit one or more of the sequence steps. In particular, it may be possible to omit testing of pilot or sub-pilot scale reactors in large vacuum chambers or in reduced gravity fields such as in aircraft tests. Most of the process operations will probably be performed in equipment surrounded by a cabin atmosphere with a simulated (centrifugal) gravity so the only significant alteration of environment may be coriolis forces.

In addition to the direct process equipment and operation technology, there are several technical areas of development which will be common to nearly all prospective processes. These include: solar electric power systems, solar thermal power systems (low, intermediate or high temperature), space radiator heat rejection systems, centrifugal countercurrent distillation and heat transfer systems, volumetric buffers (barostats), momentum buffers and vacuum materials handling systems. Since high volumetric and mass

efficiency of equipment is of prime importance, studies of modularization methods of increasing or adjusting output of reactors or other equipment would be worthwhile.

In establishment of pilot scale or sub-pilot scale units to qualify the technology of process operations, it is not necessary to match the output of individual steps. In fact, the primary reason for the establishment of pilot plant test programs for earth processing plants is to allow the design of full scale equipment which will be output matched based on rate data acquired during pilot plant testing. Under such circumstances, it is doubtful whether operation of the pilot scale or analogous units in space simulation or orbital test version could or should be attempted in continuous or quasi-continuous modes. Furthermore, several items of equipment in a complete plant such as pumps, valves, motors, boilers, sedimentation centrifuges, stirrers, tank reactors, etc., may be required in substantially equivalent capacity at several points in the process loops, and a single unit lifted into orbit could serve to test several of the process steps by sequential testing rather than launch a complete mini-plant. Under such a plan, reagent and product storage facilities in excess of that necessary for an equivalent capacity complete plant would be required, but the overall equipment and reagent mass requirements would nevertheless be substantially reduced.

It would appear to be entirely acceptable to perform almost all chemical processing tests on a simulated lunar ore using synthetic ore with or without natural earth basalt additions to approximate intended lunar composition (after beneficiation). The effect of glassy fractions could be studied by variable melting

and quenching of the artificial feedstocks. Some limited testing on a very small scale of dissolution rates of actual lunar soils should be performed, but only this first stage could differ in any appreciable manner from the results achieved with the artificial ore.

L. DETAILED RECOMMENDATIONS

It is difficult to make detailed recommendations prior to the completion of the preliminary selection process, but based on the work done to date and with the assumption that no other process will emerge which will have a clear-cut advantage over the HF-acid leach process in the absence of additional lab bench scale testing, one may delineate recommended lab scale testing programs to furnish the information required to give a refined estimate of the mass, energy, heat rejection, and reagent replacement requirements of this process. One may also make recommendations regarding development of common supportive technologies as previously mentioned as well as studies to promote interaction of the developing techniques.

L1. PROCESS TECHNOLOGY

As previously outlined, the development of process technology should logically proceed through a sequence of selection, sub-pilot scale or pilot scale testing, qualification under space simulated environment and finally, orbital qualification. Final selection will in general require some additional verification or data acquisition at the laboratory (bench) scale before reasonable projections of process sizing can be made for various competitive processes.

One cannot identify the critical data deficiencies for a given process without an in-depth study of such a process, but we can indicate a method of informational review to indicate current state of information and to monitor the progress of the technology qualification program on a step by step basis using the HF acid leach process as an example.

For any processing system, the individual steps involving chemical reaction, phase separation, or simply heating, cooling or moving of materials should be separately identified and listed. Those steps involving simple heat exchange or materials handling where no unusual temperature or corrosion conditions are involved may be presumed to require no lab scale verification, but such steps may require missing thermal or physical properties data for accurate sizing of heat exchangers. The remaining steps should be reviewed for published data on equivalent or similar operations useful for preliminary or detailed sizing and general engineering experience valuable for plant design. We may designate the "Degree of Equivalency" for published data by inclusion in one of three classes: E (equivalent in nearly all significant details), C (comparable but with minor differences in composition, temperature, acidity, etc.), or R (related where primary product or reactants are the same, but conditions of formation may differ in significant detail).

Table XI shows a listing of steps from the HF acid leach process with notes illustrating the current informational background to this basic system. In addition to the specific steps listed in the prior reports, there is a brief listing of possible process

modifications with related published data. The literature references are not meant to be all-inclusive or exhaustive, but rather to indicate the reference material uncovered to date in readily accessible sources which bear on the proposed process.

It may be noted that the process areas most in need of lab scale data and process delineation are in the areas of conversion of NaF to NaOH and MSiF_6 to $\text{M(OH)}_2 + \text{H}_2\text{SiF}_6$. Some additional basic data of solubilities of fluorides and fluosilicates and diffusion rates of fluosilicate ions in ion exchange membranes and resins is needed to quantify separation and conversion steps. These deficiencies have already been discussed and will have to be overcome before complete mass flow balances can be specified. The process can, however, be operated by steam hydrolysis of fluorides which constitutes a less desirable but more fully defined option and thus a worst case sizing could be performed.

L2. SUPPORTIVE TECHNOLOGIES

Space Electric Power

For initial small scale requirements, solar photovoltaic panels will undoubtedly be used. Use of multiple sets of panels on the lunar surface for extended periods will be required. Although some experience has been obtained from equipment deployed in earlier lunar missions, studies and simulated testing to assure satisfactory operation may be indicated. It may be advantageous to use solar panels or mirrors as solar shades to cool the lunar surface over significant areas to facilitate other operations such as processing.

New or alternative solar electric conversion systems such as vacuum photoelectric emission should also be explored, especially those which could be produced locally with low transported mass.

Larger scale industrialization will undoubtedly be keyed to the ability to fabricate solar electric power systems in space.

Space Thermal Power

A considerable reduction in power plant mass for an equivalent useful power output is indicated for direct solar thermal furnace designs. However, use of such energy sources requires some modification of chemical processing units, especially if the heat is required in a rotating zone to achieve an artificial (centrifugal) gravity. An additional complication arises in the optical/spatial requirements for introducing reactants and removing products. The heat energy may be brought in as radiation using a refractory window or by absorption on a black surface and by conduction through the wall. Such wall materials must normally be corrosion resistant to the contents of the reactor unless the energy is reradiated. Some general studies of methods of solving these design problems should be undertaken including examination of refracting, reflecting or combined optical concentrators, low vapor pressure refractory windows and walls and kinematic designs to permit centrifugal forces in image zones. For solar furnaces intended for use on the lunar surface, the rotational requirement may not be necessary, but a crude tracking system capable of at least daily adjustment must be provided and the optical elements must be able to perform under lunar gravitational loading.

Space radiators

Much of the chemical process heat rejection load will probably involve rejecting heat at 500° to 600°K, either as primary heat, or from lower temperature exothermic steps which have been heat pumped up to such temperatures. In this range, steam is probably

a nearly ideal working fluid, but may pose some problems such as freeze-up in the event of process interruption. Some studies on designs and procedures to withstand freeze-up and restart such heat rejector panels, or alternatively to use antifreeze or other working fluids should be undertaken.

If steam is used, some engineering studies of various proposed heat pump cycles involving adiabatic and/or isothermal compression using wet or unsaturated fluid in various segments should be examined.

Some need for higher temperature heat rejection may also arise. This may be achieved by direct loss from reactor walls in shadow zones. If large amounts of power are involved, it would probably be preferable to recover such heat to supplement lower temperature requirements elsewhere in the plant. Mercury or alkali metals would be the most likely candidates as working fluids. It would probably be worthwhile to perform a study to select preferred working fluids as a function of temperature for heat rejectors.

Processes requiring large heat rejection loads below 500°K would not normally be desirable due to excessive radiator weights. A study of various alternative radiator designs which do not require working fluids and by avoiding meteoritic puncture hazard can be made extremely thin and lightweight should be made to see if such a technology can be developed and what effect it would have on the choice of chemical process selection.

Centrifugal Counter-Current Processes

A number of processes employed in chemical industries use a concurrent flow arrangement in which a rising fluid (usually a gas)

interacts with a descending phase (usually liquid or solid) with heat and/or mass exchange. A related process is a fluidized bed where the descending phase may be reversed but still possesses a differential velocity from the ascending stream. In these counter-current steps, the driving force for the descending phase is often gravity. If it is desired to use such a process in orbit, the gravitational force must be replaced by a kinematic (rotational) force. This will require a substantial redesign of such structures as fractional distillation columns since the artificial gravity will be a function of radial distance.

A general survey should be undertaken to assess the implication of a radially proportional artificial gravity and coriolis forces on existing chemical process equipment with recommended design modifications to permit satisfactory operation in orbit.

Volumetric Buffers

In the course of operation of quasi-continuous or batch processes, the total volume of material present at various pressure levels may fluctuate from time to time. For those operations carried out on earth at or near atmospheric pressure, little or no problem exists unless the material (gas) is exceptionally hazardous. In space, generation of large quantities of gases at pressures removed from their condensation points (temperatures) may require a substantial interim storage capacity or buffer reserve before the gas is condensed, liquified or consumed in some process step. For lower pressures, various bellows or bladder structures may be useful, but for higher pressures, some study of practical high pressure expandable structures is required.

Momentum Buffers

In the operation of chemical process equipment, there are often created substantial levels or surges of linear or angular momentum flow rates which are of no concern on earth except for the strength of support and equipment elements. In space stations with inertia comparable to the processing plant, the effects of momentum flow upon local accelerations of spacecraft sections is no longer negligible. The problem can be compounded if the orientation of solar concentrators must be maintained accurately during plant operation. A study should be undertaken to compare various methods of absorbing process momentum surges to avoid interfering with proper functioning of equipment or personnel.

Vacuum Materials Handling Systems

Although most steps of the chemical processing plant are expected to operate under an atmosphere of some kind, there are some stages where materials must be handled in vacuum. These include transfer from a lunar transporter to storage (if under atmosphere) or from storage under vacuum to the input flow stream in the plant, transfer of output solids (metals and oxides) to vacuum storage or final drying operations in high vacuum followed by transfer to vacuum (space) storage, and intermediate storage or operations with hazardous materials such as sodium. Materials handling in such situations may require special design considerations such as vacuum lock conveyors, lubrication with non-volatiles, outgassing scavengers, prevention of cold welding or agglomeration effects, etc., which should be anticipated well in advance of actual needs.

Modular Equipment Design

In the design of chemical process equipment, a change in capacity requirement of a reactor, distillation column or the like is often accomplished by addition or substitution of units with a given unit operated intermittently when excess capacity is available. A mismatch in capacity of one unit of an overall plant may be cured by post-construction modification or replacement. Since either of these fixes would be much more difficult for a space plant, it would be useful to examine the measures that might be taken to permit adjustment of capacity or throughput with the least possible effort. One method might consist of constructing major pieces of equipment as clusters of modules (with a minimum number of modules of about eight) whereby added capacity can be achieved by insertion of additional nodules (see Fig. 24).

L3. UNCONVENTIONAL PROCESSES

In the continuing development of space processing technology, one should give objection consideration to new approaches or methods of supplying refined industrial materials of a special nature or from other sources which may be available. In this regard, silicon hydrides (silanes) are potentially interesting fuels for rocket propellants.²⁷ SiH_4 and Si_2H_6 are gases at room temperature but their critical temperatures are somewhat higher than for the corresponding carbon compounds so both are storable as liquids at reasonable temperatures. They are hypergolic toward oxygen and thus present a safety problem in storage on earth. They can be manufactured in high yield from Mg_2Si and ammonium salts with the former being made from the elements. If this was synthesized on the moon, the

hydrogen might well have to be brought from earth, but the total propellant equivalent from the silicon hydrides might be substantially greater per unit mass of hydrogen than that obtained by directly burning the hydrogen.

M. TECHNOLOGY INTERACTION STUDIES

The developments of the various technologies required for space industrialization may have major impacts on each other's opportunities, potential and cost effectiveness. Thus the transportation technology will strongly influence operational costs, while the manufacturing and fabricating technologies will determine the ability of space industry to expand and diversify. The mining and processing technologies will determine the materials limitations of the other technologies except for minor fractions of materials or specialty hardware unavailable from space sources which may be supplied from earth.

The output of space materials processing facilities may be roughly grouped into three classes:

- a. Structural materials (solids)
- b. Fluids (gases, liquids, propellants)
- c. Reactive materials (sodium, calcium), etc.

The last class is primarily used as an intermediate to produce materials of the other classes, but the reactive metals may be useful as expendable fuels in propellant systems.

The flexibility of output options of the materials processing technology will largely determine the ultimate limits of the scope of space industrialization. The impact on transportation technology will be most directly evident from the options created in materials

for propellants, spacecraft, and electromagnetic propulsion systems (mass drivers, etc.). A reverse interaction from transportation to processing in addition to cost factors would be options in the construction materials of earth-launched spacecraft to supply lunar deficient elements for recycling in space. In particular, certain key industrial elements such as copper, tin and other soft metals, carbon, tungsten, and other heavy transition metals will be needed in small amounts, while molecular materials such as polymers and elastomers will also be useful if available in recyclable form.

The impact on fabrication technology will depend on the diversity of materials and supplies which can be furnished to create the tooling, facilities, and consumables needed to perform various manufacturing and fabricating operations. Manufacturing operations can be sub-divided into hot and cold operations with the former including casting, hot flowing or drawing, hot forming, sintering, welding, brazing, etc. In this class, the tooling requires refractory properties (hot strength) plus corrosion resistance in construction materials. In cold operations, high strength, materials hardness (especially in tool bits and abrasives), and machinability (or formability) are the most important properties for equipment for metal removal or metal working. Electric and magnetic properties as well as materials compatibility are also necessary considerations in some operations. Almost any fabrication or manufacturing operation which has been conducted on earth could be duplicated in space given a diverse range of steels, refractory oxides, magnetic and electric materials and thermal insulation, with probably 10% or less of the mass requirement demanding earth supplied components.

One should not overlook the necessity of various reagent or other consumable chemicals in various stages of essentially manufacturing rather than chemical processing procedures. Recycling of rinse waters, spent plating baths, lubricating and cutting oils and regeneration of acids and bases may be imperative or preferable to replacement from earth. The ability of materials processing facilities to perform these tasks as well as to efficiently recycle scrap generated by manufacturing may be of importance in the rating of processes.

The major areas in which fabrication technology could impact on processing technology would center on the ability of the fabricators to replace critical high wear or corrosion components such as valves, nozzles, pipes, tanks and refractory liners in various process steps. This ability, or lack of it, could determine the relative merits of competing processes. The most favorable case would be where the fabricators would have a complete capability to produce pressure vessels, pipes of various diameters (and materials), castings for valve bodies, pumps, motors, etc., and refractory or sintered ware of any desired shape and size, as well as common plate, strip, beam and wire metals forms.

To promote the mutual understanding of the needs and capabilities of the progressing technologies and to further their use or application to the other technologies such that the overall space industrialization effort may benefit, it is recommended that workshops be held with participants (engineering or study groups) from transportation, mining, processing, fabrication, and assembly disciplines, to review problems, advances, and effects of materials

substitutions on proposed operations and to give direction to future efforts. Some of these should be of a quite general nature, while others could be limited to very specific topics such as propellants. All technology reports of the various groups should be transmitted to the other groups and the report writers should be encouraged to include in their summary sections brief descriptions of potential impacts on the other technologies and the overall prospects for space industrialization.

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Table I

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, 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 , 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

LUBRICANTS, HEAT TRANSFER FLUIDS

Sulfides, graphite (limited by C)

SO_2 , He

INDUSTRIAL CHEMICALS

Detergents, cleansers, solvents, acids, bases

H_2SO_4 , H_3PO_4 , CaO, NaOH

Table II

PRODUCT MIX OPTIONS

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 (whole rocks)

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 structural metal (and silicon)

Demand, oxygen may appear as an unneeded by-product, or iron

and other reductants may be a surplus material

Reinforced/normal metal ratio

Demand dependent on suitability of reinforced metals to

replace a variable portion of reinforced resins in structures

Table III

RANGES OF CHEMICAL COMPOSITIONS FOR THE MAJOR MINERALS

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%
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 III (continued)

RANGES OF CHEMICAL COMPOSITIONS FOR THE MAJOR MINERALS

Highlands Rocks

Modal Abundance (Vol. %)	Pyroxene 5 - 35%	Olivine 0 - 35%	Plagioclase 45 - 95%	Opagues (Mostly Ilmenite) 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 IV

VITREOUS SILICA

Reagent	Dissolving Rate
5% HF (RT)	96.6% (.04 mm dia.) dissolved 30 min.
1% HF	52.9% (.04 mm dia.) dissolved 30 min.
5% HCl (95°C)	$< 2.5 \times 10^{-6}$ cm 24 hr.
5% NaOH (95°C)	$\sim 1 \times 10^{-3}$ cm 24 hr.
H ₂ SO ₄	About same as HCl
H ₃ PO ₄ (150°C)	Some attack

Table V

BULK COMPOSITIONS OF PLAGIOCLASE AND ILMENITE CONCENTRATES

90% Plagioclase and 10% Residue (Weight %)			90% Ilmenite and 10% Residue (Weight %)		
	weight percent	moles per 100 gram			
SiO ₂	44.90	.747	SiO ₂	3.78	
TiO ₂	0.05	.00063	TiO ₂	48.10	
Al ₂ O ₃	33.67	.33	Al ₂ O ₃	1.07	
Cr ₂ O ₃	0.01	.000067	Cr ₂ O ₃	0.49	
FeO	1.09	.0152	FeO	43.28	
MnO	0.01	.00014	MnO	0.03	
MgO	1.35	.033	MgO	1.29	
CaO	18.59	.331	CaO	1.07	
Na ₂ O	0.45	.0073	Na ₂ O	0.04	
K ₂ O	0.16	.0017	K ₂ O	0.01	
P ₂ O ₅	0.03	.00021	P ₂ O ₅	0.01	
S	0.01	.00031	S	0.02	
Enrichment Factor			Enrichment Factors		
Al ₂ O ₃	1.96		TiO ₂	3.7	
			FeO	2.2	

Table VI

CARBO-CHLORINATION PROCESS EQUATIONS

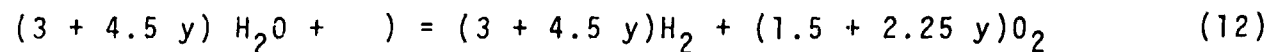
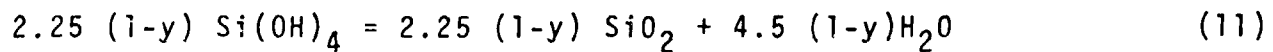
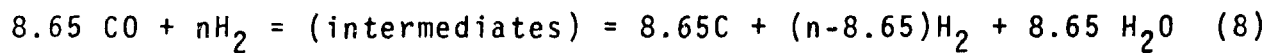
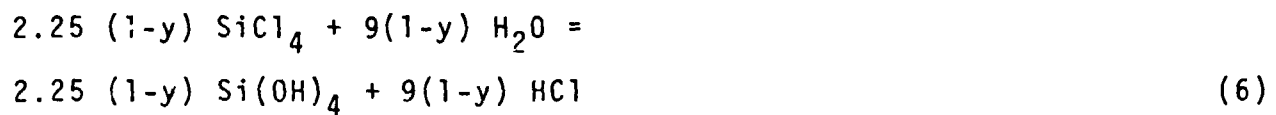
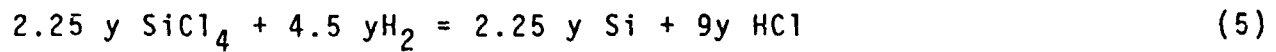
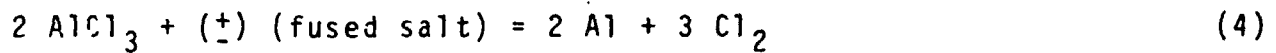
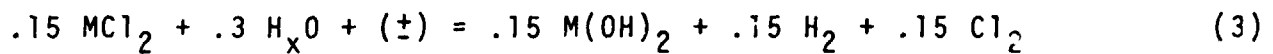
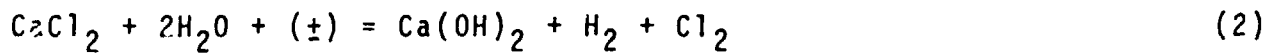
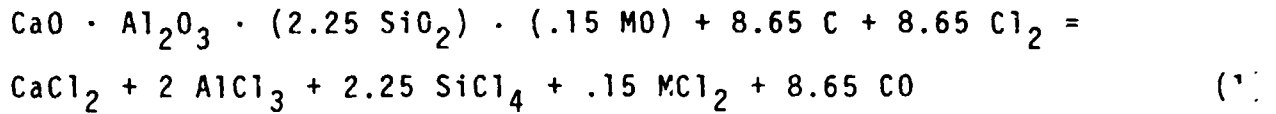


Table VIIa

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. $(1-y) [SiF_4(v) + 4H_2O = Si(OH)_4 + 4HF]$
- 3a. $(1-y) [SiF_4(v) + 2H_2O = SiO_2 + 4HF]$
4. $(1-y'-z) [xMF_2 + xH_2O = xMO + 2x HF]$
5. $y [SiF_4 + 4Na = Si + 4NaF]$
6. $y' [xMF_2 + 2x Na = xM + 2x NaF]$
7. $z [xMF_2 + xSiF_4(aq) = xMSiF_6(aq)]$
8. $z [xMSiF_6(aq) + xH_2O + elec. energy = (x/2)O_2 + xM + yH_2SiF_6]$
- 8a. $z [xMSiF_6(aq) + M'SO_3R^* = xM'SiF_6(aq) + xMSO_3R^*]$
9. $m NaF + mR^*OH = mNaOH + mR^*F$
- 9a. $m NaF + (m/2)Ca(OH)_2 = mNaOH + (m/w)CaF_2$
10. $m NaOH + elec. energy = mNa + (m/2)O_2 + (m/2)H_2O$
11. $(1-y) [Si(OH)_4 = SiO_2 + 2H_2O]$

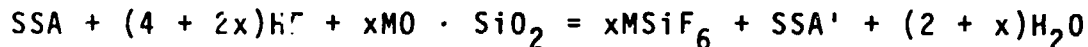
R* = ion exchange resin

$$m = 4y + 2xy'$$

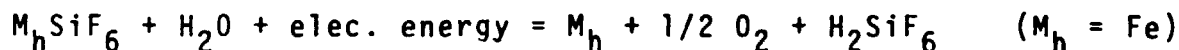
Table VIIB

METAL FLUORIDE/FLUOSILICATE SEPARATIONS
(Separations of Al, Ca, Fe, Mg ions)

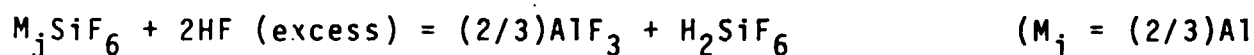
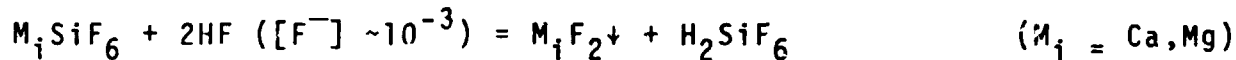
Acid leach (Eqn. 1, Table VIIa) with SSA will leave metals in soluble fluosilicate form. We may write the acid leach step as:



1. Electrolyze iron:

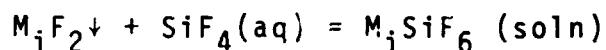


2. Selectively precipitate fluorides

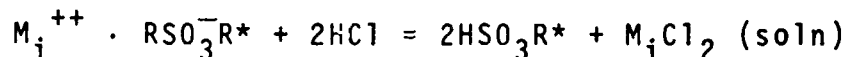
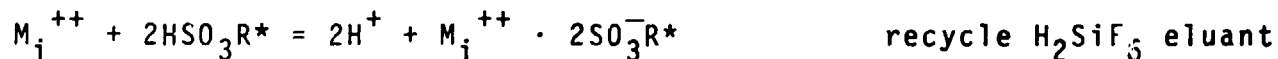


H_2SiF_6 is returned to leach cycle, AlF_3 to reduction step

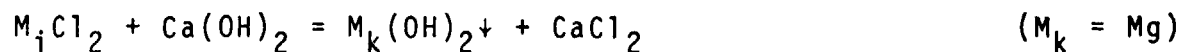
3. Redissolve M_iF_2



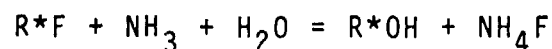
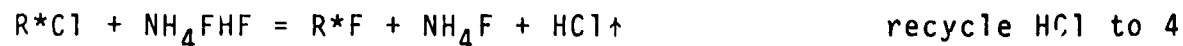
4. Salt splitting (conversion to chlorides)



5. Precipitate $\text{Mg}(\text{OH})_2$



6. Salt splitting (conversion to hydroxide)



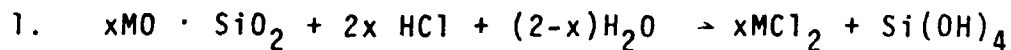
7. Reagent regeneration



R* = ion exchange resin

Table VIII

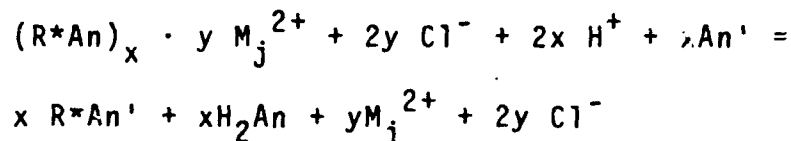
HCl ACID LEACH PROCESS EQUATIONS



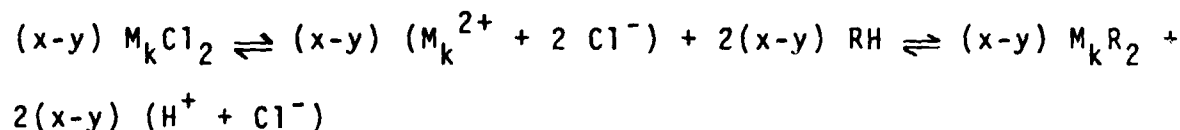
2a. (anion exchange resin)



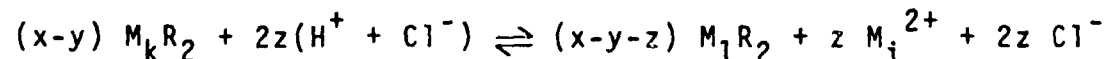
2b. (acid elution)



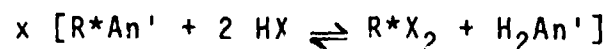
3a. (cation exchange resin)



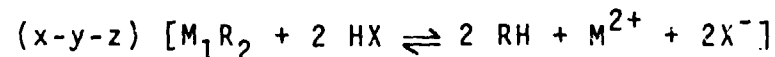
3b. (partial elution)



4. (regeneration)



5. (regeneration)



R, R* = resin polyelectrolytes

RH = R⁻H⁺ = cation exchange resin (sulfonate type)

R*An = R⁺⁺An = anion exchange resin (quaternary ammonium type)

An, An' = anions such as SO₄, 2OH, citrate or other species

Reduction, hydrolysis and pyrolysis reactions are similar to HF acid leach process as shown in Table VII.

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. $\text{Na}_2\text{CO}_3 + \text{CaO} + \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \text{CaCO}_3\uparrow$
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. $\text{Na}^+ + \text{H}_2\text{O} + \text{e} \rightarrow \text{Na}^+ + \text{OH}^- + 1/2 \text{A}_2\uparrow$
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

COMPARISON OF MATERIALS PROCESSING SYSTEMS

Characteristic	Carbo/ Silico Thermic	Electrol. Silicates	C-Cl ation	HF Acid Leach	HCl* Leach	NaOH* Leach
Percent of input mass flow subject to high temperature processing	200	100-150	100	40	40	40
Maximum process temperature °C	2300	1300	1000-1200	1200	1000-1200	1200
Reduction products: Pure metals, Si Alloys (Fe, Al, Si)	X	X	X	X	X	X
Secondary refining required (e.g., metal distillation)	X	X	X			
Silica, clear glass, refractory side demands require reoxidation	X	X				
Ratio, electrolysis equivalents: net oxygen equivalents	1.33-1.5+	1.33-1.5+	~2.5 ⁺	1	1	1
Oxygen recovery: Recycling CO Electrolysis of H ₂ O Electrolysis fused salt, alk., etc. Electrolysis fused silicates	X		partial partial	partial partial	partial partial	partial partial
Process power: Electrical watt hr/equiv. (theoretical) Thermal (theoretical)	91.4 129.7#	~100 25-40	{ 107.5- 135.7 <20	{ 72- 144+ <20	NA <20	NA <20
High purity Si, SiO ₂ obtainable				X		
Elements recycled:						
H			X	X	X	X
Cl	(A)	(A)	X		X	X ?
F				X		
Na				X	X	X
C	X		X			X(CO ₃)
Si	X			X(Mg)		X(Mg)
N				X ?		
Technological risk	high	high	medium	low	low	medium

Table X (continued)

COMPARISON OF MATERIALS PROCESSING SYSTEMS

Characteristic	Carbo/ Silico Thermic	Electrol. Silicates	C-Cl ation	HF Acid Leach	HCl* Leach	NaOH* Leach
Key Problems:						
Refractories, corrosion	X	X	X		X	
Separations - metals	X	X				
Separations - nonmetals				X	?	X
Rate (kinetic) problems		X			X	
CO conversion to C, O ₂	X		X			
Recycling efficiency	?	?	X	X	?	X
Adaptability to:						
Anorthite	X	X	X	X	X	X
Pyroxene, olivine	X	X	X	X	X	?
Ilmenite, spinel	X	?	X	X	X	

+ Depending on reduction load

* Using Na, or direct reduction

May require electric (arc) energy

(A) Additional elements may have to be recycled in metals refining operations

Table XI

Information Summary of Testing or Qualification (Scale) of
Process Steps for HF Acid Leach Process

Step	Lab Qualified	Sub-Pilot Plant, Pilot Plant or Semi-Commercial	Commercial Qualified	Space Qualified
Acid dissolution (Silicate rock)	E(1a)	E(1b)		
Precipitation, Crystallization, Filtration MF ₂	C(2a)	C(2b)	C(2c)	
Distillation, SiF ₄ , H ₂ O	E(3a)		C(3b)	
Acid hydrolysis, Si ₄	E(4a)		R(4b)	
Distillation, HF, H ₂ O	E(5a)			
Na reduction, SiF ₄ or MSiF ₆		C(6a)		
Na reduction, AlF ₃ or Na ₃ AlF ₆			E(7a)	
Na Reduction, MF ₂	R(8a)			
Electrochem reduction, Na, O ₂			C(9a)	
Exhaustive drying NaOH	E(10a)			
Steam hydrolysis, MF ₂	E(11a)			
Steam hydrolysis, Na ₃ AlF ₆	C(12a)			
Conversions NaF, NaOH	C(13a)		R(13b)	
Conversion, MSiF ₆ ,	C(14a)			
M(OH) ₂ + H ₂ SiF ₆				
Drying, M(OH) ₂ , MO			E(15a)	
Filtration, Si(OH) ₄			C(16a)	
<u>Process Modifications</u>				
Anhydrous (NH ₄ FHF) dissolution		R(17a)		
Neutral hydrolysis (NH ₃)		E(18a)		
Regeneration, NH ₃		E(19a)		
Ion membrane regeneration	C(20a)			

Table XI (continued)

References:

- 1a. Common analytical procedure, rock analyses
- 1b. Metals recovery, silicate ores
- 2a. Gravity filtration, common separation in inorganic analyses
- 2b. Manufacture, specialty fluorine chemicals
- 2c. Centrifugal filtration, AlF_3 manufacture (Chem. Engrg. 4/27/64)
- 3a. Gambaretto and Pedler, Annali di Chimica 64, 711 (1974)
- 3b. Recovery of SiF_4 by product of phosphate fertilizer manufacture
- 4a. S. Thomsen, J. Amer. Chem. Soc. 74, 1960 (1952)
- 4b. Neutral hydrolysis (using $Al(OH)_3$, see ref. 2c)
- 5a. Munter, Aepli and Kossatz, I & EC 39, 427 (1947)
- 6a. J. Eringer, U.S. Pat. #2,173,969 (1939)
- 7a. Netto Process, see Encyc. of Chem. Tech. 9, p. 540 (Kirk-Othmer)
- 8a. Reduction of rare earth and uranium fluorides, see Topp, Chem. of Rare Earth Elements, p. 128, Elsevier, Amst. (1965)
- 9a. Castner sodium cell, see Encyc. of Electrochem., p. 1062 (Hempel) N.Y.: Reinhold (1964)
- 10a. Rahmel and Kruger, Zeit. fur Physik Chem. 55, 25 (1967)
- 11a. L. Domange, Ann. Chimique 7, 225 (1973)
- 12a. Silverman and Bowen, Anal. Chem. 31, 1960 (1959)
- 13a. Recovery via O_2 , see Ref. 12a plus solubility data Encyc. of Chem. Tech. 2, p. 7 (Kirk-Othmer)
- 14a. Three alternative routes: ion exchange resins, ion exchange

membranes and pptn. as fluorides plus hydrolysis. The first requires several steps but is relatively straightforward, the second has fewer steps but is largely unexplored, the third requires several steps, including one at high temperatures and probably requires more energy than the others.

- 15a. MgO and CaO are produced commercially by this method.
- 16a. Centrifugal filtration during AlF₃ manufacture, see Ref. 2c.
- 17a. J. Hickey, U. S. Pat. #2,624,698 (1953).
- 18a. G. Cunningham, U.S. Pat. #3,101, 254 (1963), C. Faust, U.S. Pat. #3,914,398 (1975).
- 19a. F. McClenahan, U.S. Pat. #2,446,484 (1948), C. Faust, U.S. Pat. #3,914,398 (1975).
- 20a. See Membranes, Technology and Economics, R. Rickles, Noyes Dev. Corp. and trade literature, Ionics, Inc., Watertown, MA (1967).

STRUCTURAL METALS & SILICON CONTENT OF LUNAR MINERALS

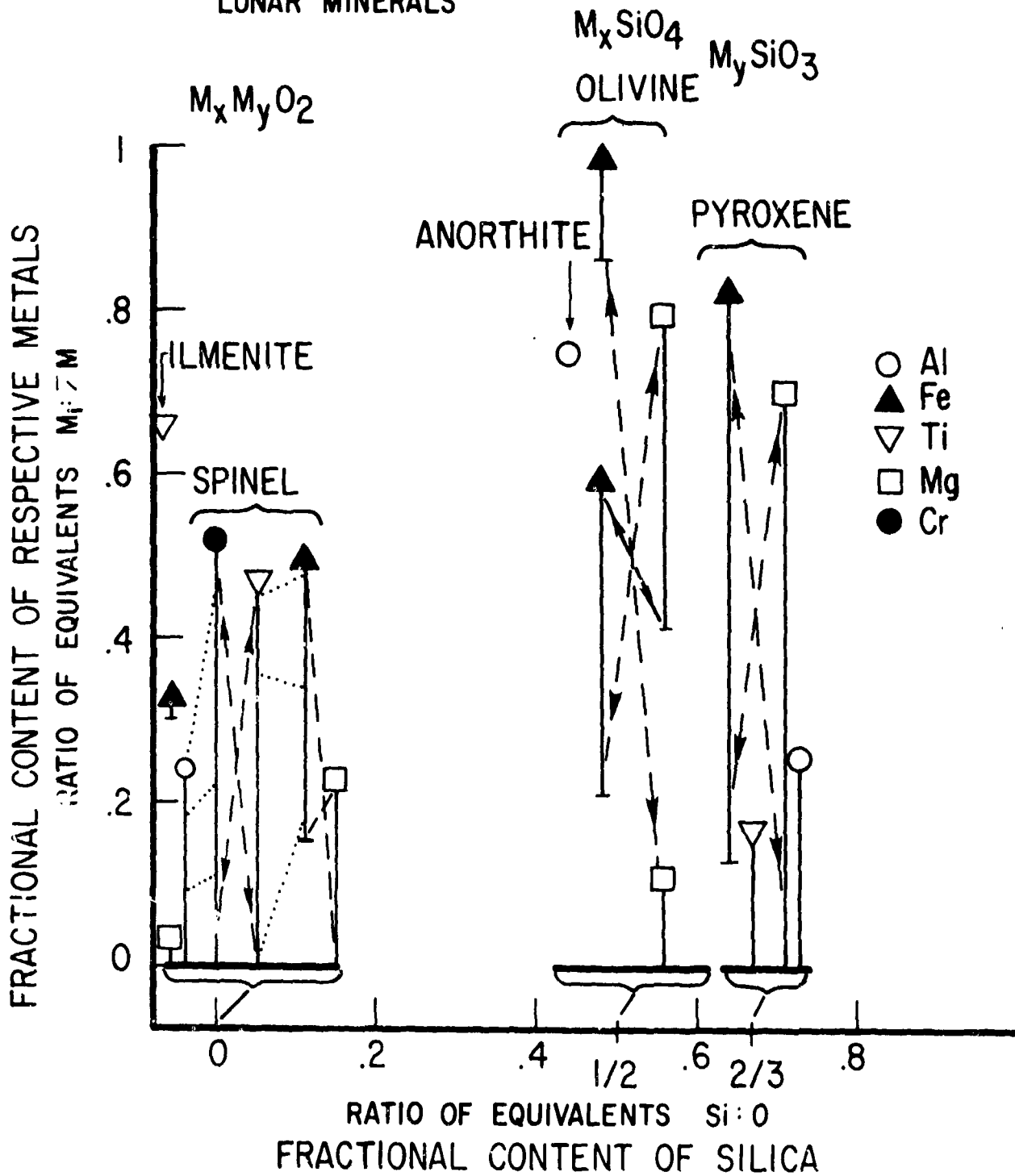
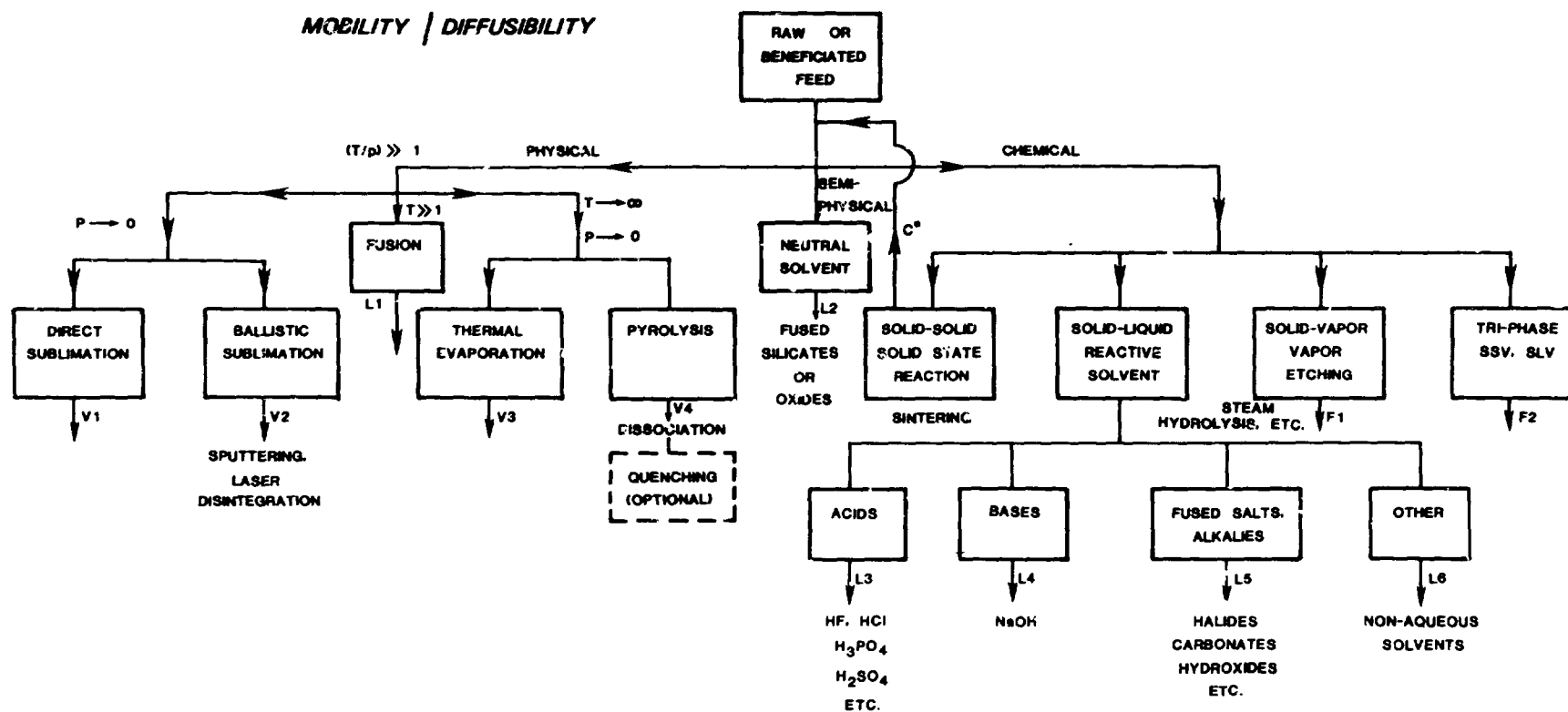


Figure II - 1



II - 101

Figure II - 2

SEPARATION

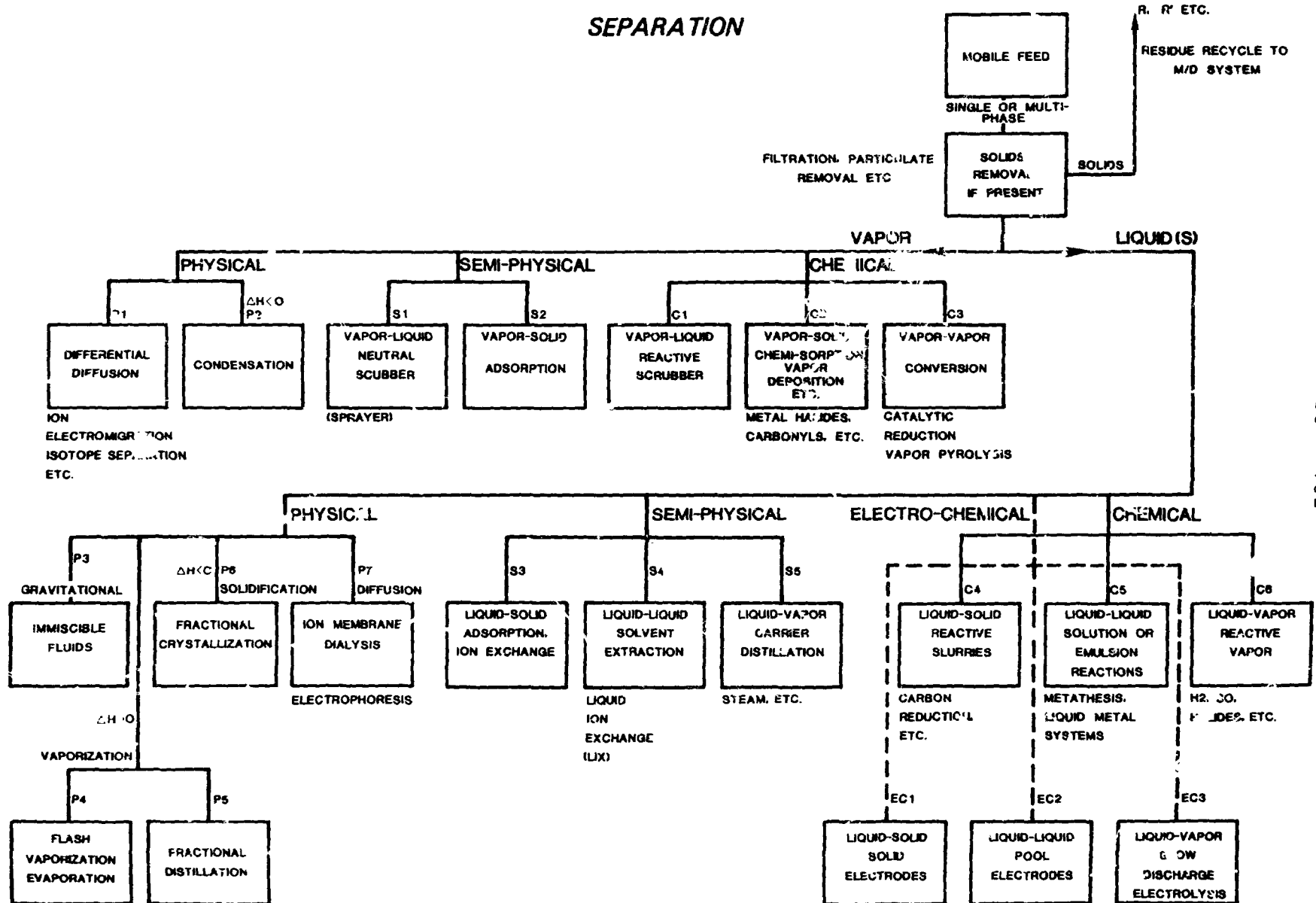
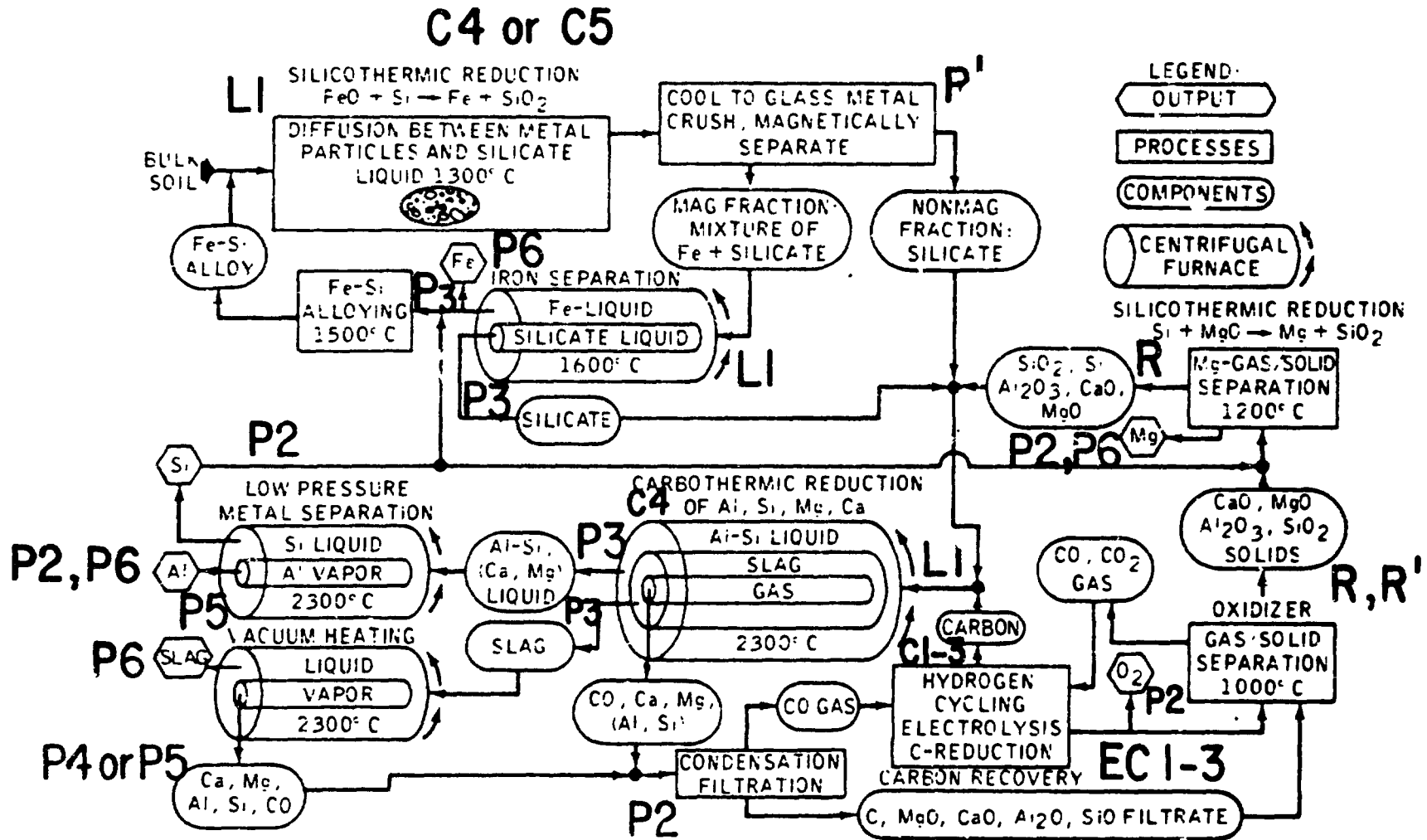


Figure II - 3



II - 103

Proposed flow diagram for processing of lunar soils. Temperatures shown are approximate. Components shown in flow-streams are not necessarily the molecular species that may be present.

Figure II - 4

FREE ENERGY OF FORMATION - OXIDES

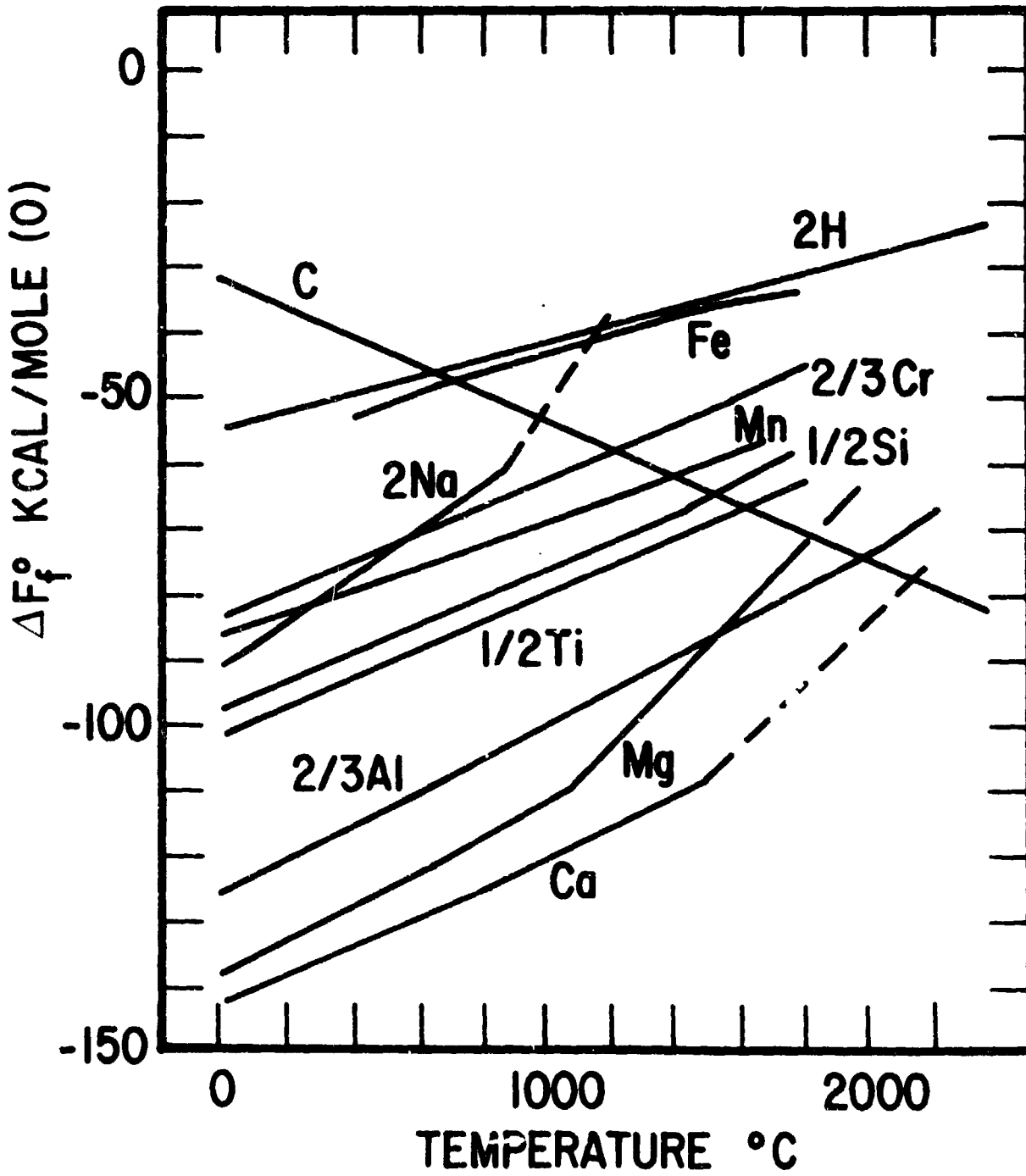


Figure II - 5

FREE ENERGY OF FORMATION
(FLUORIDES)

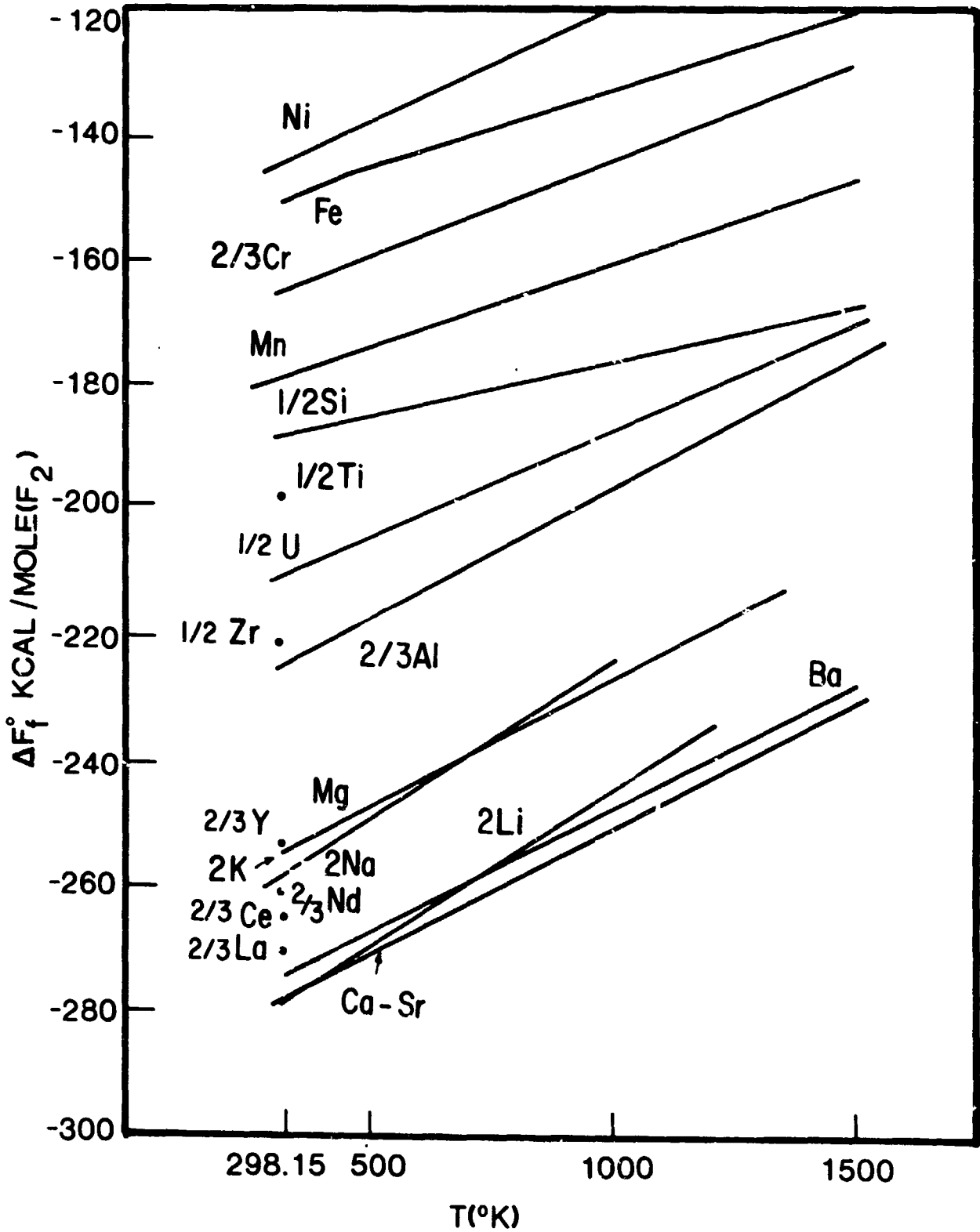


Figure II - 6

FREE ENERGY OF FORMATION - CHLORIDES

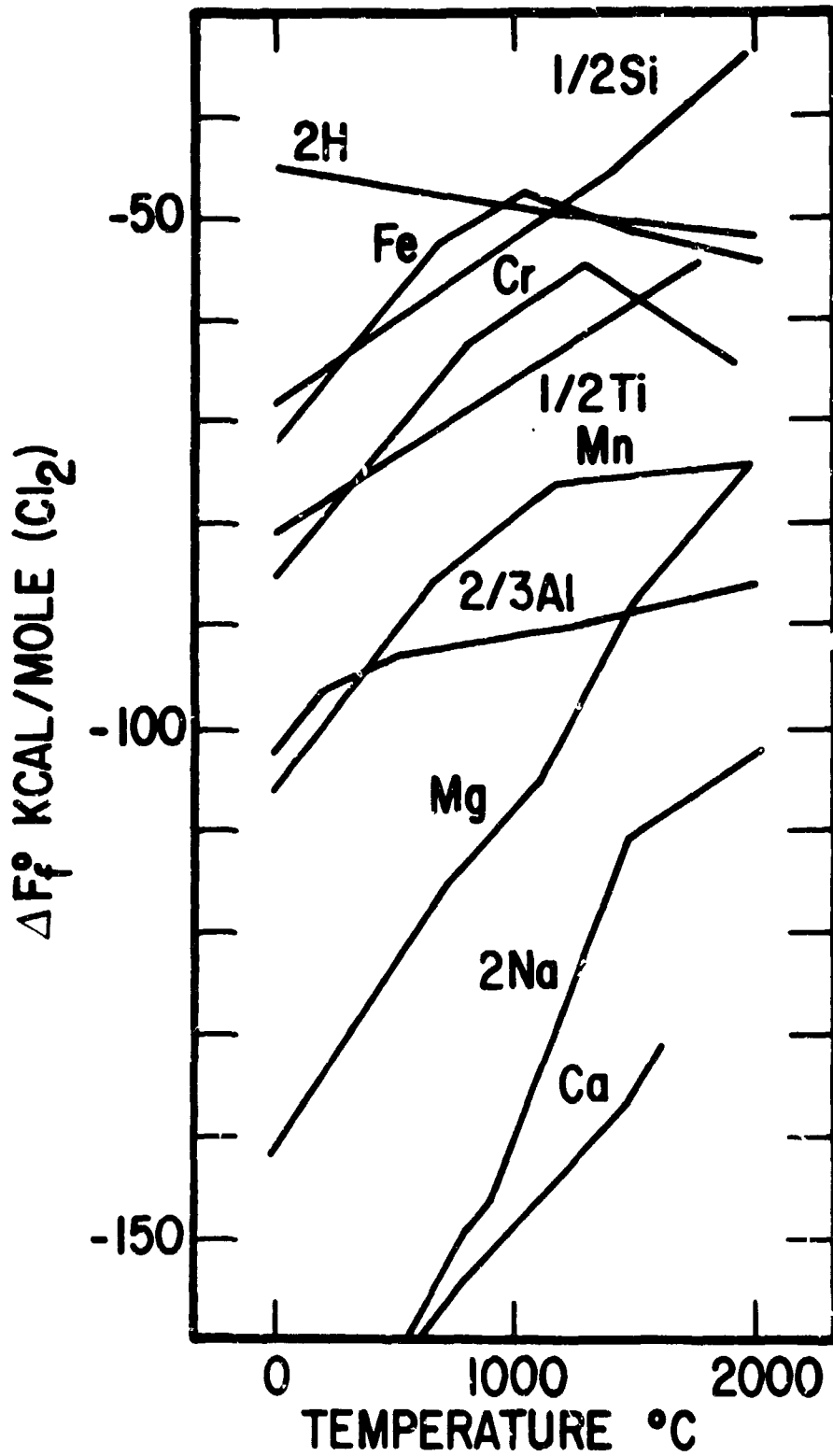


Figure II - 7

FREE ENERGY OF FORMATION - SULPHIDES

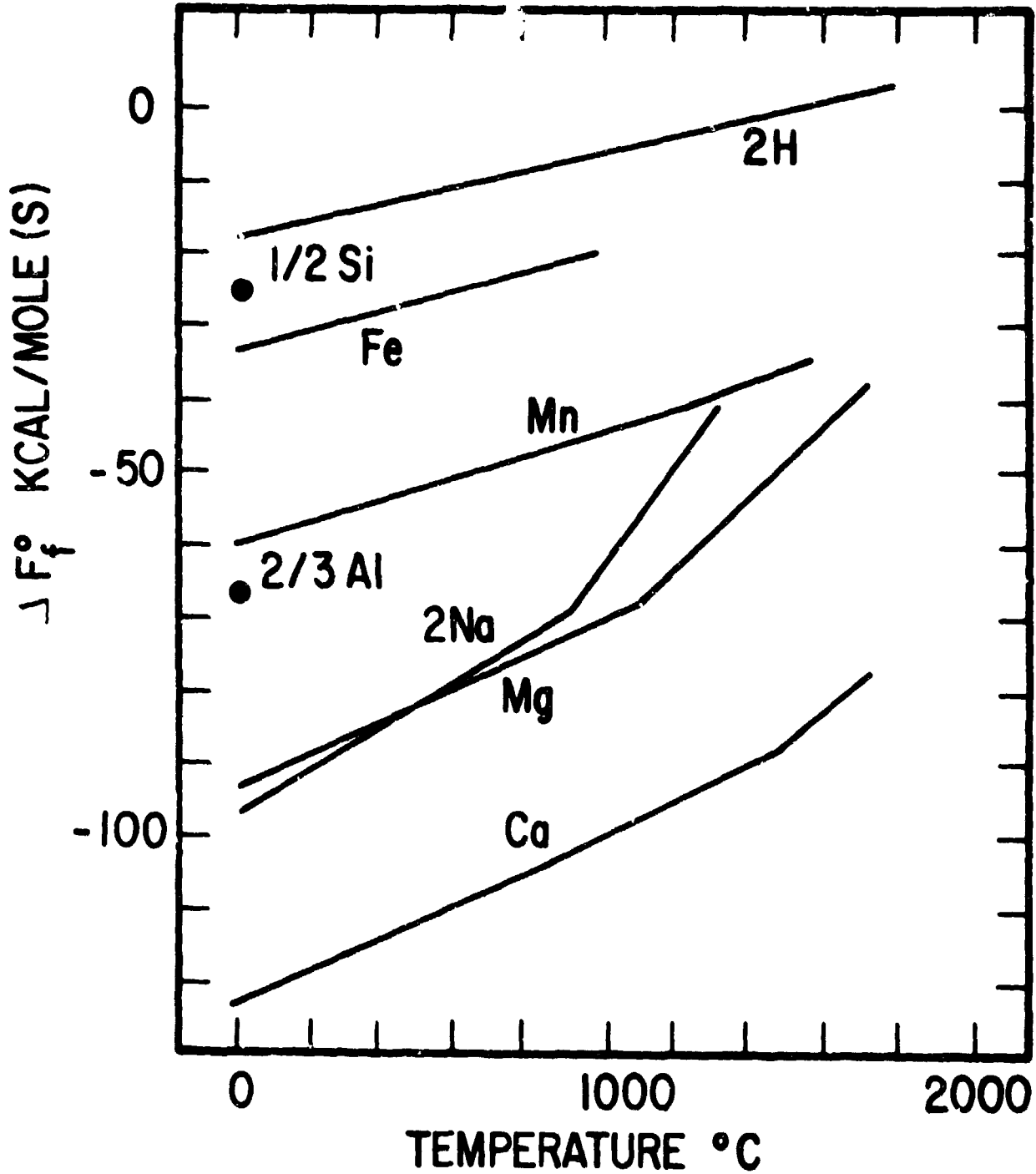


Figure II - 8

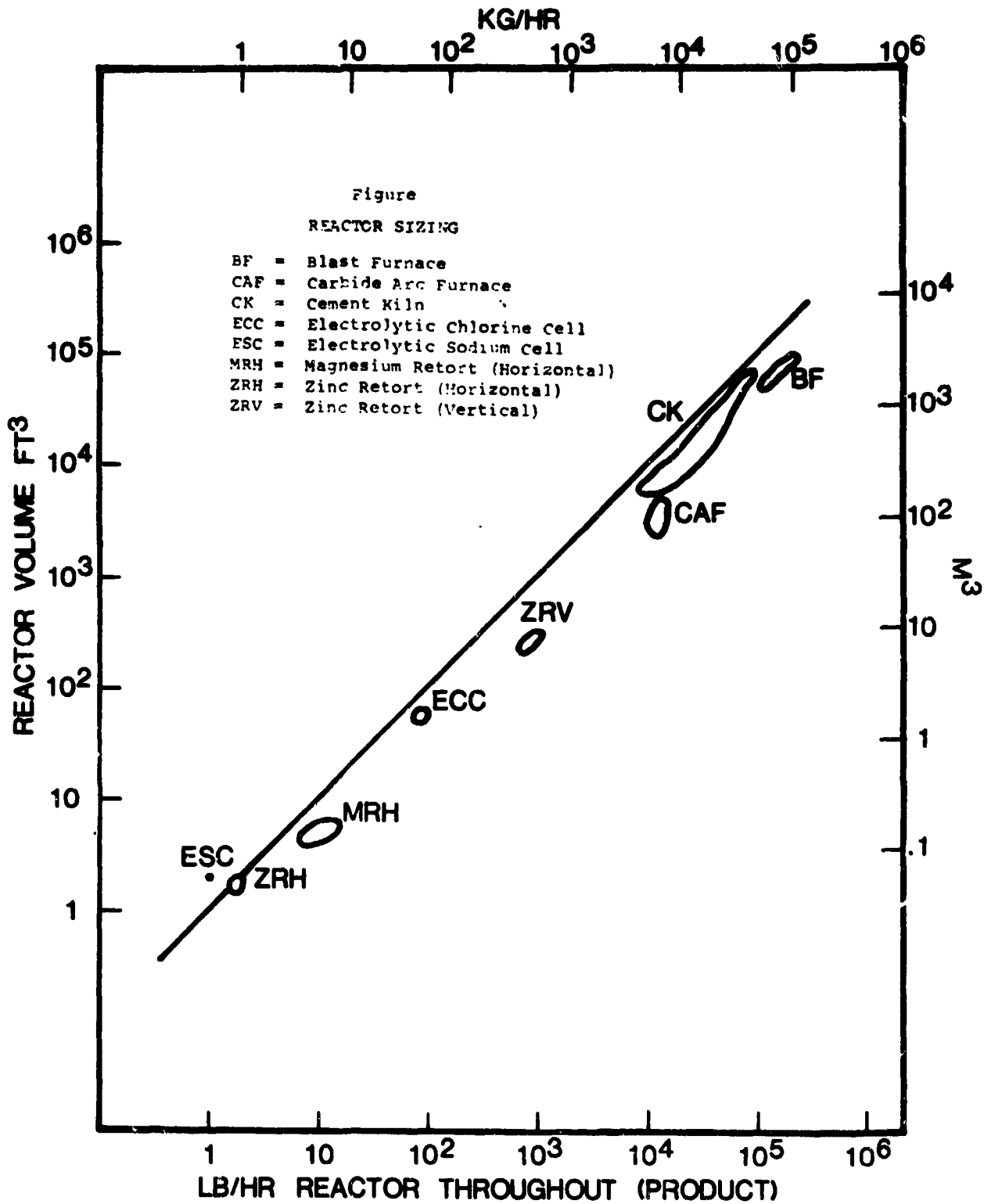
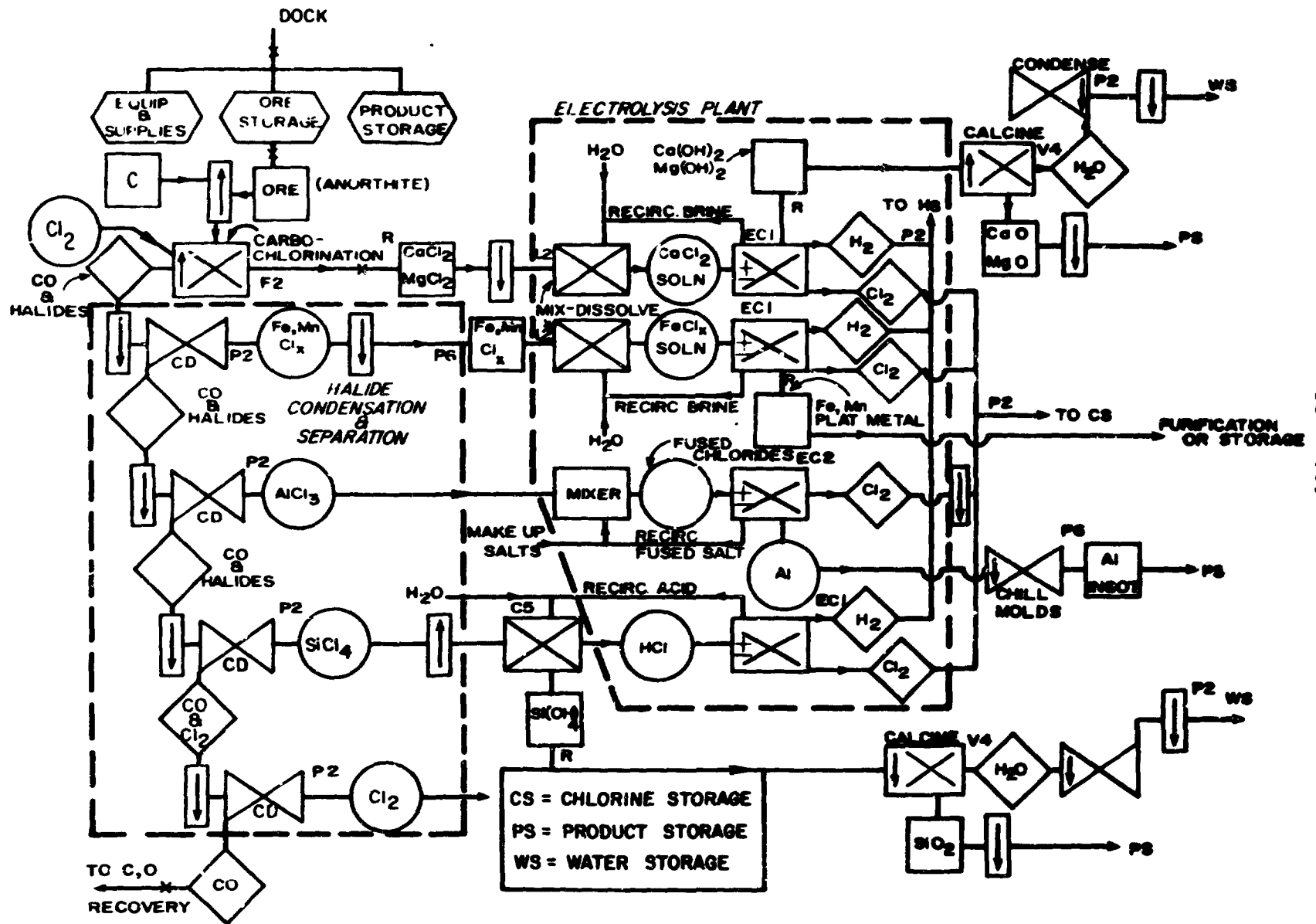
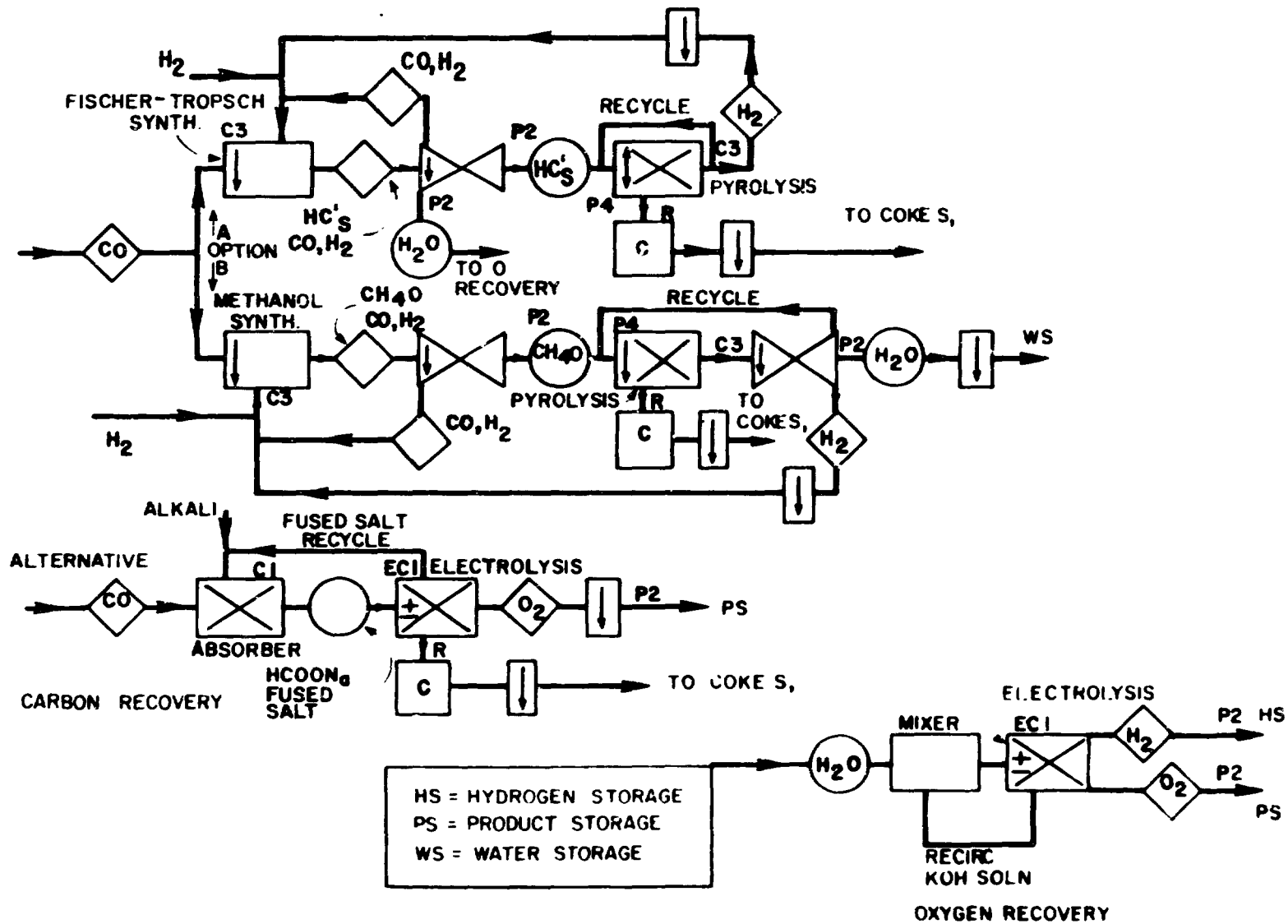


Figure II - 9



II - 109

Figure II - 10



II - 110

Figure II - 11

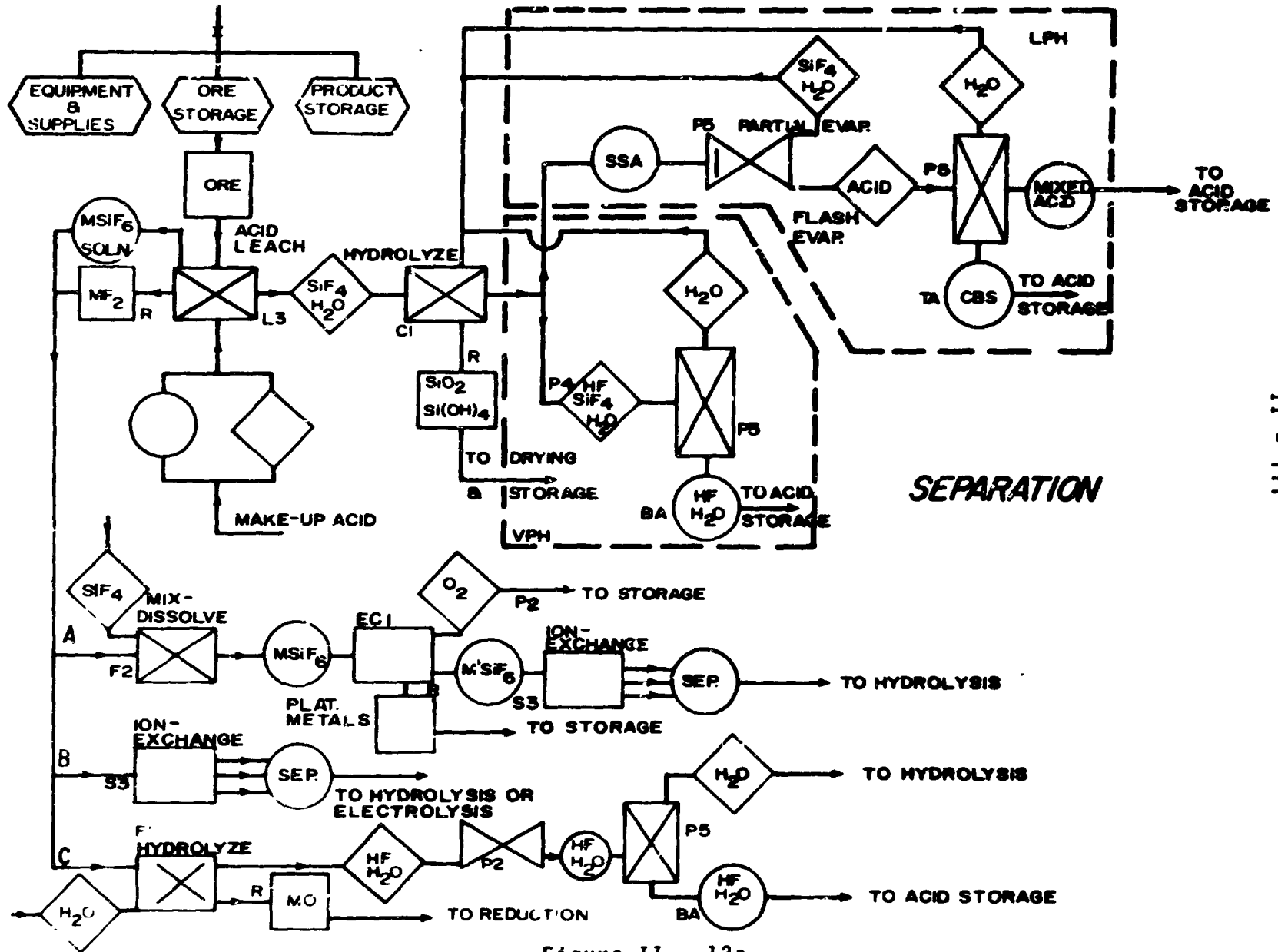
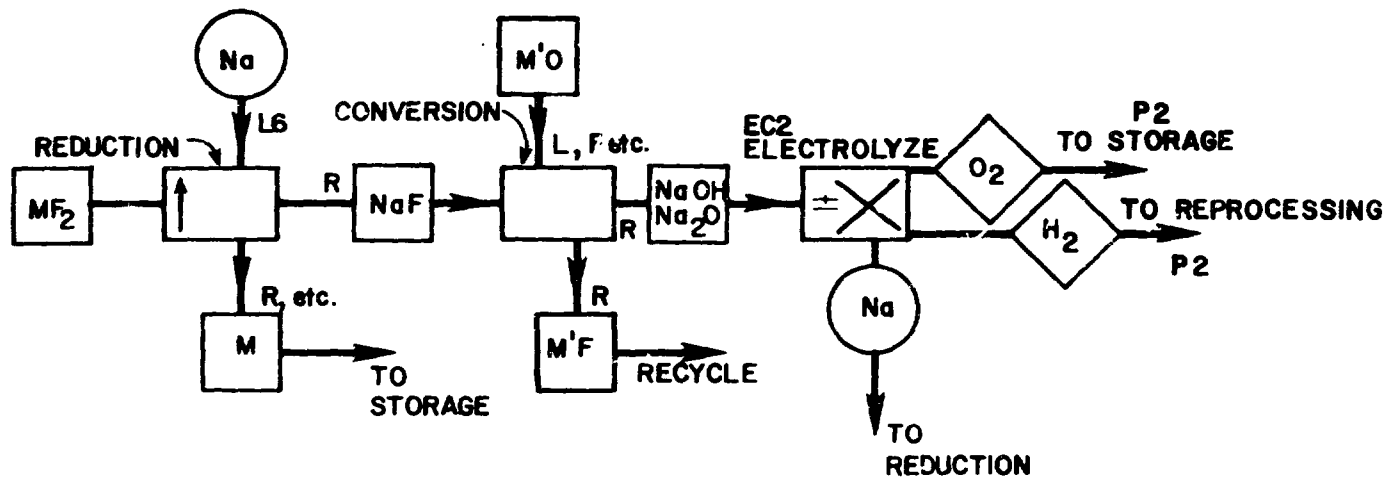
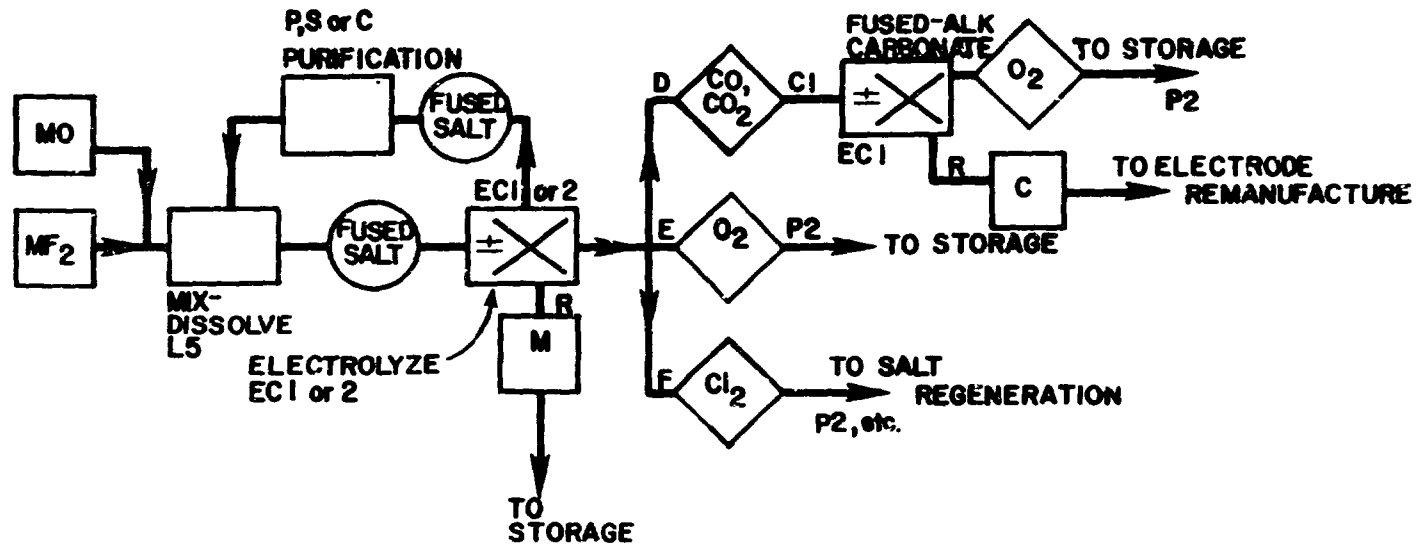


Figure II - 12a



REDUCTION

Figure II - 12b

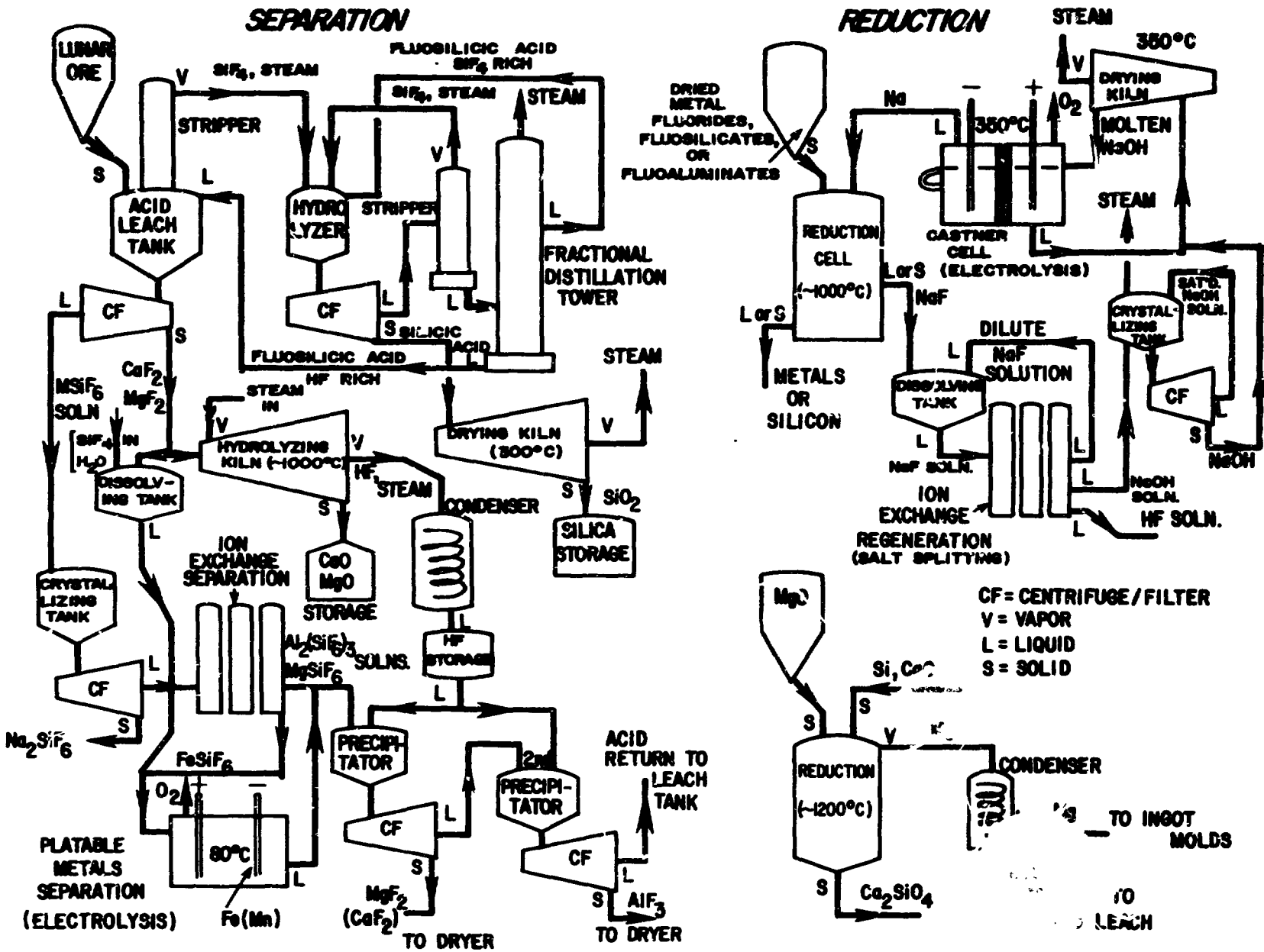
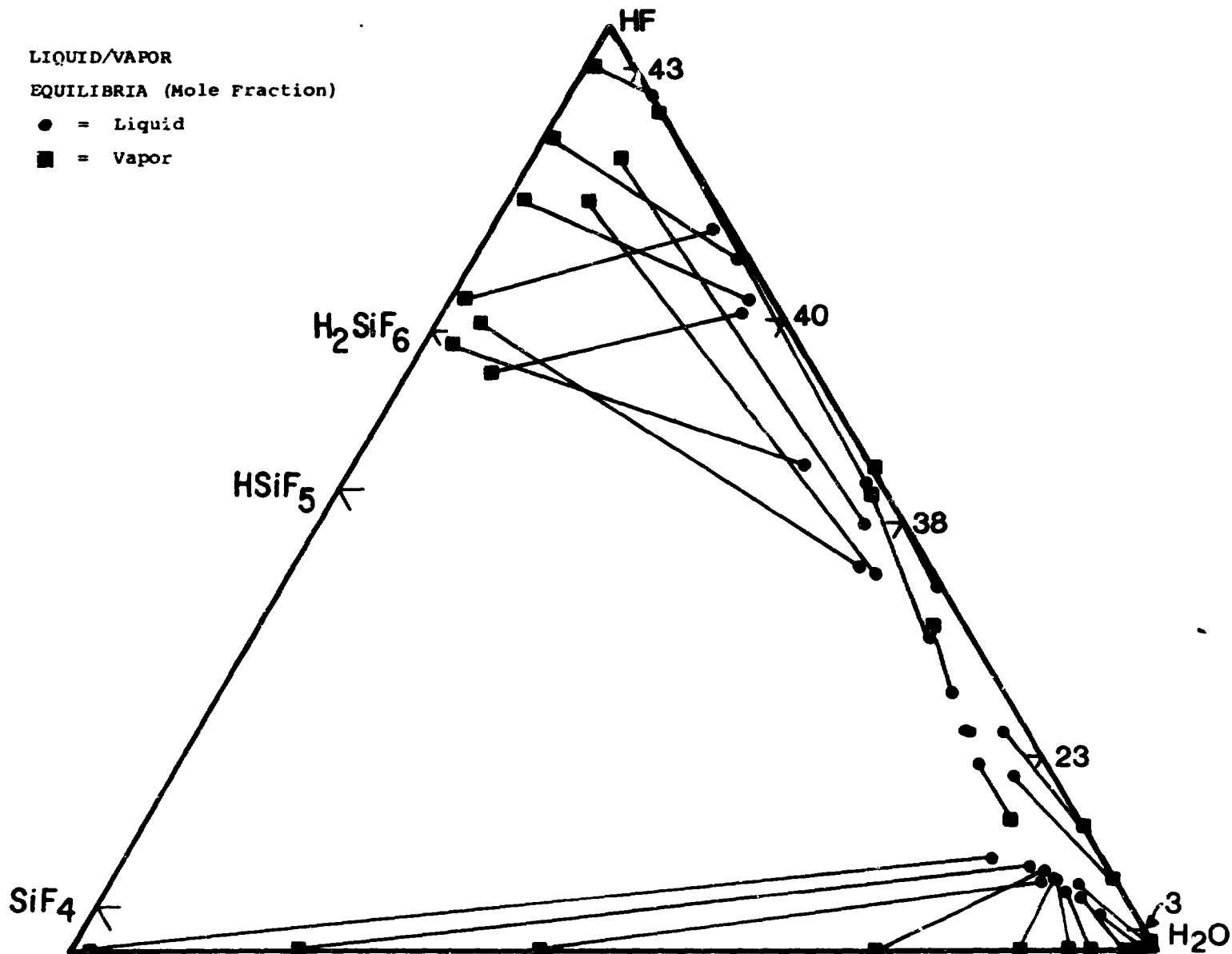


Figure II - 13



II - 114

Figure II - 14

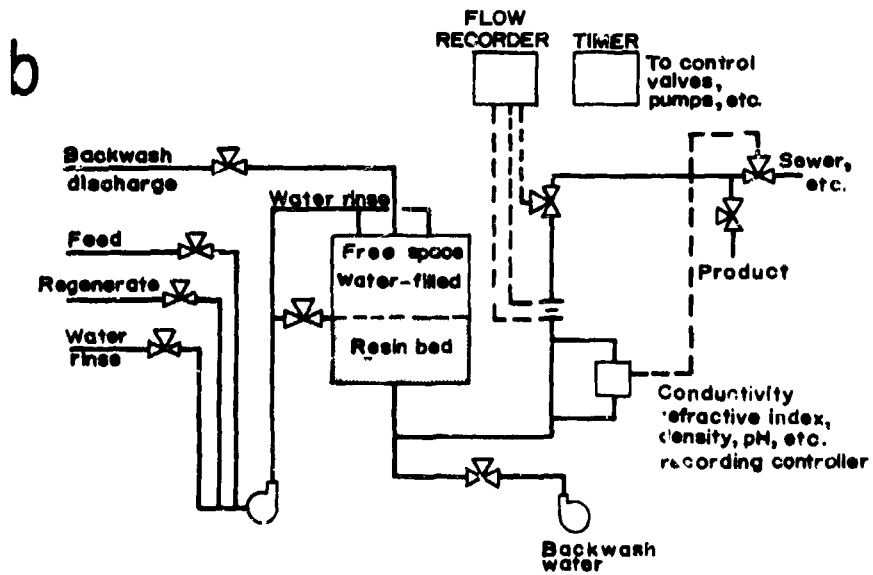
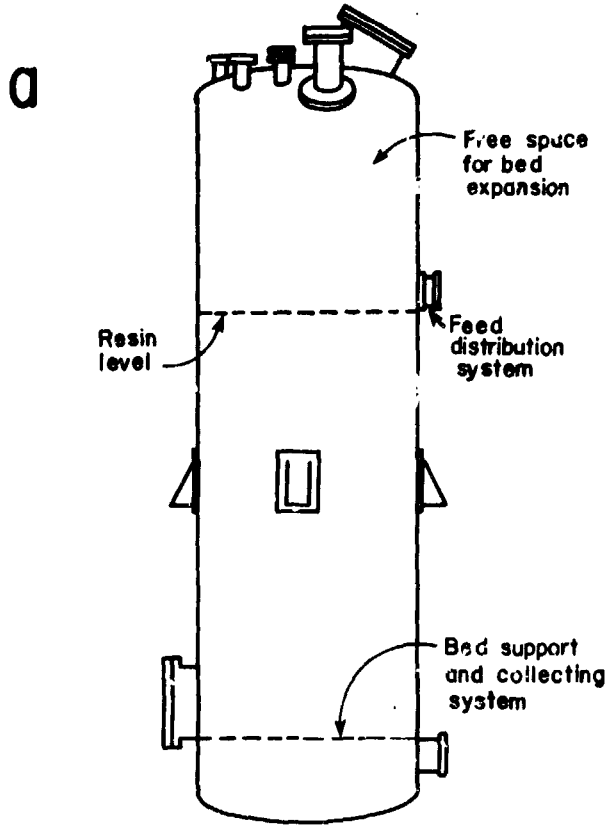
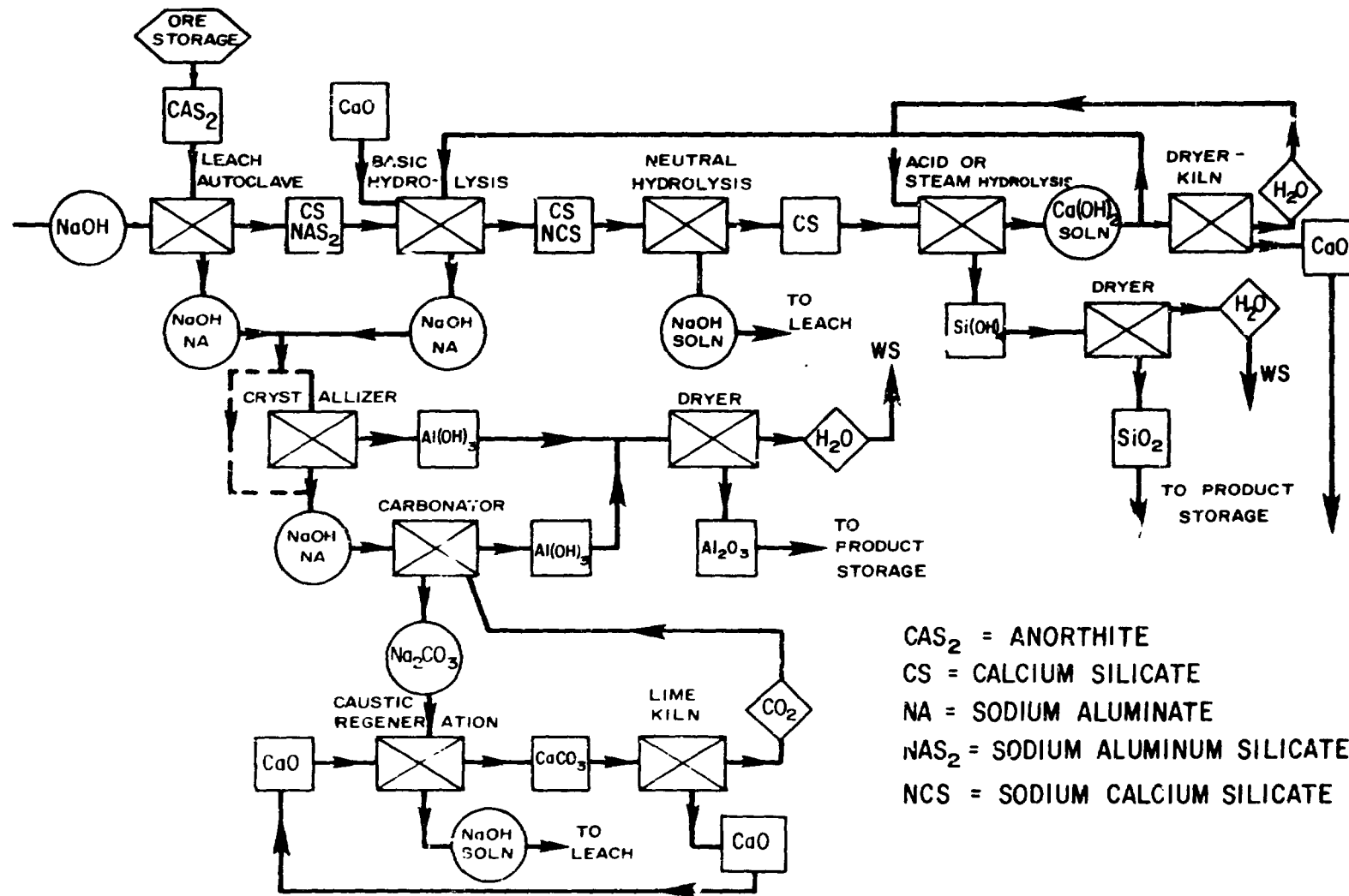


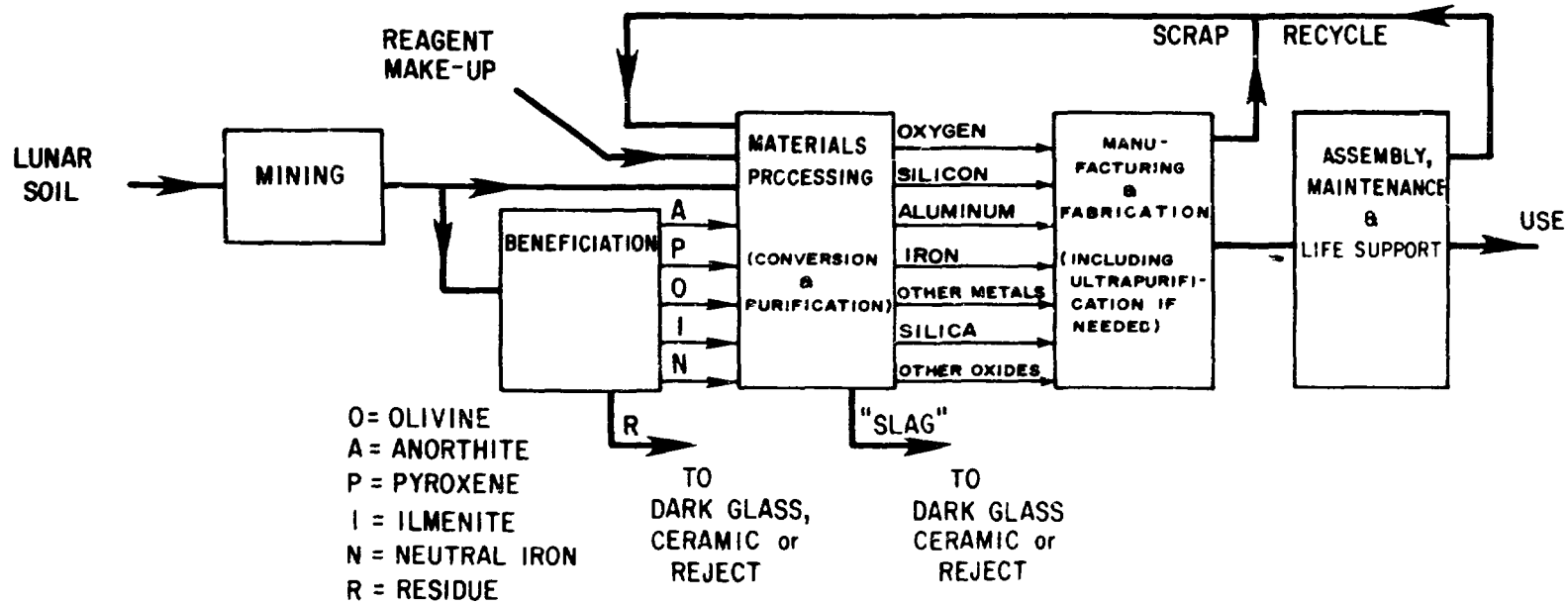
Figure II - 15a & b

SEPARATION



II - 116

Figure II - 16



II - 117

Figure II - 17

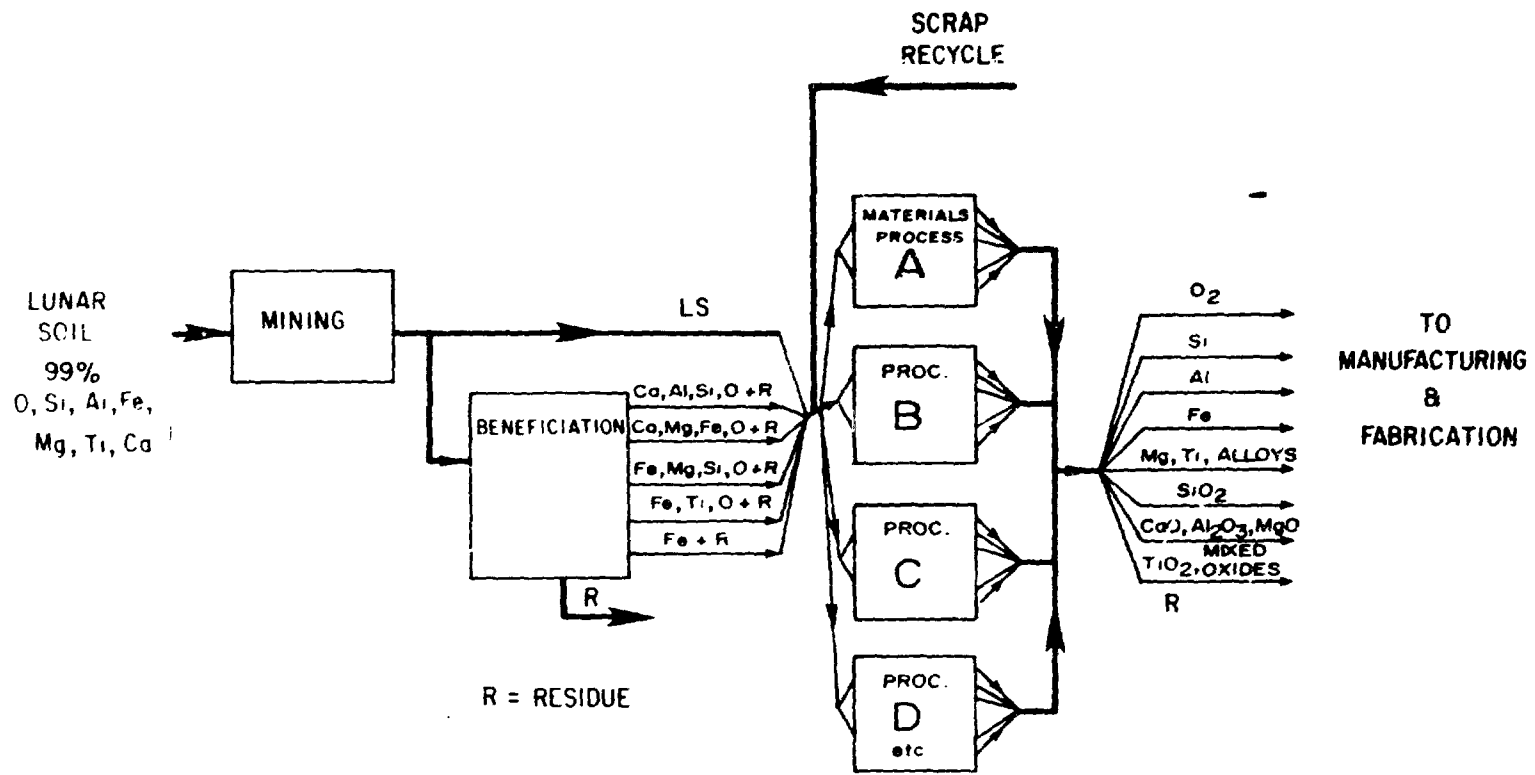
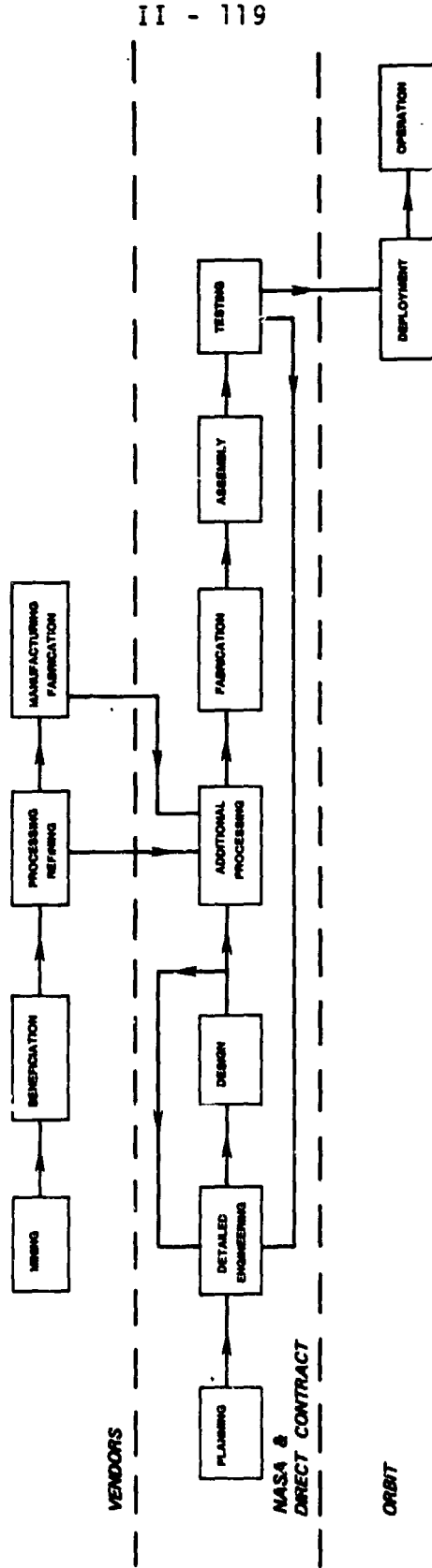


Figure II - 18



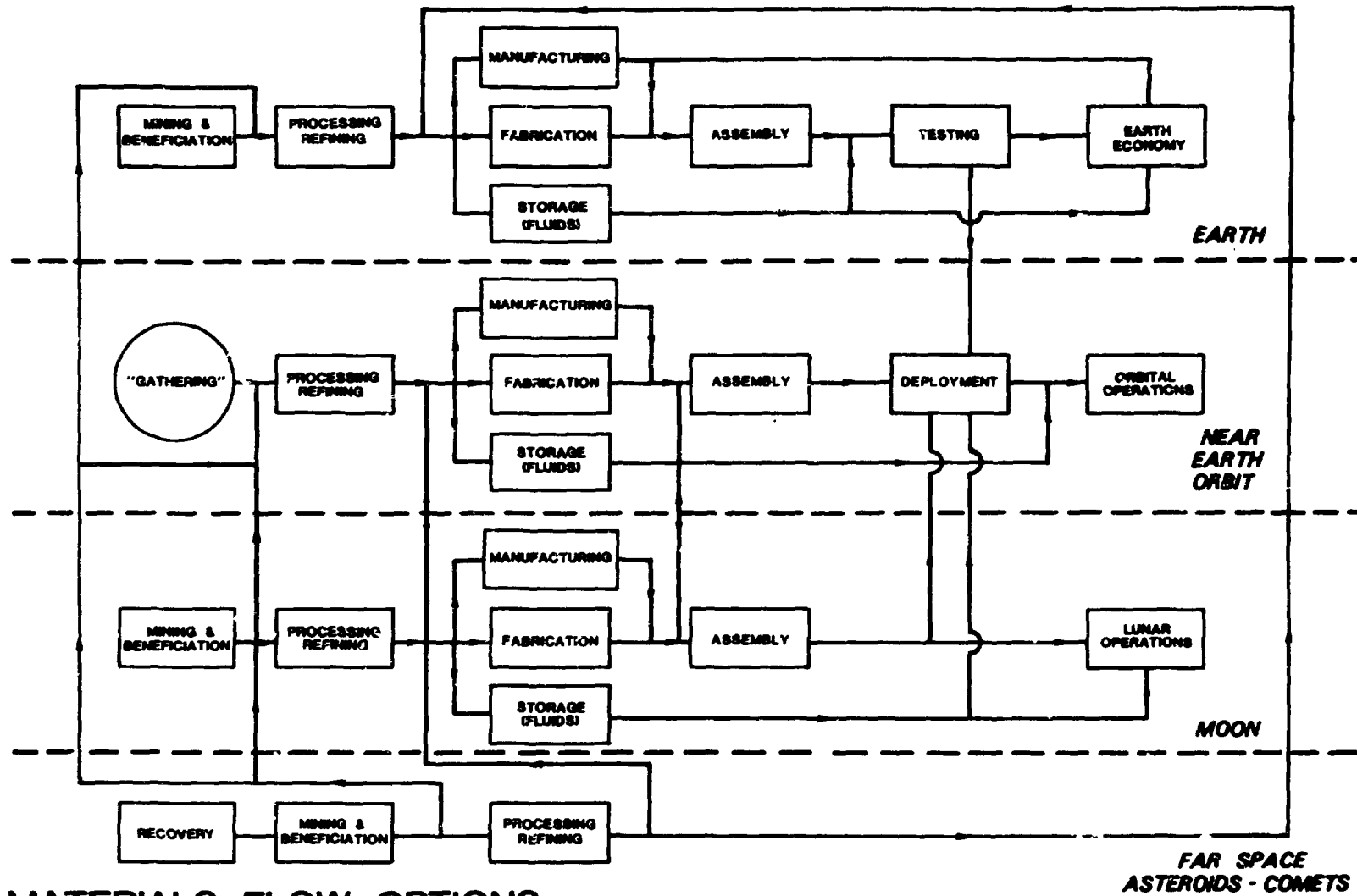
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston Texas 77058



FLOW CHART - SPACE MISSIONS

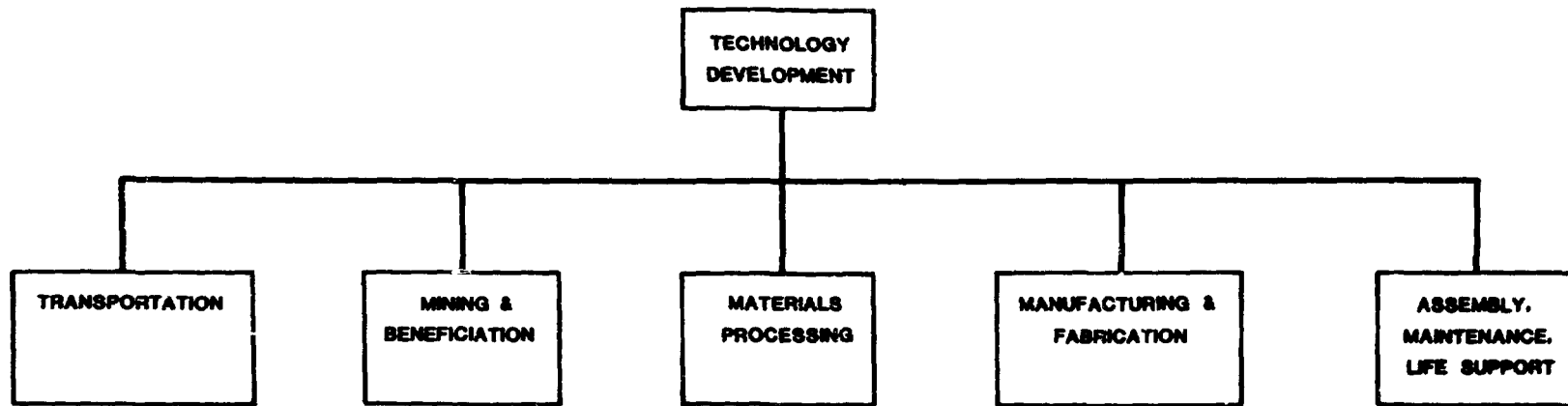
Figure II - 19



II - 120

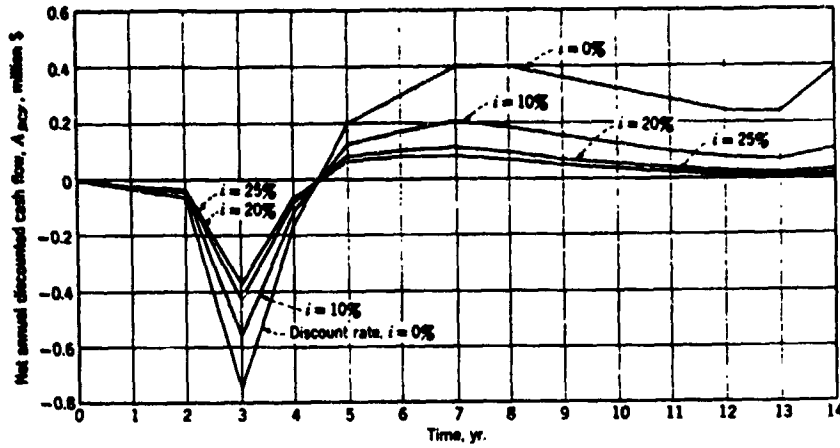
MATERIALS FLOW OPTIONS

Figure II - 20



II - 121

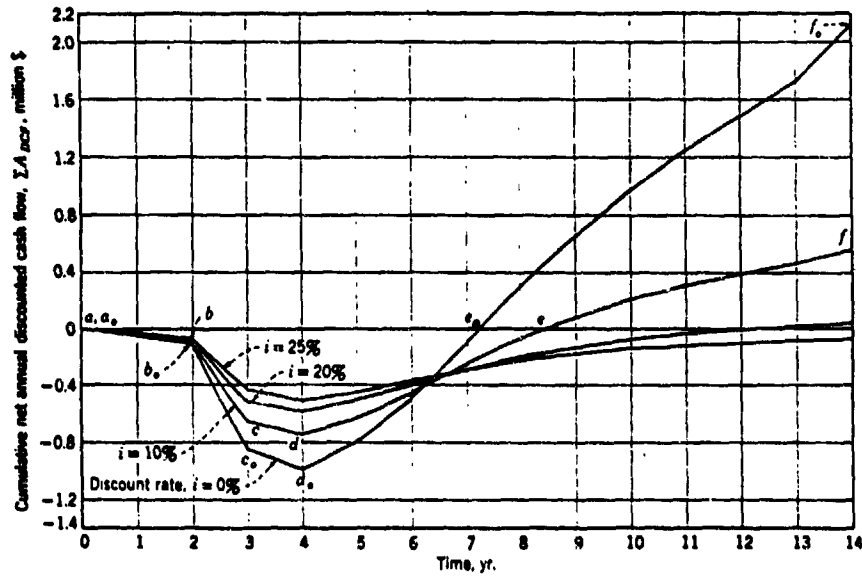
Figure II - 21



DISCOUNTED CASH FLOW

A_{DCF} = VALUE AT YEAR 0, OF ACTUAL CASH FLOW, A_{CF} AT YEAR Y
INVESTED AT INTEREST RATE i

$$A_{DCF} = \frac{A_{CF}}{(1+i)^Y}$$

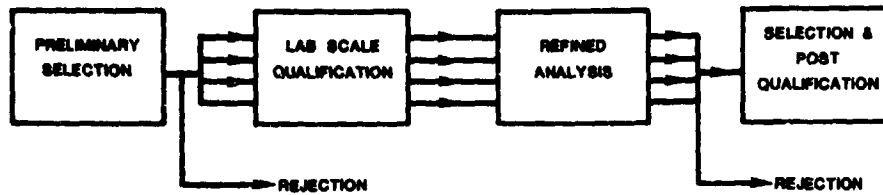


CUMULATIVE DISCOUNTED CASH FLOW

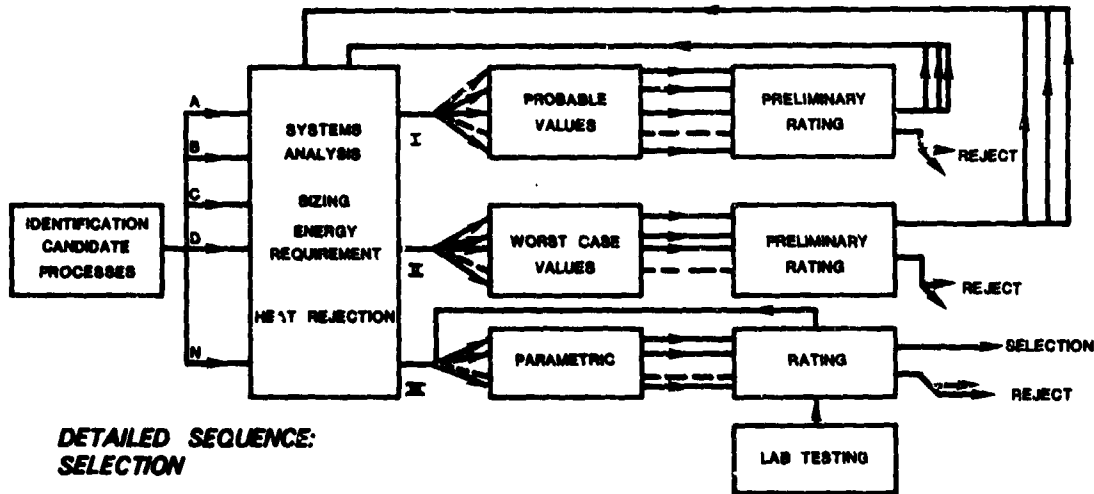
e_0 & f_0 REPRESENT TIMES AT WHICH REVENUE EQUALS TOTAL
EXPENDITURE AND DISCOUNTED REVENUE EQUALS DISCOUNTED EXPENDITURE
RESPECTIVELY.

**SIMULATED CASH FLOW FOR PROJECT WITH
FIXED - CAPITAL REQUIREMENT OF \$1 MILLION**

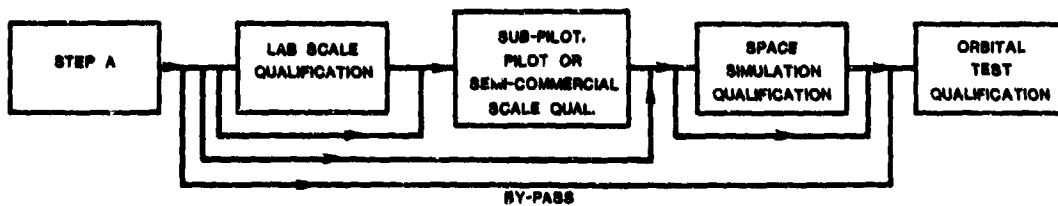
Figure II - 22



**SIMPLIFIED SEQUENCE:
MATERIALS PROCESSING TECHNOLOGY DEVELOPMENT**

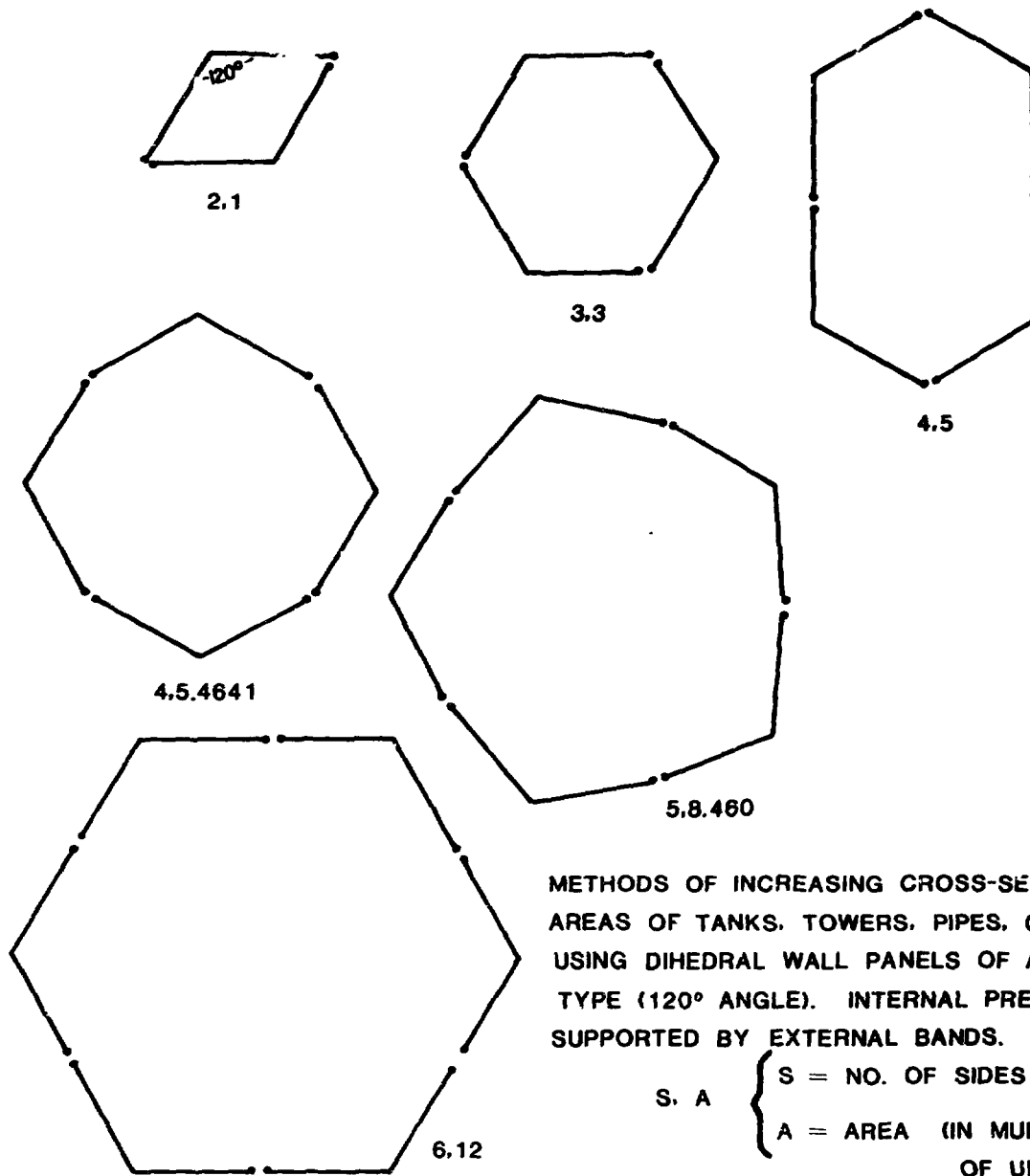


**DETAILED SEQUENCE:
SELECTION**



**DETAILED SEQUENCE:
QUALIFICATION**

Figure II - 23

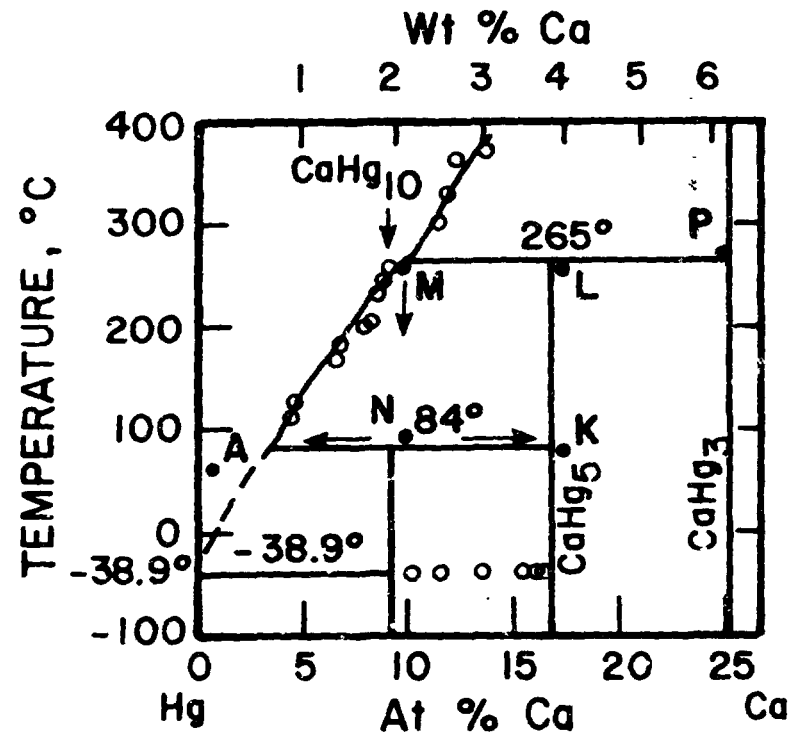
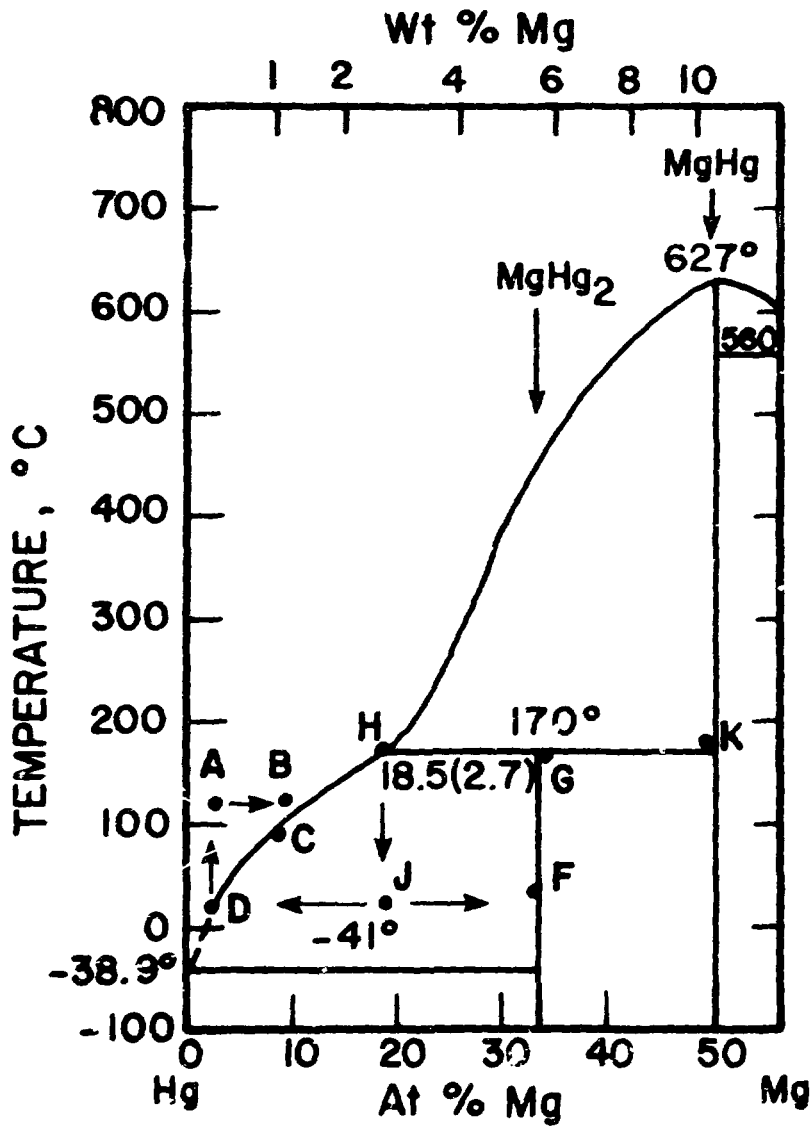


METHODS OF INCREASING CROSS-SECTIONAL AREAS OF TANKS, TOWERS, PIPES, COLUMNS, ETC. USING DIHEDRAL WALL PANELS OF A SINGLE TYPE (120° ANGLE). INTERNAL PRESSURE MAY BE SUPPORTED BY EXTERNAL BANDS.

S. A { S = NO. OF SIDES
A = AREA (IN MULTIPLES OF UNIT RHOMBUS)

Figure II - 24

Figure II - 25



II - 125

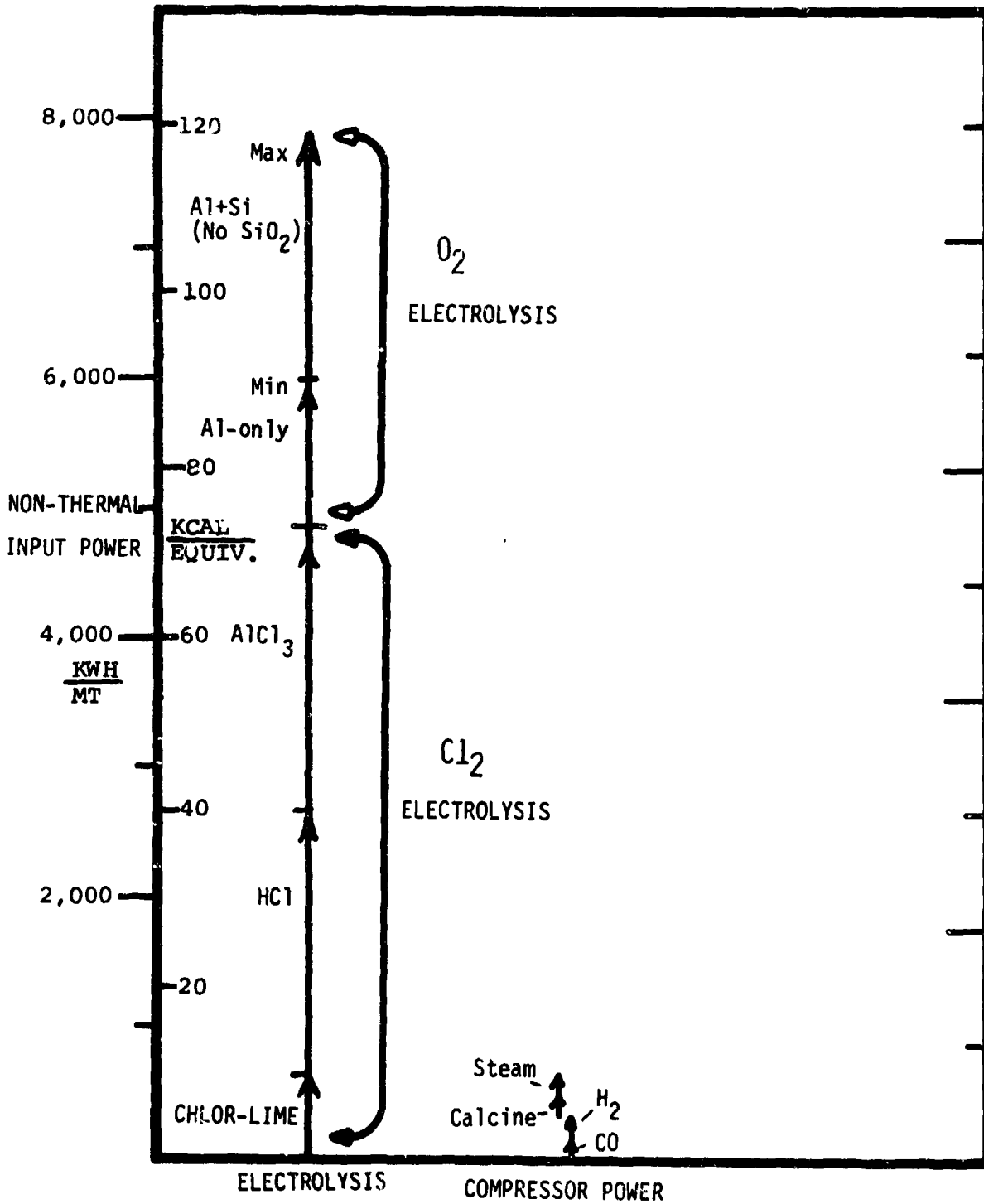


Figure II - 26

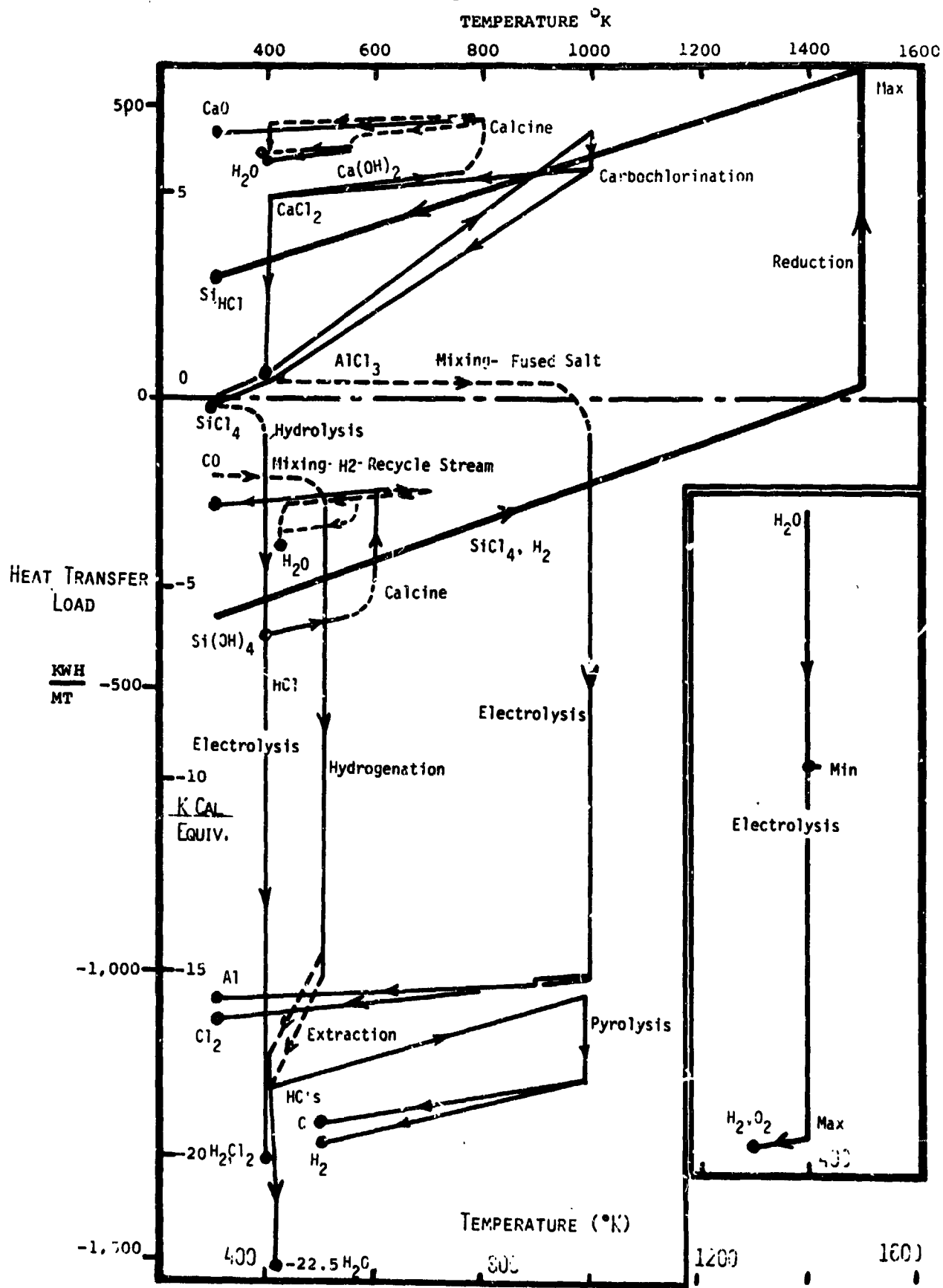


Figure II - 27

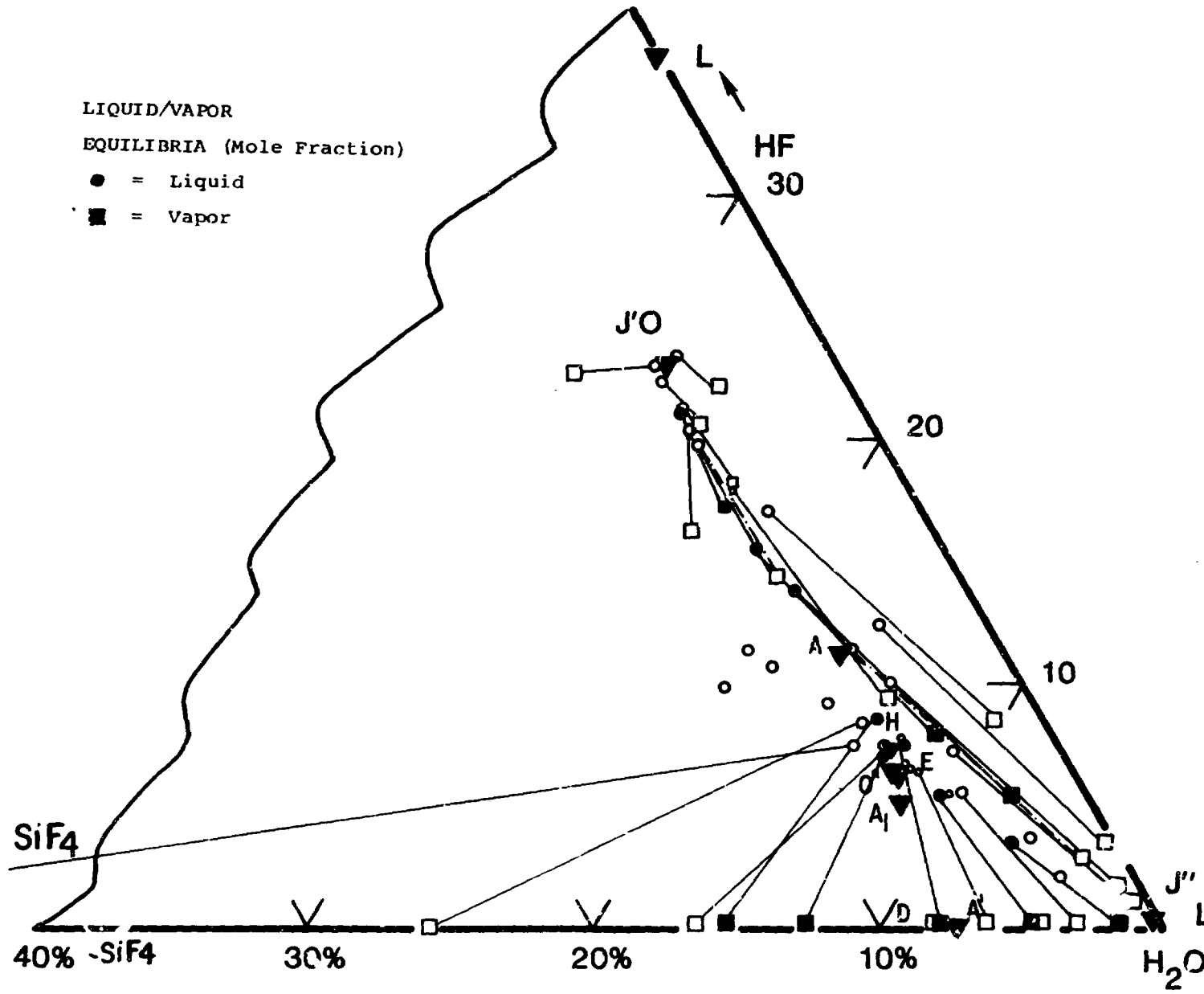


Figure II - 28

II - 128

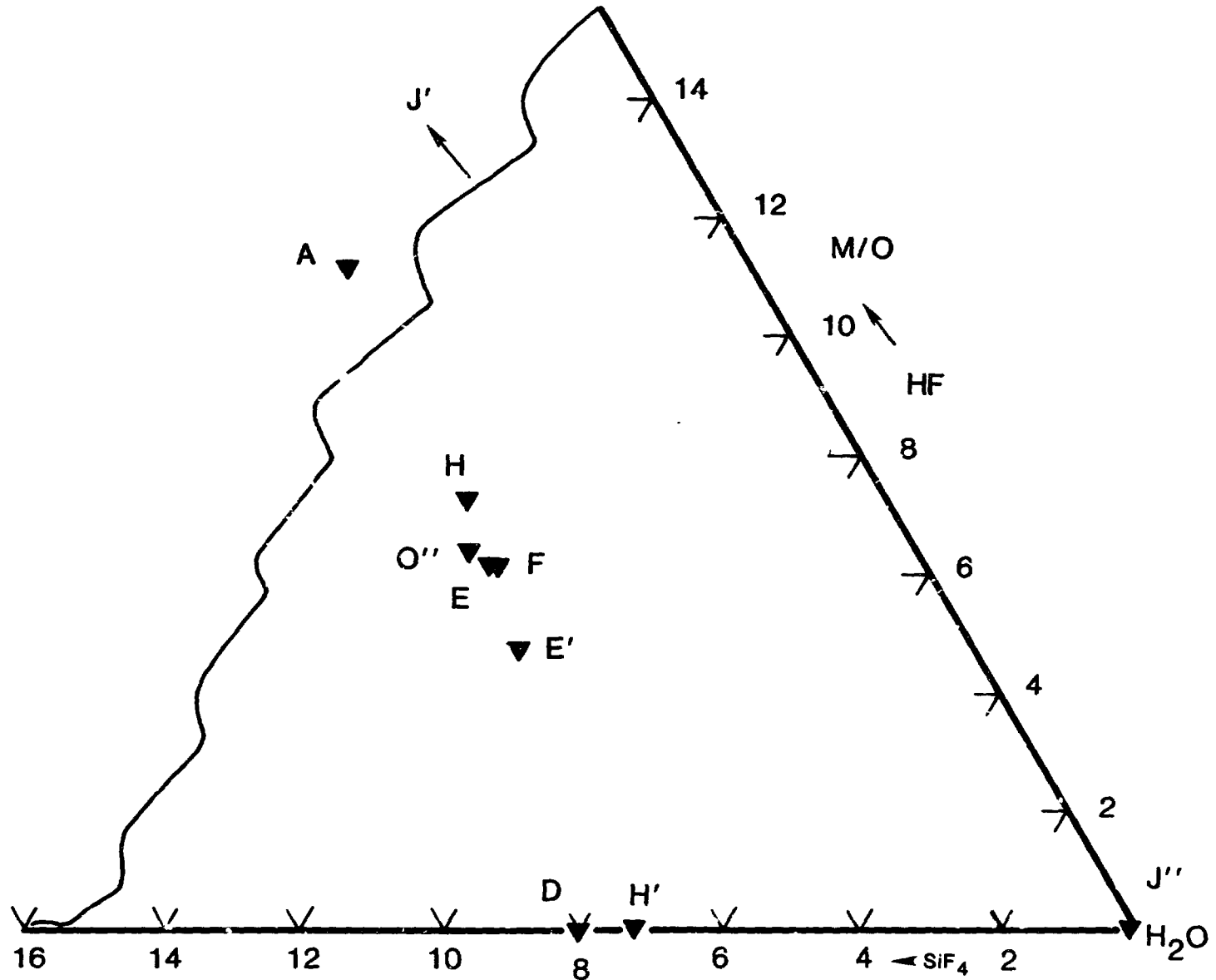


Figure II - 29

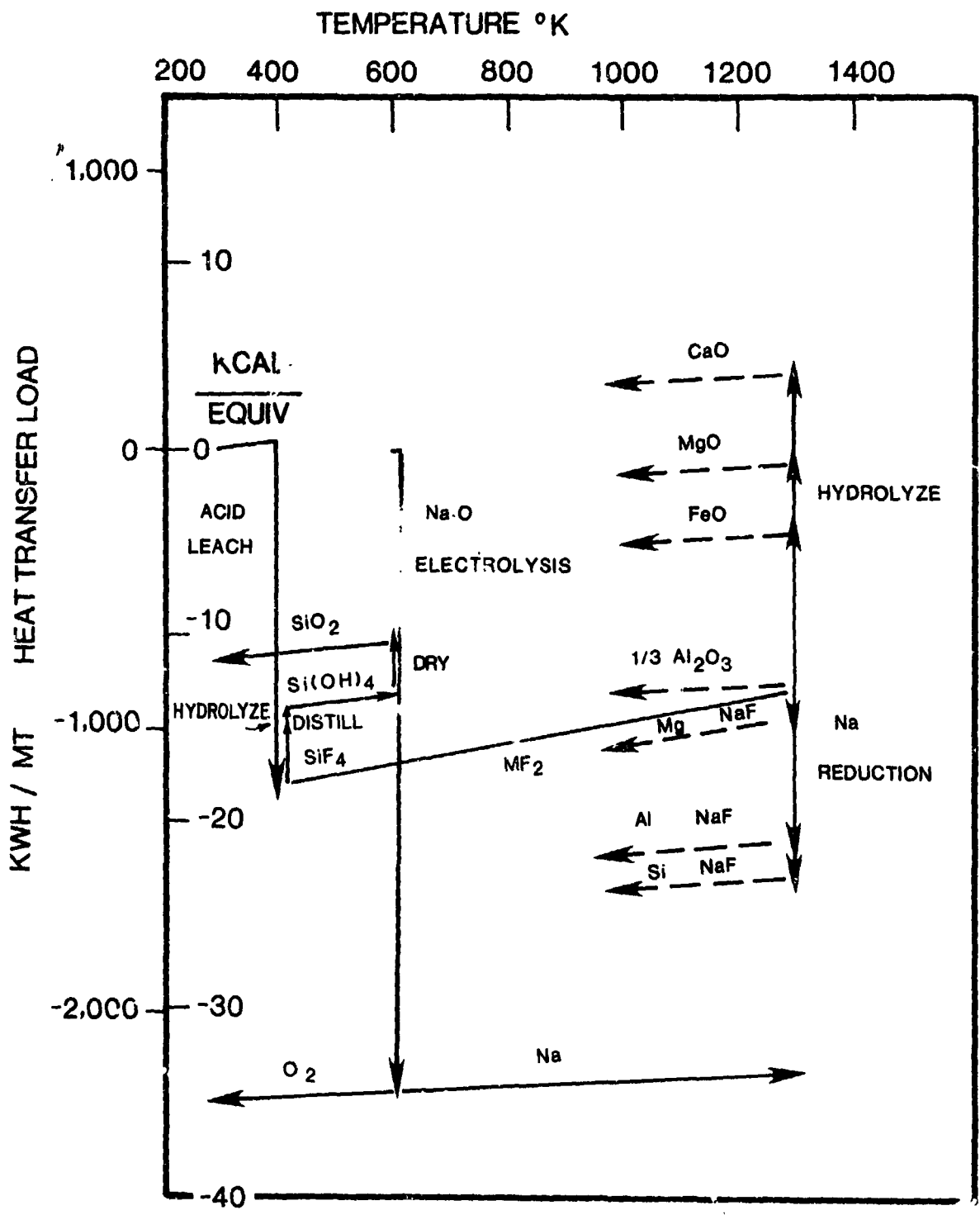


Figure II - 30

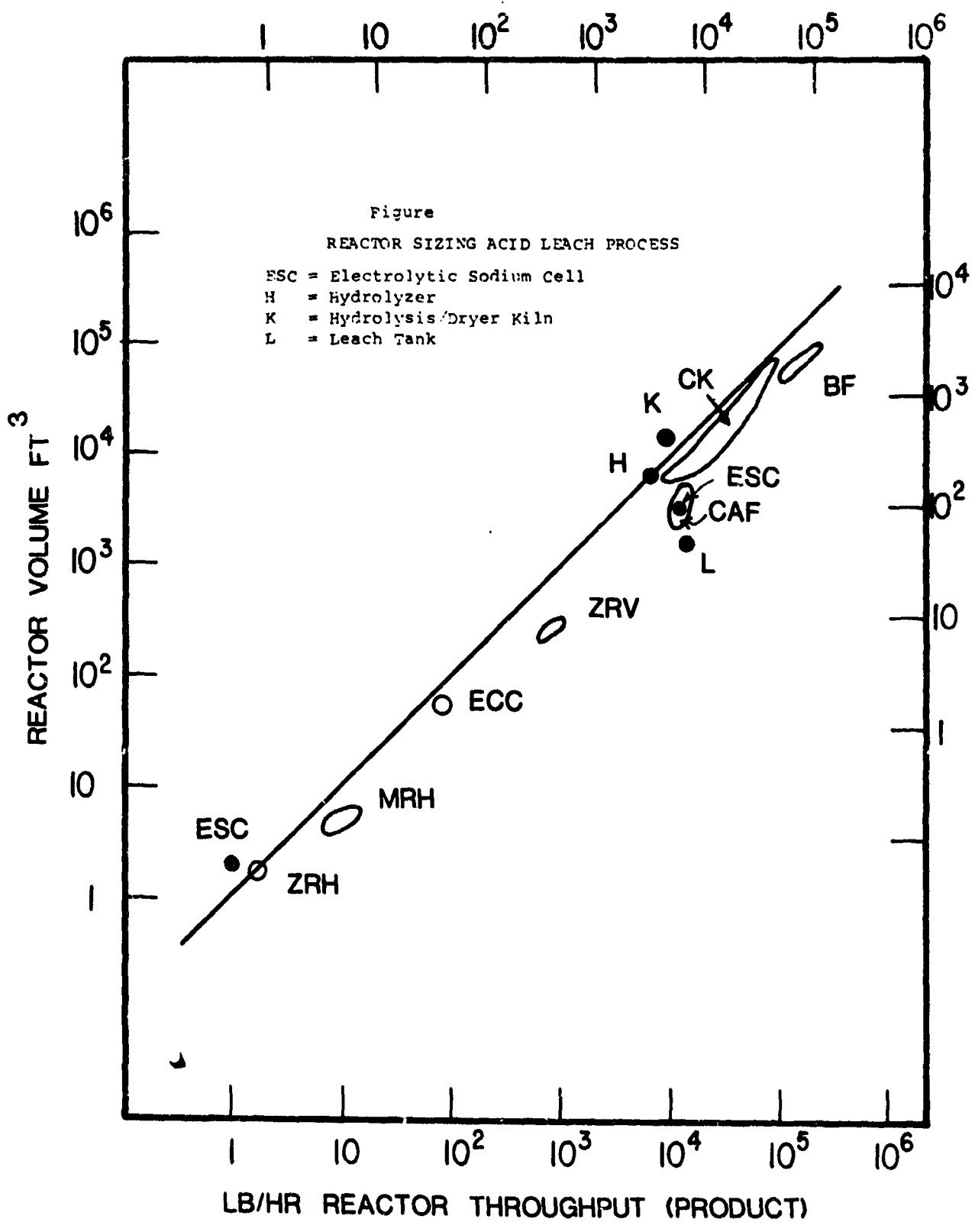


Figure II - 31

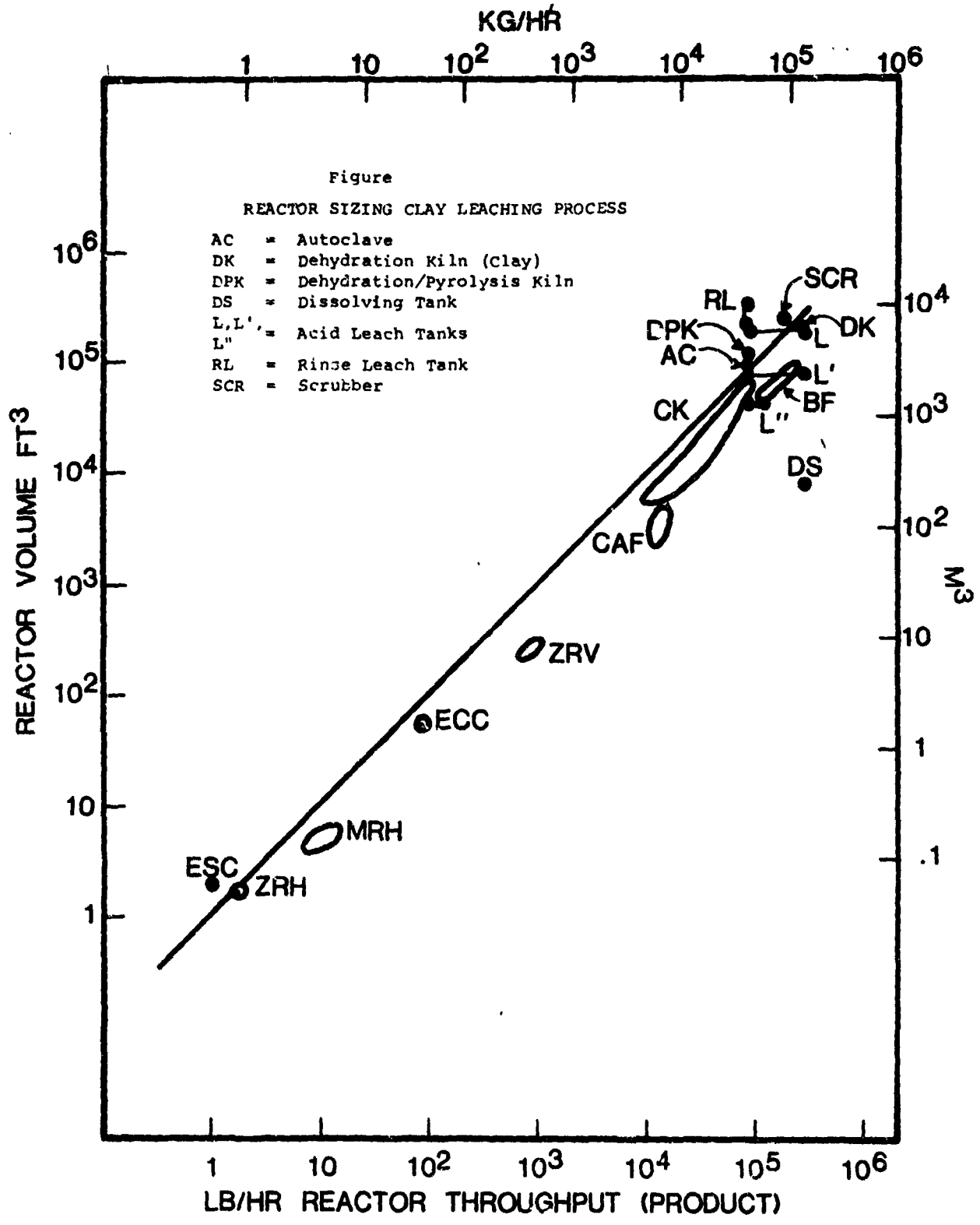


Figure II - 32

APPENDICES

- (A) MASS HEAT TRANSFER CONSIDERATIONS IN LOW PRESSURE DISTILLATIONS
- (B) ELECTRODEPOSITION OF ACTIVE METALS AS AMALGAMS
- (C) MINIMIZATION OF POWER PLUS SPACE RADIATOR MASS BY HEAT PUMPING
- (D) COMPARISON OF CONTAINER AND CONTENT WEIGHTS OF SPHERICAL AND CYLINDRICAL VESSELS
- (E) ANALYSIS OF OPTIMUM MASS FOR DRYING PROCEDURES
- (F) PROJECTED MASSES FOR SPACE ELECTRIC AND THERMAL POWER AND RADIATORS
- (G) ENGINEERING DESIGN PARAMETERS
- (H) CARBOCLORINATION PROCESS ENGINEERING DATA
- (I) HF ACID LEACH PROCESS ENGINEERING DATA
- (J) MATERIALS SPECIFICATIONS

Appendix A

MASS AND HEAT TRANSFER CONSIDERATIONS IN LOW PRESSURE
DISTILLATIONS

Kinetic theory gives the following expression for the mass flux rate striking unit area of the boundary of a region at pressure p .

$$\frac{dM/dt}{A} = \dot{m} = p \left(\frac{M}{2\pi RT} \right)^{1/2} = 4.375 \times 10^{-5} p(M/T)^{1/2} \quad \text{where } p \text{ is}$$

the pressure (dynes/cm²), M is the molecular weight of the gas, T is the temperature (°K), R is the gas constant and \dot{m} is given in units of gm/cm² sec.

As an example, for Al at 1640°K, $p = 0.1$ Torr = 1.33×10^2 dynes/cm², $M = 27$ and $\dot{m} = 7.48 \times 10^{-4}$ gm/cm² sec = 26.9 kg/m² hr.

In addition to mass transport, heat will be transported between evaporating and condensing surfaces in the form of latent heat of the transported molecules and, parasitically, in the form of radiation between the hotter vaporization and cooler condensation surfaces. The latter may be expressed as:

$$\dot{Q}_p/A = \dot{q}_p = \bar{\epsilon} \sigma (T_e^4 - T_c^4) \approx \sigma T_e^4 \left(4\bar{\epsilon} \frac{\Delta T}{T_e} \right) \quad \text{where } \bar{\epsilon} \text{ is the mean}$$

emissivity, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m² °K⁴), T_e and T_c are the evaporating and condensing temperatures (°K) and ΔT is the difference in temperatures and \dot{q}_p is given in W/m². The term $4\bar{\epsilon} \frac{\Delta T}{T_e}$ represents the fraction of the black body radiant intensity which is parasitically transferred. As an example, if $\bar{\epsilon} = 1$ and $\Delta T = .025 T_e$, a fraction = 0.1 of the black body radiant intensity (\dot{q}_{bb}) is transferred.

As an example, if $T_e = 1640^\circ\text{K}$, $\dot{q}_{bb} = 410 \text{ KW/m}^2$ and $\dot{q}_p = 41 \text{ KW/m}^2$. If one uses a value of 10.9 Kjoule/gram for latent heat of vaporization of Al, the previous mass transport example would require 81.5 KW/m^2 be transferred as latent energy. In such a case, the parasitic loss would amount to more than 50% of the vaporization energy of the process. Additional losses would arise from insulation losses on boiler and condenser structures. The use of solar thermal power would impose further constraints on the boiler insulation. For example if the external emissivity of the boiler were $\epsilon' = 0.1$ and assuming negligible temperature drop through the wall, an external radiation loss of 41 KW/m^2 would also occur.

Appendix B

Sodium is deposited from aqueous solution in the form of a dilute sodium amalgam in commercial mercury-chlorine cells, although it is not recovered in metallic form. The deposition is made possible by a combination of factors involving concentration of sodium or ions in metallic and aqueous phases, concentration of hydrogen gas or ions in aqueous solution, the standard decomposition potentials of sodium and hydrogen, and the hydrogen overvoltage against mercury.

Similar factors may make practical the deposition of magnesium and/or calcium on mercury cathodes, although the solubility limits of the alkaline earth metals in alkaline solution may render such depositions difficult. Aluminum metal may be similarly deposited if a suitable liquid ternary alloy can be found with sufficient solubility for aluminum.

Recovery of these reactive metals from dilute amalgams can be achieved without distilling off all of the mercury by separation of various intermetallics.

The phase diagrams²⁸ of Ca-Hg and Mg-Hg are shown in Fig. 25. One may separate Ca or Mg rich intermetallic phases by continuous deposition of these metals into saturated amalgams or by cooling unsaturated amalgams to temperatures above their low temperature eutectics. These solid intermetallic phases may be reheated to elevated temperatures and decomposed to phases still richer in Ca or Mg plus leaner liquid phases. The rich phases may be decomposed by fractional distillation and sublimation. Typical operating cycles are summarized below:

<u>Point</u>	<u>Stage</u>	<u>Ca</u>	<u>Mg</u>
A	Cathode input		
B	Cathode output		
C	Saturation point		
D	Lowest temperature	-35°	-35°
F	Intermetallic	CaHg ₁₀	MgHg ₂
G	Decomposition point		
H	Liquid phase		
J	Recooled liquid phase (hypothetical)		
K	Seocnd intermetallic	CaHg ₅	MgHg
L	Second decomposition point		
M	Second liquid phase		
N	Recooled second liquid phase (hypothetical)		
P	Third intermetallic	CaHg ₃	

Appendix C

MINIMIZATION OF POWER PLUS SPACE RADIATOR MASS BY HEAT PUMPING

Assume: \dot{Q} = original thermal load (MW)
 T_0 = original heat rejection temperature
 SM = specific mass of space electric power (MT/MW)
 RM = specific mass of space radiator (MT/MW)
 RM = (mass/unit area) x (area/MW) and mass/unit area
 is a constant ($MT/m^2 = k_1$); area/MW is proportional
 to $1/T^4$ ($M^2/MW = k_2/T^4$) or
 $RM = k_1 k_2 / T^4 = K/T^4$

Pumping the heat from T_0 to T would add a theoretical additional heat load of $\Delta\dot{Q} = \dot{Q} (T - T_0)/T_0$ requiring this much additional power from the space electric power facility.

The heat pump power mass penalty would then be:

$\Delta M = \Delta\dot{Q} (SM) (1 + \alpha)$ where α = weight fraction for motors, pumps and additional hardware.

The net mass of space radiators plus incremental power is then:

$$M_i = \dot{Q} \left[\left(\frac{T}{T_0} \right) \frac{K}{T^4} + (T - T_0) \frac{(SM)(1 + \alpha)}{T_0} \right]$$

Differentiating with respect to T and equating to zero we obtain:

$$d M_i / dT = \left(\dot{Q} / T_0 \right) \left[-3K/T^4 + (SM)(1 + \alpha) \right] = 0$$

or

$$T^4 = 3K / (SM)(1 + \alpha) \text{ or } T = [3K / (SM)(1 + \alpha)]^{1/4}$$

II-139

If we assume typical values (Appendix F):

$K = .153 \times 10^{12}$, $SM = 4$, $\alpha = .2$ we obtain

$T_{opt.} = 556^{\circ}K$

Appendix D

COMPARISON OF CONTAINER AND CONTENT WEIGHTS OF SPHERICAL AND
CYLINDRICAL VESSELS

For stress limited vessels, the minimum wall thickness

$$t = p D / k \tau \quad \text{where } k = \begin{cases} 2 & \text{cylinder} \\ 4 & \text{sphere} \end{cases} \quad \begin{array}{l} D = \text{diameter} \\ p = \text{pressure differential} \\ \tau = \text{wall stress} \end{array}$$

Pressure Vessel Weight

$$W = \rho t A = \rho t V / c D \quad \text{where } c = \begin{cases} 1/6 & \text{sphere} \\ 1/4 & \text{cylinder} \end{cases} \quad \begin{array}{l} A = \text{surface area} \\ V = \text{volume} \\ \rho = \text{density} \\ \quad \quad \quad (\text{wall material}) \end{array}$$

The weight/volume ratio is then:

$$W/V = \rho t / c D = \rho p / k c \tau = (1/kc) p / (\tau / \rho)$$

τ / ρ is the specific strength or stress/density ratio

where τ may be ultimate tensile strength τ_u , yield strength τ_y ,

or for design purposes operating stress $\tau_0 = \tau_y / F$ where F

is a safety factor.

(Note W/V is independent of diameter.)

The ratio of weight of container to weight of contents is given

by:

$$W/W' = W / \rho' V = (1/kc) p / \rho' (\tau_0 / \rho) \quad \text{where } \rho' = \text{density of contents}$$

For gases, p / ρ' is approximately a constant: $p / \rho' = C_1 RT$ and

independent of pressure. This gives W/W' (gas) = $(1/kc) C_1 RT / (\tau_0 / \rho)$

In English units: $\tau_0 = \text{psi}$, $\rho = \text{lb/in}^3$, $C_1 R = 18,528 / M \text{ in}/^\circ\text{R}$ where

$M = \text{molecular weight}$. As an example, for steam ($M = 18$) @ 700°R

(116°C), W/W' (steam) = $(1/kc) (18,528 \cdot 700 / 18) / (\tau_0 / \rho) =$

$(.72 \times 10^6 / kc) / (\tau_0 / \rho)$.

Assuming τ_0/ρ (max) = $.2 \times 10^6$, for a cylindrical vessel $kc = .5$ and W/W' (steam) (min) = 7.2.

For liquids or solids, p/ρ' is no longer independent of pressure. But for low or intermediate pressures p/ρ' is much lower than for gases. As an example, for $p = 1$ atm (14.696 psi), $\rho' = .03613$ lb/in³ (H₂O liquid), W/W' (liq) = $(1/kc) \cdot 406.8/(\tau_0/\rho)$. Using the previous value for τ_0/ρ , we obtain W/W' (water) (min) = .001016. Even for containers with 5 - 10% of condensed phases and lower stress/density ratios, W/W' would usually lie below 0.1 for pressures of 1 atmosphere or less.

Appendix E

ANALYSIS OF OPTIMUM MASS FOR DRYING PROCEDURES

W_0 = initial weight of damp product (kg)

w_f = weight of product at time t_f

W_{eq} = equilibrium weight (for a given temperature and pressure)

t_1 = time at which drying rate becomes linear (hr)

t_L = time at which drying is discontinued

t_s = service life (hr) of dryer

Assume: drying rate $W = dW/dt = -k (W - W_{eq})$ after time t_1
 mass of dryer, $M_d = K \dot{M}_0 t_L$ where \dot{M}_0 = output mass/hr

Then weight loss of recoverable moisture due to termination of drying at t_L is $W_L - W_{eq} = \Delta W$ corresponding to H_2 loss of $.112 \Delta W$. Solving the drying equation we obtain: $\ln (W - W_{eq}) = -kt + \text{const}$ or $\Delta W = W' e^{-kt}$ where W' is an equivalent initial weight if drying were completely linear.

Total orbital lift mass penalty over a service life of t_s hours is:

$$\Delta M = M_d + M_H = K \dot{M}_0 t_L + .112 \dot{M}_0 t_s (W'/W_{eq}) e^{-kt_L}$$

Differentiating with respect to t_L and equating to zero we obtain:

$$d\Delta M/dt_L = \dot{M}_0 [K - kt_s (.112 W'/W_{eq}) e^{-kt_L}] = 0$$

$$\text{or } t_L(\text{opt}) = -(1/k) \ln (KW_{eq}/.112 kt_s W')$$

Expressed as a function of residual moisture, we have:

$$\Delta W_{\text{opt}} = W_{eq} K/.112 kt_s$$

As an example, if $k = 1 \text{ hr}^{-1}$, $K = 3$, $t_s = 5 \times 10^4 \text{ hr}$, we obtain:

$$t_L (\text{opt}) = -\ln (W_{\text{eq}}/W') (3/.56 \times 10^4) = + 7.53 - \ln (W_{\text{eq}}/W')$$

If $W_{\text{eq}}/W' = 1$, $t_L (\text{opt}) = 7.53$ hr. Similarly $\Delta W_{\text{opt}} = W_{\text{eq}} \cdot$

5.36×10^{-4} or a residual moisture level of about .05%.

Discounting the hydrogen replacement mass to reflect time of delivery would shorten optimum process times and raise residual moisture levels.

Appendix F

PROJECTED MASSES FOR SPACE ELECTRIC AND THERMAL POWER
AND RADIATORS

Preliminary engineering of SSPS systems to deliver 10^{10} watts to earth yield masses of 80,000 to 100,000 metric tons.

The specific mass for remote power is thus:

$$SM_r = 8 - 10 \text{ MT/MW}$$

By avoiding microwave generation, transmission and conversion losses, the space power level is 1.72×10^{10} watts and a net mass savings of approximately 25,000 metric tons is achieved.

Thus, for electric power use in space (on site) we obtain a specific mass:

$$SM = \frac{55,000 \text{ to } 75,000}{1.72 \times 10^4} = 3.2 \text{ to } 4.37 \text{ MT/MW}$$

Preliminary engineering of thermal engine SSPS systems to deliver 10^{10} watts to earth yield masses of 80,000 - 100,000 metric tons.

The solar concentrator section has a mass of approximately 15,000 MT and gathers a useful $11.2 - 16 \times 10^4$ MW.

The specific mass for solar thermal power is thus:

$$SM_t = \frac{15,000}{(11.2 \text{ to } 16 \times 10^4)} = .134 - .0938 \text{ MT/MW}$$

The specific mass ratio for electric/thermal power is then:

$$\frac{SM}{SM_t} = 34.1 \text{ (low) or } 32.5 \text{ (high) with extreme values } 23.9$$

to 46.5.

For estimating purposes we shall use:

$$SM = 4, SM_t = .12$$

The space radiators for the thermal engine SSPS are calculated to require a mass of 27,600 MT to dissipate a thermal load of 136.9 MW (per module) giving a radiator specific mass:

$RM = .202 \text{ MT/MW @ } 932^\circ\text{K}$. If we assume the mass/unit area is constant (4.44 Kg/m^2) we predict the specific mass would be proportional to $1/T^4$. We then readily derive:

$$RM = .153 \times 10^{12}/T^4 \text{ MT/MW}$$

Appendix G

ENGINEERING DESIGN PARAMETERS

Equipment	Capacity	Typical Stream Velocity, V_i (Characteristic Velocity)	Process Time t'	Other
Motors, Pumps, Compressors (except vacuum)	$10^3 \frac{KW}{M^3}$	10 to 100 m/sec	1 sec	$\frac{1 \text{ kg}}{KW} \left(\frac{Mi}{MW} \right)$
Distillation Columns	mass flow rate 1-5 $Kg/m^2 \text{ sec}$	1 to 3 m/sec (vapor) (entrainment limited)	5-10 sec	length .4 - .6 m/plate
Sedimentation Centrifuges	volumetric flow rate .004-.08 $\frac{m^3/sec}{m^2}$	settling velocity (10 μ particles) 10-5 m/sec x G typical velocity: 10^{-2} m/sec @1,000 G	.5-2 min	Power 50-100 $\frac{KW}{m^2}$
Rotary Kilns	Loading Density .05 - .2 MT/m^3	3 to 10 m/hr (axial) .00083 - .0028 m/sec	2-10 hr	Rotary Power .1 - .2 $\frac{KW}{m^3}$
Ion exchange Columns	.5-3 equiv. $Kg \text{ (resin)}$.2 to .5 m/min (.0033-.0083 m/sec)	5-15 min	
Aqueous Systems Heat Transfer				
Nucleate Boiling	15-240 $\frac{KW}{m^2}$			$h = 2-16$ $KW/m^2 \cdot ^\circ K$ $\Delta T = 10-20^\circ K$
Condensation (inside tubes)	30 - 1,000 $\frac{KW}{m^2}$	30 to 150 m/sec (vapor)		$h = 3-50$ $KW/m^2 \cdot ^\circ K$ $\Delta T = 10-20^\circ K$
Electrolytic Cells	$i = 10^3-10^4$ Amp/m^2	ion migration velocity $10^{-7}-10^{-5}$ m/sec	10-50 hr	

Anode-cathode separation: $.03 - .1 \text{ m} = \frac{V}{A}$

V = electrolyte volume, A = anode area

M = electrolyte mass, ρ = electrolyte density

$M/A = V\rho/A = 30 - 200 \text{ Kg/m}^2$

$M/Ai = .01 - .04 \text{ Kg/Amp}$

@100% current efficiency, 1 Amp = .0373 equivalent/hr or $M/\dot{M}_0 =$

$(M/Ai) \div (.0373 \text{ EW}/1000)$ where $\dot{M}_0 =$ output mass rate (Kg/hr),

EW = equivalent weight (gram): For Na, EW = 23 and $M/\dot{M}_0 = 11.7$ to 46.6 hr.

For design purposes (elec. fused NaOH) we use $M/\dot{M}_0 = 27.5$ hr

Appendix H

CARBOCHLORINATION PROCESS ENGINEERING DATA

Major Energy Requirements

The energy requirements of any process can be usefully compared with the heat of formation of the input materials from their elements under standard conditions (1 atm @298.15°K). For total reduction processes, the standard heat of formation represents a lower limit to the process energy requirement, while separation or conversion processes which do not involve oxidation or reduction may only require 10 - 20% or less of the energy needed for total reduction. The standard heat of formation of our empirical silicate molecule, $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot (2.25 \text{ SiO}_2) \cdot (.15 \text{ MO})$ may be calculated by two approximate methods — first as the sum of the constituent oxides; and second as the heat of formation of anorthite,²⁹ $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{ SiO}_2$ + heats of $.25 \text{ SiO}_2$ + $.15 \text{ MO}$. These methods give:

<u>1st Approx.</u>	<u>ΔH_f</u>	<u>2nd Approx.</u>	<u>ΔH_f</u>
CaO	-151.8	Anorthite	-1009.3
Al_2O_3	-400.4	.25 SiO_2	- 54.4
2.25 SiO_2	-489.7	.15 MO	<u>- 17.56</u>
.10 MgO	- 14.38	Total	-1081.26 Kcal/mole =
.05 FeO	<u>- 3.18</u>		62.5 Kcal/equiv.
Total	-1059.46 Kcal/mole =		
	61.24 Kcal/equiv.		

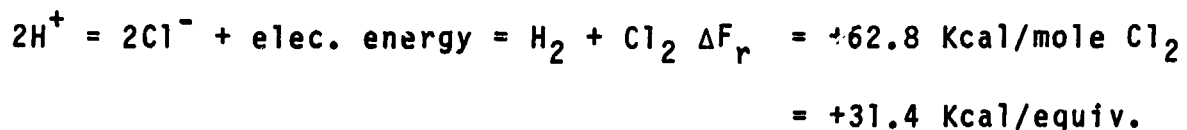
Based on 17.3 equivalents per "mole"

(Chlorine Regeneration)

Chlorine is regenerated electrochemically from three sources; 9 equivalents from electrolysis of HCl (from hydrolysis of

SiCl_4 , 6 equivalents from electrolysis of AlCl_3 (from fused salt bath) and 2.3 equivalents from electrolysis of CaCl_2 and MCl_2 . The reduction of some fraction of the SiCl_4 would also yield HCl or transfer some of the chloride to some other chloride such as NaCl , while lowering the amount of aluminum being reduced would divert some of the AlCl_3 to hydrolysis which would transfer the corresponding fraction of equivalents to the HCl electrolysis loop.

For the electrolysis of HCl we have:

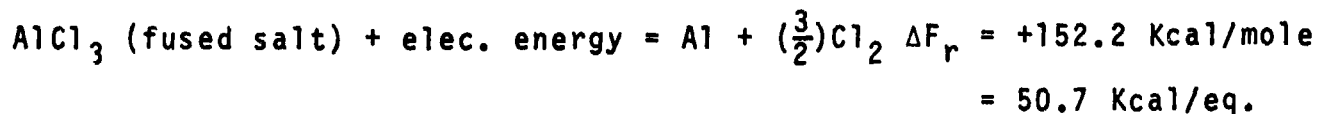


(31.4 Kcal/equiv. = 131.4 Kjoule/equiv. Since 1 Faraday = 96,500 coulombs, $V_{\text{reversible}} = 131.4/96.5 = 1.36$ volts)

Under current industrial practice^{8d} @ cell voltage = 2.3 V/plate current efficiency = 96%, the actual energy per equivalent is: $(2.3)(96.5 \text{ K})/(.96) = 231.2$ Kjoule or 55.3 Kcal/equiv.

9 equivalents would then require 497.7 Kcal.

For the electrolysis of AlCl_3 we have:

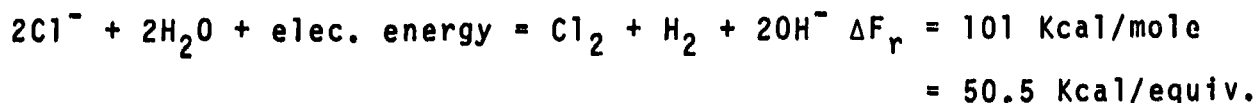


(50.7 Kcal/equiv. = 212.1 Kjoule/equiv. or $V_{\text{reversible}} = 2.20$ volts)

Under assumed industrial practice, the actual energy per equivalent is about 400 Kjoule/equiv.³⁰ = 95.6 Kcal/equiv.

6 equivalents would then require 573.6 Kcal.

For the electrolysis of salt chlorides we have:



(50.5 Kcal/equiv. = 211.3 Kjoule/equiv. or $V_{\text{reversible}} = 2.19$ volts. At 350°K, $V_{\text{reversible}} = 2.3$ volts)

Under current industrial practice^{8e} @ cell voltage = 3.82V
current efficiency = 96.5%

the actual energy per equivalent is:

$(3.82)(96.5 \text{ K})/(.965) = 382 \text{ Kjoule/equiv. or } 91.3 \text{ Kcal/equiv.}$

2.3 equivalents would then require 210 Kcal.

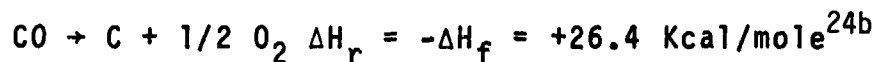
The total chlorine regeneration energy requirement would amount to

$497.6 + 573.6 + 210 = 1281.3 \text{ Kcal/mole} = 74.1 \text{ Kcal/equiv.}$

For the input molecular weight of 303.1, one metric ton would contain 3,299 g moles which would require 4.227×10^6 Kcal/MT = 4913 KWH/metric ton.

(Carbon Regeneration)

The theoretical energy requirement to recover carbon from carbon monoxide is given by



8.65 moles would then require 228.4 Kcal.

The actual power requirements will depend on chemical routes chosen — the carbon monoxide may be hydrogenated or absorbed as formate or other species. These in turn may be hydrogenated or electrochemically reduced. Under the hydrogenation routes, volatile CH or CHO compounds are formed which may be thermally cracked to C, H₂ and O₂.

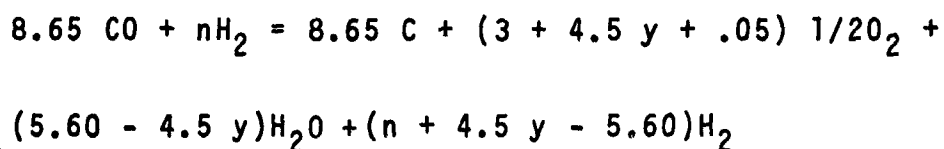
For electrochemical formation of carbon, the anodic reaction would normally yield oxygen.

In terms of process energetics, the most important considerations are the amount and method of oxygen regeneration. Thus,

while the carbon consumed and carbon monoxide formed corresponds to 8.65 g-mole/mole plagioclase concentrate, the net oxygen requirement only corresponds to the reduced metal and silicon equivalents produced unless excess oxygen is needed.

The net oxygen requirement (exclusive of any excess demand) is equal to that originally bound to aluminum plus the amount (4.5 y) bound to the fraction of silicon which is to be reduced and any oxygen bound to platable metals such as iron. Per mole of original ore, we have to regenerate $3 + 4.5 y + .05$ gram-atoms of O. This may be performed by a combination of water electrolysis and fused carbonate or other fused salt electrolysis if the latter is employed to regenerate carbon.

Depending on the fraction of oxygen generated by fused salt electrolysis, the water or hydrogen balance may require either electrolysis of water or burning of hydrogen to level reagent inventory. The desired balance may be expressed by the equation:



For carbon monoxide processed by hydrogenation routes, all of the oxygen is converted to water, while fused salt (carbonate) electrolysis would give up to 1 oxygen atom per carbon atom reduced. Since the required O:C ratio would vary from .364 to .88 depending on silicon production, combined electrolysis of formate-carbonate melts and water should total to the required ratio.

The power requirements may be estimated from these considerations as follows:

For water electrolysis from aqueous alkali solution, the

reversible cell voltage @ 298°K = 1.23 V.

The reaction $\text{H}_2\text{O} + \text{elec energy} = \text{H}_2 + 1/2 \text{O}_2$ consumes 2 equivalents ($2F = 193,000$ coulomb) so the energy change is $193,000 (1.23) = 237.4$ Kjoule/mole = 56.7 Kcal/mole + 28.4 Kcal/equiv.

Under current industrial practice, $8f 4.8 - 5$ KWH/m³ H₂ STP (44.61 moles) is equivalent to $388 - 404.5$ Kjoule/mole (H₂O) = $92.8 - 96.8$ Kcal/mole = $46.4 - 48.4$ Kcal/equiv.

If only aluminum reduction is practiced 6 equivalents of oxygen would be required, but reduction of silicon could require up to 9 additional equivalents. Thus, the oxygen generation energy requirement could vary from 290.4 to 725 Kcal/mole for a range of 6 to 15 equivalents. The corresponding requirement per metric ton would amount to $.958 \times 10^6$ to 2.395×10^6 Kcal/MT = 1113 to 2784 KWH/metric ton.

For fused carbonate electrolysis, the reversible decomposition potential³¹ is about 2V corresponding to a theoretical energy requirement of $2 \cdot F = 193,000$ joule/equiv or $386,000$ joule/mol (O) = 92.3 Kcal/mole (O) = 46.1 Kcal/equiv.

Industrial practice data is not available, but would probably raise power requirements at least 50%. If we assume 69.2 Kcal/equiv generation of 6 - 15 equivalents of oxygen (and an equal number of carbon) would require 415.2 to 1038 Kcal/mole ($1592 - 3980$ KWH/MT). Returning to the carbon regeneration problem if all the carbon monoxide is treated by hydrogenation-cracking processes, all of the oxygen will appear as water and the oxygen recovery will be by electrolysis of water as discussed above.

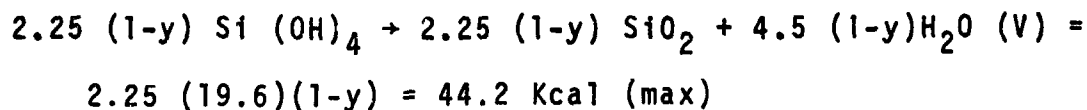
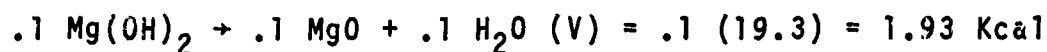
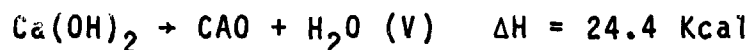
The energy of the inverse water gas reaction:



This reaction is exothermic so no power is required. When considered by individual steps, the hydrogenation is exothermic while the pyrolysis may be slightly endothermic for hydrocarbons, but exothermic for oxy-compounds, such as methanol or formaldehyde. In any case, the power requirements are much lower than involved for oxygen recovery.

(Heat of Drying and Dehydration)

The proposed process will involve generation of aqueous precipitated $\text{Ca}(\text{OH})_2$, $.1 \text{ Mg}(\text{OH})_2$ and $2.25 (1-y) \text{ Si}(\text{OH})_4$. These products must be calcined or dried to corresponding oxides and may require temperatures to 550°C . The theoretical energy requirements are:^{24,29}



or a maximum total theo. drying energy requirement of 70.5 Kcal/mole (max) for $y = 0$ or 295 Kjoules/mole (max).

40 - 80% of this energy can be recovered as heat of condensation of steam formed.

Compressors

Compressor power is necessary for operating H_2 and CO streams in the hydrogenation plant units and to recover heat from steam at elevated temperatures. The actual energy requirements are somewhat flexible, but typical values are shown in Fig. 26 along

with the electrical energy requirements. It is seen that the electrical power needs far exceed all other demands for process power.

Major additional compressor power requirements could be added if extensive heat pumping is practiced to raise heat rejection temperatures of aqueous electrolysis, hydrolysis and hydrogenation heat loads. While this would significantly raise plant power levels, it would result in a net reduction in mass due to savings in space radiator facilities. Figure 27 shows heat transfer load vs. temperature for the various process steps.

Energy Summary

The foregoing analysis indicates that the combined power requirements for the electrolysis operations amount to 92.5 - 116.8 Kcal/equivalent = 6,000 - 7,700 KWH/metric ton. These values are so high that other processing routes were considered to be virtually mandatory for practical space processing plants. As an example, for a proposed⁷ mature non-terrestrial processing facility designed to convert 399,000 metric tons/year of lunar plagioclase to industrial feedstocks, the total annual conversion amounts to 1.316×10^9 moles or 22.77×10^9 equivalents. The current (1976) U. S. production of chlorine³² is approximately ten million short tons per year which amounts to 255.8×10^9 equivalents. Operation of such a plant would require generation of chlorine equal to 8.9% of total U. S. production and would far exceed the capacity of any single plant now in existence.

Plant Sizing

A complete and detailed plant sizing for the carbochlorination process was not performed in view of the unfavorable energy

considerations. However, an estimate of the size and mass requirements for the chlorine regeneration section is instructive and is given below based on the approximation that the size and mass of HCl, CaCl₂ fused salt chlorine cells would be comparable with existing NaCl diaphragm cells. A single Diamond Alkali D-3 cell has the following specifications:^{8 & 24c}

Output	1.01 short ton (Cl ₂)/day
Current	30,000 Amperes
Voltage	3.82 Volts
Power	2720 KWH/short ton Cl ₂
Cell room area	105 ft ² /short ton Cl ₂ day
Anode life	230 days
Diaphragm life	115 days
Graphite consumption	7.5 lb/short ton Cl ₂
Asbestos consumption	1.2 lb/short ton Cl ₂
Cell room maintenance	.29 man hr/short ton Cl ₂

The cell contains an estimated 40 ft³ of electrolyte with a density of 75 lb/ft³ or about 3,000 lb of electrolyte which is about 75% water and 25% NaCl.

This cell has an output of 25,839 equiv/day or 1,077 equiv/hr so the electrolyte mass requirement is 1.264 kg/(equiv/hr). Such a cell would require 35.7 hr to generate chlorine equal to the weight of its electrolyte or 72.1 hr to generate sufficient chlorine to combine with lunar plagioclase concentrate equal to the weight of the electrolyte.

For a plant to handle 399,000 metric tons/year of lunar ore operating 330 stream days/year with 90% utilization (10% down

time) or 7128 hr/year, the hourly capacity would be $.1845 \times 10^6$ equiv/hr. This would require the equivalent of 2,964 D-3 cells with a rated power of 340 MW and requiring a floor space of 28,912 m² (311,220 ft² or 7.14 acres). The electrolyte mass would be approximately 4.034×10^6 kg = 4,034 metric tons.

The carbon monoxide conversion and separation facility would have to convert 318,800 metric tons per year of CO to 136,600 MT of carbon plus oxygen. This would involve formation of approximately 160,000 metric tons of hydrocarbons via Fischer-Tropsch synthesis followed by pyrolysis as in carbon black production. By the early 1960's only two plants operating in the free world had capacities sufficient to synthesize such quantities of hydrocarbons from carbon monoxide.^{24d} The pyrolysis section would be required to generate carbon black at a rate equal to approximately 9.4% of the annual U. S. production (1977 - est = 1.45 million Mt).³²

Appendix I

HF ACID LEACH PROCESS ENGINEERING DATA

The detailed analysis of the proposed process will depend on the value of the x parameter in the equations and the M element composition. For mass and thermochemical estimations, we have chosen $x = 2$ and $M = \text{Mg}$. The $x = 2$ value closely approximates a lunar anorthite or olivine composition, while the thermochemical properties of MgO and MgF_2 are similar to Al and approximately averages between more reactive calcium compounds and the low energy ferrous compounds. The equivalent weight of MgO is also intermediate between Al_2O_3 and CaO and FeO . The molecular weight (Forsterite) is then 140.7 which gives 7170 moles/metric ton or 56,859 equiv/MT. It is worth noting that for pyroxenes, $x = 1$ and the consumption (recirculation) of HF per mole of silica processed drops from 8 to 6 equivalents which represents a size reduction of 25% in hydrolysis equipment or even more when reduction diversions of fluorides are considered. More extensive use of pyroxenes would necessitate substitution of magnesium for aluminum in some light metal production and possibly greater use of ferrous metals (see Table I).

Materials Balance

A materials balance for the separation process is given in Table A where the number of moles of reagents present and converted or transferred per input mole of $x\text{MO} \cdot \text{SiO}_2$ is shown. The corresponding compositions are shown on the phase diagrams in Figs. 28 and 29.

It will be noted that in the leach section, 23.5 moles of

acid are added and 25.5 moles vaporized (including water content), while in the hydrolysis section, 66.6 moles of acid vapors are added and 65.6 moles are vaporized. An additional thermal load is generated from hydrolysis of the metal fluorides requiring vaporization of a minimum of 11.2 moles although equilibrium data are not sufficiently defined without composition information on M. This considerable mass transport arises primarily from the amount of water and SiF_4 which has to accompany the HF which must be removed from the hydrolysis operations to maintain a continuous or quasicontinuous process. This necessitates a large heat transfer capability although the net energy requirement can be fairly low using heat pumps.

The amount of recycled water can be greatly reduced if hydrolysis is conducted with solutions of lower water content, since then the HF can be removed (along with recycled SiF_4) without vaporizing any appreciable water. A second approach would involve neutralization hydrolysis of SiF_4 with NH_3 forming Si(OH)_4 and NH_4F and thermally regenerating the NH_3 from NH_4F with formation of NH_4FHF .³³ This option will be analyzed in the near future.

Detailed materials balance for the metal fluorides separation and reduction steps are not given since the various options would require an excessively complex and lengthy tabulation. The flows can be estimated from process equations 5 - 10 using selected values of the parameters.

Thermochemistry

The thermochemistry of the process is shown in Fig. 30 and Table B. In this analysis, the latent heat of phase change of H_2O and HF are not included since they can normally be adjusted

by the liquid/vapor ratio of acids introduced to the reactors. Similarly, the boilers in distillation columns may be heated by adiabatically compressing the distillate vapors.

It may be noted that, in contrast to the carbochlorination process, there is no large low temperature exotherm requiring excessive radiator mass. The acid leach step (Eqn 1) is exothermic, but the evaporation of SiF_4 (Eqn 2) is endothermic and by introducing part of the acid addition in vapor form, one may exactly balance the heat load of the combined equations 1 and 2 (see materials balance, Table A).

The large exotherm from the sodium-oxygen electrolysis may furnish part of the heat for distillation operations while the remainder may be supplied by compression of distillate vapors. The approximate heat transfer requirement in the evaporation and distillation operations may be estimated as 10 Kcal times the number of moles vaporized or condensed. Referring to the materials balance table, we thus estimate -285 Kcal (A), +255 Kcal (D), -666 Kcal (E'), +411 Kcal (H'), +245 Kcal (J & J'), $-(71.5 + 10n)$ Kcal (C_1), and $+(91.5 + 10n)$ Kcal (L & L'). The requirements per equivalent may be calculated by dividing by 8. Thus, the total (boiler) heat load per input equivalent is about 125.3 Kcal (8286 KWH/MT).

For the high temperature processes, the hydrolysis of metal fluorides is seen to depend on the particular element. Transfer of fluoride ion content from Ca and Mg to Fe or Al would lower process energy requirements. More importantly, FeF_2 or FeF_3 are more readily hydrolyzed,³⁴ and the reaction may be conducted at lower temperatures. The fluoride transfer may be carried out

using ion exchange resins. The sodium fluoride must be converted to hydroxide or other form since hydrolysis as NaF with steam is impractical, but by conversion to cryolite, Na_3AlF_6 , the hydrolysis may be effectively carried out.

The sodium reductions are exothermic except for Ca which would not normally be produced via that route since the equilibria are unfavorable. Reduction of iron would lead to a large exotherm but iron can be more easily recovered by aqueous electrodeposition (Eqn 8).

The energy and heat load requirements for sodium and oxygen production may be estimated from theoretical and actual values for the Castner cell using the proposed modification to remove water. The reversible decomposition voltage is estimated to be 2.3 Volts @ 300°C (corresponding to a free energy change of 53 Kcal/equiv). The industrial cell operated at 4.3 V with a current efficiency of 40%,⁸ which should be elevated to 80% by drying the electrolyte. This gives a projected energy of 518.7 Kjoule/equiv = 124 Kcal/equiv. The dissipative load would then be $124 - 53 = 71$ Kcal/equiv. If 50% of the input equivalents required sodium reduction (4 equiv per input mole), the electrolytic heat load would be 284 Kcal/input mole (2348 KWH/MT).

The electrical power load for the same 50% reduction requirement would then be 62 Kcal/input equivalent or 4100 KWH/metric ton.

Unit Operations

The acid leach operation would be conducted in one or more stirred tanks at temperatures near the boiling point (ca. 110°C). Raw or beneficiated silicate ore would be preleached with cool acid at low pressures to separate dissolved solar wind gases and

then added to the tank along with a mixture of vapor and condensed acids from hydrolysis stripping operations. Precipitated fluorides would be removed in a centrifugal sedimentation unit using some of the condensed acid makeup to leach any undissolved silicates. The reaction exotherm and condensation heat of the input acid vapors would vaporize the SiF_4 and H_2O generated in the leaching step.

These vapors would be added to additional $\text{SiF}_4\text{-H}_2\text{O}$ vapors (evaporated from the hydrolyzing solution after removal of the precipitated hydrated silica) and dissolved in a second tank used for the hydrolysis operation and operated near the boiling point. After removal of the precipitated silica with a sedimentation centrifuge and partial evaporation to supply the recycle $\text{SiF}_4\text{-H}_2\text{O}$ requirement, the residual acid (which is no longer saturated with silica) is fed to a fractional distillation column where it is separated into three streams: steam, acid azeotrope (71 m/o H_2O , 23 m/o HF, 6 m/o SiF_4), and SSA. The SSA and steam are recycled to the hydrolysis unit, while the acid azeotrope is returned to the leach cycle.

The spent leach solution would be periodically sent to a crystallizer or ion exchange column to remove NaF and KF which would otherwise gradually build up in concentration. Precipitated and crystalline fluorides would be converted to elements or oxides by several optional routes depending on the element and requirements for reduction products. Element requirements except for iron, magnesium and calcium would be met by sodium reduction. Iron would normally be electrodeposited from aqueous fluosilicate solution, while magnesium could be reduced from its oxide using

silicon as is practiced commercially. Calcium metal may not be an important end product, but it can be produced by electrolysis of fused salts such as CaCl_2 . The sodium reductions may be carried out in steel retorts or ceramic tubes made of SiC , CaF_2 or other resistant refractories at temperatures near 900°C (the boiling point of Na is 881°C).

Hydrolysis of non-structural metal or surplus fluorides to oxides would probably be best conducted in rotary kilns using superheated steam as a recirculant fluid. The HF content of the vapor stream must of necessity remain lower than the equilibrium value for coexisting MO and MF_2 solid phases. Comange measured these values for a number of fluorides and reported these results:³⁴

Fluoride	Temperature	Vol % HF*
CaF_2	1000°C	1.15
	1100°C	2.3
MgF_2	1000°C	6.6
	1100°C	12.0
FeF_2	550	56.0
FeF_3	450	66.0

Hydrolysis of sodium or potassium fluoride is probably not practical using steam and heat. It will be noted that hydrolysis of CaF_2 is much more difficult than for transition metal fluorides, so it may be advantageous to convert Ca and Mg fluorides or fluosilicates to more easily hydrolyzable or pyrolyzable (such as iron fluorides) and Ca or Mg hydroxides, carbonates, sulfates

*At 1 atm. Hydrolysis at reduced pressures yields higher fractional content of HF.

or chlorides using ion exchange or other methods.

The separation of the mixed metal fluorides may be achieved by various solution processes. Fluoride solubility³⁵ will separate NaF and KF from multivalent metal fluorides. The solubility of AlF_3 , FeF_2 and MnF_2 (ca. 1% by weight) is sufficient to permit electrodeposition (except for Al), but the sparingly soluble and insoluble fluorides may also be brought into solution by adding SiF_4 (or $\text{Si}(\text{OH})_4$ and HF) and conversion to fluosilicates. These are all soluble at the 10% or higher level³⁶ and may be separated by ion exchange or other techniques. Calcium may be separated from magnesium and aluminum by sulfate precipitation while aluminum and magnesium are separable by hydroxide precipitation at controlled pH. Unfortunately, fluosilicates are subject to anion hydrolysis and silica precipitation if the pH rises above 5.

Ion exchange methods appear to be most generally useful. Regeneration and elution of the resins will normally require a regenerable source of acids and bases. Regeneration should preferably be performed by a thermal pyrolysis or hydrolysis operation. These might include steam hydrolysis of calcium chloride or fluoride, or pyrolysis of NH_4F or $(\text{NH}_4)_2\text{SO}_4$ to N_2 plus acid salts. The calcium halide hydrolysis can regenerate strong acids and bases while the ammonium salt pyrolysis only gives a weak base. The latter route involves substantially lower energy and process times, however.

A typical process route to separate the four major metallic constituents is given in Table VIIb. Additional work in process optimization is necessary to refine the separation technology.

The unit operations required for the reduction steps consist of aqueous and fused alkali electrolysis, high temperature reactors for reduction, and alkali regeneration of the NaF formed during reduction.

Commercial electrodeposition from aqueous electrolytes is normally limited to 50% or less of the active species in the electrolyte after which the solution is purified and/or replenished. The purification is often performed in "liberator" cells where the residual metal ion content is reduced to very low values although the current efficiency drops and substantial hydrogen is released. An alternative is to remove the residual ions with an ion exchange resin and eluting them in a more concentrated solution for electrodeposition or crystallization. Because the solutions are all recycled, it may not be necessary to completely extract the platable metals in each pass, which will speed up the operation.

The electrolysis of fused NaOH is different from aqueous and most fused salt systems in that there is little or no "inert" solvent involved, and the electrolyte mass is almost completely derivable from lunar sources. The electrical conductivity is much higher than aqueous systems which permits higher current densities (ca. 10^4 amp/m²).

The sodium reduction reactions will normally be conducted in steel reaction vessels at temperatures near 900°C. Volatile fluorides such as SiF₄ or TiF₄ may be contacted with molten sodium in a reflux boiler. Solid fluorides such as AlF₃ may be mixed with sodium and charged into retort tubes. Separation of the reduced product from the NaF formed depends on the physical

properties of the reduced elements. Thus, aluminum would melt at the reaction temperatures and would separate from the NaF. Silicon and titanium would be formed at temperatures below their melting points and would occur as a sponge from which the NaF could be separated by water extraction.

Magnesium reduction would best be accomplished by conversion of MgF_2 to MgO by steam hydrolysis and reducing the latter with silicon as previously noted. This reduction process is carried out commercially in alloy steel tubes at 1100 - 1200°C. The product distills into the cooler ends of the reaction tubes and is removed in solid or liquid form.

The NaF must be reconverted to NaOH with recovery of HF to permit regeneration of sodium. This may be done using an anion exchange resin (Eqn. 9) or with CaO (Eqn. 9A). Regeneration of the resin may be accomplished with either CaO or NH_3 . (In the latter case, a weak basic resin must be used and the elution conducted with a reflux condenser with the steam condensation pre-eluting the NaF. The dilute NaOH leaving the column would accumulate in the boiler.) Regeneration of the column with NH_3 would yield NH_4F which may be pyrolyzed at temperatures below 150° - 200°C to yield NH_3 and NH_4FHF . Finally, the HF must be recovered from the acid salt by vaporization or ion exchange methods.

The aqueous NaOH formed would have to be dried prior to use in the electrolysis unit.

Plant Sizing

Calculations of the size and mass of reagents and equipment for the various process steps is inevitably linked to the estimates

of process times for the respective steps. These remain somewhat uncertain in the absence of pilot plant data, although for most of the steps which do not involve chemical reaction, the accumulated experience of equipment vendors for materials handling and phase separation serves as a useful guide to equipment size/throughput ratios.

Since most process steps require times ranging from a small fraction of an hour to several hours, the operating capacity may be conveniently expressed in gram moles/hr or equivalents/hr. The conversion from mass/year to equivalents/hr will depend on the fraction of available time the plant is in operation (equivalent hours at full capacity divided by hours per year). We shall use the previously assumed values of 330 stream days/yr, 21.6 hr/day (90% available time) or a total of 7,128 hr/year. We thus obtain:

$$\frac{\text{equiv.}}{\text{hr}} = \frac{\text{equiv.}}{\text{MT}} \times \frac{\text{MT}}{\text{yr}} \div \frac{\text{hr}}{\text{yr}} = \frac{\text{equiv.}}{\text{MT}} \times \frac{\text{MT}}{\text{yr}} \div 7,128$$

For discussion purposes, we shall calculate plant sizes for a proposed initial space processing facility with a rated capacity of 30,000 metric tons/yr (≈ 1 kg/sec). Operating 7,128 hr/yr would require a throughput of 4.209 MT/hr or 239,320 equiv/hr for an assumed equivalent weight of 17.59. Since each mole of $2\text{MO} \cdot \text{SiO}_2$ has 8 equivalents, the masses processed per hour are obtained by multiplying the values shown in Table A by 29,915.

The reagent masses per step are then given by 29,915 t times the mass value given in Table A, where t is the process time in hours.

A more general result may be derived from the mass ratio

parameters, R_m , previously defined. For any step, R_m equals the total mass from Table A divided by equivalent input mass (.1407 Kg). Then the product tR_m represents the reagent mass per (input mass/hr). Similarly, we may tabulate the net reagent mass (LDE)(mass of elements other than the 13 major and minor lunar elements) and calculate the net mass ratio R_m' . The product tR_m' then gives the net reagent mass per (input mass/hr).

Table C gives the results of such calculations for the principal process steps along with corresponding equipment mass variables, r_m and tr_m .

The equipment (container) masses were estimated from stress considerations outlined in Appendix D. Additional design parameters for materials handling equipment and other procedures are given in Appendix G and from chemical engineering reference materials. The equipment masses per process step yield tr_m products of less than 1 hr except for the rotary kiln hydrolysis/driers, the sodium electrolytic cells and the metals reduction reactors.

The process times for chemical reactors and other steps were estimated from published data on typical throughput vs. size for sedimentation centrifuges,³⁷ rotary kilns,³⁷ fluosilicate hydrolysis,³⁸ fused alkali electrolysis,⁸ metals reduction in externally heated retorts,²⁴ etc. These process times, which fix the reagent mass and volume in a given step, have been plotted on the volume vs. throughput graph in Fig. 31.

The Bureau of Mines, U. S. Department of Interior has published a series of reports³⁹ evaluating and sizing proposed plants for acid leaching of calcined clays to separate silica and alumina contents (and iron impurities) and recover the alumina.

The processes have many features similar to acid treatment of lunar silicate materials. We have calculated process equipment size/throughput ratios from their data and displayed these on Fig. 32. (It may be noted that the tradeoffs between equipment sizing and process reagent and power conservation would favor larger but more efficient apparatus for earth-based plant design.) It is seen that the reactor sizing procedures for both the lunar process and the clay/alumina process yield points in general agreement with industrial design experience.

Summation of the tR_m , tr_m and tR_m' products illustrates some interesting points: 1) the reagent mass tends to dominate the mass of direct containers and equipment. 2) The net reagent mass (LDE) which represents primarily hydrogen and fluorides is comparable with the process equipment mass, and 3) the mass of peripheral equipment including space solar electric power, space solar thermal power, radiators, compressors, heat exchangers, pipes, valves, electrical, structural and miscellaneous items will probably exceed the mass of all other earth-lift requirements.

The masses of peripheral and support equipment and structures is also shown in Table C. The masses shown were estimated for a plant of input capacity 30,000 MT/yr and the "equivalent hours" are also listed.

Start Up Procedures

An initial space processing facility in orbit will consist of earth manufactured components and structural parts and reagents delivered to some orbital location. Solar cell panels will be erected and deployed to provide operating power. Large reaction vessels will have to be assembled and made leak-tight. For low

and medium temperature processes, there is little mass savings to be gained from large reactors, and multiple smaller vessels will probably be desirable from a reliability standpoint. This will also aid in the start up operation by allowing functional operation at less than design capacity.

When the lunar ore begins arriving, the first requirement is to generate oxygen, water and sodium. Since sodium is a minor lunar element, enough water (or hydrogen and oxygen) must be brought from earth to treat lunar ore to extract its sodium content and hydrolyze major elements back to oxides. Enough water must also be brought to recycle NaF and NaOH. The initial oxygen supply can best be provided by electrolyzing the iron fluosilicate solution and plating the corresponding number of equivalents of iron. All of the other fluorides would be initially hydrolyzed and stored for later use.

The NaOH requirement for full capacity sodium cell is 6.1 MT (for a 30,000 MT/yr plant) corresponding to 4.73 MT of Na₂O. The full amount would require the processing of about 1,000 MT of lunar ore for sodium extraction. It would be desirable to initially transport a high iron ore such as ilmenite or pyroxene, since the oxygen derivable from the FeO content may be just able to replace the water loss from the materials processing.

Water may be generated in a fuel cell from earth-lifted hydrogen and electrolytic oxygen. The key to establishing full capability for the plant is the generation of water which, depends on oxygen production which, in turn, depends on the accumulation of iron and sodium.

High temperature reactors such as the hydrolysis/drying kilns may require a miniature sub-pilot unit to operate during startup procedure at 5% or less of the rated capacity of the main reactor.

As water accumulates, successive leach tank and hydrolysis tank modules would be filled and brought on line until full capacity operation is achieved.

Reagent Replacement Mass

Although some regular transportation of earth replacement parts, personnel and other special requirements will be necessary, the mass of reagent replacement will probably represent the greatest fraction of continued earth-lift operations.

The HF acid leach process will require the recycling of compounds containing H, F, Na and optionally N (if NH_4^+ salt reagents are used).

All anticipated compounds containing H are volatile or dissociable at elevated temperatures. Hydrogen will appear principally in H_2O , HF and NH_3 (NH_4^+) during recycle operations. It is anticipated that all other loss routes of hydrogen or water will be a small fraction of that represented by chemically bound or absorbed water in silica, metal oxide or other solid effluents from the processing facility. One may anticipate a low loss of H from exit streams consisting of kiln dried (high temperature/vacuum) oxides, solid elements (metals, and silicon) and fused slags. Moisture content of 1/2% or lower would correspond to less than .06% H. Hydrogen in O_2 gas may appear as H_2O or H_2 . The former should be efficiently removed by cold traps (1/2% H_2O is equivalent to a dew point of 5.4°C) prior to liquefaction

while the latter can be catalytically oxidized or fractionally distilled. Hydrogen content below 0.1% appears to be easily achieved. If the exit material has an average water content of 1% by weight, the equivalent hydrogen content will be 0.112%. The total input mass would approximate the output mass, so the 30,000 MT/yr plant would lose 300 MT H₂O/yr which would require 33.6 MT H₂/yr to replace. This should represent a "worst case" limit with careful management.

The principal potential loss mechanism for F appears to be residual fluoride remaining in oxides after steam or acid hydrolysis. Studies of steam hydrolysis (@1200°C, 15 minutes) as an analytical technique for F determinations⁴⁰ have shown titratable recoveries averaging 99.29% (S.D. = .23%) for five aluminum fluoride-containing materials. Since the original charges contained 51-68% F, we may assume an average upper limit of .36 - .48 wt% residual F. Given normal process development including vacuum degassing stages, it is reasonable to expect recycle efficiencies in excess of 99.5%. Loss of fluoride should preferably be kept at 0.25% or less in oxide products and near zero in reduced (elemental) products. If we assume an average fluorine content of .15%, the earth replacement requirement of fluoride (as HF) would be 45 MT/yr for a 30,000 MT/yr plant. (Anhydrous HF is an easily storable and transportable fluid with a boiling point of 19°C.)

Sodium may be lost in small quantities in metals formed by Na reduction or in oxide exit streams. The former route will probably not exceed a few ppm, but the latter may potentially result in greater Na loss. Such sodium losses would probably arise from coprecipitation of Na with Al, Ca or Mg fluorides or

hydroxides from originally acid solutions. Of these, only $\text{Al}(\text{OH})_3$ would possibly lead to a problem at levels in excess of 1/4%. If such a problem would arise, an ion-exchange replacement of Na^+ by NH_4^+ would eliminate such Na^+ losses. It would appear that Na losses can be held lower than Na content of input material at least for anorthite processing.

Nitrogen will appear mainly as $\text{NH}_3\text{-NH}_4^+$ compounds depending on pH. Pyrolysis of any NH_4^+ compounds will lead to volatilization of NH_3 and negligible retention in the solid phase. NH_3 may be easily cold trapped or acid scrubbed from oxygen streams.

NH_4^+ may suffer a small fractional oxidation at electrochemical anodes to N_2 or other oxidation states. This is not expected to be a problem, but N_2 in an oxygen stream may be removed by glow discharge oxidation to acidic nitrogen oxides which may be absorbed in alkaline scrubbers. These nitrates may be reconverted to NH_3 by conventional chemical processes. (The $\text{N}_2\text{-NH}_3\text{-nitrate}$ dynamic cycle may be established with a significant mass inventory in space agricultural operations.) Replacement requirements for all other reagents should be a minor consideration.

Table B

THERMOCHEMISTRY OF PROCESS EQUATIONS (HF ACID LEACH)

<u>Equation No.</u>	<u>ΔH_r Kcal @ 298°K</u>	
1, 1'	-126.4	
2, 2'	23.4	
3	4.4 (1-y)	
3A	23.5 (1-y)	
4	94.6 (1-y')	M = Mg
	131.6 (1-y')	M = Ca
	65.4 (1-y')	M = Fe
	3.8 (1-y')	M = (2/3)Al
5	-158.0 y	
6	- 17.0 y'	M = Mg
	36.6 y'	M = Ca
	-206.6 y'	M = Fe
	-129.3 y'	M = (2/3)Al
7	5.4 z	
8	variable	
8A, 9	low	
9A	- 3.5 m	
10	$F_r = 63.3 m$	
11	19.9 (1-y)	

Standard state of HF and H₂O: vapor, 1 atm. or saturation pressure except where noted.

Table C

TIME - MASS RATIO FACTORS

STEP	t Process Time (hr)	R_m <u>Mass contents</u> Equiv. input m.	r_m <u>Mass container</u> Equiv. input m.	tR_m hr	tR'_m hr	R'_m <u>Net mass (LDE)*</u> Equiv. input mass	tR'_m
Acid Leach (A1)	.5	22.2	.48	11.1	.24	7.95	3.97
Sedim. centrifuge/ Distill (A1)	.0167						
		22.2	28.8	.371	.48	7.95	.133
Hydrolyze (F)	.5	44.9	.96	22.5	.48	14.7	7.36
Sedim. Centrif. (F)	.0167						
		44.9	42.6	.75	.71	14.7	.207
Distill/ Condense (H1)	.00278	7.06	86.4	.0196	.24	2.14	.006
Distill (1/2)	.00278	22.5	86.4	.0625	.24	7.36	.020
Hydrolyze-dry (C+G' H ₂ O)	3.0	3.0	.55	9.0	1.66	.728	2.18
Distill (R)	.00278	7.63	86.4	.021	.24	1.36	.004
Electrolysis (zC+yS1+mNa)· (2z+4y+m=5)	27.5	1.45	.173	40.05	4.75	.036	1.0
Metals Reduction	3.0	1.76	.48	5.28	1.43	.7	2.1
Regeneration (est)	.5	5.0	.48	2.5	.24	.7	.35
Misc.	.5	1.0	.4	.5	.2	1.0	.5
<u>Subtotal</u>	<u>35.54</u>			<u>92.15</u>	<u>10.91</u>		<u>17.83</u>

EXTRA MASS	(metric tons)	equiv. hrs
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
<u>Subtotal</u>	<u>220</u>	<u>52.24</u>

Appendix J

MATERIALS SPECIFICATIONS

The proper functioning of industrial, commercial and consumer processes, equipment, products and supplies demands a variety of standards or specifications covering composition, performance, dimensions, textures, finishes and various other factors. In this discussion we will be concerned mainly with compositional specifications for materials produced primarily for industrial feedstocks. These include structural materials (metals and alloys), optical materials (glasses), (electrical-magnetic) materials, and oxygen. In addition, specifications may be required in reagent purity and water quality if process water is used interchangeably with bioprocess water in life support systems.

A. Structural Metals

The primary purpose of compositional specifications for metals and alloys is to provide adequate mechanical properties such as ultimate and yield strengths in tension and shear, ductility as measured by elongation or reduction in area, fatigue and creep strength, and rigidity and hardness although corrosion resistance is often an important factor. The commercially pure elemental metals derivable from major lunar elements Al, Fe, Mg, and Ti have typical mechanical properties on listed in Table A. The low strengths in comparison with their ordinary commercial alloys dictates preference be given for the use of selective alloying elements and/or hot or cold working or heat treatment to improve the mechanical properties of these metals. The strength and ductibility can be substantially modified by alloying, but the

modulus of elasticity is only slightly affected.

It would be practically mandatory to produce alloys already used on earth and for which engineering properties are well established rather than to attempt to develop new alloys (based on availability of alloying elements). Fortunately a good selection of commercial alloy compositions requiring little or no content of LDE is available for space production. We shall discuss such alloys for all of the major lunar structural metals.
(Aluminum)

The following elements are used in various commercial aluminum alloys: Be, Bi, Co, Cr, Cu, Mg, Mn, Ni, Pb, Si, Sn, Ti, Zn, and Zr. Of these, only Cr, Mg, Mn, Si and Ti can be readily obtained from the moon. Although Cu and Zn are widely used in aluminum alloys, a fairly good selection of alloys is available using only the five lunar-indigenous alloying elements listed above, while several commonly used alloys could be made by importation of small amounts of LDE's. Table B lists compositions and representative properties of these alloys.

Special alloys have been developed for powder metallurgy production. Table B shows the composition for a high performance alloy which would, however, require 10.6% by weight of LDE's for alloying.

(Ferrous Metallurgy)

Steels are produced and fabricated with a highly diverse range of compositions and techniques to obtain desired properties and economic considerations for different applications. The diversity of a space industry will not require such an extensive range of alloys and techniques, but a modest range of alloys

suitable for casting, ingot working and powder metallurgy is available with compositions based entirely or substantially on lunar indigenous elements.

Steels may be conveniently classified into low alloy and carbon steels, medium alloy steels, and high alloy steels based on the general content of alloying elements. Low alloy steels may contain up to 1.8% Mn, .6% Si or Cu and 1% or less of Cr, Ni and/or other elements with C content generally held below 1%. Medium alloy steels usually contain 1 - 3% or more of (Cr, Ni and/or Si) plus small amounts of various other elements often including refractory elements such as Mo, V, etc. High alloy steels usually contain 10% or more of at least one element (usually Ni or Cr) and may contain 30% or more total alloying elements.

Steels may be also classified on the basis of end use rather than composition into such categories as structural steels, pipe steels, corrosion resistant steels, tool steels, etc., but we will not use such a system in our analysis.

Carbon is the most common and least expensive hardener of steels for earth-bound metallurgy. Carbon may also be used in lunar or orbital metallurgy even if it requires importation, since it is very effective at low concentrations and is rarely used above 1% in structural steels and 1.5% in tool steels. Carbon and nitrogen are conveniently used also for surface hardening.

Table C lists some compositions and properties for low alloy and carbon steels derivable primarily from lunar indigenous elements. Of particular interest for space industrialization are the HSLA (high strength, low alloy) steels, which not only offer substantial property improvements over LDE's and are

exceptionally formable and weldable for alloys of such strengths. One may also note that very high strengths at both room and elevated temperatures are obtainable from such alloys as AISI 1340, 4140, and 5140.

Table D lists some compositions and properties for medium alloy steels derivable primarily from lunar indigenous elements. This group includes heat treatable alloys such as AISI 4042, 4340, 8640, 9260 and some tool and electrical steels.

High alloy steels include most of the stainless steels, high speed tool steels, oxidation resistant alloys, etc. Some representative examples with their properties are listed in Table E.

Casting steels are similar in composition to corresponding wrought alloys except that additional S and Mn are often added to insure deoxidation and promote soundness in castings. Steel parts may also be produced by powder metallurgy techniques using alloys of standard or special composition.

(Magnesium)

Commercial magnesium alloys generally contain one or more of the following elements: Al, Ca, Mn, rare earths, Th, Zn, and Zr. As in the case with aluminum, most magnesium alloys contain LDE's (primarily Zn and/or Th). Table F lists compositions and representative properties of alloys derivable solely or primarily from lunar indigenous elements. It may be noted that the addition of small amounts of Zn improves the strength of Mg alloys while the use of Th or rare earths improves the high temperature properties.

(Titanium)

The elements used in commercial titanium alloys include Al, Cr, Fe, Mn, Mo, Nb, Ni, Sn, V, and Zr. Most alloys use V and/or Mo which are LDE's. Table G lists compositions and representative properties of alloys derivable primarily from lunar indigenous elements.

Optical Materials (Glasses)

Commercial glasses contain in addition to SiO_2 , Al_2O_3 , CaO , and MgO , alkali oxides (Na_2O , K_2O , and Li_2O), B_2O_3 and/or heavy metal oxides such as PbO , BaO , TiO_2 , ZrO_2 , and rare earth oxides. Table H gives the compositions of a number of commercial glasses derivable primarily from lunar indigenous elements. Table J lists the thermal shock resistance and working temperatures for these and other commercial glasses.

Transparencies for these glasses will depend primarily on the impurity level of various constituents such as Fe, Cr, etc., although the resistance to radiation darkening varies widely and will be important for space applications. Refractive index is not expected to be a critical property in most cases.

It may be noted that the high performance fiber "S-Glass" may be derived entirely from lunar indigenous materials.

(Electrical/Magnetic (E/M) Materials)

Within this category we might group conductors, insulators and permanent (hard) and soft magnetic materials, but we shall exclude insulators from the following discussion.

The electrical resistance of commercially pure metals is given in Table A. One notes that Ti is unsatisfactory for general conductor applications.

Fe and Mg are not commercially used as general conductors, but aluminum is widely used as a conductor, primarily as the EC alloy.

Metals composition and purity requirements for electrical conductor applications in power service are substantially different from those encountered where mechanical properties only are required. In the latter case, properties are almost always improveable by proper use of alloying elements, while in the former, the addition of virtually any alloying element leads to a deterioration in electrical conductivity. For aluminum, the addition of as little as 0.8% Mg reduces the electrical conductivity 20% while silicon additions beyond the solid solution limit at the eutectic temperature (1.65%) result in a conductivity drop of 32%. Such alloys would require 25% and 47% more weight of metal respectively to gain a system conductance compared with 99.5% Al.

Detailed compositional limits for 1060 alloy (which is comparable in electrical properties with EC) include: Minimum: 99.6% Al; Maximum: .25 Si, .35 Fe, .05 Cu, .05 Zn, .03 @Mg, Mn, Ti, other (all wt. %). While some of these limits may be set primarily for corrosion resistance, all impurities may be expected to adversely affect conductivity. In this regard, the behavior parallels that of copper.

The effect of alloying elements on the conductivity of magnesium is much less accessible or known due to lack of electrical applications on earth. We may expect to find a similar behavior, however. (The electrical resistance of all commercial alloys at room temperatures is, of course, readily available and listed for Al and Mg alloys.

For applications where volume limitations are unimportant, a useful figure of merit for general conductors might be electrical conductance per unit cross sectional weight or conductivity: density ratio. On such a scale, the pure metals would rate as shown in Table K.

While iron is a rather poor electrical conductor, it might be useful for some direct current applications on the lunar surface. Alternating current applications would be generally unsatisfactory due to skin effect and hysteresis losses.

Special resistance alloys and non-metallics such as Fe_3O_4 would be available for specific applications with properties corresponding to those available in earth bound commercial materials.

Magnetic Materials

The dominant magnetic mass requirements would probably arise for soft magnetic laminations for transformers, motors, etc. These are customarily made of high silicon steels such as shown in Tables D and L. High permeability material needs can be filled using alloys such as sendust.

All of the high efficiency permanent magnet alloys require substantial amounts of lunar deficient elements — principally Co and Ni. However, ceramic permanent magnets can be made primarily from lunar indigenous elements — primarily Fe_2O_3 . Magnetic properties of these materials are given in Table L.

Ceramic soft magnetic materials are useful in a number of high frequency (communications) applications. These ferrites and magnetic garnets are also composed primarily of lunar indigenous materials.

Oxygen

Oxygen derived from decomposition of lunar ores is unlikely to be admixed with substantial amounts of other volatiles. Depending on the method of generation, there may be other solid or liquid dusts or mists, moisture and/or permanent gases such as chlorine, CO or CO₂. Oxygen will undoubtedly have to be liquified to be stored, and a combination of cold trapping and filtration should remove all normal impurities except N₂ and CO by catalytic oxidation at moderate temperatures prior to cooling and liquifaction. The CO₂ produced may be removed by trapping or alkaline scrubbing.

Table A

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

II-184

*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

Table B

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							
EC	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; +500 kg load, 10 mm ball

M = Maximum

Table B (Continued)

PROPERTIES OF CAST ALUMINUM ALLOYS

Alloy	Composition				Si	Ti	Cr	Tensile Strength (psi)	Yield strength (psi)	Elongation (%)	Bhn* Hardness	Shear Strength (psi)	Fatigue Limit (psi)	Electrical Conductivity (% IACS)
	Zn	Cu	Mn	Mg										
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		25-31,000	20-34,000	2-6	60-80	20-30,000	8-13,000	39-43
260				9.5%	5.5%			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	5.8	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 C

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 D

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

11-188

M = Maximum

Table E

Properties of High Alloy Steels

AISI No.	Composition					Tensile Strength (μ si)	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	1.0	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

Table F

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

11-190

Table G

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	

Table H

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 } electric	62.0	17.0	8.0	7.0	1.0		5.0	
1723 }	57.0	15.0	10.0	7.0			5.0	
6720 } general/ lighting	60.0	10.0	5.0		9.0	2.0	1.0	
6810 }	56.0	10.0	4.0		7.0	1.0	1.0	3.0 PbO
7900 } high temperature	98.0	0.3					3.0	
7913 }	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 J

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	Annealing	Softening	Working
				Point	Point	Point	Point
				10 ^{14.5}	10 ¹³	10 ^{7.65}	10 ⁴
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	770	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	860
8363				300	315	380	460
8871	(55)	(45)	(35)	350	385	525	785
9010				405	445	650	1010
9606						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

Table K

ELECTRICAL CONDUCTIVITY OF PURE METALS

Element	Resistivity	Conductivity		Density	Mass Conductivity	
	$10^8(\text{m})$	$10^{-8}(\text{mho}/\text{m})$	(%IACS)	$10^{-3}d(\text{kg}/\text{m}^3)$	$10^{-3}(\text{mho m}^2/\text{kg})$	(%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

11-194

Table L
 PROPERTIES OF MAGNETIC MATERIALS
Soft Materials

Type	Induction (T.sla)		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	$45-69 \times 10^{-6}$
M8	2.01	.66-.86	.05-.1	(4-8)	.8	2,500	55-60,000	740	$45-52 \times 10^{-6}$
M5					.5				
Sendust (Mg,Mn)Fe ₂ O ₄	1.0		.035			30,000	120,000	500	81×10^{-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 L (Continued)

PROPERTIES OF MAGNETIC MATERIALS

Hard Materials

Type	Induction (Tesla)			H_c	H_d	$(BH)_{max}$	(Gauss-Oersted)	Curie Temp.	Resistivity
	B_{max}	B_{rem}	B_d				/(Tesla-Amp/m)	$^{\circ}C$	Ω cm
MO- $6Fe_2O_3$ 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)									
MO- $2FeO \cdot$ } $8Fe_2O_3$.48							450	

III. LUNAR STRIP MINING ANALYSIS

A lunar strip mining system is presented which is capable of excavating and transporting 3 million 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.

A. 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 geo-synchronous 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 report 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. Reports are being prepared by others which describe:

1. An electrostatic beneficiation system for use on the moon.
2. An electromagnetic propulsion system for launching the beneficiated ore into space.
3. A chemical processing system in space which would convert the ore into construction materials.
4. And a Satellite Manufacturing Facility which would assemble the solar power satellites in earth-orbit.

The mining system described in this report consists 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 shroud sleeve environment. This is a critical requirement.

The mining plan is described in Sec. B. The number of haulers is calculated in Sec. C, and the mass of the mining equipment is presented in Sec. D. The energy and personnel requirements are described in Sec. E and Sec. F, respectively. Recommendations for additional studies are presented in Sec. F.

B. MINING PLAN**B.1 MINING RATE**

The proposed Satellite Manufacturing Facility (SMF), as presently conceived, would require a feedstock of approximately 600,000 Tons/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 T/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.

B.2 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 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 density 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 measurements¹.

B.3 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. Studies are being conducted to determine if this beneficiation can be performed concurrently at the mine. Even if it can, it has been assumed 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.

C. NUMBER OF HAULERS AND EXCAVATORS

C. 1 GENERAL EXPRESSION

The number of haulers required to transport the ore on the lunar surface is dependent upon many factors, including:

Gross Mining Rate

Distance from plant to mine

Time available to mine per lunar day

Speed of hauler

Payload of each hauler, etc.

Most of these factors are assumed to be constant. However, for the mining plan discussed above, two factors will vary: gross mining rate and distance from plant to mine. The gross mining rate accelerates rapidly during the first few years of operation and then remains constant at 3,000,000 T/yr. In addition, the distance from the plant to the mine gradually increases throughout the life of the project. Thus, even after the gross mining rate levels off, additional haulers

will have to be phased in at appropriate time intervals to maintain the desired quantity of ore.

Mining companies and manufacturers of haulers have developed many computer programs to predict vehicle performance and to assist in equipment selection² (p. 553). In fact, the U.S. Energy Research and Development Administration (now part of the Department of Energy), has recently made available a computer program to analyze coal strip mine operations³. Eventually, similar computer programs will have to be written to analyze the lunar mining plan. However, at this stage in the study, such programs are not considered to be necessary.

Instead, the following expression has been derived for determining the number of haulers required at any time during the life of the project:

$$N = \frac{M'f}{TmAE} \left[\frac{G}{v} + t_1 + t_u \right] \quad (1)$$

where,

- N = number of haulers required
- M' = gross mining rate (Tons/year)
- f = fraction of ore transported to plant
- T = time available to mine per year (hours)
- m = payload of each hauler (Tons)
- A = availability of equipment
- E = efficiency of equipment
- G = geometric factor (kilometers)
- v = speed of hauler (kilometers/hour)
- t₁ = time required to load hauler (hours)
- t_u = time required to unload hauler (hours)

Each of these factors are discussed in detail in the following sections. 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 summarized in Table 2.

It must be noted that this expression neglects stockpiling of ore at the plant. It simply calculates the number of haulers necessary to maintain the gross mining rate. Thus, the calculated value of N is always rounded up to the nearest whole number. As a result, this expression is conservative even under ideal conditions, because there will always be excess hauler capacity. If significant stockpiling were possible, then the phasing in of additional haulers could be stretched out considerably.

C.2 DISCUSSION OF FACTORS

C.2.1 GROSS MINING RATE, M'

The gross mining rate has already been discussed in Sec. B.1 and is summarized in Table 1. It varies from 30,000 T/yr in the first year to 3,000,000 T/yr in the fifth and subsequent years.

C.2.2 FRACTION OF ORE TRANSPORTED TO PLANT, f

The fraction of ore transported to the plant depends on whether or not electrostatic beneficiation of the ore can be performed concurrently with the excavating operation. If it cannot, then obviously all of the ore will be transported to the plant and 80% waste will be returned to the mine for dis-

posal. 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 are considered: with and without concurrent electrostatic beneficiation.

C.2.3 TIME AVAILABLE TO MINE PER YEAR, T

Under ideal conditions, it would be possible to mine continuously, night and day, year-round. This amounts to 8,766 hours per year.

More likely, it will not be possible to operate during lunar night because of the extreme temperature variation. Nominal conditions assume daytime mining only, with a one-shift (8-hour) loss at sunrise and sunset. This amounts to 4,185 hours per year.

Unfavorable conditions assume a two-shift (16-hour) loss at sunrise and sunset. This amounts to 3,987 hours per year.

C.2.4 PAYLOAD OF EACH HAULER, m

Obviously, the payload of each hauler is inversely related to the number of haulers. It is important that a reasonable match be achieved. A mining plan based on a small number of high-capacity haulers would be vulnerable to a major disruption if one of the haulers failed. On the other hand, a large number of low-capacity haulers would unnecessarily complicate the operation. Thus, the payload of each hauler is handled as a variable, with a range from 5 to 200 T.

C.2.5 AVAILABILITY OF EQUIPMENT, A

A certain amount of working time will be lost to inspection, maintenance, and re-fueling. Availability will depend very strongly on how the equipment is operated. On earth, the availability of large excavating systems ranges from as little as 34% to as much as 90% for continuous operations up to a year⁵. Presumably, equipment destined for the moon will be designed and constructed to higher standards than ordinary terrestrial equipment. Even so, some maintenance will be required over the life of the project and it is felt that 80% represents a reasonable estimate of availability under ideal (continuous) conditions.

On the other hand, if mining only occurs during the day, then it should be possible to design the equipment so that inspection and maintenance will not be required during operations, but instead will be performed at night. An interview with Me. George Eger, Vice President for Engineering of International Harvester, confirms that even on earth, equipment manufacturers are developing systems to extend the normal maintenance cycle⁵. Furthermore, the trend in the industry has been toward modular design. For example, with new equipment, it is now possible to remove a transmission in a few hours instead of a few days. It should certainly be possible to incorporate a similar design philosophy in lunar equipment. In which case, working time would only be lost during re-fueling. Under nominal conditions, availability is assumed to be 95%, and under unfavorable conditions, 85%.

C.2.6 EFFICIENCY OF EQUIPMENT, E

In any mining or soil-moving operation, there are always unavoidable delays that are not associated with maintenance. An efficiency factor is used to account for these delays. Under ideal conditions, the efficiency factor would be 1.0. Under nominal and unfavorable conditions, the values would be 0.83 and 0.67, respectively² (p. 578).

C.2.7 GEOMETRIC FACTOR, G

The geometric factor is defined as follows:

$$G = w(4l^2 + \frac{8M}{B\theta h\rho} \times 10^{-6})^{1/2} \quad (2)$$

where,

- w = wander factor along haul route
- l = radial distance from plant to mine (km)
- M = cumulative ore mined (T)
- B = mineability factor
- θ = mine angle (radians)
- h = thickness of mineable ore (m)
- ρ = bulk density of ore (T/m³)

This expression is based on the geometry of the mine plan described in Sec. B.2. Obviously, a different expression would be used for a different geometry. As discussed in Sec. B.2, the following values are assumed:

- l = 2 km
- θ = $\pi/2$
- h = 2 m
- ρ = 1.8 T/m³

C.2.7.1 WANDER FACTOR

Large boulders and craters on the lunar surface will prevent the haulers from traveling in straight lines. The wander

factor accounts for this: 1.0 (ideal), 0.9 (nominal, and 0.85 (unfavorable).

C.2.7.2 CUMULATIVE ORE MINED, M

The cumulative ore mined has already been discussed in Sec. B.1 and is summarized in Table I. Note that as M increases during the life of the project, G also increases, although at a declining rate.

C.2.7.3 MINEABILITY FACTOR, B

Not all of the ore deposit will be mineable: some boulders will simply be too large for excavation and processing. The mineability factor is: 1.0 (ideal), 0.98 (nominal), and 0.95 (unfavorable).

C.2.8 SPEED OF HAULER, v

The velocity of the hauler is given by:

$$v = Sv_{\max} \quad (3)$$

where,

S = speed factor

v_{\max} = maximum speed of hauler (kph)

C.2.8.1 SPEED FACTOR, S

The maximum speed is determined from performance charts as discussed in the following section. The speed factor accounts for the additional time required to accelerate to v_{\max} . The product of S and v_{\max} is the average speed.

The speed factor depends on the length of the haul, the grade conditions, and the transmission gear ratios. The following values have been assumed: 0.9 (ideal), 0.85 (nominal), and 0.7 (unfavorable)² (p. 574).

C.2.8.2 MAXIMUM SPEED OF HAULER, v_{\max}

As noted above, v_{\max} is determined from a performance chart; an example of a performance chart for a Caterpillar 777 is shown in Fig. 3. It can be seen that v_{\max} is a function of the total resistance which is equal to the rolling resistance plus (or minus) the grade. A total resistance of 2% corresponds to a level, well-compacted dirt road. The maximum speed under these conditions has been plotted in Fig. 4 for a variety of terrestrial haulers. It can be seen that v_{\max} is not particularly dependent upon the payload of the hauler and falls in a range from 43 to 68 kph. Obviously, as hauler payloads have been increased, the terrestrial design practice has been to increase the power of the engine and modify the transmission such that the performance of the vehicle remains essentially unchanged. It is presumed that v_{\max} would be 68 kph under ideal conditions.

Under nominal conditions, the rolling resistance, μ , would be about 5% and the grade, Δ , would be +3%. That means the total resistance would be 8% in one direction and 2% in the other direction. As can be seen in Fig. 5, the maximum speed on the 8% leg will be significantly less, amounting to approximately 32% of v_{\max} on the 2% leg. As a result, the weighted maximum speed would equal 33 kph. This assumes the hauler is loaded in both directions, which is approximately correct if electrostatic separation cannot be performed concurrently at the mine. Recall that for Case 2 conditions, the hauler returns from the plant with an 80% load of waste for backfilling in the mine.

For Case 1 conditions, the hauler is empty on the return leg to the mine. If this happens to be the 8% leg, then Fig. 6 shows that the speed would be somewhat higher. However, if the hauler is empty on the 2% leg, the speed is essentially the same and the weighted maximum speed remains unchanged at 33 kph. It has been conservatively assumed that the maximum total resistance will invariably occur on the loaded leg and that the minimum total resistance will occur on the empty leg.

Under unfavorable conditions, the rolling resistance is assumed to be 7% and the grade to be $\pm 5\%$. By a similar calculation, the weighted maximum speed is determined to be 23 kph.

C.2.9 TIME REQUIRED TO LOAD HAULER, t_1

It has been assumed that a front-end loader will be used to excavate the ore and load it into the haulers. The excavating system will be discussed in more detail in Sec. C.5.

The time required to load each hauler, t_1 , in hours, is given by:

$$t_1 = \left[\frac{mt_e s}{F \rho q_e} + t_{s1} + t_i \right] + 3600 \quad (4)$$

where,

- m = payload of each hauler (T)
- t_e = cycle time for front-end loader (s)
- s = swell factor
- F = bucket fill factor
- ρ = bulk density of ore (T/m³)
- q_e = bucket capacity of front-end loader (m³)
- t_{s1} = spotting time (s)
- t_i = re-load time at plant (s)

The factors m and ρ have previously been discussed.

C.2.9.1 CYCLE TIME FOR FRONT-END LOADER, t_e

The cycle time is the time required for the front-end loader to excavate a bucket of ore, raise the bucket, drop the ore into the hauler, and return to the starting point. The length of time depends on the size of the front-end loader and can range from 24 to 90 seconds² (p. 572). Under ideal, nominal, and unfavorable conditions, t_e has been assumed to equal 30, 45, and 60 seconds, respectively.

C.2.9.2 SWELL FACTOR, s

As the ore is excavated and dumped into the hauler, the disturbance causes it to loosen, or in effect, to swell. Under ideal, nominal, and unfavorable conditions, s has been assumed to equal 1.0, 1.15, and 1.3 respectively² (p. 466).

C.2.9.3 BUCKET FILL FACTOR, F

The percent of the bucket capacity that can be achieved is dependent upon the ease of excavation. Under hard digging conditions, the bucket fill factor can be as low as 0.5² (p. 572). However, lunar excavation is expected to be easy to medium. Under ideal, nominal, and unfavorable conditions, F would be equal to 1.0, 0.95, and 0.9 respectively.

C.2.9.4 BUCKET CAPACITY OF FRONT-END LOADER, q_e

For short hauls, it is the usual practice to select a bucket capacity such that the hauler can be filled in three to five passes. On longer hauls, the time required to load the hauler is less critical and more passes can be accommodated. However, for this study, it is felt that four passes represents a reasonable number. This implies that q_e is given by:

$$q_e = \frac{1}{4} \frac{ms}{F_p} \quad (5)$$

C.2.9.5 SPOTTING TIME TO LOAD, t_{s1}

The spotting time to load is the amount of time required to position the hauler near the front-end loader at the mine. On earth, t_{s1} depends on the hauler type: bottom-dump, rear-dump, or side-dump, and can range up to one minute² (p. 577). On the moon, where control of the hauler will be automatic, t_{s1} should be less. Under ideal, nominal, and unfavorable conditions, t_{s1} is estimated to be 0, 10, and 20 seconds.

C.2.9.6 RE-LOAD TIME AT PLANT, t_1^r

For Case 2 conditions, the hauler will be re-loaded at the plant with waste material for return to the mine. This material would be loaded by means of an overhead bin and chute arrangement and would occur immediately after the ore had been dumped without moving the hauler to a new location. In the usual order, t_1^r is estimated to be 10, 20, and 30 seconds.

C.2.10 TIME REQUIRED TO UNLOAD HAULER, t_u

The time required to unload each hauler, t_u , is given by:

$$t_u = [t_d + t_u^1] + 3600 \quad (6)$$

where,

t_d = dump time (s)

t_u^1 = unload time at mine (s)

C.2.10.1 DUMP TIME, t_d

The dump time is the amount of time required to position the hauler at the plant and to dump the ore. Similar to the spotting time discussed in Sec. C.2.9.5, t_d on earth depends on the hauler type and can require as long as two minutes² (p. 577).

Again, t_d on the moon should be less and has been estimated to be 15, 25, and 40 seconds, respectively.

C.2.10.2 UNLOAD TIME AT MINE, t'_u

For Case 2 conditions, the hauler will pause in the mine to unload waste material before proceeding to the front-end loader. The unload time, t'_u , is estimated to be approximately equal to t_d .

C.3 COMPLETE EXPRESSION

All of the various factors that influence the number of haulers required to transport ore on the lunar surface have been discussed in excruciating detail in the preceding sections. By combining Eqns. (1), (2), (3), (4), and (6), the following complete expression is obtained:

$$N = \frac{M'f}{T_{mAE}} \left[\frac{w(4l^2 + \frac{8M}{B\theta h\rho} \times 10^{-6})^{1/2}}{Sv_{max}} + \frac{1}{3600} \left(\frac{mt_e s}{F\rho q_e} + t_{s1} + t'_1 + t_d + t'_u \right) \right] \quad (7)$$

C.4 NUMBER OF HAULERS REQUIRED

By substituting the appropriate factors from Table II into Eqn. (7), the number of haulers required, N , can be calculated for any case and condition. This has been done and is summarized in Table III.

As can be seen in Table III, the payload of each hauler is significantly less for Case 1 than for Case 2. As noted in Sec. C.2.2, electrostatic beneficiation at the mine has an enormous influence on the ore transport system. Later studies will determine which case is optimal: it remains to be determined whether or not the decreased mass and energy requirements for the transport system in Case 1 offset the increased

mass, energy, and operational complexity of concurrent beneficiation.

Examining Table III 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. Recall that ideal conditions assume day and night mining 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.

Consequently, for planning purposes, nominal conditions have been assumed. Referring to Table III, a hauler payload of 10 Tons for Case 1 results in a reasonable fleet size, even after 30 years. Similarly for Case 2, a hauler payload of 50 Tons is appropriate. The growth in the number of haulers for these two cases over the life of the mine is shown in Fig. VII. 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 ten haulers is required by the 30th year.

It should be noted that the fleet size under unfavorable conditions is typically 2 to 2.5 times the fleet size under nominal conditions. This is primarily due to the difference in the calculated speed of the hauler, which is based on performance charts for terrestrial vehicles (see Sec. C.2.8.2). Terrestrial haulers, of course, have been designed to operate over a wide range of conditions. Presumably, if the lunar haulers had to operate on steep grades and loose soil, the drive systems would be designed for those specific conditions and higher speeds could be achieved (at some trade-off in extra mass and energy, of course). Thus, the fleet size under unfavorable conditions would not necessarily be as great as implied in Table III.

One final point should be considered: the mine geometry presumed in this study is rather arbitrary. For example, in Sec. B.2 it was stated that the thickness of mineable ore, h , was assumed to be 2 m, but that it might, in fact, be greater. In the early years of the mine, the value of h does not greatly affect the calculated number of haulers, because the travel time is dominated by the distance from the plant to the mine. In later years, as it becomes necessary to travel ever farther for ore, the value of h is very important. Referring to Equ. (7), if h were doubled to 4 m, the number of haulers required in the later years, under all conditions, would decrease by a factor approaching $\sqrt{2}$. This same factor would also apply to the mass of the haulers and the net energy required. The mine angle, θ , has a similar effect. In addition, if it is necessary

to mine in two locations (e.g., for plagioclase in one area and ilmenite in another), then the mining fleet would also be affected. If the mining equipment could alternate back and forth between the two areas, and the two mine layouts were the same as in Fig 2, the number of haulers, mass, and energy would also decrease by a factor approaching $\sqrt{2}$. Conversely, if two areas were to be mined with similar layouts, except that $\theta = \pi/4$, instead of $\pi/2$, then the fleet size would be exactly as calculated for the single mine in Table III. Obviously, these sorts of number games can be played ad infinitum and it is important that actual candidate sites on the lunar surface be evaluated as early as possible.

C.5 HAULER-EXCAVATOR MATCH

As discussed in Sec. C.2.9.4, it has been presumed that it will require four passes by the front-end loader to fill the hauler. The bucket capacity, q_e , can be calculated by substituting the appropriate factors from Table III, into Equ. (5):

$$q_e = \begin{array}{ccc} \text{Ideal} & \text{Nominal} & \text{Unfavorable} \\ 6.9 \text{ m}^3 & 8.4 \text{ m}^3 & 10.0 \text{ m}^3 \end{array}$$

This is not a wide variation, and for convenience, the bucket capacity will be taken as 10.0 m^3 . The mass per bucketful would be 12.5 T. 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.

C.6 SPARE VEHICLES AND SPARE PARTS

As discussed in Sec. C.2.5, under nominal conditions, all of the scheduled maintenance will be performed during lunar night. Occasionally, however, a vehicle will break down during lunar day. To accomodate this situation, a spare vehicle would be necessary to substitute for the failed vehicle, which could then be repaired at a more convenient time later.

Of course, spare parts will also be necessary. As an estimate, one-tenth of each vehicle is assumed to be replaced each year; in other words, a total replacement time of ten years. Obviously, the parts inventory at the plant will have to be replenished periodically from earth.

C.7 SUMMARY OF MINING EQUIPMENT

The anticipated growth in the mining fleet is summarized in Table IV. Note that the spare parts represent a sizeable portion of the total number of vehicles transported to the moon. By the 30th mining year, in Case 1, the equivalent of more than 19 haulers (20 haulers in Case 2) have been required as spare parts, compared to a fleet size of ten haulers plus one spare.

D. MASS OF MINING EQUIPMENT

D.1 MASS OF HAULERS

A plot of empty vehicle mass, m_h , versus payload, m , for a variety of terrestrial haulers is presented in Fig. VIII. As can be seen, there are numerous haulers available which have a payload of 10 to 50 T. In fact, the largest commercially available hauler has a capacity of nearly 320 T. Note also that the points in Fig. III 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.

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 $m/m_h = 2.4$. The LRV obviously falls at the low end of the scale, with an empty vehicle mass of only about 0.2 T.

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:

<u>Case</u>	<u>Payload</u>	<u>Vehicle Mass</u>	
1	10 T	1.2 to 4.2 T	(see Table V)
2	50 T	6.2 to 20.8 T	

D.2 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. 9. 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 mass² (p. 466). 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 T (see Sec. C.5), a tipping mass of 15 T is used to enter Fig. 9, from whence a vehicle mass of 23.5 T is found (see Table V).

D.3 CUMULATIVE MASS OF MINING EQUIPMENT

By combining Table IV and Table V, the cumulative mass of the mining equipment can be determined. This is presented in Table VI and Fig. 10.

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 26 T must be shipped the first year, and an additional 26 T 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 T for Case 1, to 320 to 780 T for Case 2.

E. ENERGY REQUIRED FOR MINING SYSTEM

E.1 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:

$$E = (0.139) G a m_h \left[\left(1 + \frac{m}{m_h}\right) (\mu + \Delta) + \left(1 + \frac{(f-0.2)m}{m_h}\right) (\mu - \Delta) \right] \quad (8)$$

where,

E = net energy per load (kW-hr/load)

a = acceleration of lunar gravity = 1.63 m/s^2

and all of the other terms have previously been defined.

The net energy required for any given mining year is then approximately given by:

$$y = E \frac{M' f}{m} \quad (9)$$

where,

Y = annual energy required (kW-hr/yr)

Once again, by substituting all of the appropriate factors into Eqns. (8) and (9), the net energy required for the mining system can be calculated. This has been done and is presented in Table VII and Fig. 11. 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.

The large differences between ideal and unfavorable conditions are primarily due to the differences in total resistance: 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 Table VII and Fig. 11 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.

E.2 BALLISTIC TRANSPORT

Ballistic transport is an entirely different concept that is impossible on earth, but which could be very practical on the moon.

In this system, the ore would be mechanically propelled (similar to a snow blower) along a ballistic trajectory directly from the mine to a collection point near the plant. Thus, the entire hauler fleet would be eliminated.

Such a system would not work on earth, of course, because atmospheric drag would quickly dissipate the ore and create a dust cloud.

It is envisioned that the launcher could be moved within the mine as required, but that it would be stationary while ore was being propelled to the plant. A front-end loader could be used to excavate the ore and carry it to the launcher. As the ore was depleted, the launcher would be periodically moved

to a new location. If electrostatic beneficiation could be performed at the mine, the beneficiation module and launcher could be physically combined into one mobile structure.

The ballistic transport system would require less mass than the hauler transport system and would also be less complex (fewer moving parts). On the other hand, maintenance would be more difficult, since the launcher would probably not return to the plant each lunar night. Presumably, a solution could be found for this problem. Also, some additional equipment would be needed to gather the ore at the collection point and transport it to the plant.

Much more important is the fact that ballistic transport requires considerably more energy than hauler transport. This is shown graphically in Fig. 12. It can be seen that ballistic transport requires six times as much net energy as hauler transport under nominal conditions. Even under unfavorable conditions, the ratio is still four-to-one. Furthermore, a system would have to be devised to supply energy to the launcher.

Nonetheless, in a region of rugged terrain, such as mountains or rilles, the haul road may be excessively long, and consequently the number of haulers may be impractical. In which case, a ballistic transport system could be very attractive.

F. PERSONNEL

F.1 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.

F.2 AUTOMATIC HAULERS

The haulers can undoubtedly be designed to operate in 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.

F.3 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 (Ref. 7).

G. ADDITIONAL STUDIES

This report has been in the nature of a pre-feasibility study. There are many questions which must be resolved before final design and implementation. Some of the additional studies

that must be performed include the following:

1. Additional parametric studies need to be performed using the equations developed in this report.
2. The conditions under which other systems would be used, such as conveyors or ballistic transport, need to be examined.
3. Computer studies need to be performed using existing programs written for terrestrial strip mines.
4. Detailed computer programs need to be developed for the lunar mining system, using actual topographies from candidate sites.
5. The fraction of ore returned to the plant, f , plays an enormous role in the mass and energy requirements for the mining system. Studies regarding electrostatic beneficiation at the mine should continue apace.
6. The second-most important factor affecting the mining system is the total resistance (rolling resistance plus or minus grade). Candidate sites need to be examined to determine what the grade really is. More important, trafficability studies are absolutely essential. Although considerable information has already been obtained for the Lunar Roving Vehicle, the front-end loader and haulers would be considerably larger and heavier. Trafficability experiments will probably have to be performed on the lunar surface at an early stage.

7. Terrestrial sites must be located for performing prototype simulations of the mining operations.
8. Computer and telemetry specialists need to quantify the design requirements for remote control of the front-end loader and automatic operations of the haulers. Computer programs must be written for simulation exercises.
9. Preliminary designs of the haulers and front-end loader should be prepared so that the mass and energy requirements can be refined.
10. Re-fueling, or rather, re-energizing, of the mining equipment presents some interesting technical challenges that need to be studied. What will be the energy system: Battery, or perhaps spinning fly-wheel? How will these be recharged: physical replacement, mechanical linkage, electrical connection, microwave beam, or something else?

Despite these uncertainties, the lunar mining system will not require major technological breakthroughs. Rather, the design will be a natural extension of terrestrial mining experience, coupled with the invaluable knowledge gained during the Surveyor and Apollo programs.

H. REFERENCES

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7. 2003: A construction odyssey, Construction Equipment, p. 11-14 (March 1978); see also International Harvester 1977 Annual Report.

I. TABLES

<u>Number</u>	<u>Title</u>
I	LUNAR MINING PLAN
II	FACTORS USED TO CALCULATE NUMBER OF HAULERS REQUIRED FOR MINING PLAN
III	NUMBER OF HAULERS REQUIRED
IV	CUMULATIVE MINING EQUIPMENT
V	MASS OF MINING EQUIPMENT
VI	CUMULATIVE MASS OF MINING EQUIPMENT
VII	NET ENERGY REQUIRED FOR MINING SYSTEM

TABLE I

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

TABLE II
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 III		
Fraction of ore returned to plant	f	— Case 1*	0.2	0.2	0.2
		Case 2	1.0	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
Geometric factor	G	km	See Eqn. (III-2)		
Wander factor	w	—	1.0	1.1	1.15
Radial distance from plant to mine	l	km	2.0	2.0	2.0
Cumulative ore mined	M	T	See Table III		
Mineability factor	B	—	1.0	0.98	0.95
Mine angle	θ	radians	$\pi/2$	$\pi/2$	$\pi/2$
Depth of mineable ore	h	m	2.0	20	2.0
Bulk density of ore	ρ	T/m ³	1.8	1.8	1.8
Speed of hauler	v	kph	See Eqn. (III-3)		
Speed factor	S	—	0.9	0.85	0.7
Maximum speed	v _{max}	kph	68.0	33.0	23.0

III-33

TABLE II
(continued)

FACTORS USED TO CAULCULATE NUMBER
OF HAULERS REQUIRED FOR MINING PLAN

Factor	Symbol	Units	Conditions		
			Ideal	Nominal	Unfavorable
Grade	Δ	--	0	+0.03	+0.05
Rolling Resistance	μ	--	0.02	0.05	0.07
Time required to load hauler	t_l	hr	See Eqn. (III-4)		
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
Bucket capacity of front-end loader	q_e	m ³	See Eqn. (III-5)		
Spotting time to load	t_{s1}	s	0	10	20
Re-load time at plant	t_l'	s	Case 1* 0 Case 2 10	0 20	0 30
Time required to unload hauler	t_u	hr	See Eqn. (III-6)		
Dump time	t_d	s	15	25	40
Unload time at mine	t_u'	s	Case 1* 0 Case 2 15	0 25	0 40

III-34

* Case 1: With concurrent electrostatic beneficiation
Case 2: Without concurrent electrostatic beneficiation

TABLE III

NUMBER OF HAULERS REQUIRED

Mining year	Case 1 With Concurrent Electrostatic Beneficiation									Case 2 Without Concurrent Electrostatic Beneficiation														
	m = 5			= 10			= 20			m = 10			= 20			= 50			= 100			= 200		
	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U	I	N	U
3	1	2	4	1	1	2	1	1	1	1	5	11	1	3	6	1	1	3	1	1	2	1	1	1
4	1	5	11	1	3	6	1	2	3	3	12	28	2	6	14	1	3	6	1	2	3	1	1	2
5	2	10	23	1	5	12	1	3	6	6	24	60	3	12	30	2	5	12	1	3	6	1	2	3
7	3	11	26	2	6	13	1	3	7	6	27	68	3	14	34	2	6	14	1	3	7	1	2	4
10	3	12	30	2	6	15	1	3	8	7	31	78	4	16	39	2	7	16	1	4	8	1	2	4
15	3	14	36	2	7	18	1	4	9	8	36	92	4	18	46	2	8	19	1	4	10	1	2	5
20	4	16	41	2	8	21	1	4	11	9	41	104	5	21	52	2	9	21	1	5	11	1	3	6
25	4	18	45	2	9	23	1	5	12	10	44	115	5	22	58	2	9	23	1	5	12	1	3	6
30	4	19	49	2	10	25	1	5	13	10	48	124	5	24	62	2	10	25	1	5	13	1	3	7

m: Payload of Each Hauler (Tons)

I: Ideal Conditions

N: Nominal Conditions

U: Unfavorable Conditions

TABLE IV
 CUMULATIVE MINING EQUIPMENT
 Nominal Conditions

Mining Year	Excavators (Case 1 or 2)				Case 1: 10-Ton Haulers With Concurrent Electrostatic Beneficiation				Case 2: 50-Ton Haulers Without Concurrent Electrostatic Beneficiation			
	Front-End											
	Loaders	Spares	Parts	£	Haulers	Spares	Parts	£	Haulers	Spares	Parts	£
1	1	0	0.1	1.1	0	0	0	0	0	0	0	0
2	1	1	0.2	2.2	0	0	0	0	0	0	0	0
3	1	1	0.3	2.3	1	0	0.1	1.1	1	0	0.1	1.1
4	1	1	0.4	2.4	3	0	0.4	3.4	3	0	0.4	3.4
5	1	1	0.5	2.5	5	1	0.9	6.9	5	1	0.9	6.9
7	1	1	0.7	2.7	6	1	2.0	9.0	6	1	2.0	9.0
10	1	1	1.0	3.0	6	1	3.8	10.8	7	1	3.9	11.9
15	1	1	1.5	3.5	7	1	6.9	14.9	8	1	7.5	16.5
20	1	1	2.0	4.0	8	1	10.5	19.5	9	1	11.6	21.6
25	1	1	2.5	4.5	9	1	14.6	24.6	9	1	16.1	26.1
30	1	1	3.0	5.0	10	1	19.2	30.2	10	1	20.7	31.7

TABLE V
 MASS OF MINING EQUIPMENT

HAULERS

<u>Case</u>	<u>Payload, m</u>	<u>Vehicle Mass, m_h</u>	
		<u>m/m_h = 8</u>	<u>m/m_h = 2.4</u>
1	10 T	1.25	4.17
2	50 T	6.25	20.83

FRONT-END LOADER

<u>Bucket Load</u>	<u>Factor of Safety</u>	<u>Tipping Mass</u>	<u>Vehicle Mass</u>
12.5 T	1.2	15 T	23.5 T

TABLE VI

CUMULATIVE MASS OF MINING EQUIPMENT
(Tons)
Including Spares and Spare Parts

Nominal Conditions					
Mining Year	Front- End Loaders	Case 1*: 10-Ton Haulers With Concurrent Electrostatic Beneficiation		Case 2: 50-Ton Haulers Without Concurrent Electrostatic Beneficiation	
		Haulers	Haulers + Front- End Loaders	Haulers	Haulers + Front- End Loaders
1	26	0	26	0	26
2	52	0	52	0	52
3	54	1-5	55-59	7-23	61-77
4	56	4-14	60-70	21-71	77-127
5	59	9-29	68-88	43-144	102-203
7	63	11-37	74-100	56-187	119-250
10	70	14-45	84-115	74-248	144-318
15	82	19-68	101-150	103-344	185-426
20	94	24-81	118-175	135-450	229-544
25	106	31-102	137-208	163-544	269-650
30	118	38-126	156-244	198-660	316-778

*Does not include mass of beneficiation-disposal module.

TABLE VII

NET ENERGY REQUIRED FOR MINING SYSTEM*
(MW-hr/yr)

Mining Year	Case 1**			Case 2		
	Ideal	With Concurrent Electrostatic Beneficiation Nominal	Unfavorable	Ideal	Without Concurrent Electrostatic Beneficiation Nominal	Unfavorable
1	3	8	12	3	8	12
2	15	43	63	15	43	63
3	3	11	18	23	67	100
4	8	30	49	61	180	270
5	16	67	100	140	390	600
7	19	81	120	160	460	690
10	23	95	150	190	550	810
15	28	120	180	230	660	1000
20	32	130	200	260	770	1200
25	35	150	230	290	860	1300
30	38	160	260	320	930	1400

* Assuming $m/m_h = 8$ for Mining Year 3 and subsequent

**Does not include energy requirement for beneficiation-disposal module

J. FIGURES

<u>Number</u>	<u>Title</u>
1	LUNAR MINING PLAN
2	MINE LAYOUT
3	EXAMPLE OF PERFORMANCE CHART FOR CATERPILLAR 777
4	MAXIMUM SPEED OF LOADED TERRESTRIAL HAULERS
5	PERFORMANCE OF LOADED TERRESTRIAL HAULERS
6	PERFORMANCE OF EMPTY TERRESTRIAL HAULERS
7	NUMBER OF HAULERS REQUIRED UNDER NOMINAL CONDITIONS
8	MASS OF TERRESTRIAL HAULERS
9	MASS OF TERRESTRIAL FRONT-END LOADERS
10	CUMULATIVE MASS OF MINING EQUIPMENT
11	NET ENERGY REQUIRED FOR MINING SYSTEM
12	ENERGY REQUIREMENTS FOR BALLISTIC TRANSPORT VS. HAULER TRANSPORT (ONE-WAY)

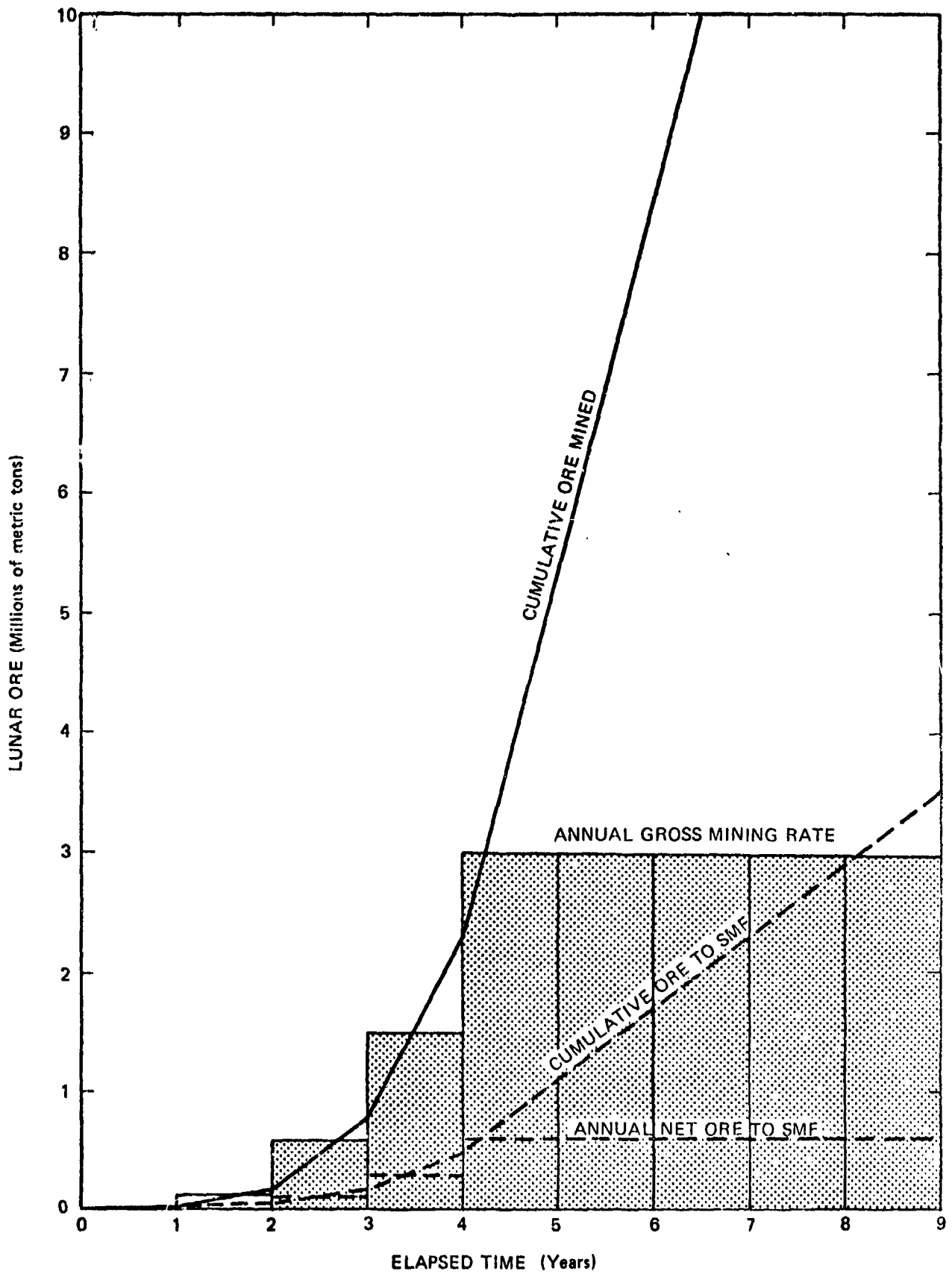
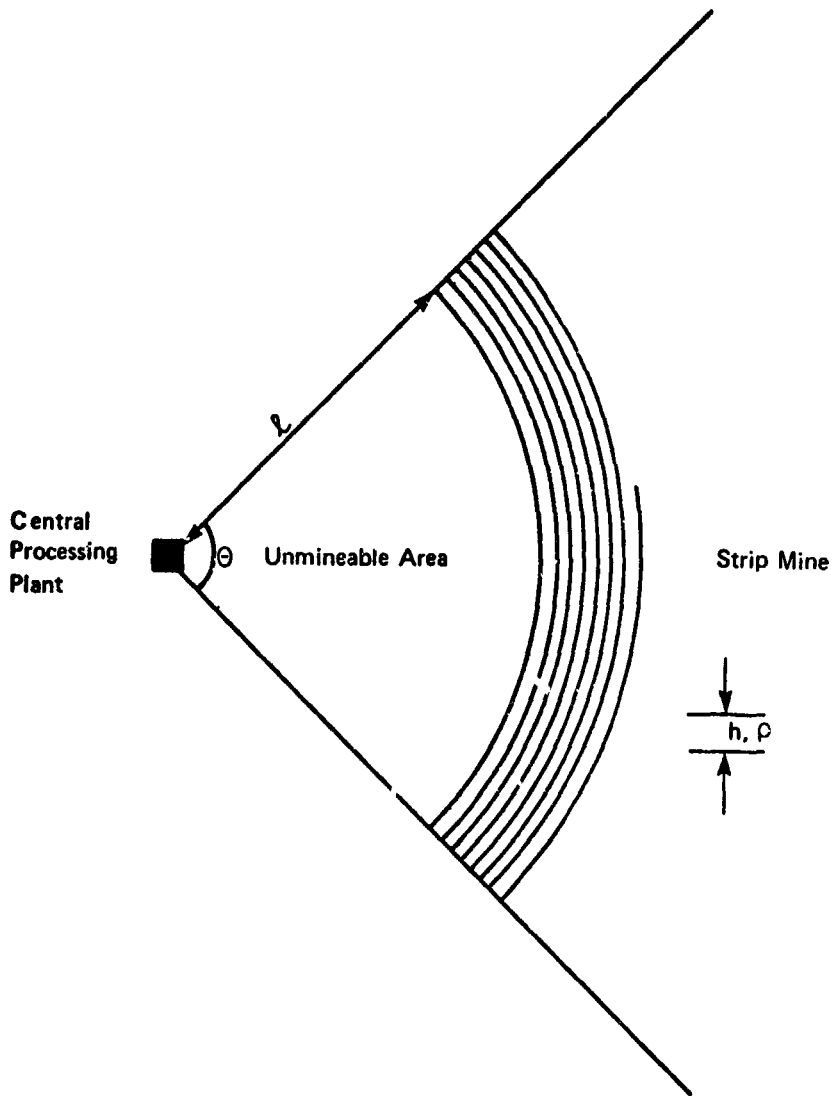


Figure III-1 Lunar Mining Plan



- ℓ : Radial Distance from Plant to Mine over Unmineable Area
- Θ : Mine Angle
- h : Thickness of Mineable Ore
- ρ : Bulk Density of Ore

Figure III-2 Mine Lay Out

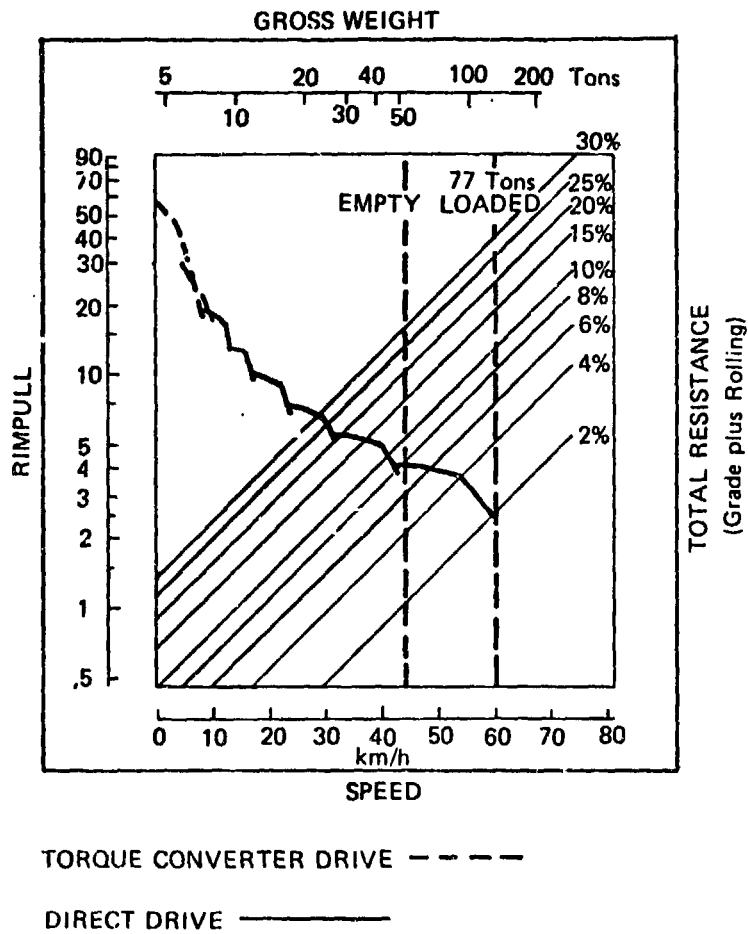


Figure III-3 Example of Performance Chart for Caterpillar 777

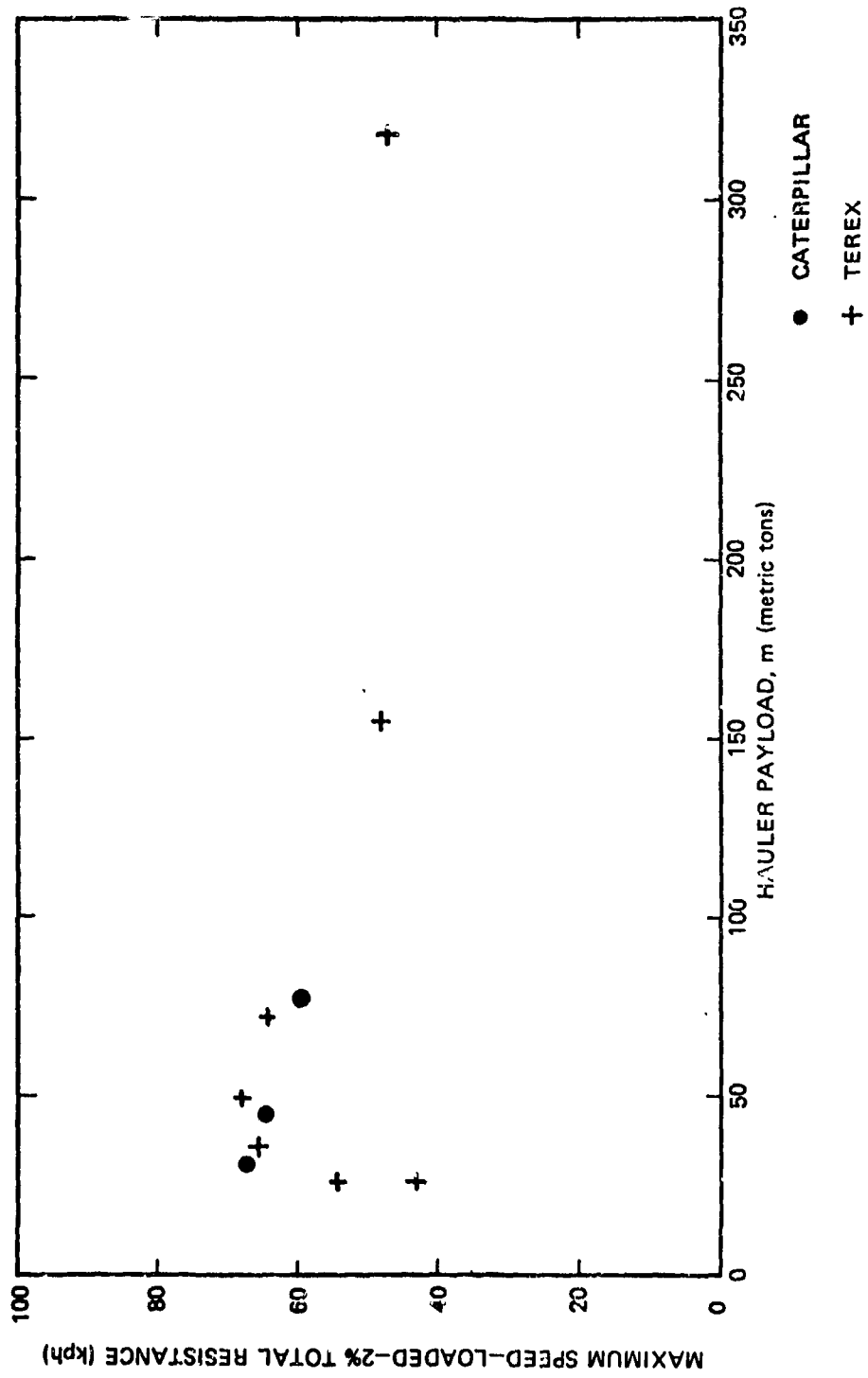


Figure III-4 Maximum Speed of Loaded Terrestrial Haulers

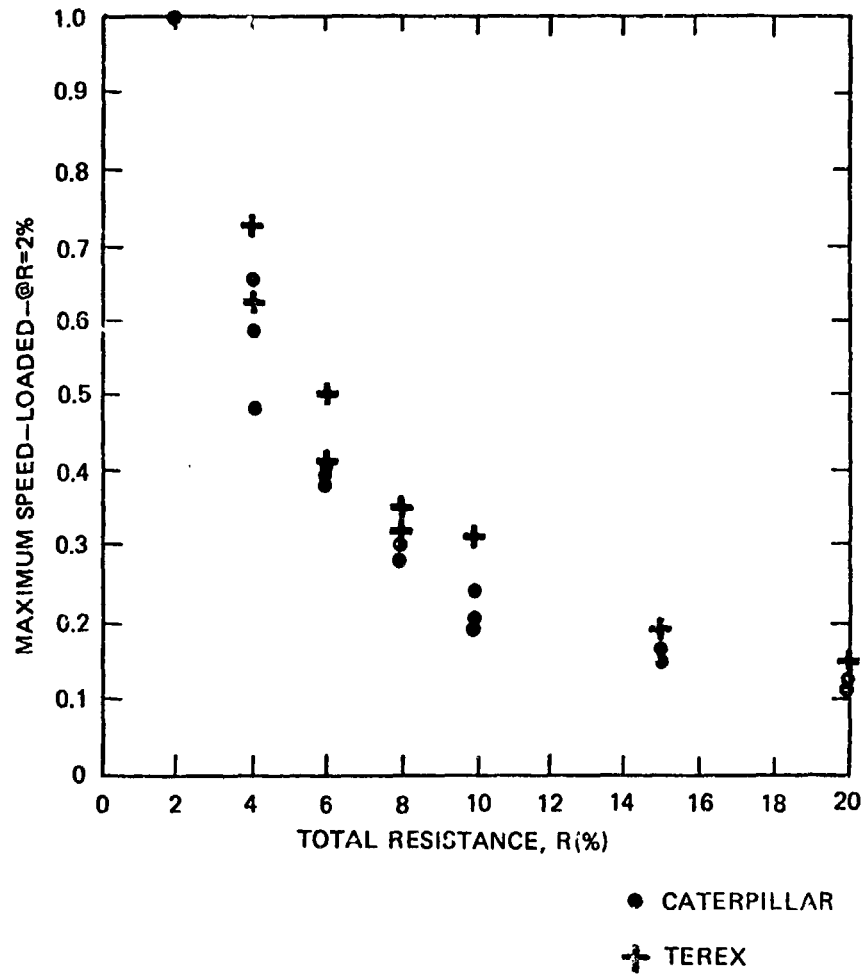


FIGURE III-5 Performance of Loaded Terrestrial Haulers

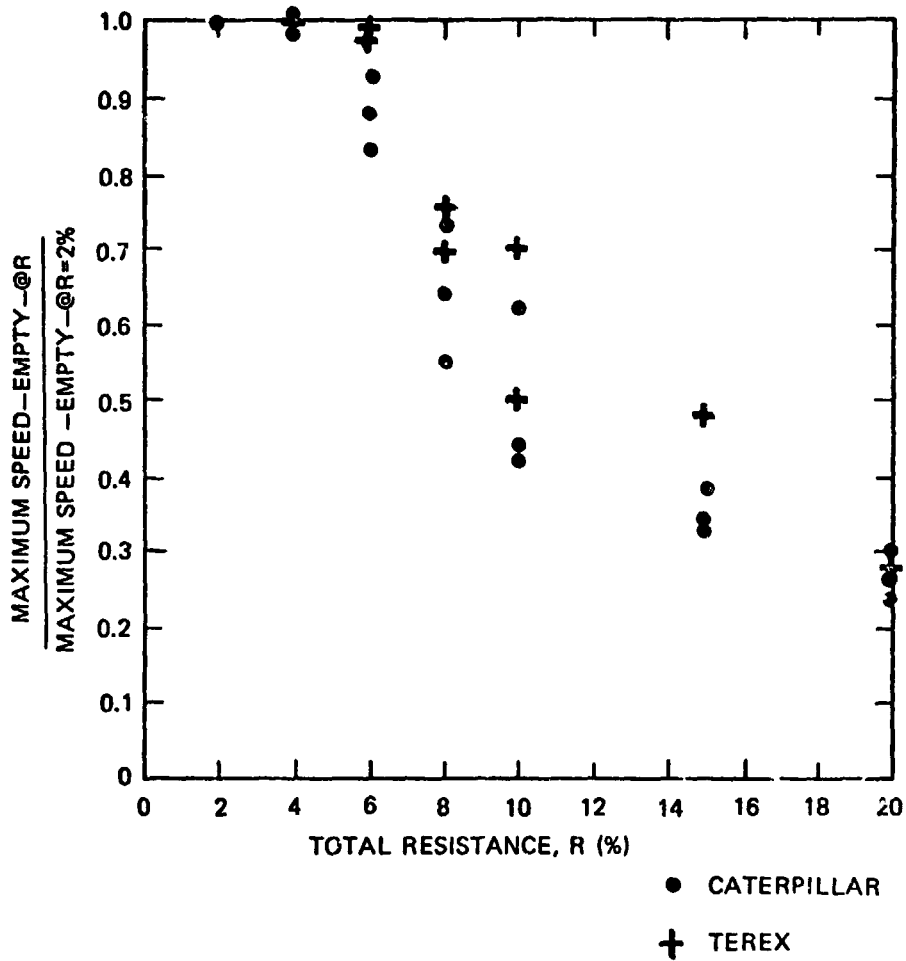


Figure III-6 Performance of Empty Terrestrial Haulers

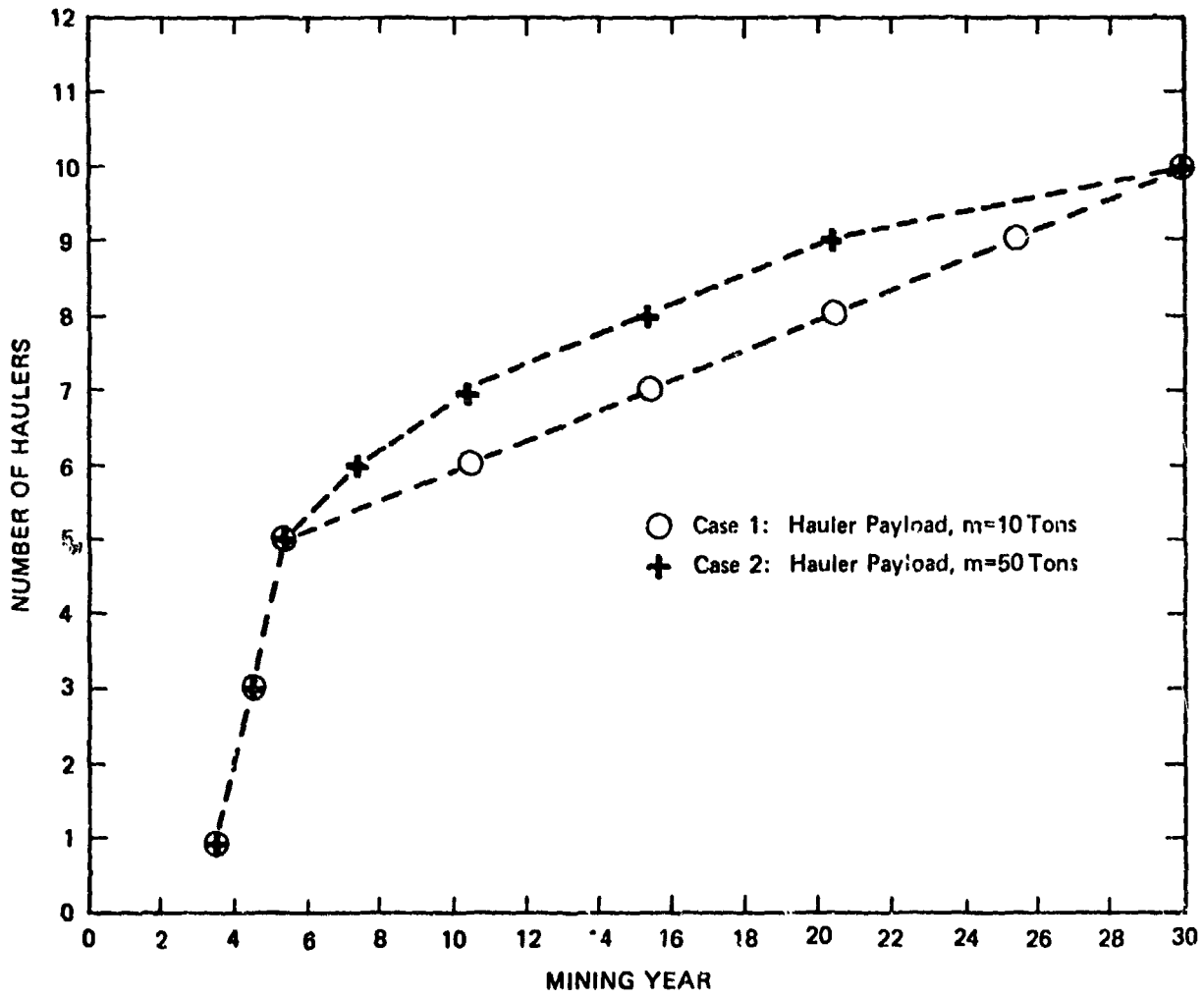


Figure III-7 Number of Haulers Required Under Nominal Conditions

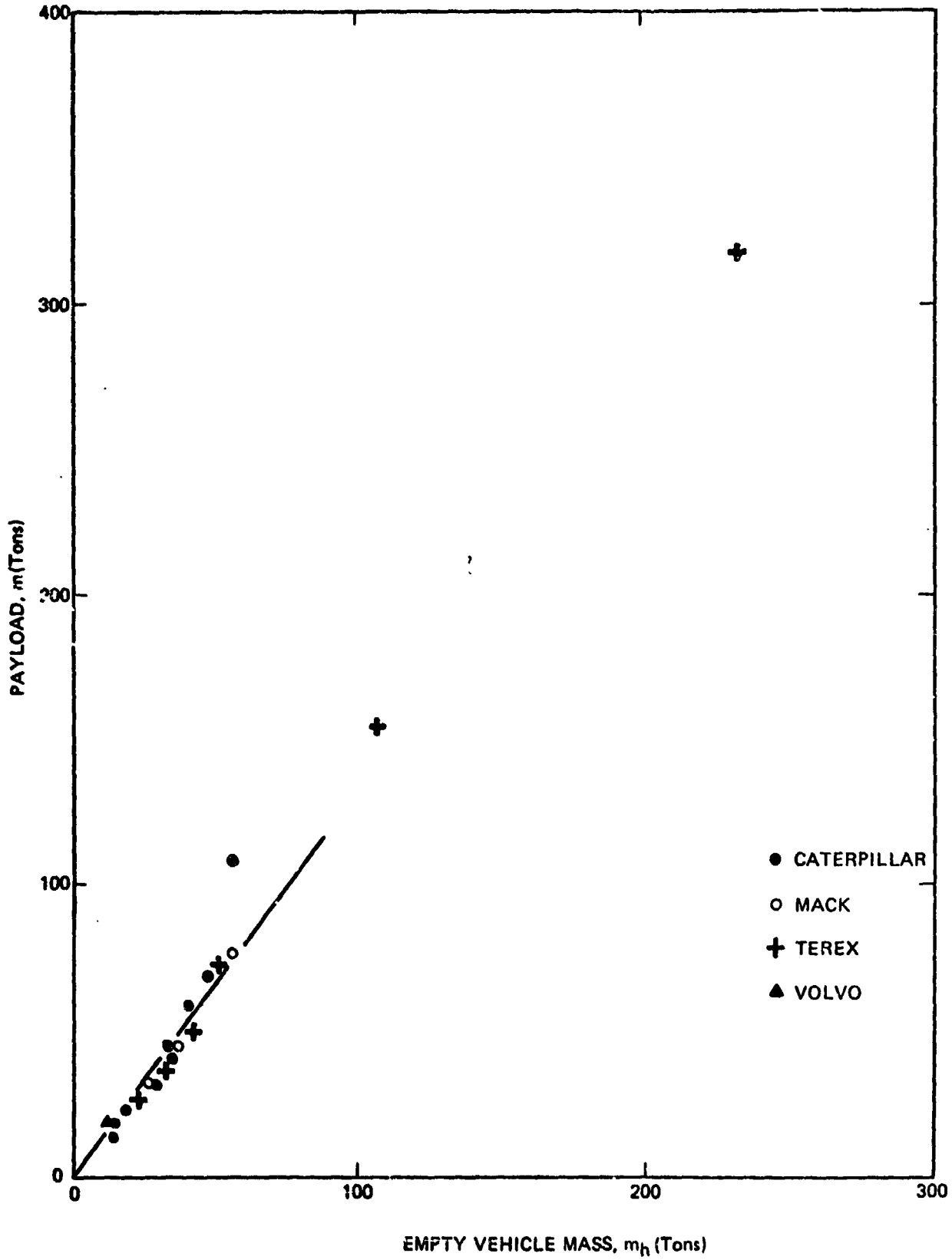


Figure III-8 Mass of Terrestrial Haulers

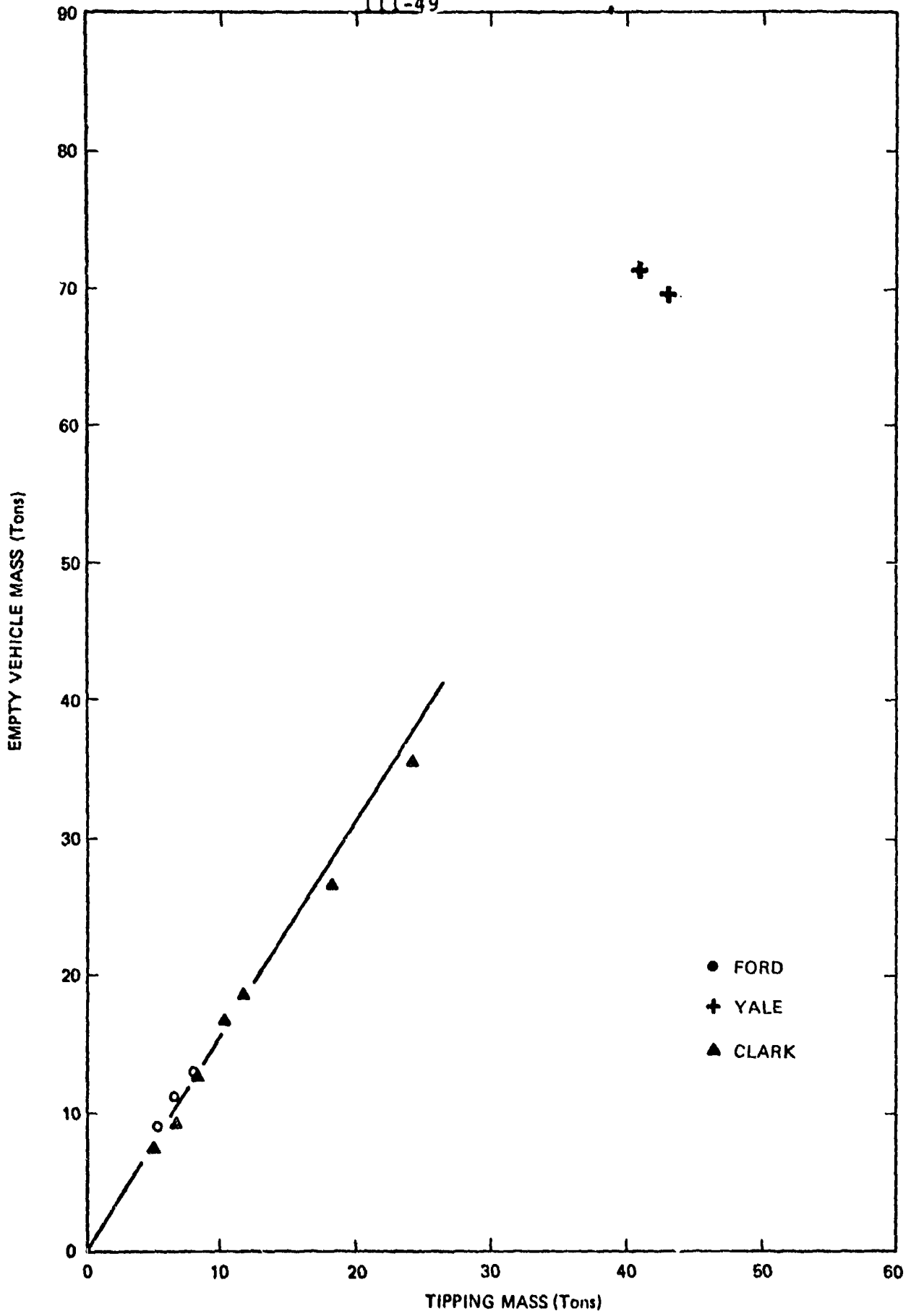


Figure III-9 Mass of Terrestrial Front-End Loaders

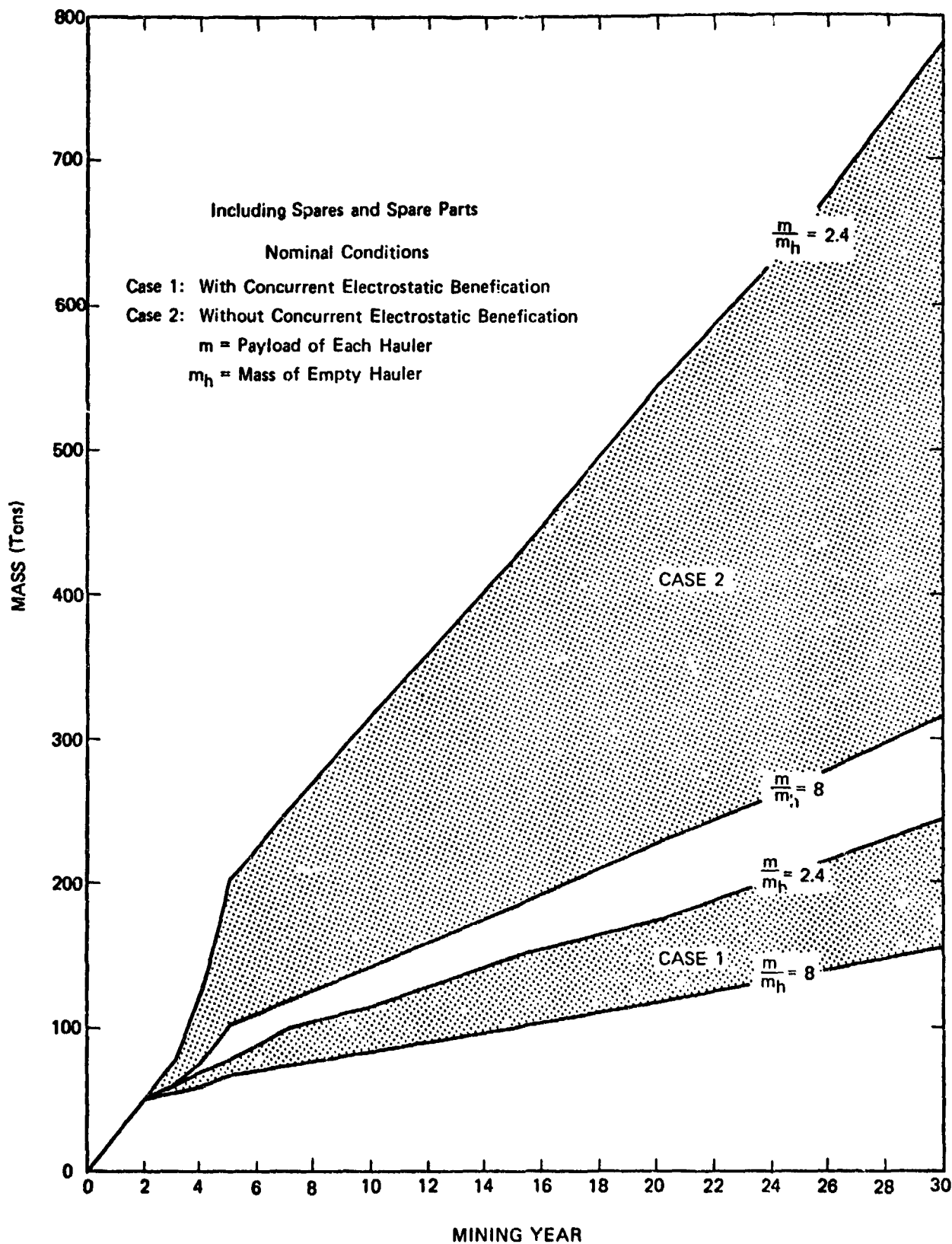


Figure III-10 Cumulative Mass of Mining Equipment

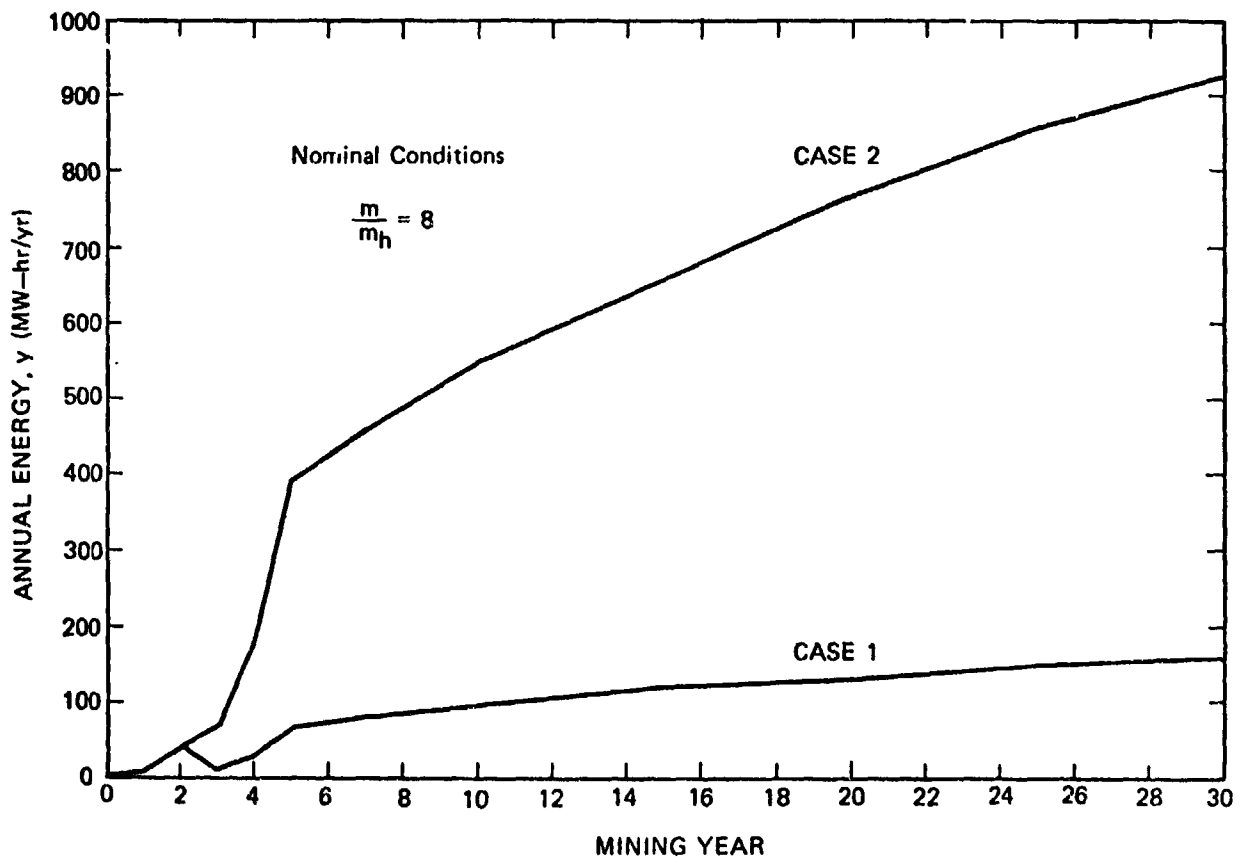


Figure III-11 Net Energy Required for Mining System

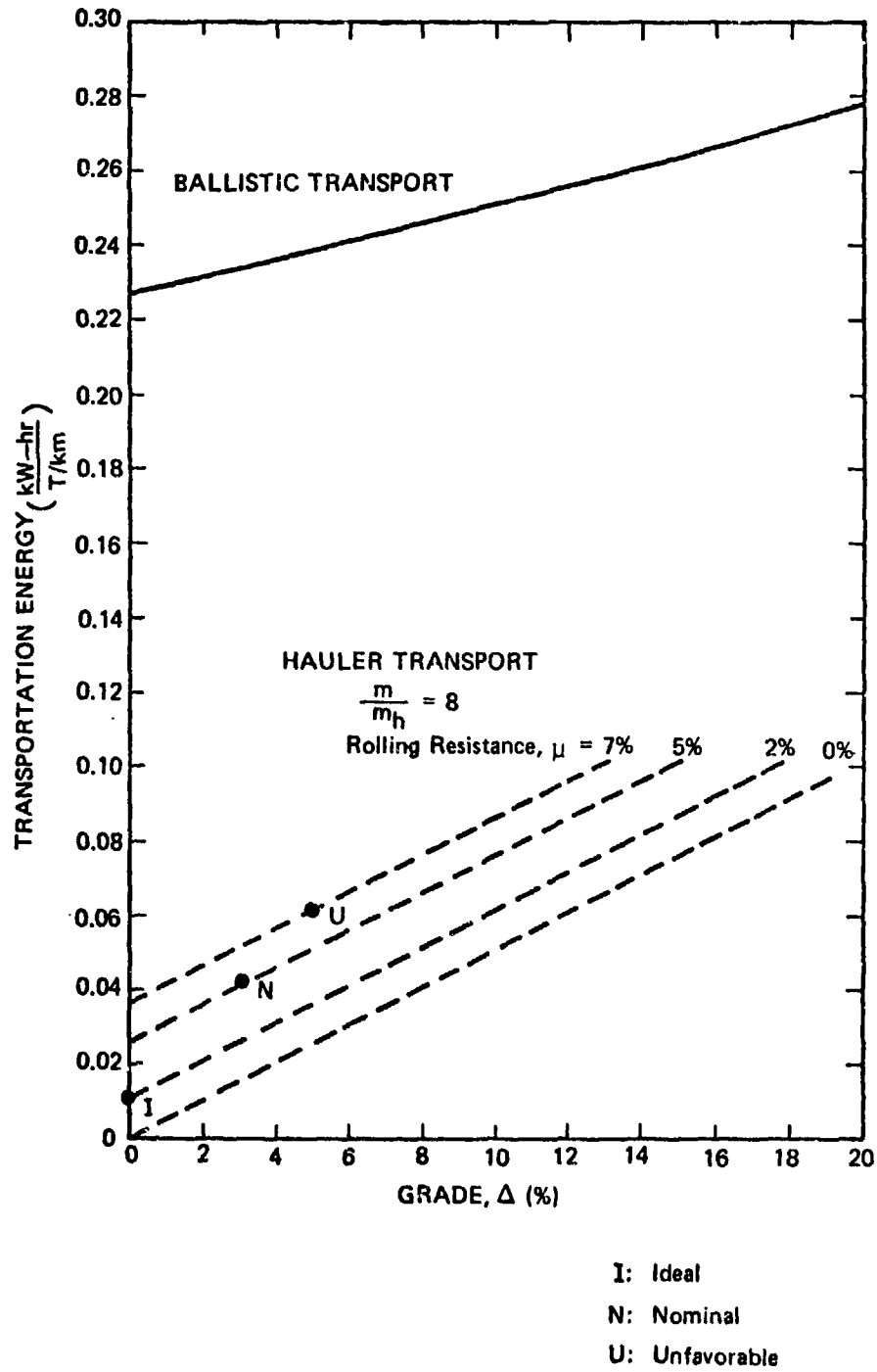


Figure III-12 Energy Requirements for Ballistic Transport vs. Hauler Transport (One-Way)

IV. BENEFICIATION OF LUNAR SOILS

Summary

Following a review of: 1) the electrostatic separation techniques, 2) the lunar environment as it may affect such techniques, and 3) the data available for two of the important lunar minerals — anorthite and ilmenite, the report concludes that the lunar environment is about as ideal as one could imagine for the electrostatic beneficiation of all the minerals, both magnetic and non-magnetic. To predict the beneficiation efficiencies, several analyses and experiments are recommended to be carried out with the actual lunar soils in a high vacuum ambient. To produce 1 megaton of beneficiated ore per year, sixty combined mining and beneficiation (30 ton/hour) units are recommended. Such conceptual units (approximately $12 \times 6 \times 3 \text{ m}^3$ overall size) will have a mass in the order of 20 tons, and power requirements in the order of 7 kW for the beneficiation.

A. GENERAL

Subsequent to the considerable effort put into the exploration of the moon and towards the advancement of man's knowledge of space, the building of space colonies^(1,2) and/or space manufacturing facilities is now within the range of technical capabilities developed on earth. Among the many contemplated space projects, space solar power stations (SPS) [to beam power by microwaves to earth and alleviate future energy problems] offer the greatest immediate incentive.

The construction of such colonies in space would become prohibitively expensive if all materials were to come from earth.

The moon and space asteroids offer far more attractive solutions. Based on 1975 estimates,³ the transportation cost of a mass of 1 kg from the moon to the L-5 orbit (Lagrangian sphere) 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 the SPS, aluminum and silicon are currently considered to involve the largest mass. In addition, other materials will be necessary, such as iron, titanium, oxygen, and a substantial shielding mass for the people.

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:

- 1) Seven major elements: Si, Al, O, Mg, Fe, Ca, and Ti
- 2) Six minor elements: Cr, Mn, Na, K, S and P
- 3) A few trace elements: H, He, C and N.

The approximate mean composition³ of the various soil samples (less than 1 mm fraction) is shown in Table I.³

It can be seen from the table 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.

The energy intensive chemical processes for the extraction of the metals require a prior physical beneficiation of the raw ores.

In the background of the decision to evaluate the possibilities of electrostatic beneficiation of the lunar soils, there were several observations:

- 1) A large amount of the lunar soil is already in fine particulate form, an essential requirement for electrostatic processing.⁴
- 2) The observation of the horizon glow and of the motion of the lunar soil explained as due to electrostatic forces led the scientists of LPI to suspect very strong electrification properties of the dust.⁵
- 3) The lack of water on the moon ought to make the electrostatic beneficiation, which is a dry process, considerably more attractive than flotation or the usually wet magnetic separation.
- 4) The vacuum conditions eliminate the problem of air turbulence entrainment of the very fine particles (<40 μ m).
- 5) Electrostatic methods can beneficiate both magnetic and non-magnetic ores, thus eliminating the heavy masses usually associated with magnetic separators.

Of particular interest is the vacuum of outer space which 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 and too idealistic can now come to practical application.

B. PRINCIPLES OF 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, while the external electric field can be easily produced and controlled, the selective charging of the particles to be separated usually requires most of the development effort prior to the building of an industrial installation.

B.1. GENERATION OF CHARGES

A review of what is known of the environmental conditions on the moon and of the lunar soils and their electrical and magnetic properties, points to three types of selective electrification processes which will very likely find application in a space manufacturing complex:

- 1) Triboelectrification
- 2) Conductive induction
- 3) Electron bombardment from heated cathodes in the space vacuum in combination with a conductive discharge.

B.1.1. TRIBOELECTRIFICATION

The principle is shown schematically in Fig. 1. Let us assume that the particles placed on the Surface D are made to repeatedly contact one another as well as the Surface D. This is typical of a Syntron Vibrator²⁰ or a Travelling Electric Field¹⁸ conveying system. If W_A , the work function of the surface of Particle A, is smaller than W_D , the work function of the Surface D, and W_D is smaller than W_B , the work function of the surface of Particle B, then, upon contact and separation, Particle A will become positively charged, Particle B negatively charged, and the Surface D will respectively acquire electrons from Particle A and give electrons to Particle B.

The triboelectrification of various materials in contact in vacuum has been extensively studied and proven to be a very effective way of charging.^{6,7,8}

In experiments on earth, it has been found that vacuum is essential for any fundamental studies on triboelectrification, and particularly from the point of view of the reproducibility of the results. [A monomolecular layer of adsorbed gas can substantially alter the work function of the material.] Triboelectrification is essentially a surface phenomenon, and, as such, any transient surface changes at the point and time of contact will have profound effects on the charge transfer. Generally, it involves two processes: a) a charge transfer during contact, and b) a charge backflow just before separation. It is known in practice that two good conductors will not triboelectrify. As an example, consider the attached Fig. 2(a) and (b).⁹ It represents the experimental results obtained when contacting borosilicate glass and quartz with gold and nickel, in 10^{-9} Torr vacuum over a range of temperature [(-) 45 → (+) 130°C], and a range of applied external electric fields given by the respective electric potential range [(-) 14 → (+) 14 kV]. The potential is considered (+) when the electric field intensity at the point of contact is directed from the metal to the glass (or quartz). For "pure" triboelectrification, consider the values on the ordinate axis only (at zero applied electric field).

In vacuum, at +125°, gold and borosilicate glass when contacted and separated will no longer triboelectrify because of the increased electrical conductivity of the glass. [The electrical conductivity of glass increases some three orders of

magnitude between 0°C and 100°C.] It is interesting to notice in the same figure that the low electrical conductivities associated with the lower temperatures result in very consistent tribo charging.

B.1.2. ELECTRIC CHARGING BY CONDUCTIVE INDUCTION

The principle is shown in Fig. 3. The positive high voltage electrode attracts or "induces" greater negative charges on the conductive particles than on those particles assumed to be of insulating or of smaller electrical conductivity materials. The resultant electrical forces pull the negatively charged particles away from the drum.

Upon separation from the drum, while still under the influence of the electric field, the conductive particles will retain their negative charge and be deflected towards the collecting bin.

Referring to Fig. 2, one can see the conductive induction effects at various temperatures. The experiments carried out at temperatures from -55°C to ambient show the tribo charging to be dominant over any conductive induction effect on account of the very low conductivity of the borosilicate glass and quartz at those temperatures. At $\geq 125^\circ\text{C}$, the higher electrical conductivity of the glass produces conductive induction charging, as evidenced by the change in the polarity of the charge for positive and negative fields. The gold charges positively when the field is directed towards the gold, and negatively when directed towards the glass. On the other hand, at this temperature the quartz still retains some of the triboelectrification dominance.

By proper choice and control of operating temperatures, or

mere fast surface temperature conditioning, one could effectively charge some particles by conductive induction while not charging others.

Of further interest in understanding the advantages of electrostatic beneficiation of ores in vacuum, are experiments carried out in air at various relative humidities.¹⁰ Fig. 4 shows the electrification of pyrex glass in contact with stainless steel in air at four relative humidities. At very low relative humidities the triboelectric charging is effective and dominant over the electrification by conductive induction. At relative humidities in excess of 60%, the triboelectrification disappears on account of the charge backflow.

The advantages of a vacuum environment for generating tribo charges are obvious.

B.1.3. ELECTRON BOMBARDMENT FROM HEATED CATHODES IN SPACE VACUUM IN COMBINATION WITH SELECTIVE CONDUCTIVE DISCHARGE

Corresponding to the corona charging which is used in various beneficiation applications in an air environment, an electron bombardment from heated cathodes could be used effectively for electric charging of ore particles in vacuum. To achieve a selective discharge, the ore falls over a rotating drum maintained at ground potential. The conductive particles lose their charge and fall into the first collecting bin (see Fig. 5). The charge on the insulating particles remains and the particles stay attached to the drum held by the image charge until they are scraped off in the second collection bin.

B.2. THE EXTERNAL ELECTRIC FIELD FOR SEPARATION OF PARTICLES

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 component.

The horizontal acceleration intensity and direction are determined by the polarity and magnitude of the charge, by the direction and magnitude of the electric field, and by the mass of the particle. Positively charged particles will move in the direction of the field, negatively charged particles will move in a direction opposite to that of the field. The initial horizontal acceleration of each particle will be proportional to its charge to mass ratio and to the intensity of the electric field.

From the above it is obvious that when one uses the tribo-electrification process, all positively charged particles will move in a direction opposite to that of the negatively charged particles regardless of their charge to mass ratio. Given sufficient time and space to spread, there will be a complete separation of the two types of particles. Hence particles with different surface work function may be very effectively separated.

If one chooses conductive induction to charge the particles, the separation is based primarily on the difference in the electrical conductivities of the materials at the time of processing.

With proper design and strategically located collection bins, both triboelectrically and conductive induction charged particles may be also partly separated according to their size on account of the specific charge to mass ratios.

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, in the high vacuum of the outer space the field could be raised to 300 kV/cm 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 (ref. 4 - copy of the pertinent section of the paper in Appendix D shows the calculation of such forces under ideal conditions).

In summary, once particles are charged by one of the three methods outlined above, the external electric field can selectively separate:

- a) positively from negatively charged particles
- b) charged from uncharged particles
- c) particles of various ($\frac{\text{charge}}{\text{mass}}$) values.

C. A LOOK AT THE EXPECTED LUNAR MINERAL BENEFICIATION TO BE CARRIED OUT ON THE MOON SURFACE

C.1 OVERVIEW

For a realistic estimate of the expected electrostatic beneficiation of a particular mineral, it is necessary that the following data be considered:

- 1) The frequency distribution of the content percentage of the sought mineral in discrete particles for the entire particle-size spectrum in the ore.
- 2) The triboelectrification and conductive induction properties of the various particles forming the lunar ore to be processed.

- 3) The influence of temperature on the triboelectricity and conductive induction properties of the ore particles.

The size of the particles in the lunar soils is in an ideal range for electrostatic beneficiation.¹¹ The mean grain size of lunar soils ranges from 40 to 802 μm with most falling between 45 and 100 μm as seen in Fig. 6.

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, with the coarsest samples being the most poorly sorted.

The weight percents in each grain size fraction are shown in Table II for Apollo 11 soil — 10084 — which is a typical mare soil. Note that about one-fourth of the soil is finer than 20 μm ."

Under the high electric field intensities which can be used in the vacuum of outer space, and with particles falling under the influence of the low lunar gravity, it is estimated that particles as large as 2 mm in diameter could be successfully charged and separated; as such, referring to the same table, only 4.06% of the weight may have to be eliminated by coarse sieving prior to the beneficiation of the ore.

Regarding the actual minerals' distribution among the various particle sizes, any successful electrostatic beneficiation will require that a good number of discrete particles or grains have

a substantially higher content of the sought mineral than the average content in the whole ore, and that a good portion of the mineral is exposed at the surface of the particle. As the electrostatic beneficiation is a physical separation process, it would be futile to attempt to beneficiate any mineral value which is evenly distributed among all discrete particles.

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 aluminum, silicon, titanium, iron and oxygen.

Furthermore, as all the surveying to date has failed to reveal any anorthite or ilmenite-rich regions on the moon, a beneficiation of the two minerals will very likely be necessary in any contemplated processing of these. 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 is no data for the triboelectrification and conductive induction properties of the lunar soils, nor is there much from the earth data which could be used. Apart from a few reported vacuum studies with pure metals and plastics, any data which we have on the triboelectrification and conductive induction of the minerals on earth are based on measurements taken in air, at atmospheric pressure. As a monomolecular layer of gas adsorbed on the surface of a material is sufficient to substantially change

the work function of that material, none of the existing data on minerals is usable.

Regarding the influence of the temperature on the triboelectrification and conductive induction, here again there is no experimental data available which would be directly applicable to the lunar soils.

However, considering that the lunar environment is an ideal environment for an electrostatic beneficiation process, i.e.,

- 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, with proper research and development work, 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.

C.2 MINERAL TYPES

Anorthite (Ca Al₂ Si₂ O₈)

Anorthite is considered to be the lunar aluminum ore, with silicon and oxygen as bi-products.

By weight percentage, the anorthite elements are:

- 19.4 aluminum
- 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 reported in reference 12. For the 90 to 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 Fig. 7.

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:

$$\frac{\text{total anorthite in the ore extracted}}{\text{total extracted ore}}$$

*Whereas the Al_2O_3 content in various lunar soils is very well documented, the data on the anorthite mineral content in discrete particles will require more quantification.

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 >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. Assuming well mixed grains of anorthite and other soils and a uniform extraction, regardless of the percentage of material separated, the original anorthite content of 60% will remain the same in all fractions.

The segmented line is what the real beneficiation may look like: it represents some value between the other two lines. This curve could only be estimated after the triboelectrification and the conductive induction properties of the materials are known. Through research and development in the areas outlined in Section B, the beneficiation efficiency could undoubtedly be improved further towards the ultimate objective, represented by the ideal line.

A second example of the possibility of electrostatic beneficiation of anorthite is based on the data presented in reference 13. It deals with very fine particles, less than 37 μm diameter, which were individually analyzed from five Apollo 14 surface samples and five Apollo 14 core samples.

Out of a total of 2427 particles which were individually analyzed, 415 of them were plagioclase feldspars (90% anorthite content).

Figure 8 shows a conjectured beneficiation curve for this ore. The top line is the ideal beneficiation. By extracting 17% of the grains, one could expect "pure" anorthite. Any quantity in excess of 17% will reduce the anorthite content as shown. For this particular analysis the total percentage of anorthite in the ore (not given in the report) was also assumed at 60. 90% is considered "pure".

The actual beneficiation curve will be represented by the segmented line on which one could choose the operating point M. At point M, by extracting 10% of the ore, the anorthite content will be 85%.

In summary, if one assumes that the two cases shown are indicative of major areas of the lunar soils which could be mined, and that the triboelectrification and conductive induction properties of the anorthite are at least as favorable as those of some other ores which are electrostatically separated in the earth's atmosphere, the electrostatic enrichment of the anorthite ought to be fully investigated in well simulated lunar conditions.

While the anorthite is thought to be available in large quantities in the lunar highlands, an investigation of the mare soils for the electrostatic beneficiation of the mineral is also recommended. As will be seen in Section D, mobile combined mining and beneficiation units are recommended which will dump the rejected fractions at the place of mining. Only the beneficiated material will be transported to the chemical plant. Depending on the number of beneficiation stages required and on the efficiency of separation of the anorthite from mare soil as compared to that

of separating it from the highland soils, it may be that the beneficiation of the anorthite from the mare soils, in combination with the beneficiation of other minerals such as ilmenite and pyroxene, could be economically justifiable.

Ilmenite (Fe Ti O₃)

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.

Due to the nature of the electrostatic forces, any contemplated beneficiation of this mineral will have to confine itself to the lunar regolith rather than to larger sized rocks. [Analysis of some mare rocks shows substantially higher ilmenite content than in the regolith.]

It is estimated¹² that the 90 - 150 μ m fraction of the lunar regolith contains an average of 4.6% ilmenite, and that the same figure is representative for the whole soil.

From various studies it appears that using physical methods, 90% ilmenite concentrates are feasible from the mare soils.

It is also believed that the general trend is to find the ilmenite in the finer grain sizes.

Based on the above, Fig. 9 shows the possible ilmenite beneficiation curves. The top line is the ideal beneficiation. By extracting 5% of the material, one could obtain 90% pure anorthite. The bottom line represents a completely ineffective electrostatic beneficiation. The segmented line is what the

real beneficiation may look like; again, the true values could only be estimated after the triboelectrification and the conductive induction properties of the ilmenite in the regolith mixture are known.

In conclusion, as one looks ahead at the possibilities of electrostatic beneficiation of all minerals from lunar soils (both magnetic and non-magnetic), one could state that:

- 1) No better conditions could be imagined for an environment in which to process the materials.
- 2) The ores to be beneficiated are already in an ideal form for electrostatic separation.
- 3) With combined mining and beneficiation mobile units adapted for a variety of special surface conditionings of the minerals for triboelectrification and conductive induction charging, one could visualize several such units, following one another and each beneficiating a different mineral while reprocessing the waste from the unit ahead. As the variety of minerals is reduced by beneficiation, the electrostatic separation efficiency and selectivity may substantially improve.

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D. KEY STUDIES NECESSARY FOR A DEFINITIVE EVALUATION OF THE APPLICABILITY OF ELECTROSTATIC SEPARATION TO LUNAR SOILS

As outlined in the description of the principles of electrostatic separation, any definitive evaluation will require an in-depth study of:

- 1) the triboelectrification
- 2) the conductive induction charging and discharging.

All investigations will be related basically to a study of the surface properties of the particles in contact, and of the factors affecting the charge transfer from particle to particle or from the 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, subject to further experimentation and thought, at this time it appears that the only parameter to be thoroughly investigated as to conditioning of such surfaces just prior to any electrostatic beneficiation process is the temperature.

By introducing radiant heating and also by making use of the temperature variation and the moon 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.

Heating treatments involving an extremely small layer at the particle surface would not involve large amounts of energy.

To quote from reference 14: "Heating is one of the simplest means by which the energy structure of minerals can be modified. An increase in temperature causes a shift in the Fermi level towards the center of the forbidden band, enhancing it in the p-type and lowering it in the n-type semiconductors."

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' surface, in the surface

electrical conductivity, etc., while the ambient itself changes from day to day.

In the vacuum of outer space one could determine the true triboelectrification and conductive induction effects generated by temperature changes, and any such studies will be universally valid and reproducible.*

Temperature effect studies will have to cover a practical range of achievable temperatures of the surfaces in contact in the lunar ambient. The profound change from a triboelectrification charging to a conductive induction charging for borosilicate glass when the temperature is increased from 25 to 125°C has already been shown in Section B (Fig. 2).

Further examples of temperature influence on separation and beneficiation methods are given in reference 15, dealing with fluidized beds, and reference 16, showing the effect of heating in oxygen and separation at high temperature.

Agglomeration of Particles

In the lunar environment, this is a key processing parameter which will have to be investigated. Some studies on the electrostatic interparticle adhesion¹⁷ have shown that under the respective experimental conditions, the electrostatic forces were comparable in magnitude to the adhesion forces between fresh crystal cleavage surfaces in high vacuum.

Depending on the conveying and the triboelectrification system chosen for the minerals' beneficiation, a recent development

*By contrast, a survey of the various publications on triboelectrification properties of materials in the earth's atmosphere often shows difficulties of reproducibility, not only of the electrostatic charges obtained, but even of the polarity of the charge.

at the University of Tokyo¹⁰ may find application, not only in the conveying of some of the lunar fines but also in the de-agglomeration of such particles. The development involves basically a stationary dielectric surface and a travelling electric field produced by suitably designed electrodes. It is shown schematically in Fig. 8 and Appendix B.

In such a system, fine particles placed on top of the dielectric sheet (be they negatively or positively charged) will all move in the direction of the travelling electric field while describing a more or less spiral motion. The system may be an ideal one to transport, triboelectrify and at the same time de-agglomerate the lunar soils. A full investigation of this is strongly recommended, particularly for the very fine ores (<20 μm) with ilmenite content.

In summary, a thorough investigation of: a) triboelectrification, b) conductive induction charging, c) temperature influence, d) de-agglomeration, and e) conveying by means of electrostatic fields, will be valuable and essential for the development of the electrostatic beneficiation process. The results will be universally valid in any future processing in space.

E. CONCEPTUAL DESIGN FOR AN EXPERIMENTAL APPARATUS TO STUDY THE ELECTROSTATIC SEPARATION OF THE LUNAR SOILS

The apparatus is shown schematically in Fig. 10. It comprises in a vacuum enclosure (recommended capability to 10^{-11} Torr), an electrostatic separation tower with two electrodes, each energized by a separate power supply - one positive and one negative polarity.

At the top of the tower a vibratory and/or travelling electric field feeder supplies the ore which falls into the tower by gravity. Over the surface of the conveyor belt, as well as at the point of separation of particles from the conveyor, there will be means of heating the ores and controlling the temperature. In addition, ultraviolet radiation capabilities are envisaged. The material will be separated on a continuous or batch-type basis in two fractions, and provisions are made for measuring both the mass and the charge developed. A conveying system will allow to reprocess either of the two fractions. As the apparatus will handle the very scarce actual lunar soils, it will have to be essentially miniaturized with capabilities of handling a few grams of materials at a fast rate for simulating the space charge and possible agglomeration effects.

An important aspect of the study will be the rates of feed for optimum triboelectrification. In case of a syntron vibrator, sufficient data will have to be accumulated to determine the maximum ore height on the conveyor and the velocity of transport.

The electrodes in the vacuum equipment will require careful design to take maximum advantage of the insulation capabilities of vacuum.

The triboelectrification which develops on the static conveyor will be of considerable interest, and it is proposed that the minimum conveying length which will generate adequate electrification be determined. As the triboelectrification is also sensitive to the contact pressure between the particles,

and between the particles and the supporting surface, some provision will have to be made to take into consideration the lower gravity acceleration on the moon surface. Also, it would be very desirable to have ways of analyzing the separated fractions while they are still in the vacuum environment, possibly in a continuous way.

The same apparatus could be used for studying the conductive induction charging of the lunar ores by incorporating a rotating drum and an induction electrode immediately after the feeder.

In summary, it is believed that actual electrostatic separation experiments with lunar soils carried out in an ambient as close as possible to that on the moon surface would be essential for the contemplated project.*

Regarding the actual lunar soil which will be processed in the apparatus, it will require a very careful analysis, practically grain by grain, and in conjunction with the experimental apparatus the development of a fast analysis technique ought to be pursued.

F. CONCEPTUAL DESIGN OF A LUNAR FACILITY FOR PRODUCING 1 MEGATON OF BENEFICIATED ORE PER YEAR

It is recommended that the electrostatic beneficiation of the various minerals be carried out with combination (minimised beneficiation) mobile units for processing 30 tons/hour. Assuming an approximate 20% overall yield, and 2700 operating hours/year, sixty units will produce 1 megaton of beneficiated ore per year.

*Facilities are available at the Applied Electrostatics Laboratory at the Faculty of Engineering Science of The University of Western Ontario, and at the NASA/J.S.C. Laboratories which are suitable for a joint investigation along these lines.

A conceptual design of such a unit is shown in Fig. 11.

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 , the entire processing unit will travel at a snail's pace of 4.2 m per hour. During the slow motion there will be sufficient time for an automatic self-levelling system to maintain the unit horizontally.

The "mined" lunar soil will be lifted by a sideloader to the first feeder in the mobile unit. The overall dimensions of such a unit are envisaged as $12 \times 6 \times 3 \text{ m}^3$. However, both the mass and the dimensions of the unit will be substantially influenced by the actual beneficiation results and the number of beneficiation stages which are required. In the conceptual design it was assumed that the two stages would be sufficient.

On account of the unique mining conditions on the moon where the raw material is ready to process immediately, it is realistic to envisage that a second unit designed to beneficiate another mineral component of the soil could easily reprocess the waste from the first unit which would otherwise be dumped back into the same trench.

The general steps of a beneficiation process are shown in Fig. 12. The raw material is coarse-sieved, possibly electrostatically sized and then processed through one or several beneficiation stages. Fig. 13 shows schematically a conceptual design for a mobile unit using triboelectrification as the charging process. 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 syntron 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 triboelectrification 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. For the particular arrangement shown in Fig. 13, the rejects from the second stage beneficiation tower will be at the bottom of the trench followed by the rejects from the first beneficiation tower and the coarse-screening rejects on top. 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 mineral. Table III shows the very approximate weights of the envisaged units, power requirements, overall dimensions, etc.

An alternate possible arrangement of the two beneficiation stages with tribo charging is shown in Fig. 14. The final design height may be sufficiently small to allow such an arrangement which could eliminate one conveyor.

For the separation of electrically conductive ores from the less conductive ores, Fig. 15 shows the conceptual design of a unit similar to that shown in Fig. 13 except using drums and induction or heated cathode electrodes. Dimensions and power requirements have been assumed comparable to those of the unit in Fig. 13.

Also, for earlier considerations of lunar soil beneficiation schemes, a review of reference 21 is highly recommended.

Regarding other ideas for future construction of the beneficiation apparatus, Appendices K of the report include the drawings of seven pertinent patents for processing ores on earth.

G. CONCLUSIONS

1. The lunar soil is already "comminuted" in an ideal range for an electrostatic beneficiation of the minerals.
2. The lunar environment is about as ideal as one could imagine:
 - a) Sustained high vacuum
 - b) Low temperature (at night)
 - c) Acceleration of gravity one-sixth of that of the earth's surface.
3. 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.
4. The ore body being located on more or less flat surfaces and at the very surface of the moon, simultaneous mining and beneficiation is recommended.
5. In order to estimate the maximum expected beneficiation efficiencies for the lunar soils, it will be necessary to carry out a detailed study of the respective soils to determine the frequency distribution of the sought mineral content percentage in discrete particles for the spectrum of particles in the ore.

6. Three ways of electric charging of the lunar soils for electrostatic beneficiation appear attractive at this time:
 - a) Triboelectrification
 - b) Selective conductive induction charging
 - c) Heated cathode charging and selective conductive induction discharging.
7. The design of the separating equipment can only be decided upon after an experimental study of the:
 - a) Triboelectrification properties of the sought minerals when contacting the other components of the respective soils
 - b) Conductive induction properties of the minerals in the lunar soils
 - c) Temperature effects on the separation efficiencies.
8. It is recommended that combined mining and beneficiation mobile units ("electrostatic worms") be built to each process ≈ 80 kilo tons/year. To process the envisaged ≈ 5 mega tons/year, sixty such units will be required. The units could be made to operate in series or in parallel. When operating in series, some units could beneficiate a second mineral using the waste produced by the units ahead. The final waste will be dumped back into the trench from where the ore was mined in the first place.

It is recommended that in the first year only one such unit be built to gain operating experience, and then in

subsequent years build the number of units dictated by the production requirements. The standardization of the construction of the units will offer distinct advantages, both in the manufacture and in the maintenance of the equipment.

9. The size of such mobile units will be in the order of $12 \times 6 \times 3 \text{ m}^3$ and the expected mass approximately 20 tons.
10. It is expected that the beneficiation power requirement to operate an individual mobile unit will be 7.0 kW.
11. The beneficiation units will process both magnetic and non-magnetic materials.
12. Critical to immediately pursue the development of a small apparatus and technique to carry out some preliminary work on such separations.

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I. TABLES

Table I. MEAN COMPOSITION OF SOIL SAMPLES (< 1 mm FRACTION)

	Maria					Highlands	
	Apollo 11 (%)	Apollo 12 (%)	Apollo 14 (%)	Apollo 15 (%)	Luna 16 (%)	Luna 20 (%)	Apollo 16 (%)
SiO ₂	42.04	46.40	47.93	46.61	41.70	45.40	44.94
TiO ₂	7.48	2.66	1.74	1.36	3.38	0.47	0.58
Al ₂ O ₃	13.92	13.50	17.60	17.18	15.33	23.44	26.71
FeO	15.74	15.50	10.37	11.62	16.64	7.37	5.49
MgO	7.90	9.73	9.24	10.46	8.78	9.19	5.96
CaO	12.01	10.50	11.19	11.64	12.50	13.38	15.57
Na ₂ O	0.44	0.59	0.68	0.46	0.34	0.29	0.48
K ₂ O	0.14	0.32	0.55	0.20	0.10	0.07	0.13
P ₂ O ₅	0.12	0.40	0.53	0.19	—	0.06	0.12
MnO	0.21	0.21	0.14	0.16	0.21	0.10	0.07
Cr ₂ O ₃	0.30	0.40	0.25	0.25	0.28	0.14	0.12
Total	100.30	100.21	100.22	100.13	99.26	99.91	100.17

TABLE II - 10084,853 OLD SOIL

	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 III - CONJECTURED* DATA FOR A COMBINED MINING
AND BENEFICIATION UNIT

Processing rate	30 ton/hour
Overall dimensions	12 m long
	6 m wide
	3 m high
Power	High Voltage Power Supplies 0.5 kW
(a two-stage unit)	Conveyors and Feeders 6.5 kW
	Total 7.0 kW
Mass assumed mainly Al	20 tons
Progressing velocity	1.2 mm/s
while mining a 2 X 2 m ² trench	

*In Table III: 1) The mass of the unit has been estimated, starting from the mass of an equivalent front end loader and adding an estimated mass of the conveying and electrostatic processing components.

2) The power requirements listed exclude the power necessary to mine the ore, which is covered in a separate report.

3) The overall dimensions were primarily determined by the size of the dilute phase streams of particles which will be beneficial.

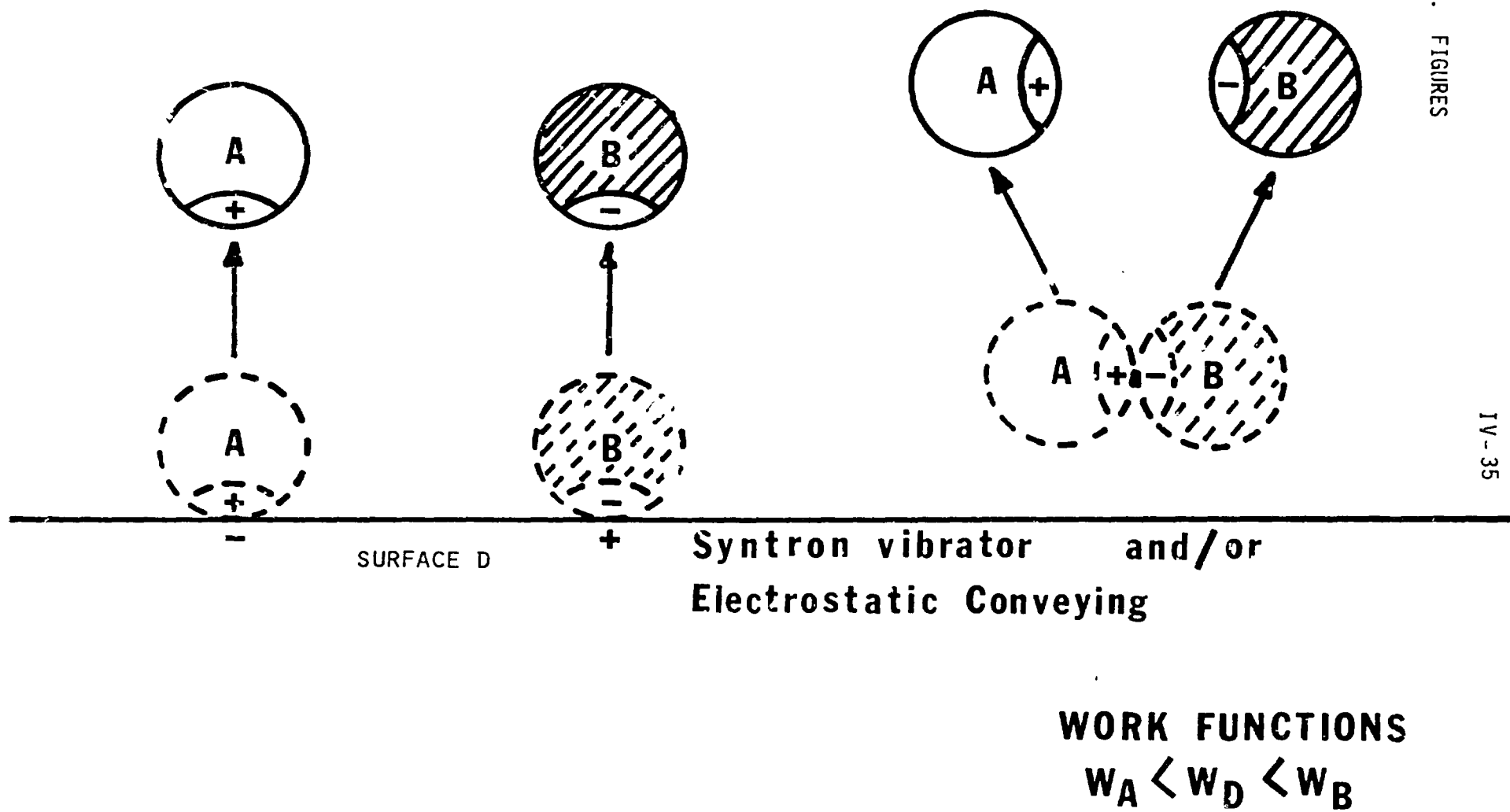


FIG. 1. TRIBOELECTRIFICATION BETWEEN PARTICLES A AND B AND SURFACE D

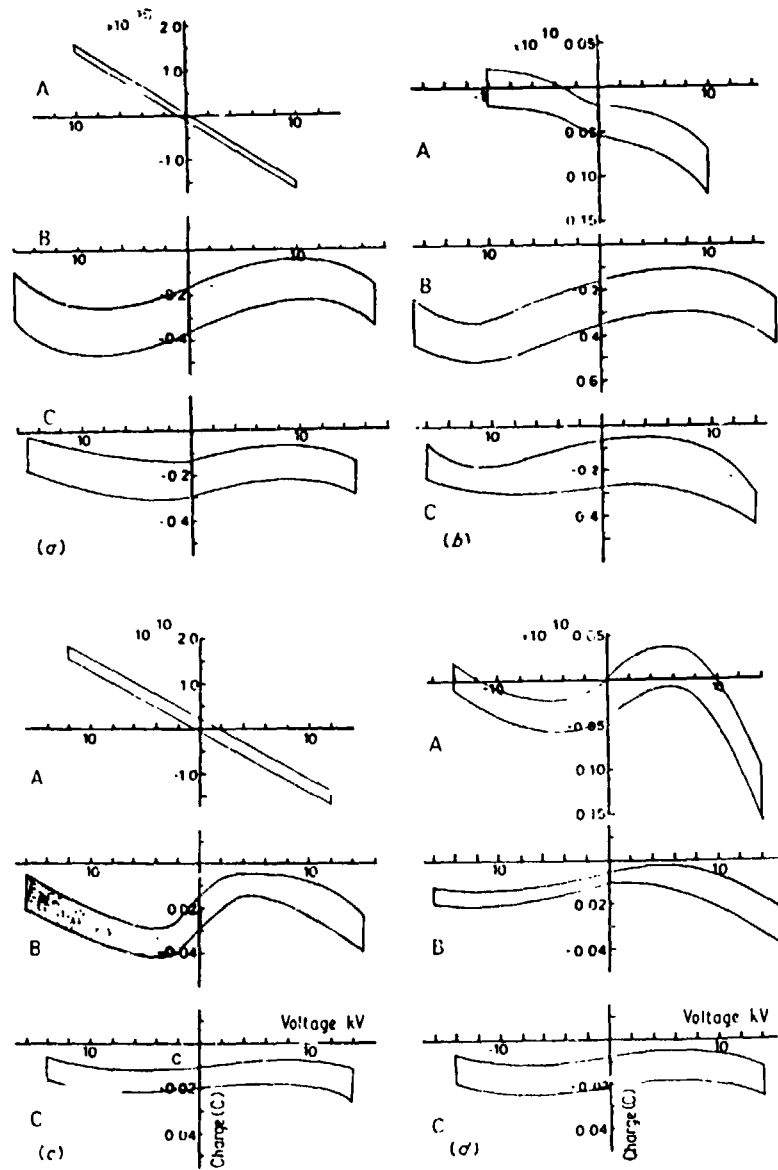




FIG. 2. (a) Electric charges developed on gold contacting borosilicate glass plotted against voltage: A, +125 to +130°C; B, +25°C; -55 to 19°C. (b) Electric charges developed on gold contacting quartz plotted against voltage: A, +125 to 130°C; B, +25°C; C, -45 to -17°C. (c) Electric charges developed on nickel contacting borosilicate glass plotted against voltage: A, +125°C. B, +30°C; C, -45 to -25°C. (d) Electric charges developed on nickel contacting quartz plotted against voltage: A, +125 to +130°C; B, +30°C; C, -45 to -20°C.

IT IS ASSUMED THAT THE ELECTRICAL CONDUCTIVITY OF THE  PARTICLES IS SUBSTANTIALLY HIGHER THAN THAT OF THE  PARTICLES

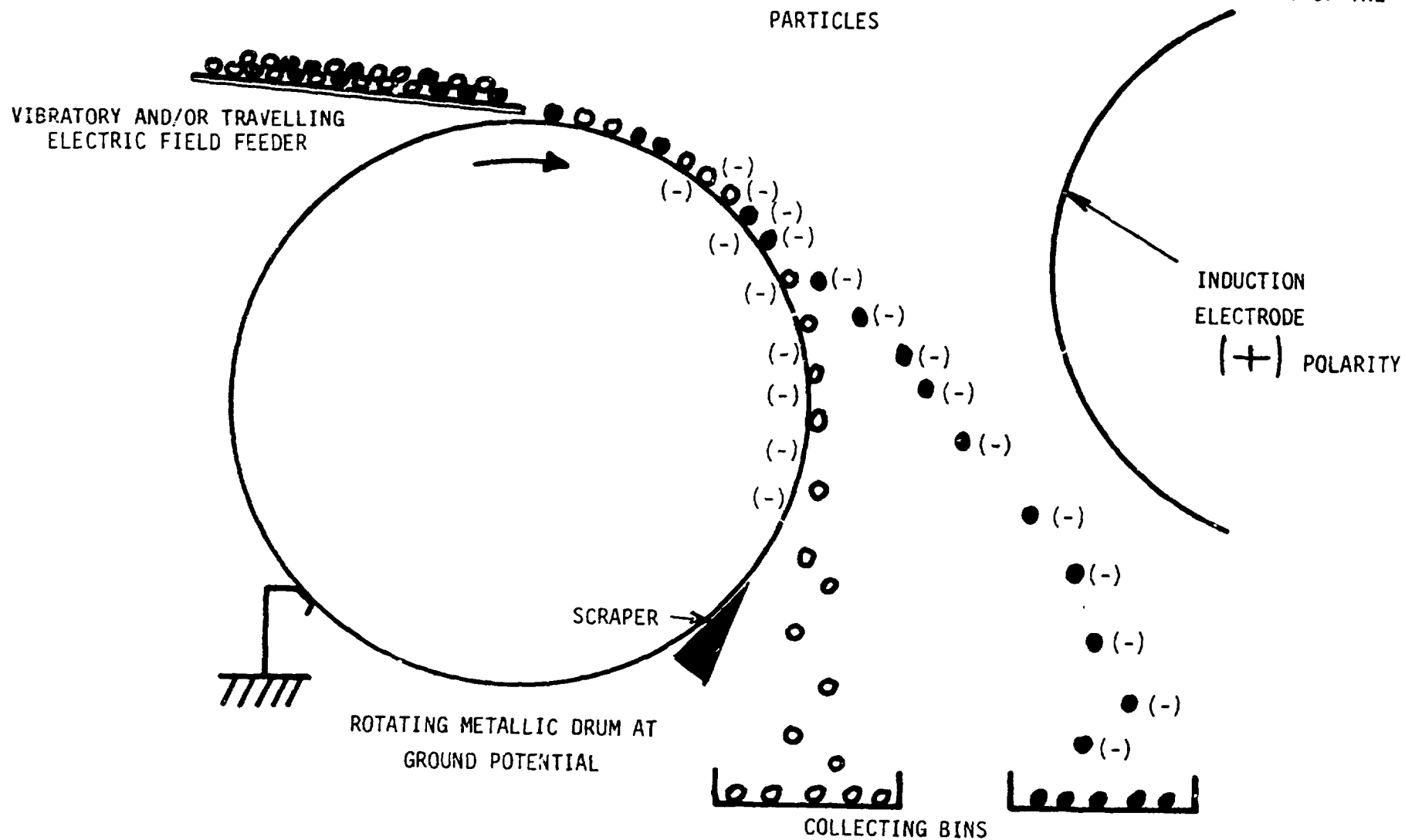


FIG. 3. BENEFICIATION WITH CONDUCTIVE INDUCTION ELECTRIFICATION

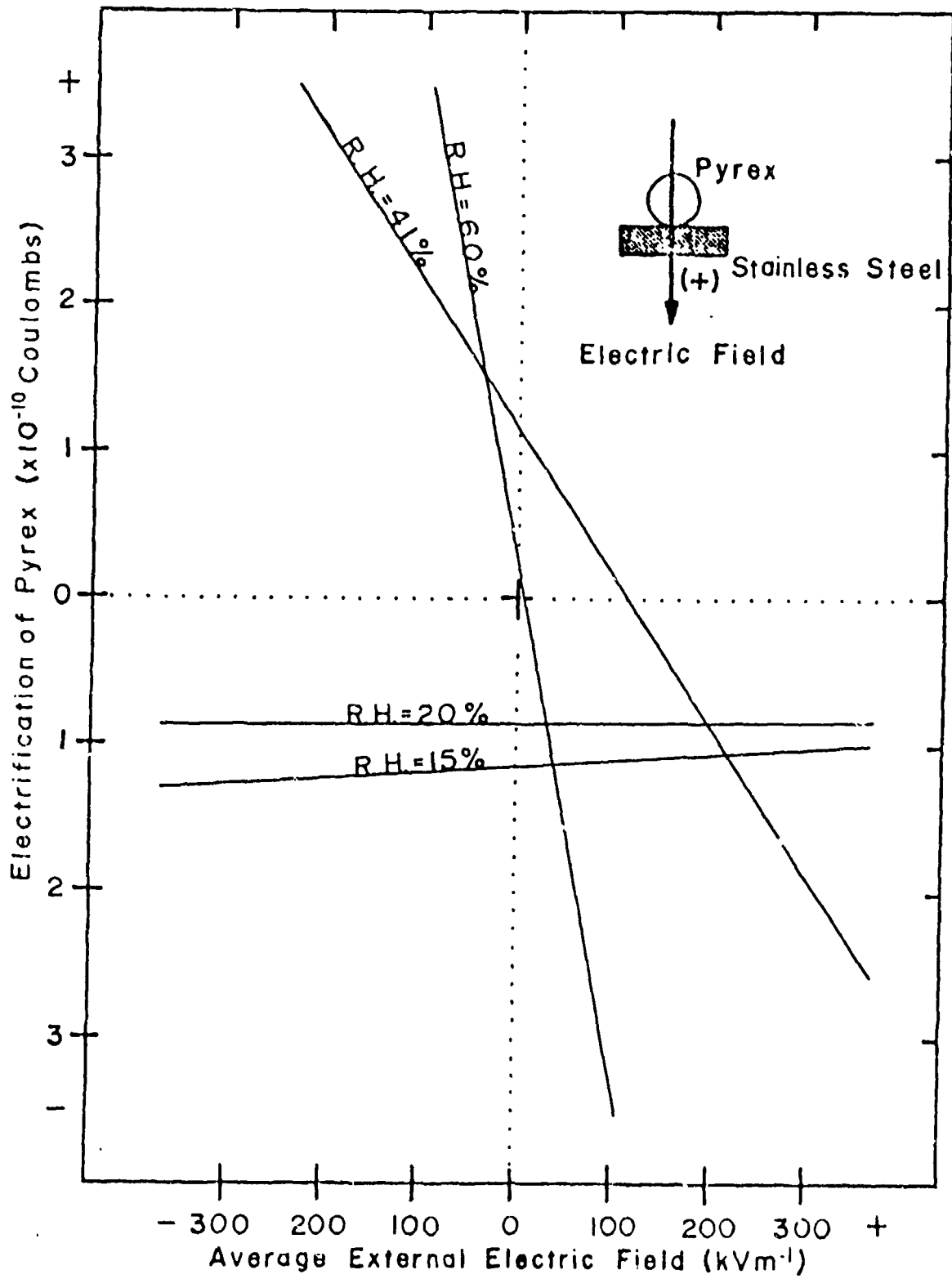


FIG. 4. RELATIVE HUMIDITY AND EXTERNAL ELECTRIC FIELD INFLUENCE ON THE ELECTRIFICATION OF PYREX GLASS IN CONTACT WITH STAINLESS STEEL [Greason, 1972]

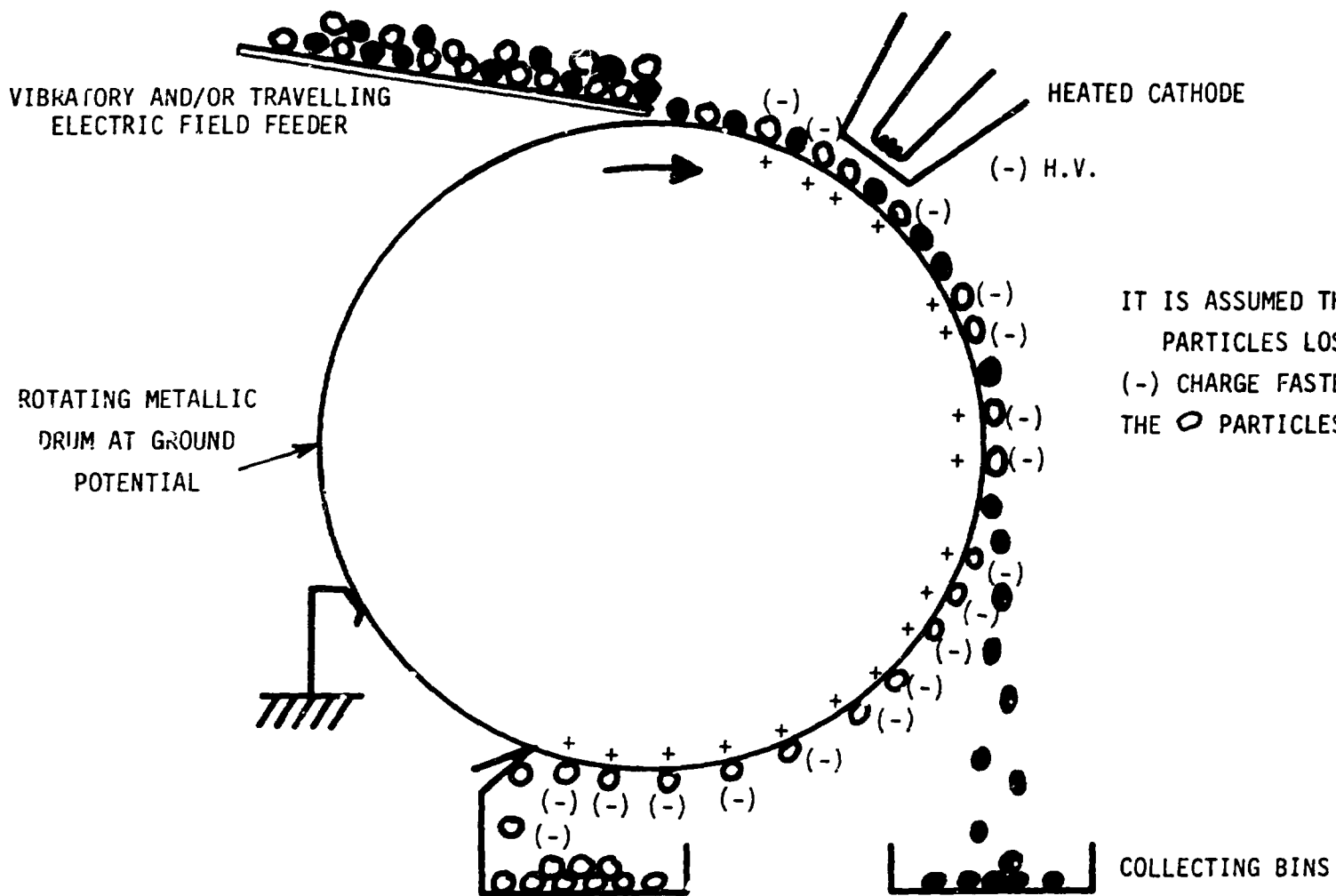


FIG. 5. BENEFICIATION WITH ELECTRON BOMBARDMENT FROM HEATED CATHODES IN THE SPACE VACUUM IN COMBINATION WITH CONDUCTIVE DISCHARGE

GRAIN SIZE DISTRIBUTION IN LUNAR SOIL

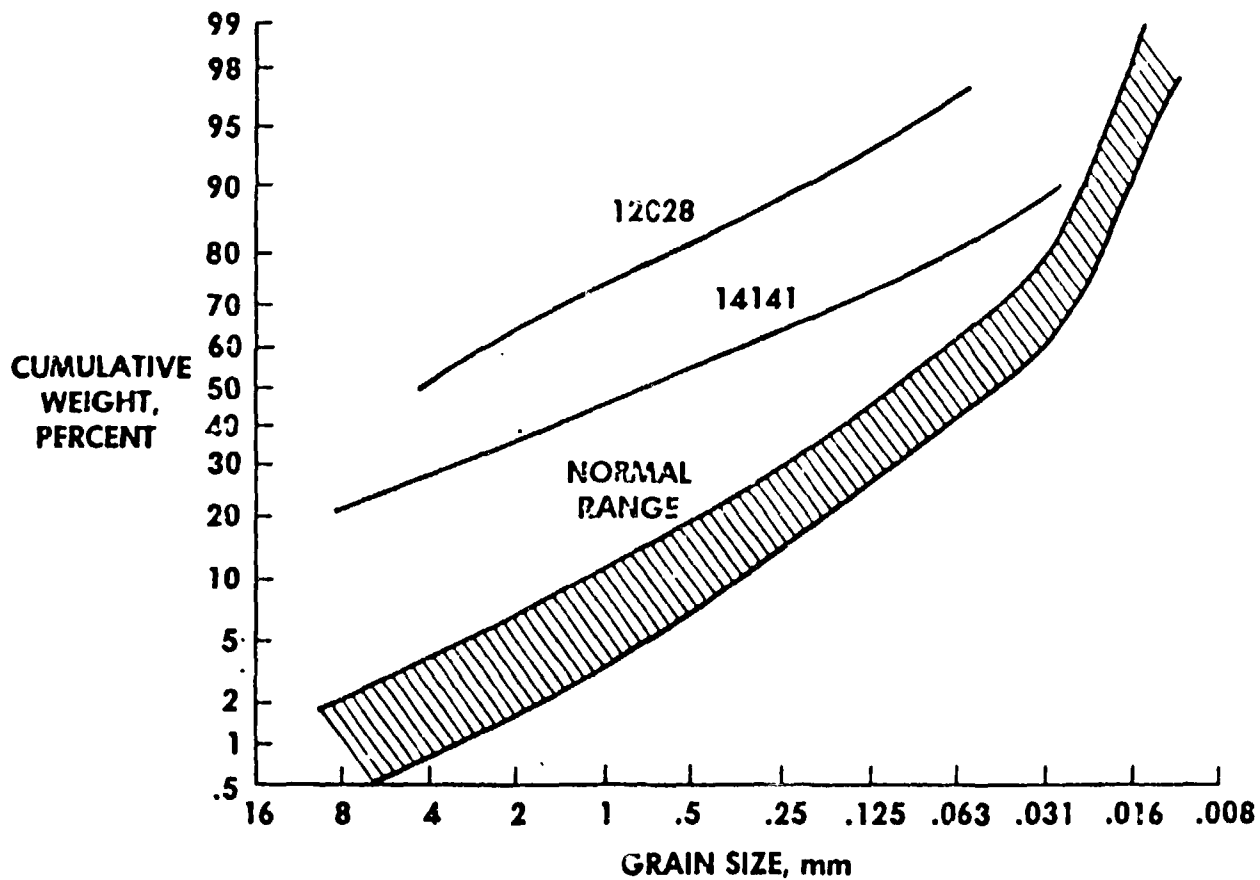


FIG. 6. CUMULATIVE GRAIN SIZE DISTRIBUTION FOR LUNAR SOILS. MOST SOILS LIE WITHIN THE ENVELOPE. TWO PARTICULARLY COARSE SOILS ARE ALSO SHOWN. NASA PHOTO S-76-30404.

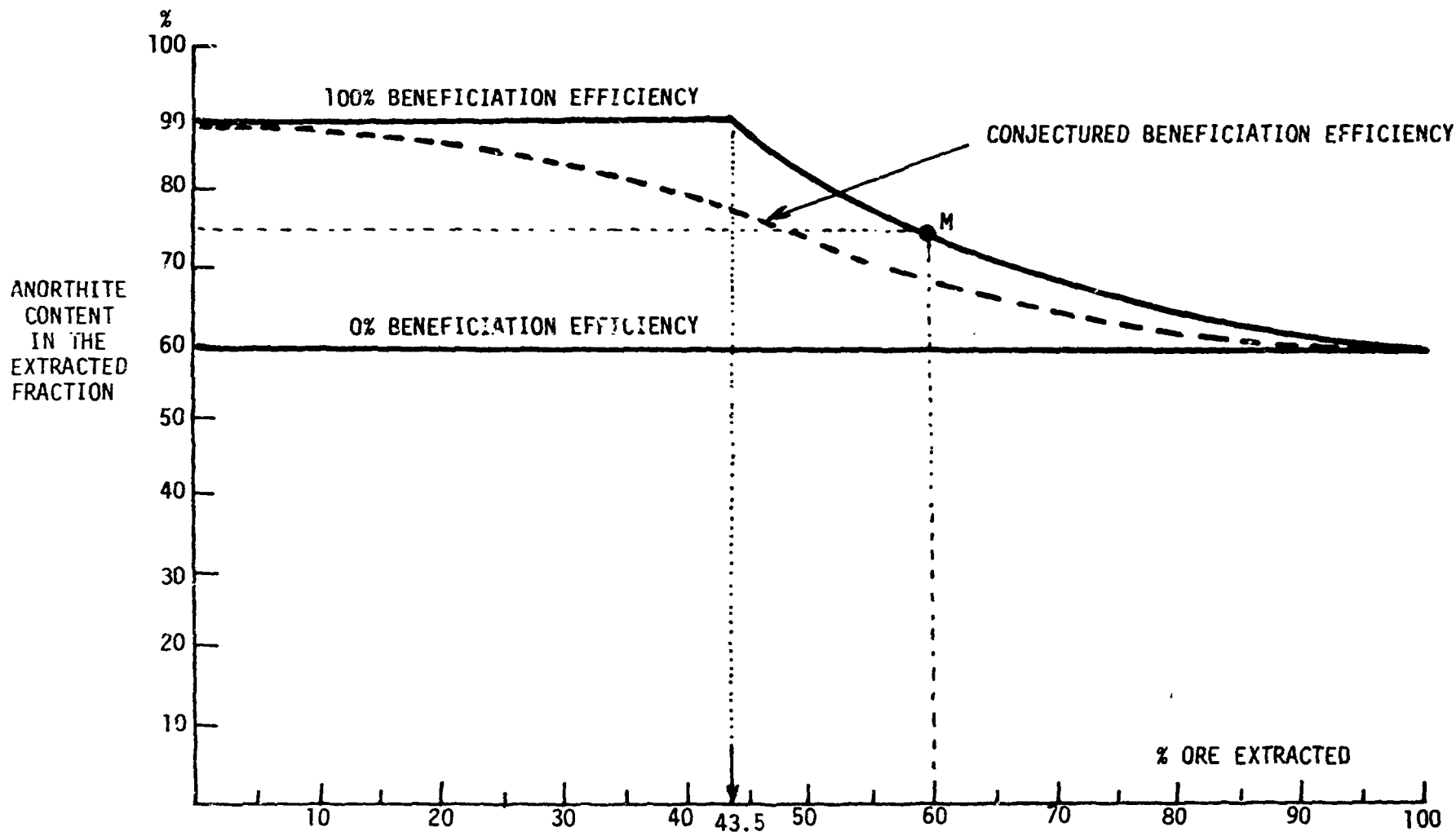


FIG. 7. ELECTROSTATIC BENEFICIATION OF ANORTHITE [90 - 150 μ m FRACTION FROM LUNAR HIGHLANDS [APOLLO 16 SAMPLES]

IV-41

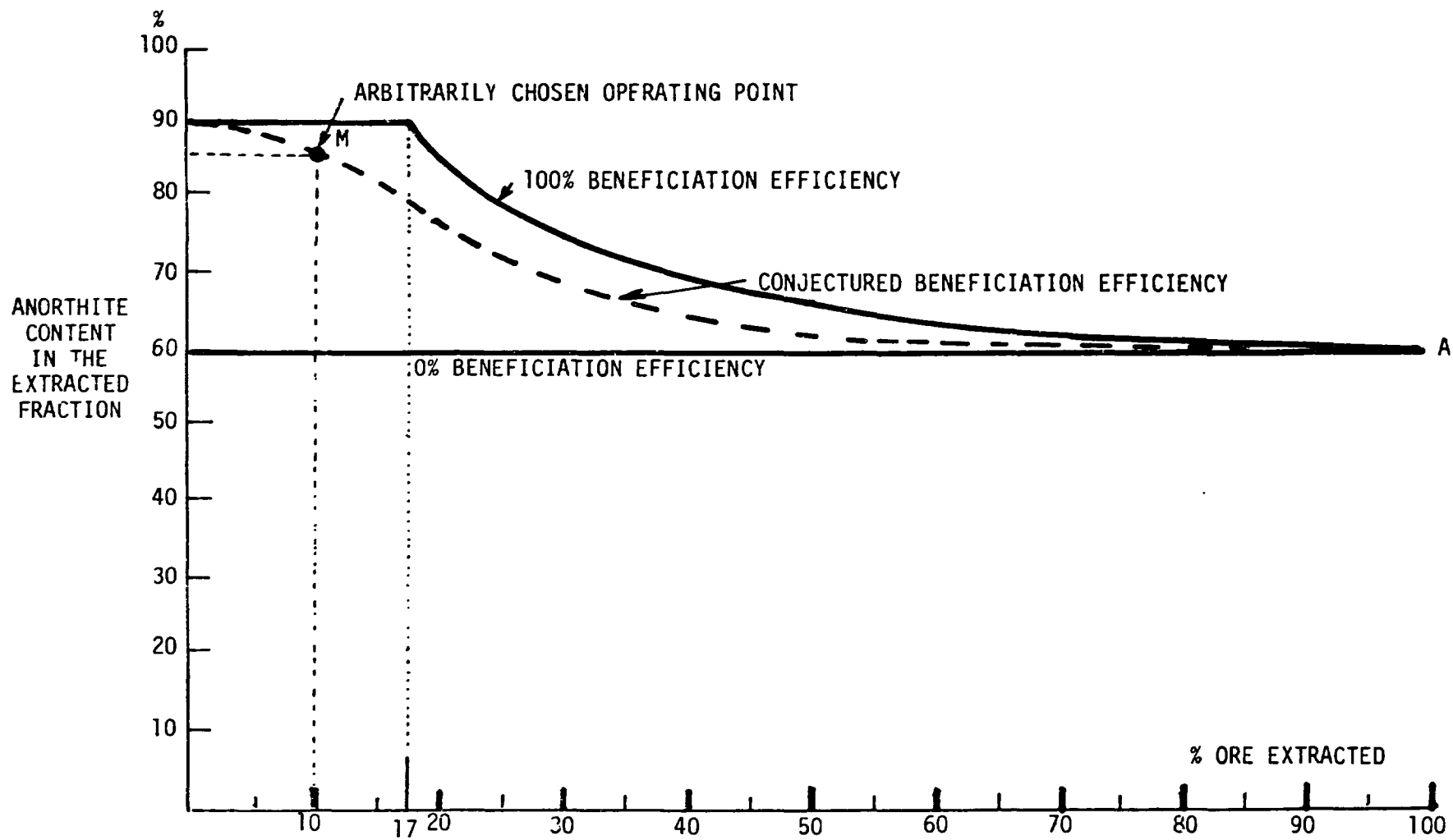
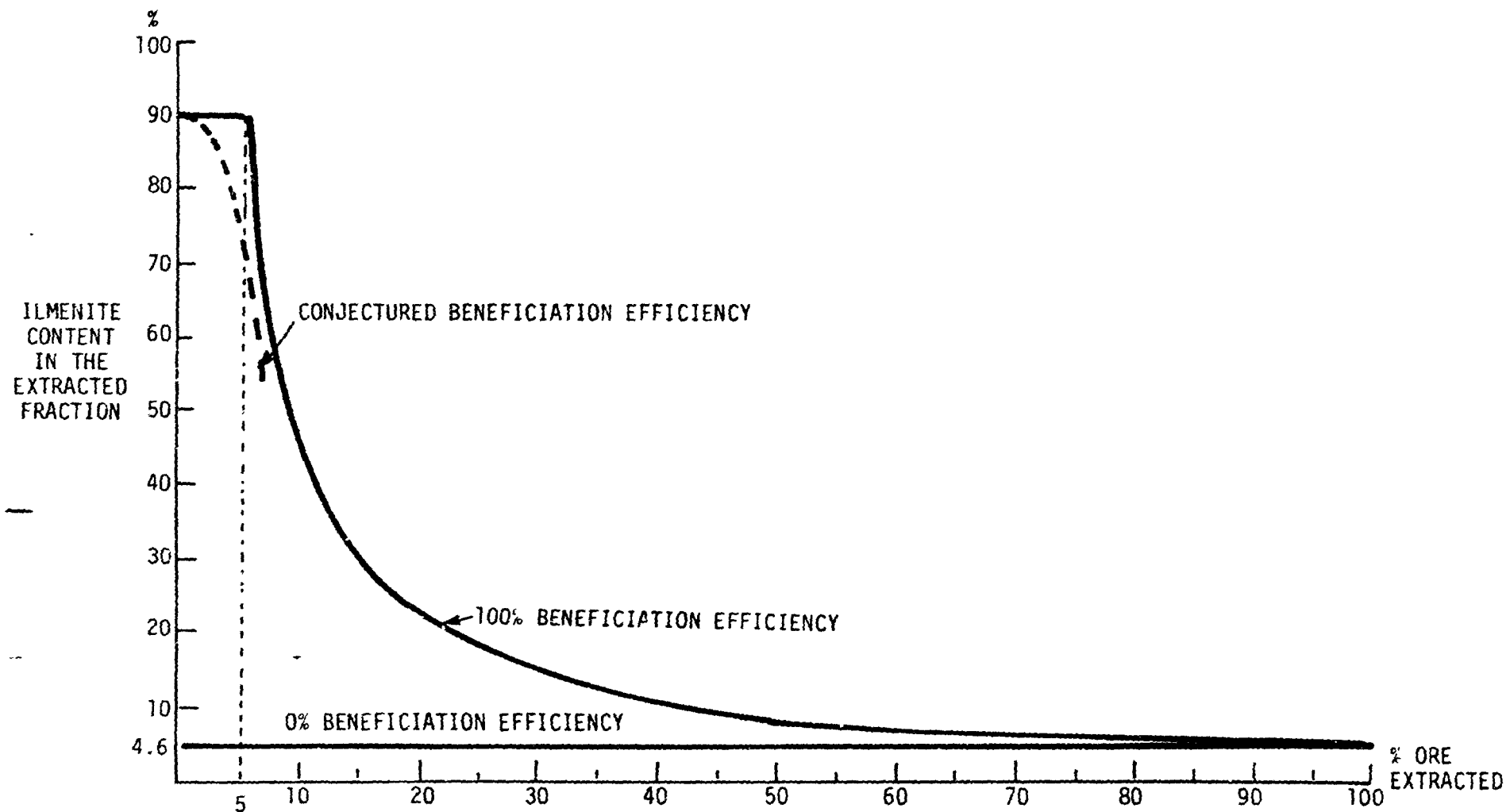


FIG. 8. ELECTROSTATIC BENEFICIATION OF ANORTHITE FINES [$< 37 \mu\text{m}$] FROM LUNAR HIGHLAND REGOLITH [APOLLO 14 SAMPLES]



IV-43

FIG. 9. ELECTROSTATIC BENEFICIATION OF ILMENITE [90 - 150 μ m FRACTION] FROM LUNAR MARIA [APOLLO 11 AND 17 SAMPLES]

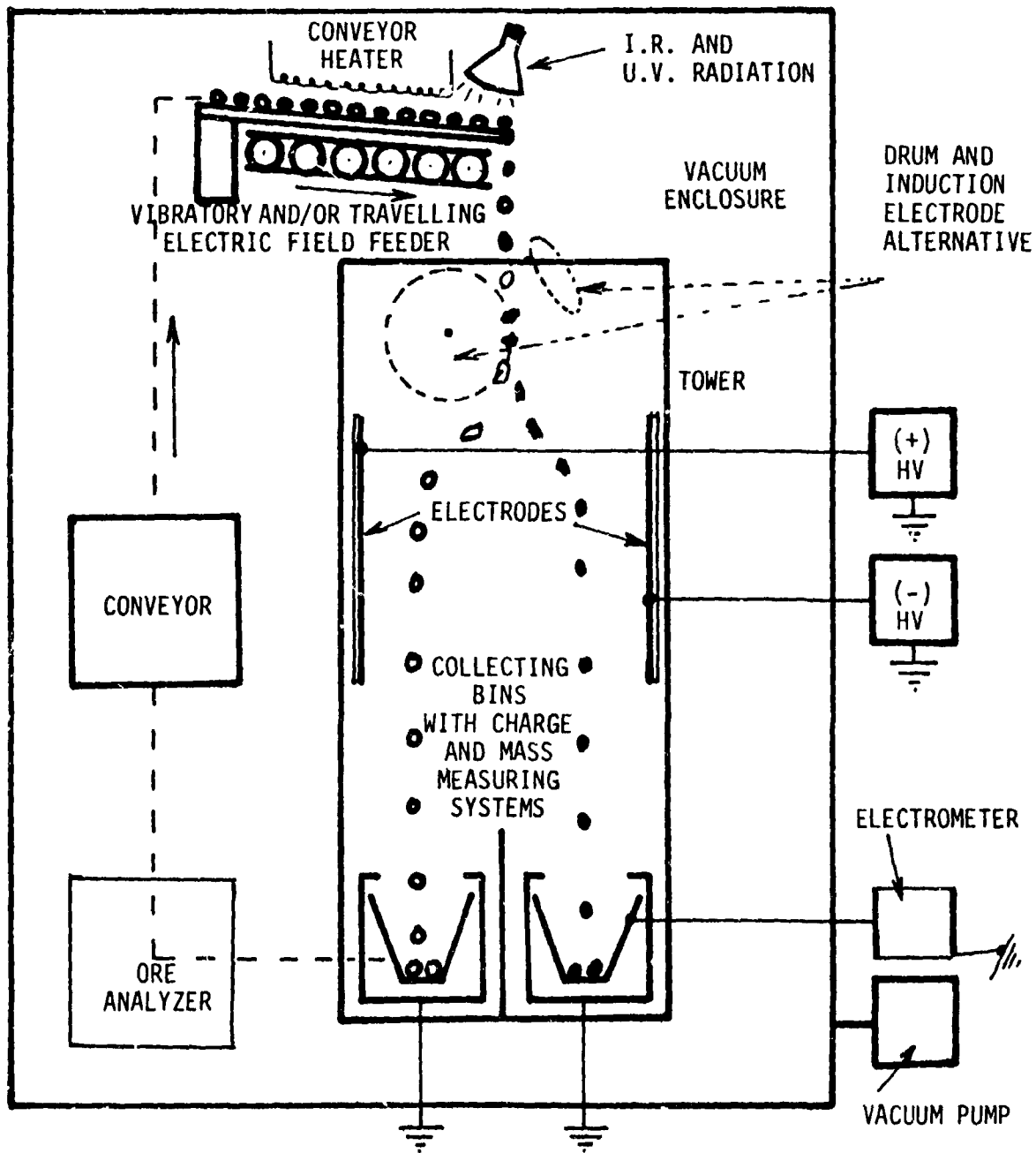
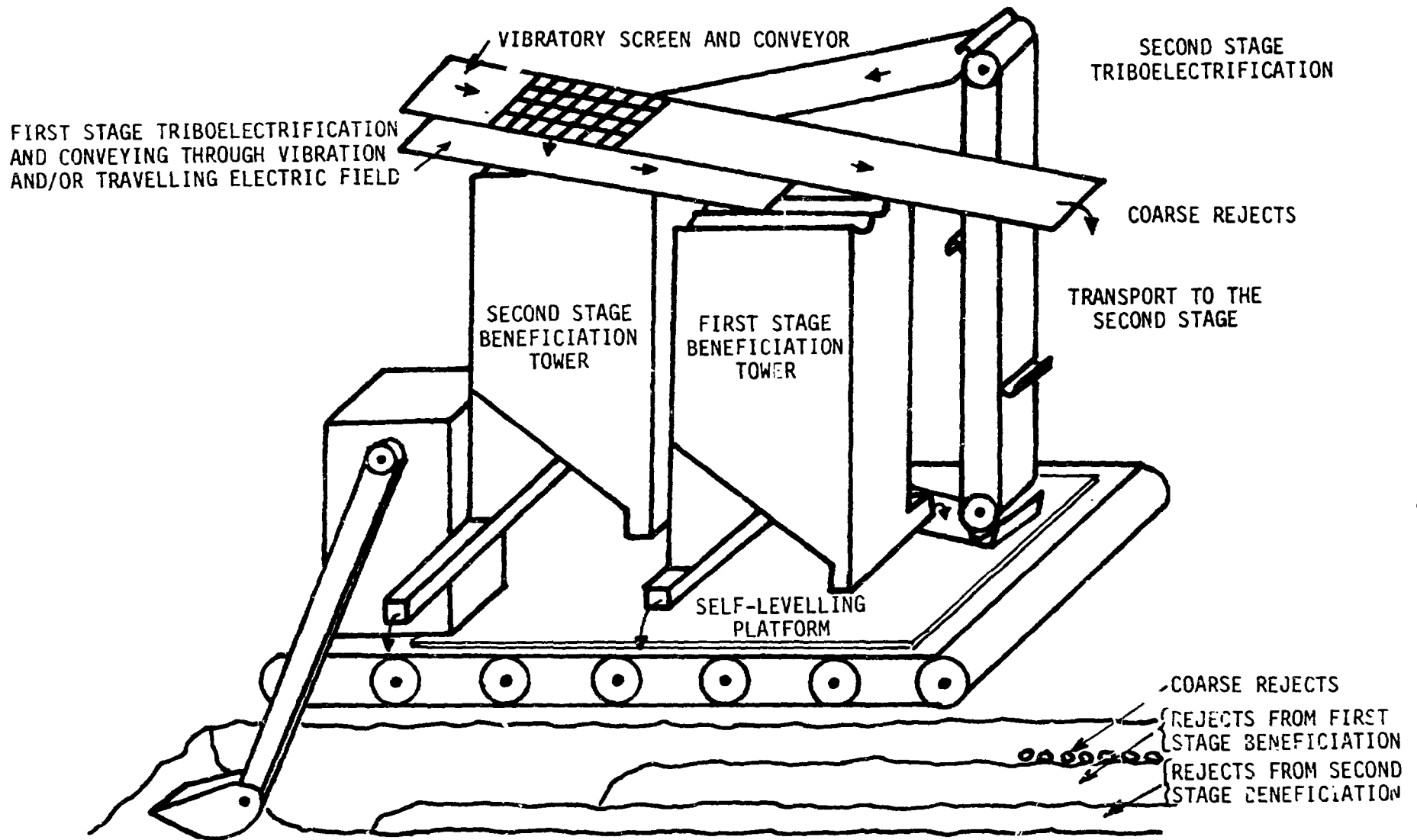


FIG. 10. CONCEPTUAL DESIGN FOR AN EXPERIMENTAL APPARATUS WITH WHICH TO STUDY THE ELECTROSTATIC SEPARATION OF THE LUNAR SOILS ON EARTH



IV-45

FIG. 11. CONCEPTUAL DESIGN FOR A MOBILE UNIT FOR SIMULTANEOUS MINING AND BENEFICIATION OF ORES USING TRIBOELECTRIFICATION AS THE CHARGING PROCESS

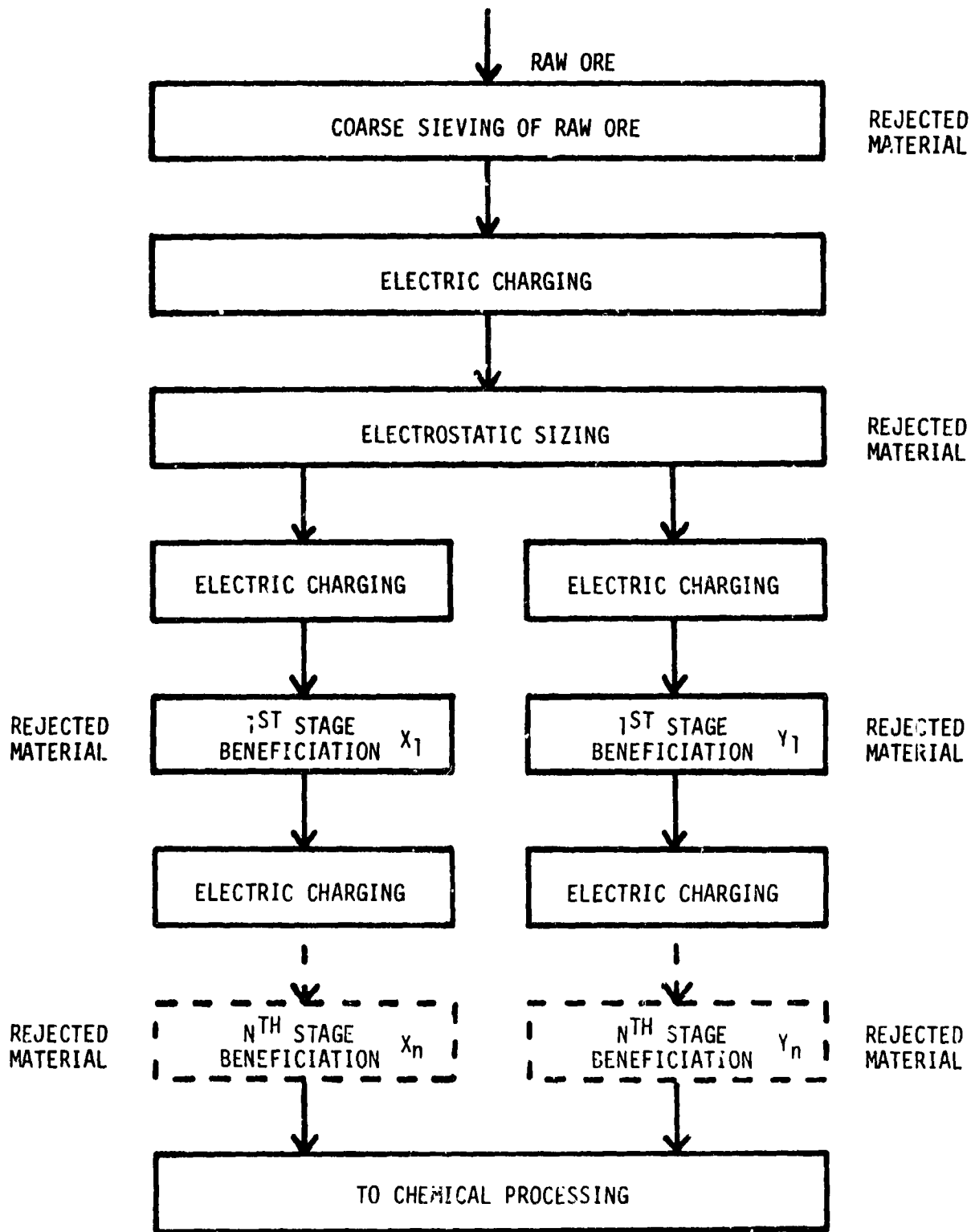


FIG. 12. ELECTROSTATIC BENEFICIATION OF ORES MATERIAL FLOW CHART [GENERAL CASE]

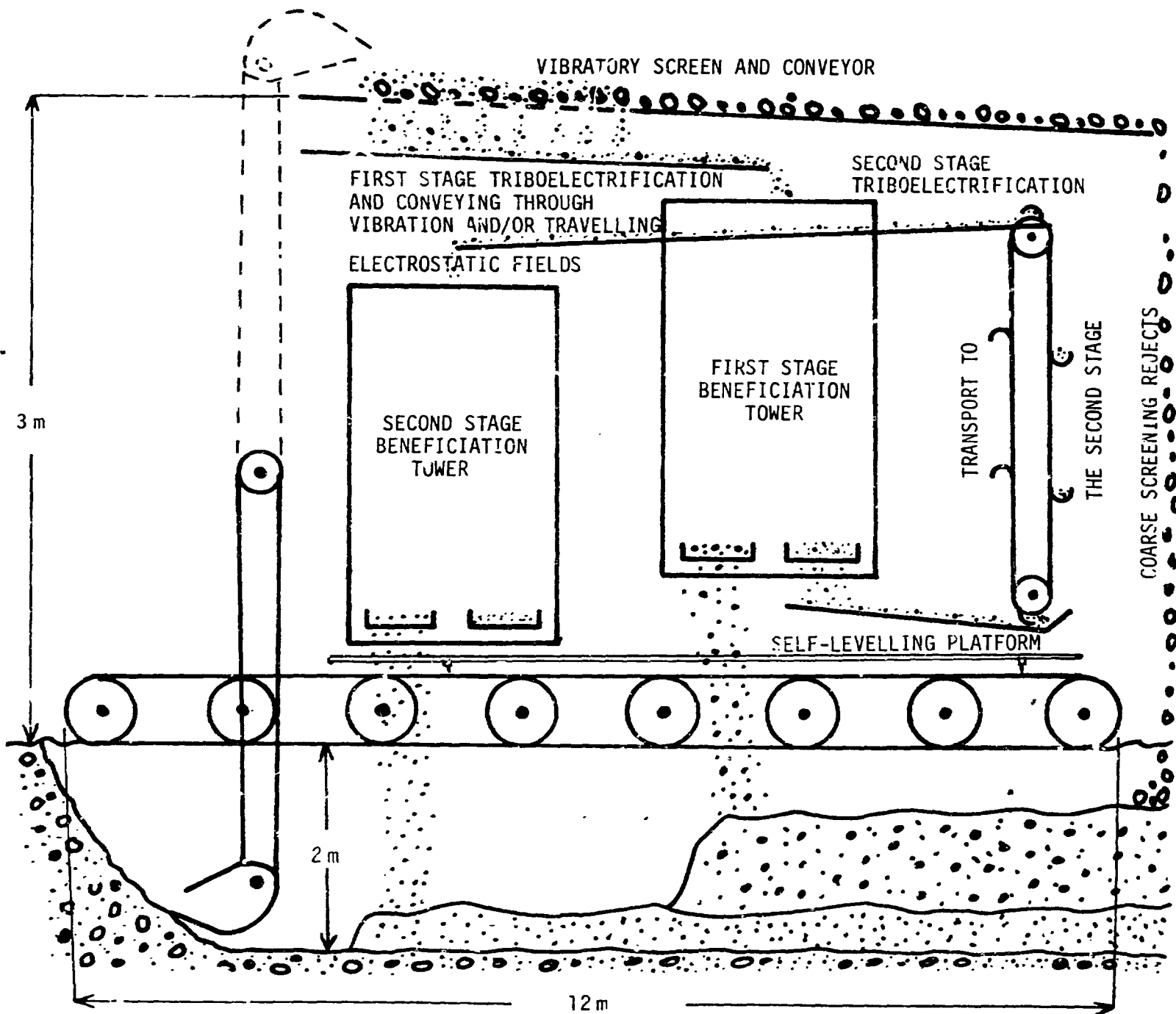


FIG. 13.

CONCEPTUAL DESIGN FOR A MOBILE UNIT FOR SIMULTANEOUS MINING AND BENEFICIATION OF ORES USING TRIBOELECTRIFICATION AS THE CHARGING PROCESS

[CONJECTURAL DIMENSIONS]

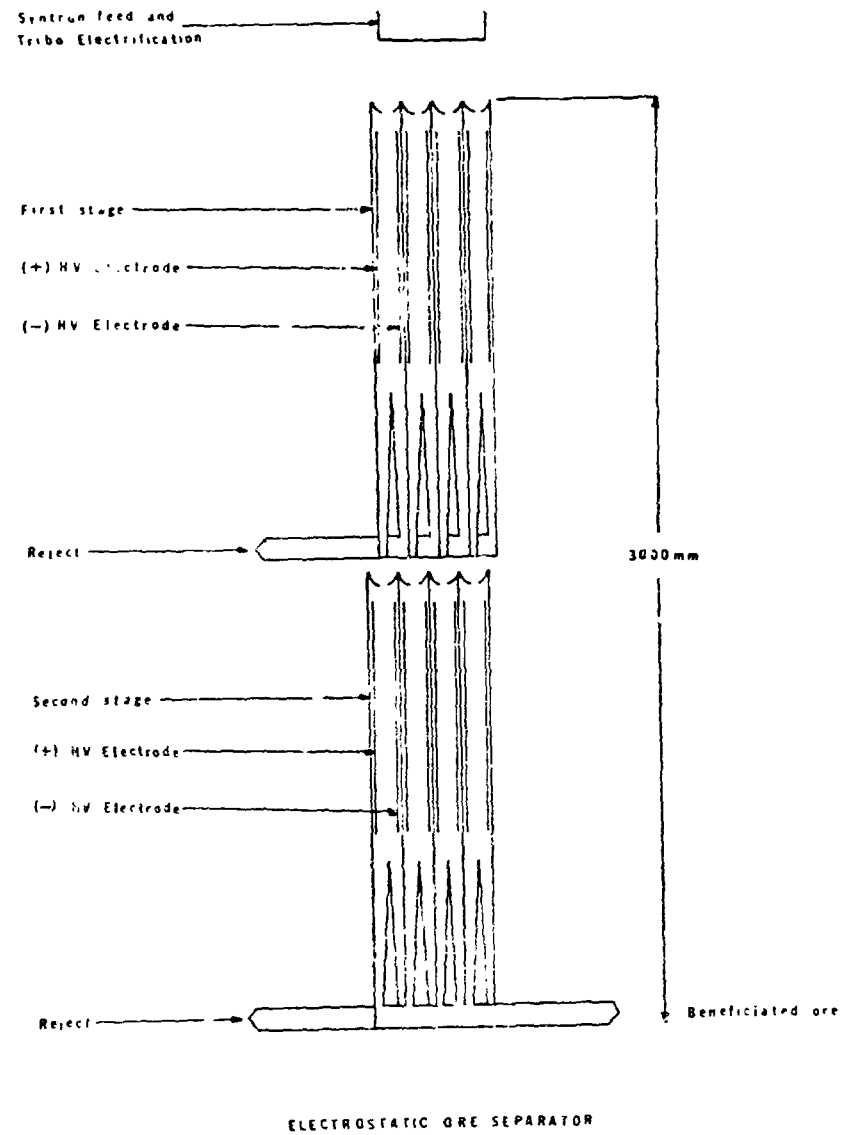
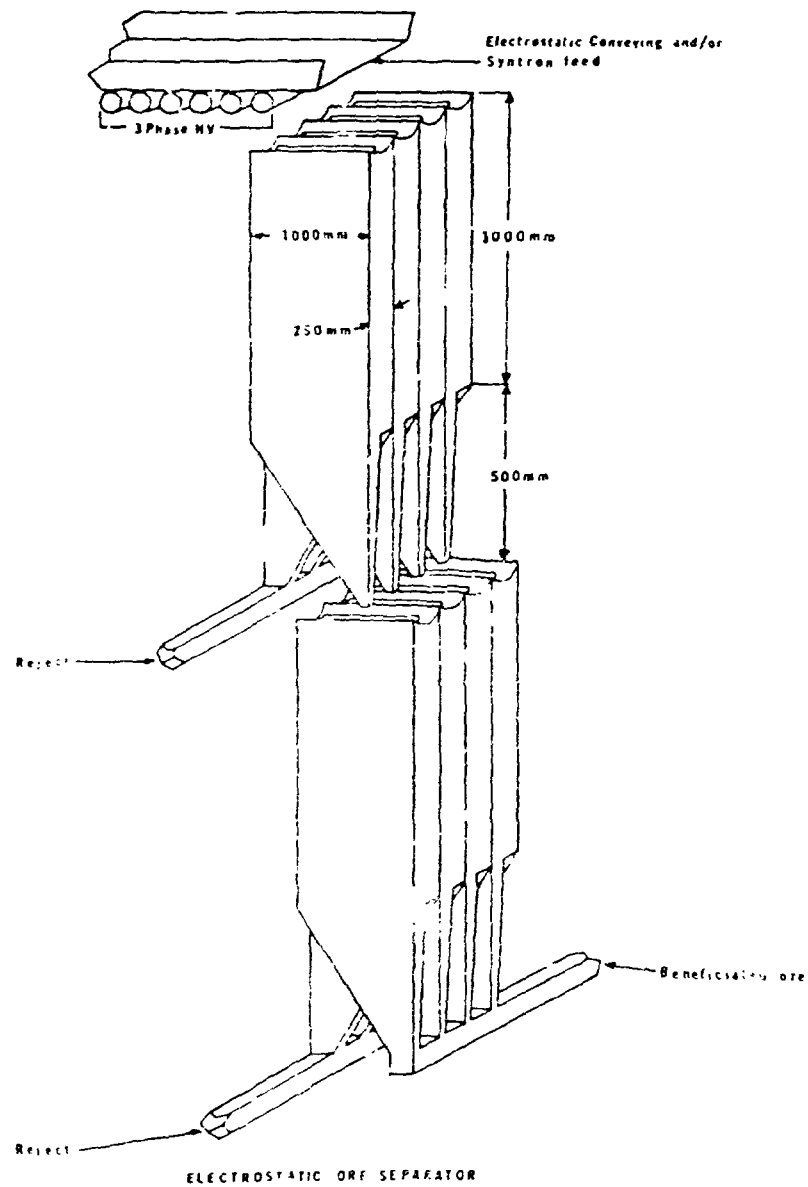


FIG. 14. CONCEPTUAL DESIGN OF A VERTICAL ARRANGEMENT, TWO-STAGE ELECTROSTATIC SEPARATOR TO HANDLE 30 TONS/HOUR [CONJECTURAL DIMENSIONS]

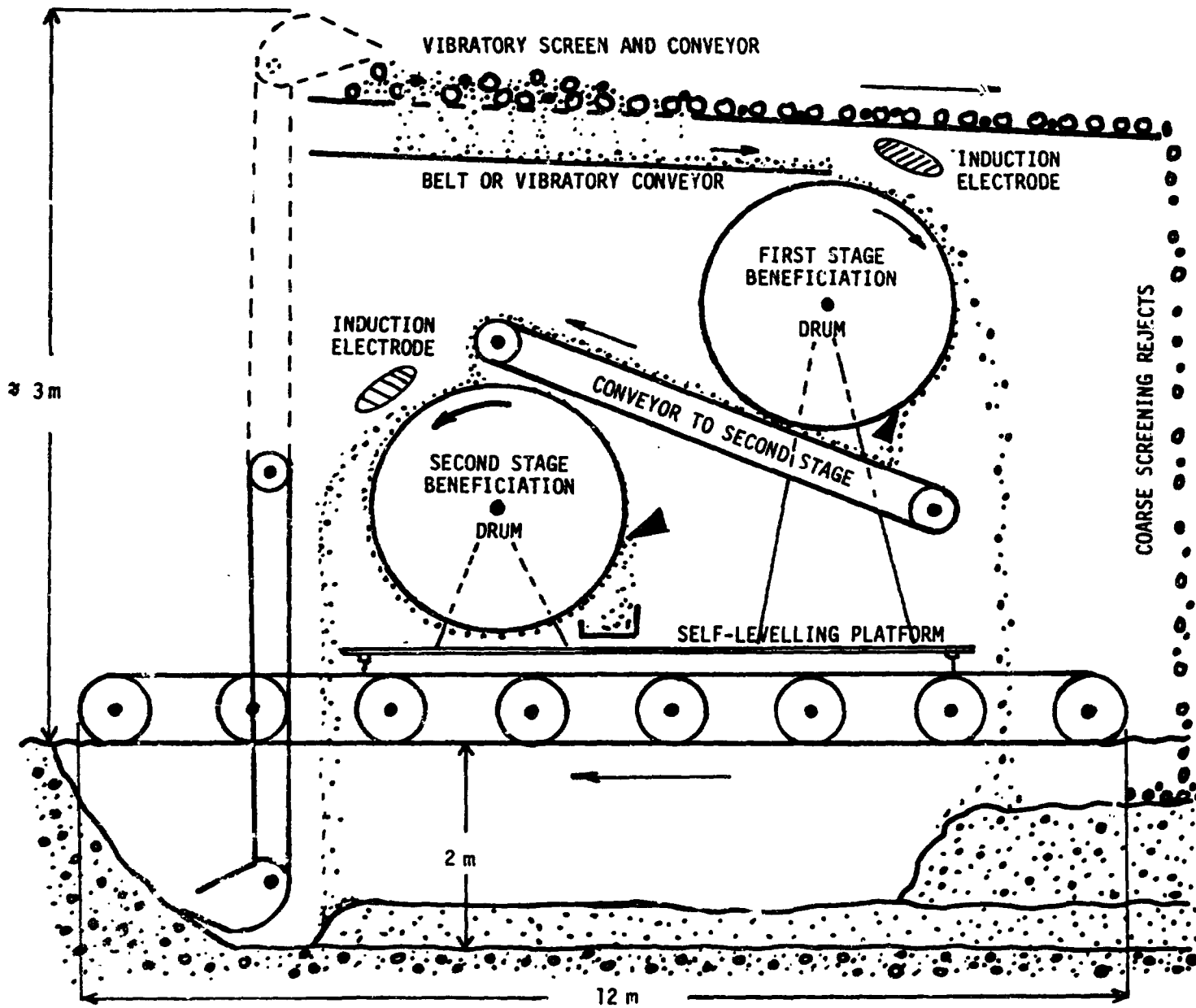


FIG. 15.
 CONCEPTUAL DESIGN
 FOR A MOBILE UNIT
 FOR SIMULTANEOUS
 MINING AND BENE-
 FICIATION OF ORES
 USING DRUMS AND
 INDUCTION OR HEATED
 CATHODE ELECTRODES
 [CONJECTURAL DIMENSIONS]

K. APPENDICES

A. PATENTS

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2. U.S. Patent #2,805,769 - "Beneficiation of Nonmetallic
Minerals," J.E. Lawver. Sept. 10, 1957.
3. U.S. Patent #3,249,225 - "Electrostatic Separation Means,"
O.M. Stuetzer et al. May 3, 1966.
4. U.S. Patent #3,477,568 - "Electrostatic Separation of Round
and Nonround Particles," R.W. Madrid. Nov. 11, 1969.
5. U.S. Patent #2,328,577 - "Process and Apparatus for Grading
and for Coating with Comminuted Material," N.E. Oglesby.
Sept. 7, 1943.
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Conductors from Non-Conductors," L.I. Blake and
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Sept. 10, 1957

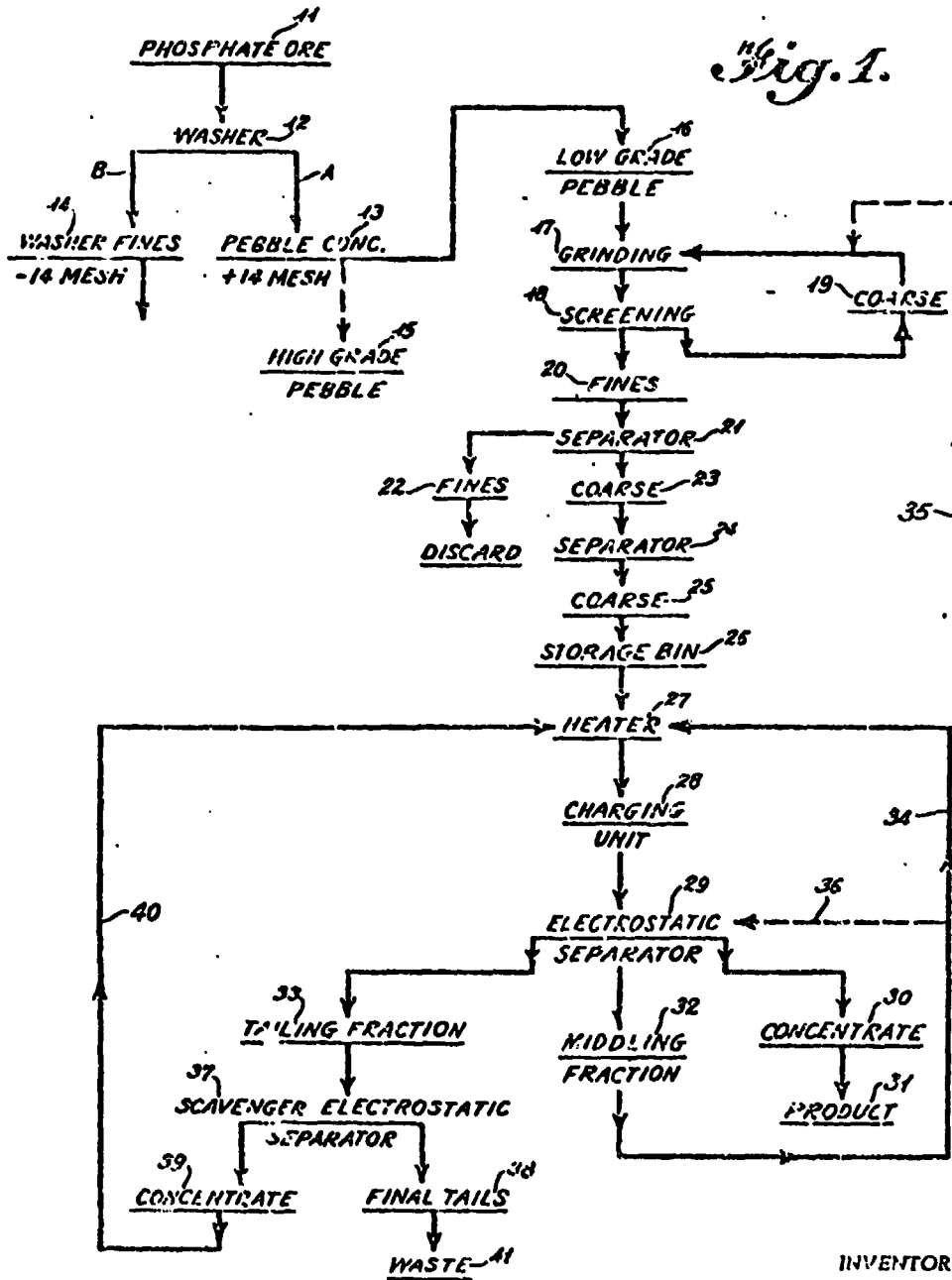
J. E. LAWVER

2,805,769

BENEFICIATION OF NONMETALLIC MINERALS

Filed June 20, 1957

3 Sheets-Sheet 1



INVENTOR
James E. Lawver

BY
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ATTORNEYS

Sept. 10, 1957

J. E. LAWVER

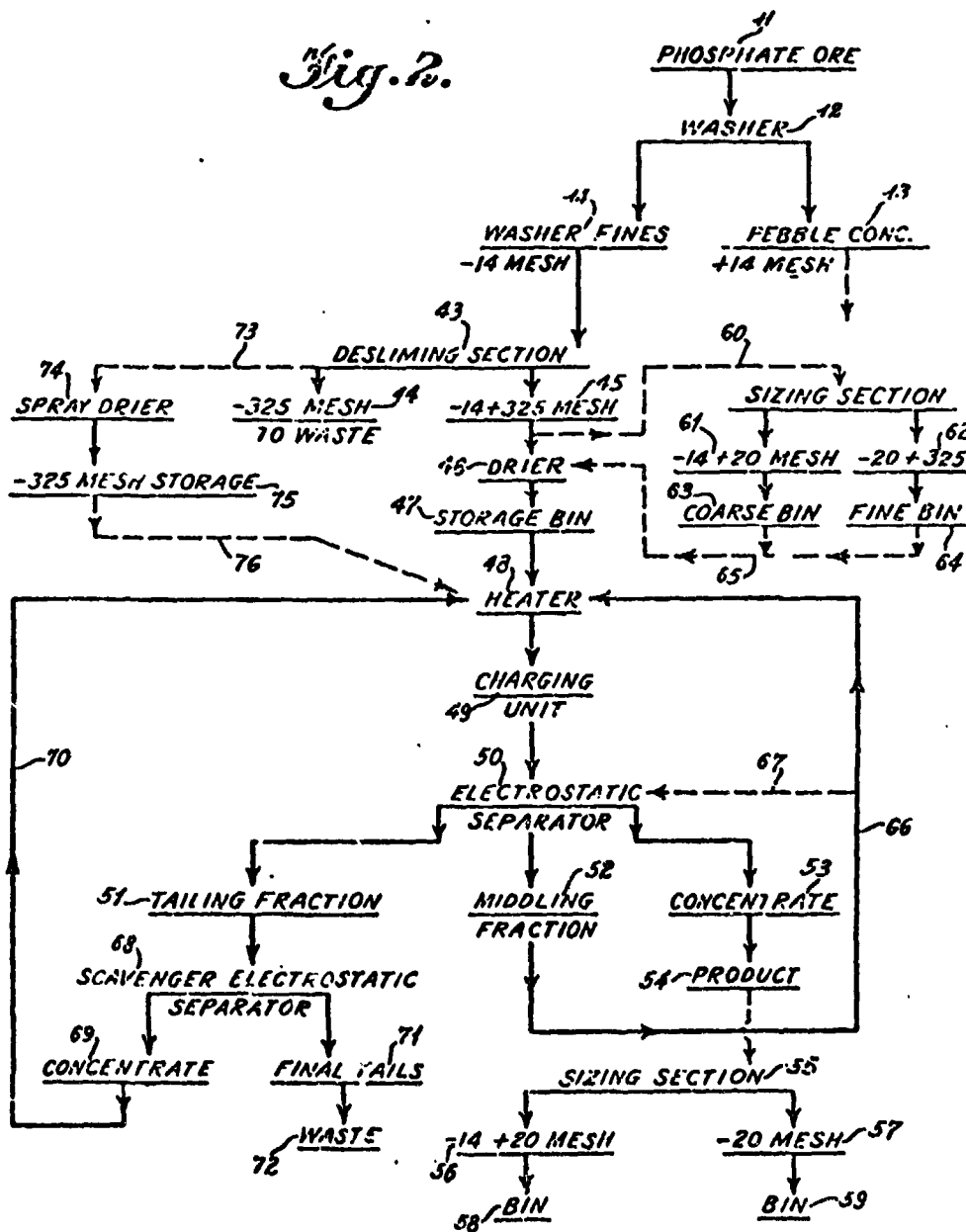
2,605,769

BENEFICIATION OF NONMETALLIC MINERALS

Filed June 20, 1957

3 Sheets-Sheet 2

Fig. 2.



INVENTOR

James E. Lawver

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J. E. LAWVER

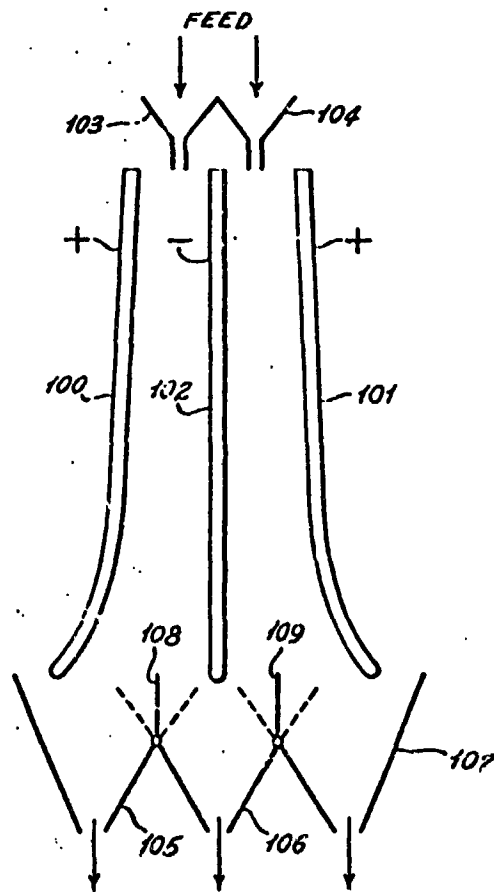
2,805,769

BENEFICIATION OF NONMETALLIC MINERALS

Filed June 20, 1957

3 Sheets-Sheet 3

Fig. 3.



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INVENTOR

James E. Lawver

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ATTORNEYS

May 3, 1966

O. M. STUETZER ET AL

3,249,225

ELECTROSTATIC SEPARATION MEANS

Filed Feb. 9, 1962

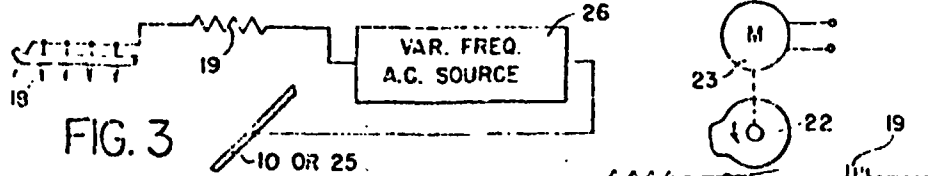


FIG. 3

FIG. 1

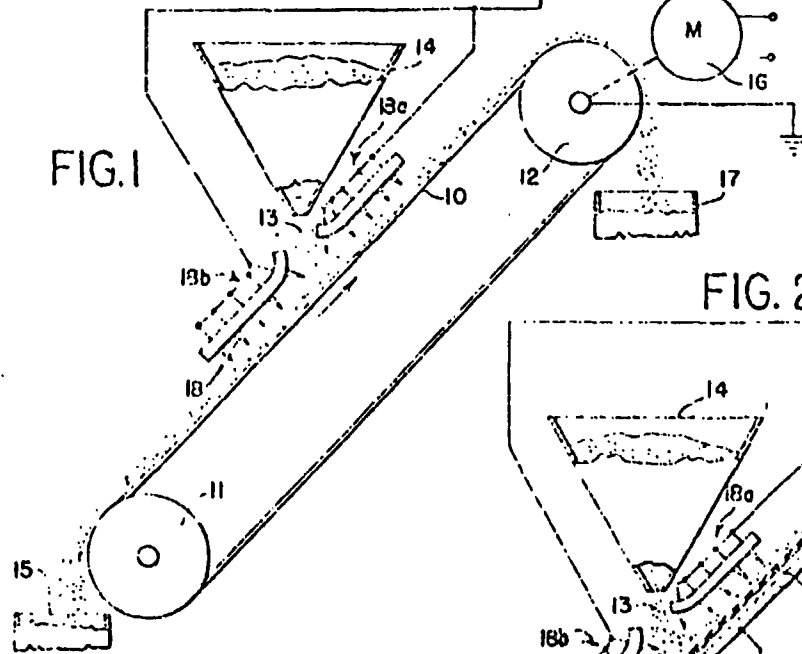


FIG. 2

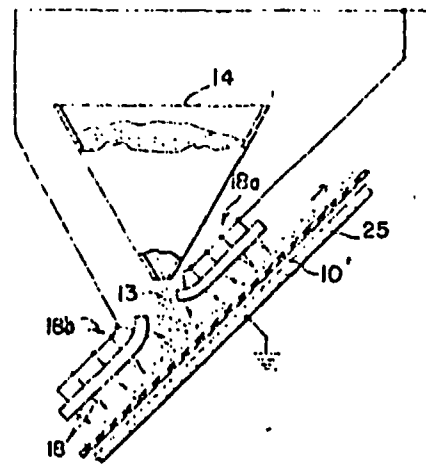
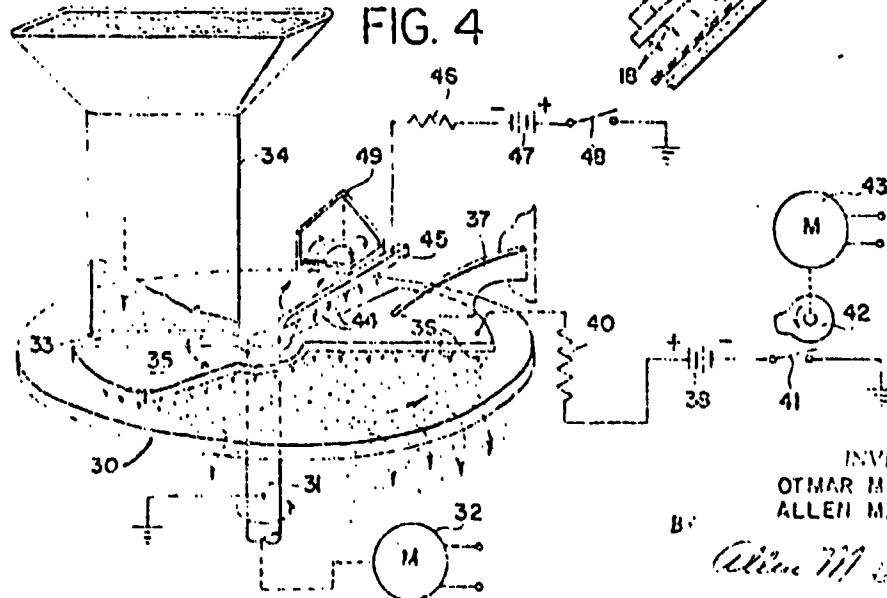


FIG. 4



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INVENTORS
OTMAR M. STUETZER
ALLEN M. SUTTON

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ELECTROSTATIC SEPARATION OF ROUND AND NONROUND PARTICLES

Filed Nov. 1, 1966

2 Sheets-Sheet 1

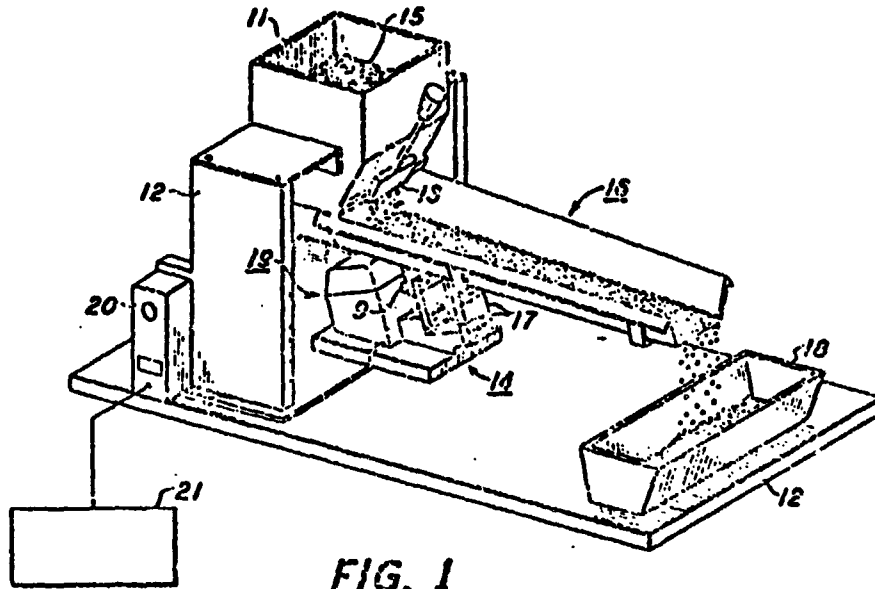


FIG. 1

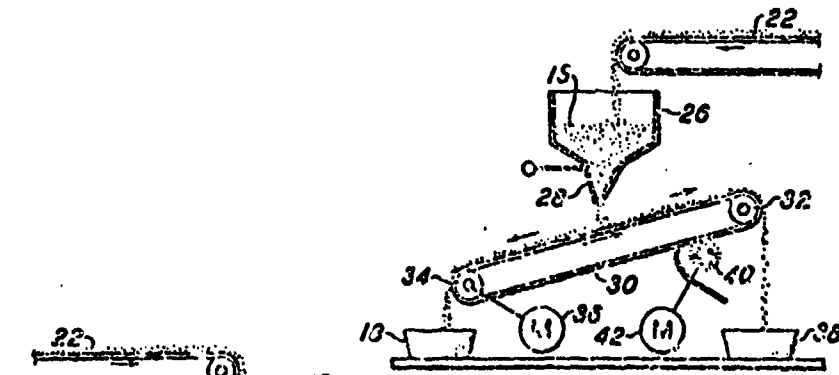


FIG. 2

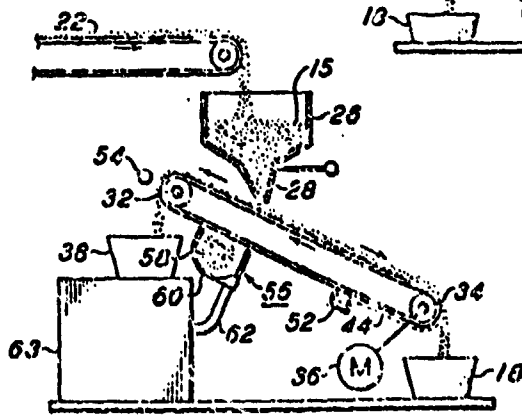


FIG. 3

INVENTOR
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Nov. 11, 1969

IV-57

R. W. MADRID

3,477,566

ELECTROSTATIC SEPARATION OF ROUND AND NONROUND PARTICLES

Filed Nov. 1, 1966

2 Sheets-Sheet 2

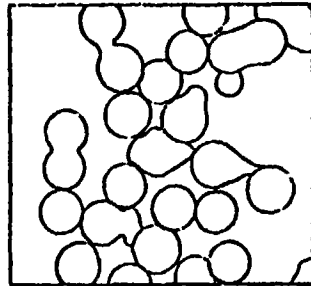


FIG. 4A

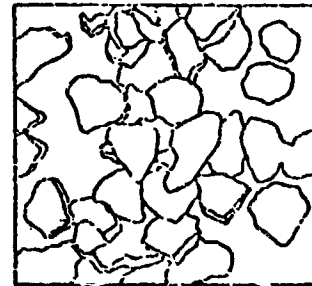


FIG. 4B

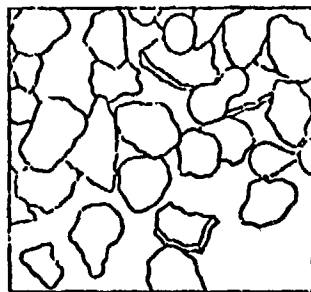


FIG. 4C

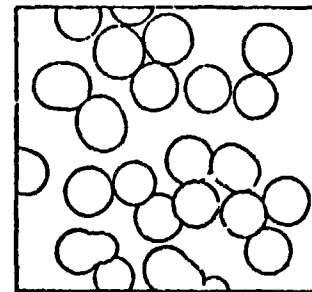


FIG. 4D

INVENTOR
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James J. Roeschke
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Sept. 7, 1943.

N. E. OGLESBY
 PROCESS AND APPARATUS FOR GRADING AND FOR
 COATING WITH CONDUCTIVE MATERIAL
 Filed Jan. 12, 1940

2,328,577

2 Sheets-Sheet 1

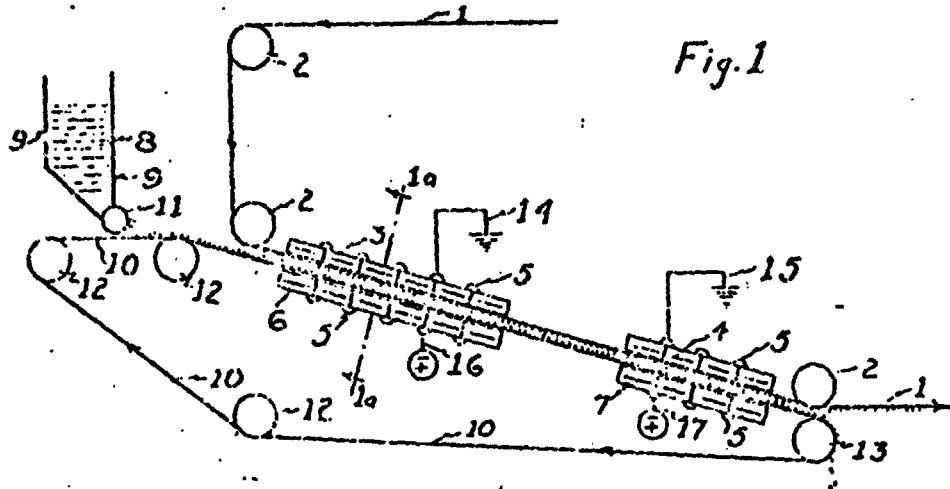


Fig. 1

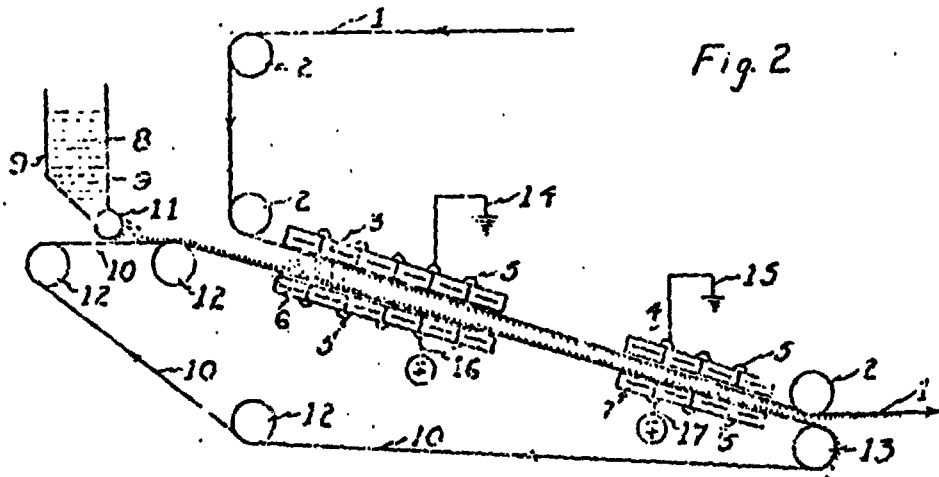


Fig. 2

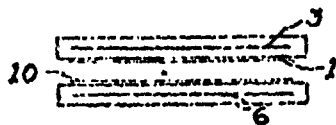


Fig. 1a

INVENTOR

Nicholas E. Oglesby

BY

William D. ...
 ATTORNEYS

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 OF POOR QUALITY

Sept. 7, 1943.

N. E. OGLESBY
PROCESS AND APPARATUS FOR GRADING AND FOR
COATING WITH COMBUSTIBLE MATERIAL
Filed Jan. 12, 1940

2,328,577

2 Sheets-Sheet 2

Fig 3

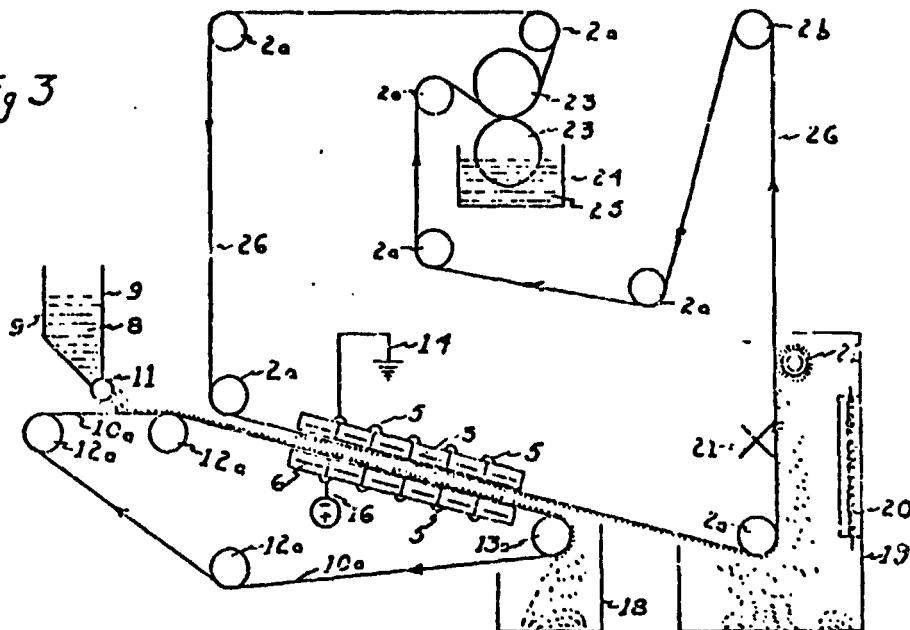
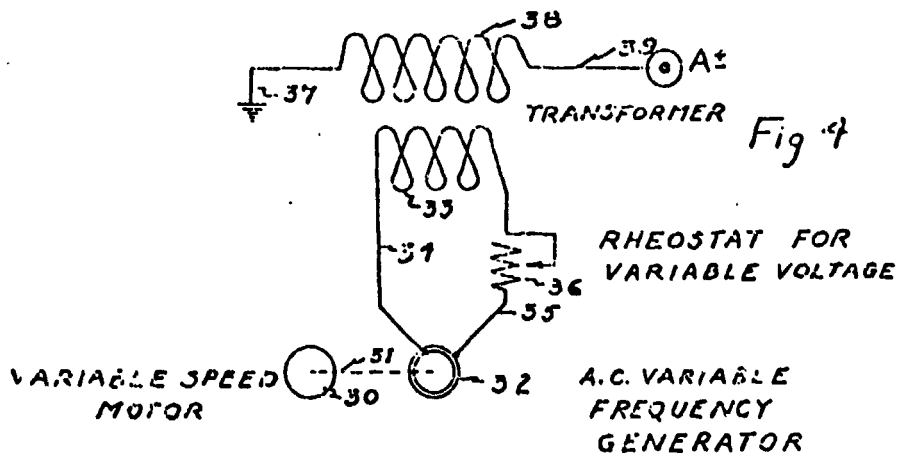


Fig 4



INVENTOR

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BY

William D. ...
ATTORNEYS

No. 668,791.

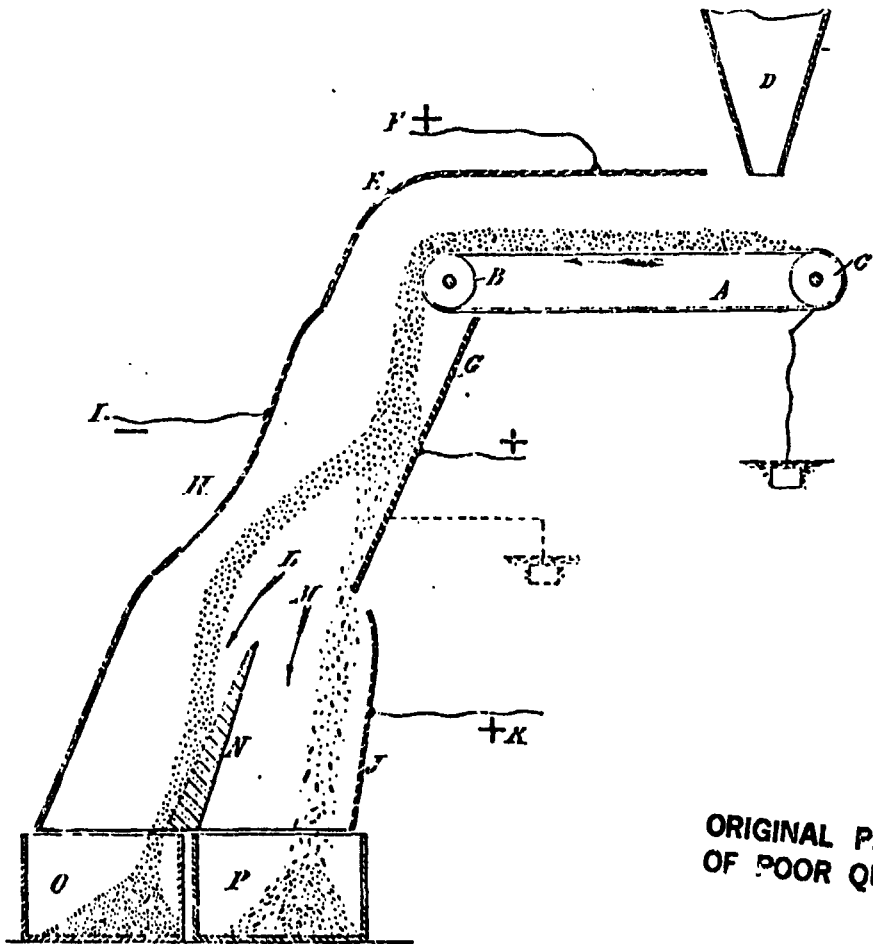
Patented Feb. 26, 1901.

L. I. BLAKE & L. N. MORSCHER.

PROCESS OF ELECTRICAL SEPARATION OF CONDUCTORS FROM NON-CONDUCTORS.

(Application filed Mar. 16, 1900.)

(No Model.)



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WITNESSES:

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B. TRIBO AND TRAVELLING FIELDS

(Excerpt from "Applications of Electric Curtain in the Field of Electrostatic Powder Coating", S. Masuda, S. Mori and T. Itoh. Speech at the 1975 Conference of the Electrostatics Society of America, Univ. of Michigan, June 24-26, 1975.)

1. Introduction

A set of parallel cylinder electrodes, insulated from each other and connected to a single-phase or poly-phase ac source, forms in its surroundings a series of non-uniform standing or travelling wave fields, which act on charged particle cloud just like a contactless barrier or contactless conveyor. The apparatus based on this principle was named "Electric Curtain". In the practical use of the electric curtain apparatus, it often becomes necessary to combine suitable dielectric sheet in contact with the electrode series, in order to prevent leakage of poorly charged particles. (Fig. 1) In this case however, it was observed that, without any pre-charging, the powder deposited on the sheet could sometimes be violently ejected into space and then transported.

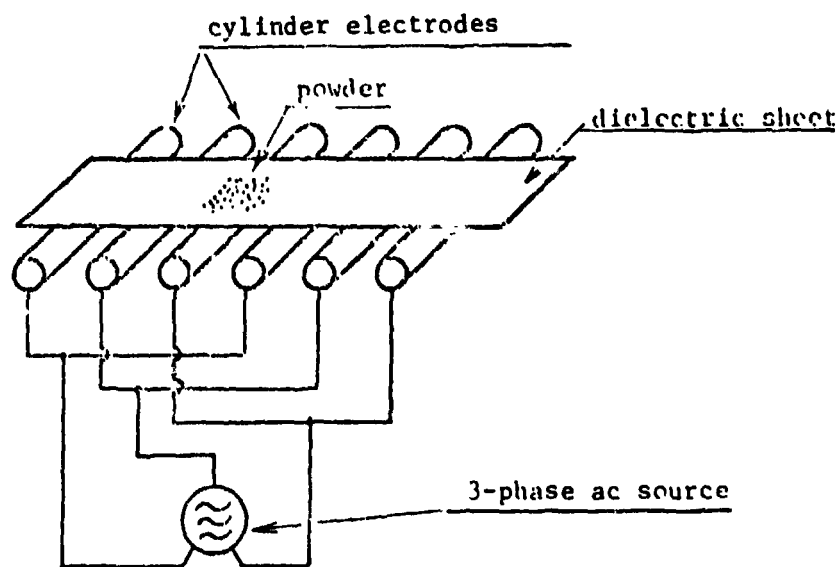


Fig. 1 Structure of contact-type electric curtain (travelling wave type)

Considering this special effect brought about by the contact sheet, one of the authors named this type of the apparatus "Contact-type Electric Curtain". Based on its possible action of exciting contact-electrification, the dielectric sheet was named "Exciter"⁽¹⁾. The contact-type electric curtain has various fields of application, such as powder feeder, powder conveyor, powder recovery apparatus, powder gun for powder coating, dust removal device for cloth filters, etc.

In this paper, the applications of both the contact-type and noncontact-type electric curtain in the field of electrostatic powder coating are reported, with special emphasis on Electric Curtain Booth⁽²⁾, which allows quick color change and highly efficient recovery of overspray and the inside lining system⁽³⁾ with powder paint for small diameter steel pipes.

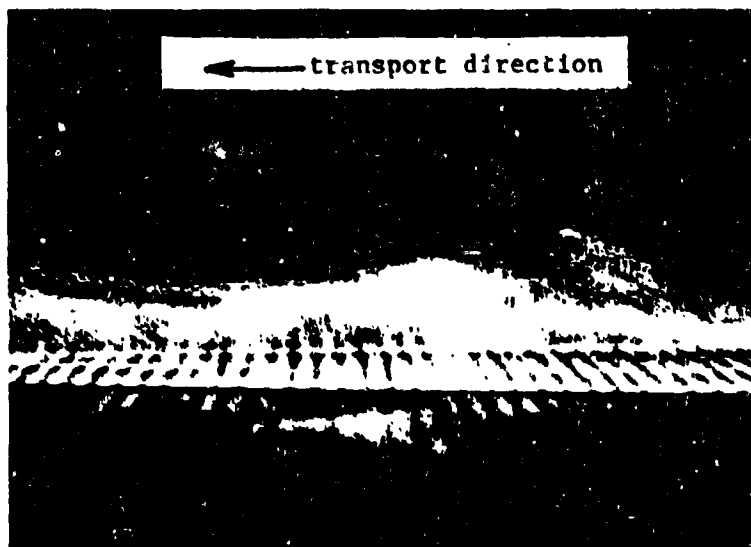


Photo. 1 Ejection and transport of powder deposit (polyethylene powder paint)

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C. FORCES ON CHARGED PARTICLES

(Excerpt from "Electrostatics in Industry", I.I. Incelet. *Journal of Electrostatics*, 4, No.2, 175-192, 1977/1978.)

2.1 Forces on conductive spherical particles of radius r placed into a uniform electric field E_0 in air at standard pressure and temperature

Referring to Fig.1:

(a) The electric field is distorted as shown. On the surface of the particles, the field is perpendicular to it and varies sinusoidally, reaching a maximum of three times the value of E_0 along the z -axis.

(b) Two equal and opposite resultant electrostatic forces F_R appear which tend to pull the particle apart.

(c) If the particle is a liquid, it will change its shape becoming elongated, and if the surface tension is exceeded by the electrostatic forces, the particle will break into two or more particles — some positively, and an equal number negatively, charged.

2.2 Maximum force on a conductive spherical particle of radius r charged by ion bombardment to saturation and placed in a uniform electric field E_0

Referring to Fig.2, where it is assumed that the saturation charge is represented by the situation in which no field lines of E_0 land on the charged particle and that the resultant electric field intensity at the upstream point $E_{pu} = 0$:

(a) Under these conditions, the resultant electric field intensity on the surface of the particle can be described by the sinusoidal expression $E_r = 3 E_0 (1 + \cos \theta)$ and has a maximum value of $6E_0$.

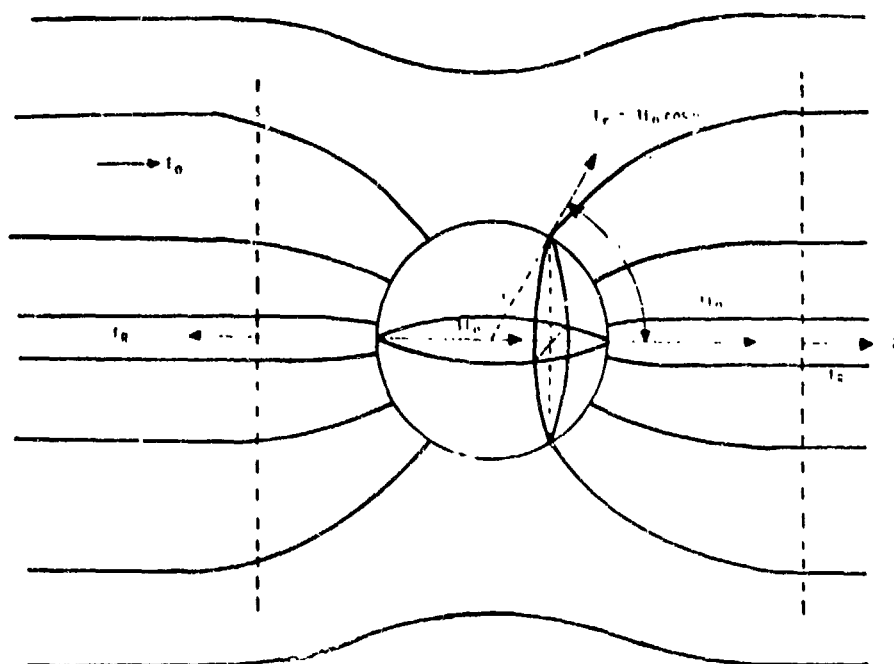


Fig.1. Conductive spherical particle in a uniform electric field E_0 .

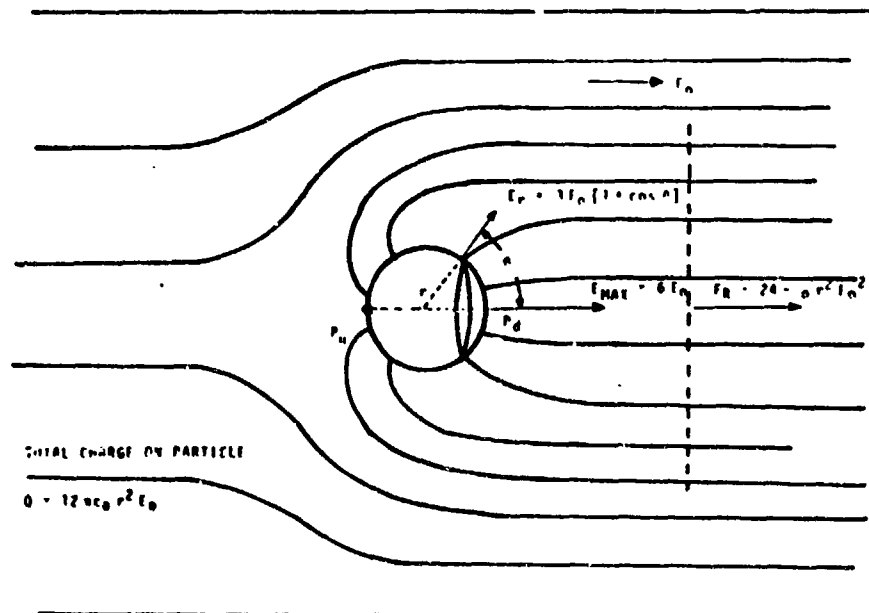


Fig. 2. A "fully" charged *conductive* spherical particle in a uniform electric field.

(b) The total force on the particle = $24 \pi \epsilon_0 r^2 E_0^2$.

It is worth noting that whatever is the maximum value of the dielectric strength in the particular medium (under the particular conditions of temperature, pressure and radius of the sphere), to avoid the discharge of the particles, one must consider a value for the applied uniform electric field which is smaller than one-sixth of the dielectric strength of the medium.

2.3 Size of *conductive** spheres of radius r which electrostatic forces can lift under ideal conditions using a value of 3 MV/m^{**} as the dielectric strength of the air

Equating the electrical force with the gravitational force, one finds the maximum radius for a spherical particle of iron to be $r_{\text{max}} \approx 1 \text{ mm}$, and for a spherical particle of water, $r_{\text{max}} \approx 8 \text{ mm}$.

*For a dielectric material, a correction factor is introduced in the calculation of the saturation charge. Saturation charge may be defined as the minimum charge which prevents any ion of the same polarity which may be present in the field from landing on the particle. Neglecting the tangential components of the electric field at the surface of a dielectric sphere placed in a uniform electric field, the radial component may be approximated by

$$E_r = [2(\epsilon_r - 1)/(\epsilon_r + 2) + 1][E_0 \cos \theta + 1].$$

$$\text{Assuming } \epsilon_r = 4, E_r = 2 E_0 (\cos \theta + 1).$$

Hence, at the maximum force conditions, the value of the uniform electric field into which the charged sphere may be placed is greater than for the *conductive* sphere case.

**One must realize that depending on the radius of the particle, this value may be ten or more times greater.

At the other end of the scale, very small particles such as a 10- μ m-radius conductive droplet of water may be lifted by electrostatic forces which are 400 times greater than that of gravity.

Correspondingly, a 10- μ m-radius spherical particle made out of steel may be lifted by means of an electrostatic force which is 50 times greater than that of the force of gravity.

2.4 Dielectrophoretic forces (electrostatic forces on particles in non-uniform electric fields)

These arise from the polarization of the matter and the particles move towards the region of increasing field strength if the permittivity is greater than that of the medium. Contrary to the forces on charged matter, their direction is independent of the direction of the electric field.

In an idealized case of a very small neutral body which is linearly, homogeneously and isotropically polarizable, in a conservative static field at equilibrium, the force $\vec{F} = (\vec{p} \cdot \nabla) \vec{E}_0$ where \vec{p} is the dipole vector.

V. LUNAR GLASS AND CERAMIC PRODUCTS

A. 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 industry in 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.

B. 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:

- (1) Lunar soil as found
- (2) Anorthite from purified plagioclase
- (3) Silica from silicon oxidation
- (4) Alumina and Magnesia

B.1 LUNAR SOIL AS FOUND

The chemical compositions of three samples of lunar soils³ (Apollo 11, Apollo 12 and Apollo 16) are shown in Table I 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 soil, as found, that is not separated into lithic fragments, mineral fragments, glass and agglutinates,¹ is thus a very feasible raw material for the manufacture of glass fibers and glass wool.

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 I had to be melted at 1500°C but the melt also formed glass readily on cooling.

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.⁹ 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.

B.2 ANORTHITE FROM PURIFIED PLAGIOCLASE

Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) obtained from plagioclase, has been suggested a raw material 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 anorthite,¹⁰ 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 by the addition of small amounts of Na₂O and the probability of devitrification can be reduced by the addition of SiO₂.¹² In general then, it can be concluded that colorless glass windows can be produced from basically anorthite alone or with additions of Na₂O 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.

B.3 SILICA FROM SILICON OXIDATION

Silica (SiO₂) is obtainable from the oxidation of silicon.¹ 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 instance, 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 SiO_2 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.

B.4 ALUMINA AND MAGNESIA

If fused silica does not have sufficient stability at temperatures in excess of 1700°C for long times, alumina (Al_2O_3) 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.

C. PROCESSING OF LUNAR MATERIALS - GENERAL CONSIDERATIONS

In the above section, it has been suggested that glass fibers and windows and glass-ceramics (pipes, tiles and load-bearing structures) can readily be made from lunar materials. Containers 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.

A comparison is made of the important differences of processing glass and ceramics on earth and on the moon or in space. Industrial productions of glass fibers, glass windows, glass-ceramics and refractories on earth are all highly complex technologies based on many years (and perhaps even centuries) of learning and experience. Such technologies are successful, and only successful, if the conditions of Table II are strictly adhered to. If one or more of such conditions are altered, both research and development must be done prior to pilot plant-scale process and large-scale production can be attempted. However, not all the new conditions are totally unpredictable or unacceptable. Of all the conditions listed in Table II, the processing of glass under high vacuum is the most difficult one envisaged. 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 advantages 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 unavoid-

able. 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 requires cooling water. 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, and 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 mirrors to melt glass to sinter ceramics has been practised for many years.¹⁷ It appears that "batch-type" processes (in contrast to "continuous" process) should be applicable to extraterrestrial operations without too many problems although large volume processing has not been studied on earth. The sintering of

ceramics such as SiO_2 , Al_2O_3 and MgO is particularly compatible with direct solar heating.

D. SOME SPECIFIC EXAMPLES OF PROCESSING COMMON GLASS AND CERAMICS IN SPACE AND ON THE MOON

D.1 PRODUCTION OF GLASS WINDOWS IN SPACE

Conditions: 1 atmosphere, zero gravity
 Energy Source: Electric resistance
 Glass Composition: Anorthite or modified anorthite

A specially designed melting furnace is shown in Figure 2. Flat glass is drawn through the opening 2 of the top 1 of the furnace. The molten glass 3 is not in contact with the bottom and walls of the furnace. A "bait" 4 is dipped into the melt to start the draw upwards. The pelletized batch is fed continuously at 5 and the hot drawn glass cooled by compressed air at 6. The solidified sheet is guided upwards by the rollers 8 and annealed inside furnace 7. The sheet is finally cut in the enclosure 9. The process shown is the so-called "Pennvernon" process. Horizontal draw can be made by a so-called "Fourcault" process. Even the "float-process" can be adopted. The most advantageous aspect of this space process is the minimal contact with refractory and the minimal loss of volatile components through the closed-up furnace and radiant electric melting. Normal energy requirement on earth is approximately 100 kw per tpd of glass products. 50% of this energy is actually wasted because of massive heat loss when gas or oil is combusted. It is envisaged that a space furnace utilizing electric heating probably needs only 50 KW per tpd*. Most industrial plants on earth produce approximately 400 to 600

* tpd= ton per day

tons of windows per day. Such large continuous operations are obviously not suitable for space. Smaller plants, and perhaps even "batch" rather than "continuous" processes may be more suitable in space.¹⁸

D.2 PRODUCTION OF GLASS WOOL IN SPACE OR ON THE MOON

Conditions:	1 atmosphere, zero gravity or 1 atmosphere, 1/6th g
Energy Source:	Electric resistance
Glass Composition:	Lunar soil, as found

A specially designed furnace is shown in Figure 3. The batch is either pelletized lunar soil or pre-melted lunar soil in the form of marbles. The batch is fed through a pre-heater at 1 and melted at 2. The molten glass runs into a rapidly rotating tray 3 and is ejected by centrifugal force at the nozzles at 4. The molten glass jet is broken-up into short lengths by compressed air at 5 and 6. The loose wool is collected at 7.

A glass wool production plant on earth producing 10,000 tons per year would require a capital investment of about \$5 million.¹⁹ Water usage is about 10 million gallons per year and energy need is about 100 kW per tpd. Approximately 10 persons are needed to operate the plant on a single shift, five-day week basis.

D.3 PRODUCTION OF REFRACTORIES ON THE MOON

Conditions:	Vacuum, 1/6th g
Energy Source:	Solar via focussing mirrors
Compositions:	SiO ₂ or Al ₂ O ₃ or MgO

The process suggested by Ho and Sobon can be adapted for this plant.² Because the vapor pressures of SiO₂, Al₂O₃ and

MgO are relatively low at sintering temperatures, vacuum processing of the pressed solid powders should pose no problem. Tromba has already designed the apparatus for such applications.¹⁷ Refractory bricks or panels, and indeed tubes can be made this way.

E. SPECIAL "GLASSES" BASED ON HIGH VACUUM AND/OR ZERO GRAVITY

High vacuum and zero gravity in space has led Happe to suggest the preparation of specialty glasses of high refractive index through the suppression of heterogeneous nucleation.¹⁴ The evaporation of solid oxides under a high vacuum and condensing the vapor on a relatively cold substrate can lead to many "amorphous" solids.²⁰ Non-crystalline silica made this way is practically indistinguishable from melt-formed silica glass. It is possible that by direct mirror focusing methods, by electric resistance heating or by laser, many oxide powders can be melted or sublimed in high vacuum. The vapor, if no disproportionation occurs, can be collected on a substrate. Flat plates of silica can probably be made this way to give transparent windows.

High purity glass fibers made for wave-guide applications cost about \$1 per foot for a 10 μ diameter fiber. Most of these fibers are based on SiO₂ prepared by vapor-phase deposition. Such wave-guides are predicted to become the dominant components in communications. The \$1 per foot cost is equivalent to more than \$100 million per ton of fiber. With the possibility of containerless melting plus the ready availability of ultra high vacuum, the processing of high

purity glass fibers can probably be achievable at much reduced costs in space and then shipped back to earth.

F. CONCLUSIONS AND RECOMMENDATIONS

Preliminary considerations have indicated that many glass and ceramic products can be produced by the use of lunar materials, notably the as-found soil, anorthite, silica, alumina and magnesia. The most useful products are likely to be glass wool for insulation, glass-ceramics for pipes and structural loadbearing building components, glass windows and refractories. Although the conditions in space and on the moon are very different from those on earth for the production of these products, the processes and equipments appear to be fairly simple to develop. Obviously laboratory scale research must first be done. The high vacuum and zero gravity in space are particularly suitable for the production of high purity glass fibers for shipment back to earth as components of wave-guides. It is recommended that laboratory scale experimental research as well as economic analysis be conducted as soon as possible as the next phase of a program to evaluate the above ideas and suggestions.

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H. TABLES

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 16	Basalt	Basalt	Shale
SiO ₂	42.0	46.4	44.9	49.1	45.4	45.0
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 II

IMPORTANT DIFFERENCES OF PROCESSING GLASS
AND CERAMICS ON EARTH AND IN SPACE

	Earth	Moon	Space
1. Ambient atmosphere	0 /N	----	----
2. Ambient pressure	1 atm.	vacuum	vacuum
3. Gravity	1	1/6	0
4. Common Energy Sources	Oil/Gas	Elec/Solar	Elec/Solar
5. Industrial Water	Plenty	Scarce	Scarce
6. Organic Chemicals	Plenty	Scarce	Scarce

I. FIGURES

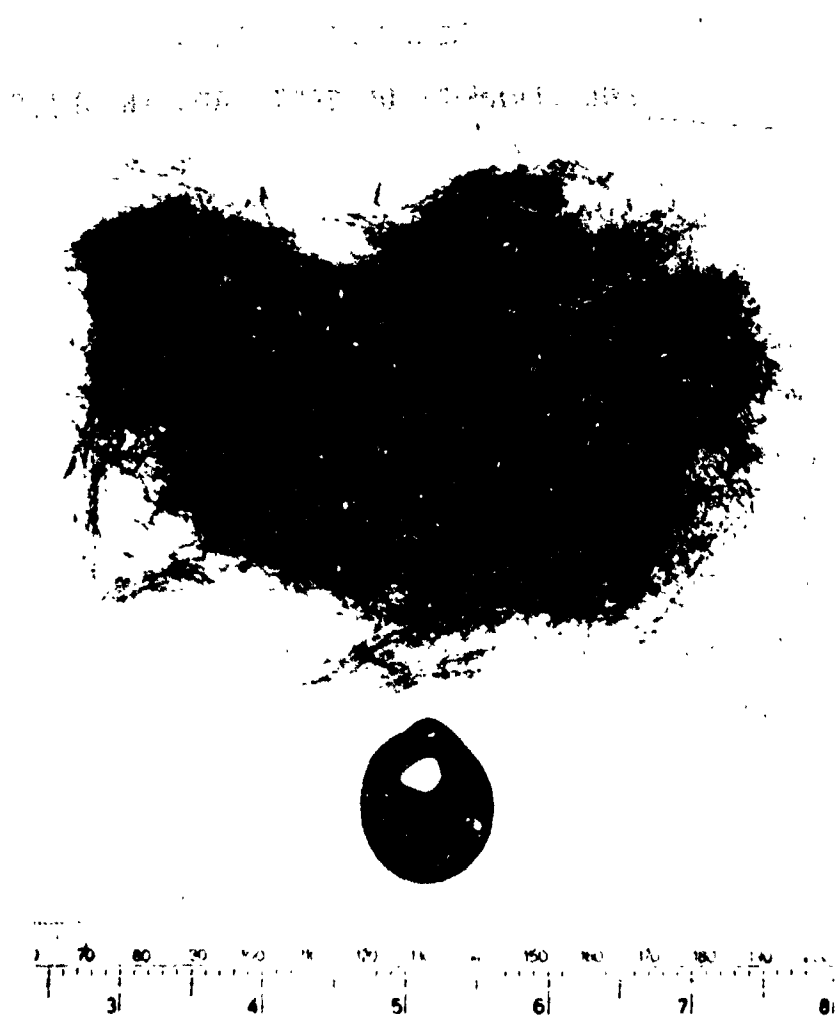


Figure V - 1 Glass wool and glass from the melting of oxide mixtures corresponding to Apollo 12 composition.

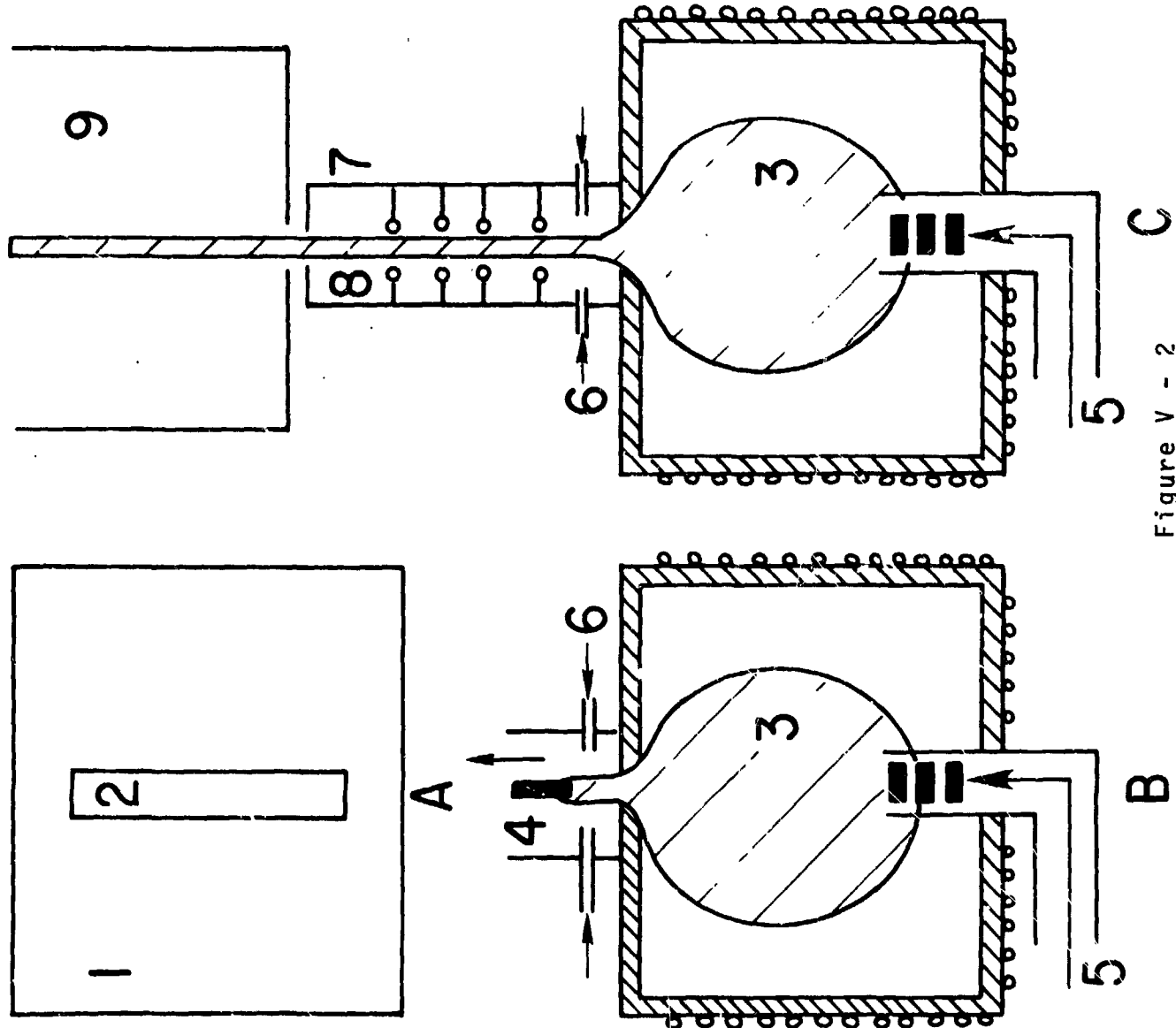


Figure V - 2

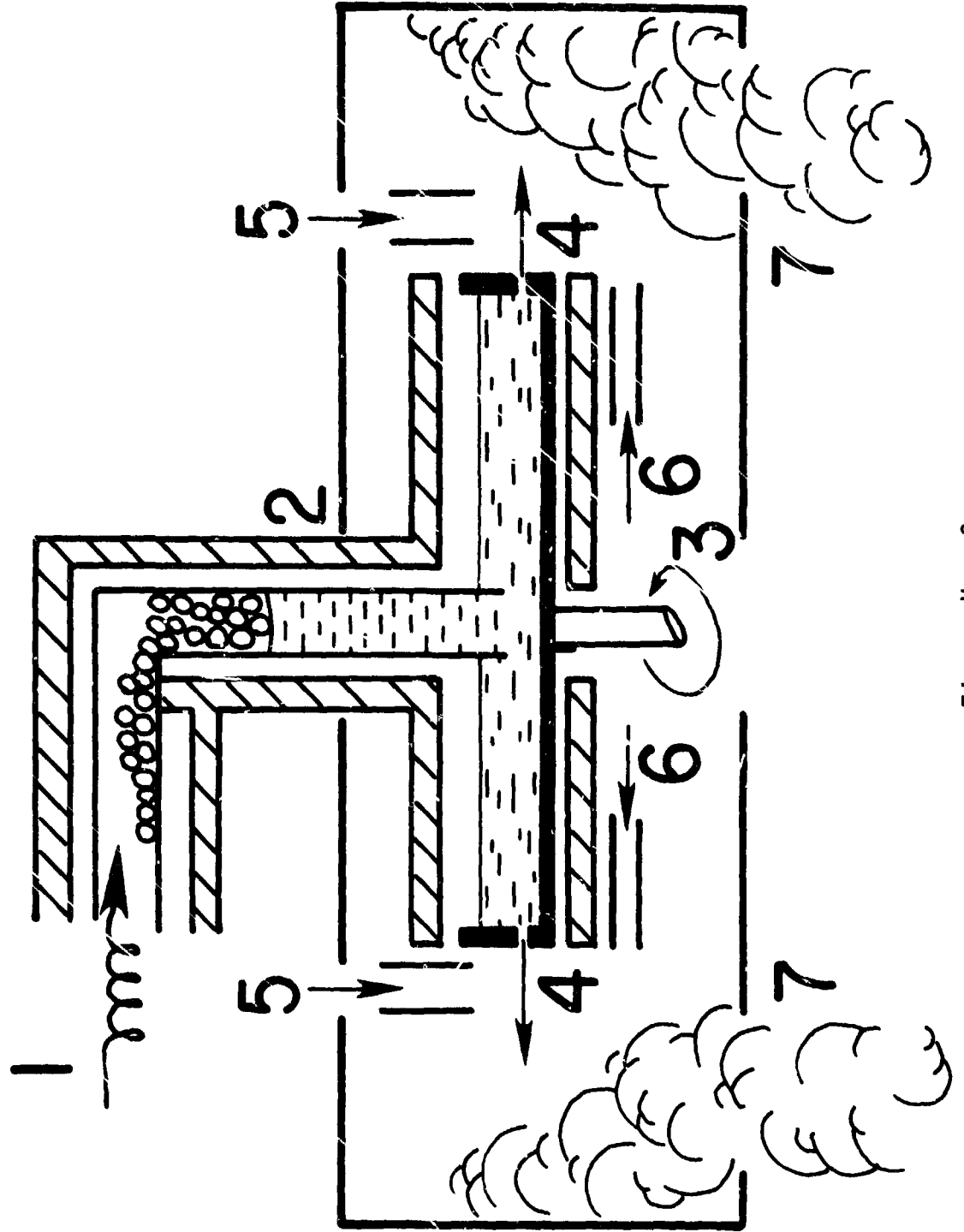


Figure V - 3

VI. INTRINSIC VALUE (\$/KG), TOTAL MASS (KG) AND PRODUCTION ENERGY OF SELECTED GOODS

A. BACKGROUND

Progressive development of a materials industry in space will depend on acquiring a source of relatively inexpensive material to process into suitable industrial feedstock. Extensive analyses have been presented in the preceding section detailing the acquisition and processing of lunar materials in bulk. 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 ask what goods in the present United States economy can be produced wholly or in part from lunar materials. 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 were 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 469 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 0.285 \$/kg (Iron and Steel Foundries). 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 figure 1 show how the total shipped value of these goods was distributed on a \$/kg basis averaged over 1 \$/kg ranges.

Also shown in figure 1 are the clear or open 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. Total shipped value 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. Prior to presenting the tabulated data we will discuss the selection procedures for the 230 SIC's included in tables I and II. These are 1972 data.

To the best of our knowledge this is the first time that the value of materials 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 operations 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 fiber glasses 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:

- 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 characterize 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.

B. SELECTION CRITERIA

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.

Thus, one can exclude as export those 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 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.

How, then, can metals be produced on an industrial scale in a lunar or space environment at minimum costs of terrestrial materials, assuming high quality sources of ore are available (e.g. from the lunar regolith)? In the distant future such devices as the plasmarc¹ may offer promise, but the technology is hardly likely to be applied on an industrial scale until fusion power itself is more fully developed. Meanwhile electro-metallurgy is a very attractive approach and is being explored for terrestrial use and will be applicable to space operations.

Hydrogen is intrinsically scarce in the low latitude soils of the lunar surface and consequently may have to be imported.² Other possibilities are being explored, such as the possible existence of hydrogen or methane under some of the craters,³ extraction from lunar water—itsself scarce⁴—or extraction from lunar dust itself.⁵ It seems very unlikely that elemental hydrogen will be available in the early stages of industrialization on the moon in quantities justifying its use as a reductant for extracting iron or other ferrous metals from oxides, unless the by-product water is valued as highly as the metal. Open-loop hydrometallurgical processes (acid or alkali leach) can be ruled out of contention for similar reasons, since 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, shep (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. Three processes are discussed in chapter II of this report. 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 ($\text{MgCO}_3 \cdot \text{CaCO}_3$)
- trona (NaCO_3)
- sulfur (S)
- fluorspar (CaF_2)
- alumina, from bauxite (Al_2O_3)
- phosphate rock [$\text{Ca}_{10}(\text{PO}_4)_{6+}(\text{F,OH,Cl})_2$]
- 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 ancient sedimentary deposits (oyster shell, coral) or inorganic precipitate deposits from supersaturated ground water. Fluorspar is often associated with contact metamorphic zones, as 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.

C. METHODOLOGY

Based on the foregoing discussion, we have 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 impure 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) will be omitted from further consideration, while the second group (166 sectors) will be included in the following analysis, but listed separately. 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 have 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 for 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 producing industry, and again as part of the output of the primary production of that 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 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 complex 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 though 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 recognizably 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 raw steel in some form produced by the steel industry itself--say galvanized strip--it is a direct input. When a sector buys a product containing steel from some other sector, steel is an indirect 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 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 (broad curve)	0.5 kg/yd (suggested 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/ft 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.

D. TABULAR RESULTS DESCRIBED

Tables I and III summarize the results of the extended computer computations of the inputs from references 11, 12, 13 and 14. The input data were for 1967 and 1972. The results shown in the following tables are for 1972 only. Table I applies to the MORE LIKELY class of goods whereas Table III refers to the previously described LESS LIKELY class of goods. The headings in both tables are identical. 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 10^6 \$) 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.

Tables II and IV relate the sequence numbers in tables I and III to the SIC codes under which the original data were obtained and organized for the 1967 and 1972. The Department of Commerce number is also included. Thus, the original input data can be checked from these numbers.

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 0.28\$/kg for "iron and steel foundries." 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 tables I and III. 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.

An asterisk in tables II or IV indicates that the correspondence between 1967 and 1972 SIC definitions is inexact.

In the "less likely" group the highest (plating and polishing) is probably spurious because the weights of some of the products being plated or polished are not always counted. No weight data was available for "industrial chemicals" and "gaskets and insulation. The chemical industry is too complex to summarize, in any case.

The corrected weight used in column 5 of tables I and III 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.

Portions of the various parts of the studies in this report were done early on in the program and were not able to make full use of the growing knowledge of what could be done with materials from the moon, especially when only small quantities of terrestrial supplement was required to extend the range of useful

possible products. Thus, the less likely listing contains many entries which could be transferred to space in modified forms. Possible examples are designated by sequence numbers 5, 7, 15, 23, 46, 52, 54, 63, 77, 82, 91, 96, 103, 117, 127, 131, 144, 147 and 153 among others. It is an interesting exercise to examine tables I and III which list the technical processing operations of which man is capable and ask, "What can be done in space with lunar and eventually asteroidal materials?"

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Table I
 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	Primary aluminum (SEC - 28195)	8.05	1,591.	0.198	84.6
3	Industrial Patterns	6.76	161.	0.024	NA
4	Optical + Radio + TV + Sighting Equipment	6.17	7,848.	1.271	NA
5	Semiconductors	6.33	2,182.	0.362	3.3
6	Telephone and Telegraph Apparatus	5.68	3,674.	0.647	5.2
7	Porcelain Electrical Supplies	5.55	223.	0.040	2.0
8	Calculating, Accounting, Office Machines-NEC	5.29	1,007.	0.190	1.9
9	Aircraft Engines & Engine Parts	5.15	3,538.	0.687	6.5 (1)
10	Electronic Computing Parts	5.11	5,186.	1.015	4.1
11	Vitreous China Food Utensils	4.83	67.	0.014	NA
12	Aluminum Rolling & Drawing	4.29	3,338.	0.778	25.9

Table I - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^6 \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
13	Engineering & Scientific Instruments	4.09	846.	0.207	2.0
14	Mechanical Measuring Devices	4.02	1,448.	0.360	NA
15	Watches & Watch Cases & Clocks	3.89	761.	0.196	0.9
16	Industrial Controls	3.85	1,115.	0.289	1.7
17	Ophthalmic Goods	3.84	461.	0.120	0.9
18	Automatic Temperature Controls	3.82	591.	0.155	1.0
19	Small Arms	3.81	320.	0.084	NA
20	Non-clay Refractories	3.76	278.	0.075	4.8
21	Jewelers Finding & Materials + Lapidary	3.60	264.	0.073	NA
22	X-Ray Apparatus & Tubes	3.56	120.	0.034	0.3
23	Abrasive Products	3.51	721.	0.205	3.9
24	Radio & TV Receiving Sets	3.51	3,605.	1.029	2.1
25	Fine Earthenware Food Utensils	3.46	60.	0.017	NA

Table I - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁺⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
26	Electronic Components - NEC	3.44	3,808.	1.106	7.9
27	Primary Non-Ferrous Materials - NEC	3.19	325.	0.102	6.7
28*	Machine Tools - Metal Cutting Types	3.16	1,152.	0.365	3.1
29	Surgical Appliances & Supplies	3.07	1,182.	0.385	1.5
30	Hand Saws & Saw Blades	2.98	158.	0.053	NA
31	Electron Tubes	2.76	1,142.	0.413	2.9
32	Special Dies & Tools & Accessories	2.59	2,985.	1.150	7.4
33	Cutlery	2.57	347.	0.135	0.9
34	Costume Jewelry	2.57	383.	0.149	0.6
35	Pumps & Compressors	2.38	2,254.	0.946	4.0 (1)
36	Aluminum Castings	2.27	1,031.	0.454	7.4
37	Measuring & Dispensing Pumps	2.10	189.	0.090	0.3
38	Non Ferrous Rolling & Drawing - NEC	2.08	1,011.	0.486	4.2

Table I - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
39	Hand & Edge Tools - NEC	2.07	1,001.	0.483	2.9
40	Other Ordnance & Accessories	1.99	388.	0.195	NA
41	Surgical & Medical Instruments	1.95	781.	0.400	1.0
42	Ball & Roller Bearings	1.95	1,243.	0.636	4.6
43	Engine Electrical Equipment	1.91	1,652.	0.864	3.0
44	Ammunition (No Small) - NEC	1.87	1,206.	0.644	NA
45	Pens & Mechanical Pencils & Marking Devices	1.83	380.	0.207	0.6
46	Power Transmission Equipment	1.83	1,225.	0.670	3.0 (1)
47	Needles & Pins & Fasteners	1.83	467.	0.255	0.9
48	Internal Combustion Engines - NEC	1.80	2,701.	1.503	5.1
49	Machine Tools - Metal Forming Types	1.68	563.	0.336	1.4
50	Hardware - NEC	1.45	2,634.	1.822	5.7
51*	Motor Cycles & Bicycles & Parts (SIC-3799)	1.37	536.	0.390	0.9

Table I - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^6 \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
52	Non ferrous castings - NEC	1.37	479.	0.350	2.5
53	Welding Apparatus	1.36	536.	0.309	1.0
54	Games & Toys & Childrens' Vehicles(Exc.Bikes)	1.26	1,412.	1.119	2.1
55	Household Cooking Equipment	0.990	751.	0.759	1.9
56	Fabricated Metal Products - NEC	0.988	158.	1.577	NA
57	Motor Vehicles Parts & Accessories	0.981	14,841.	15.132	36.6
58	Metal Foil & Leaf	0.793	232.	0.292	0.7
59	Typewriters	0.756	551.	0.729	0.8
60	Glass & Glass Products (Exc. Containers)	0.728	2,868.	3.938	41.5
61	Architectural Metal Work	0.525	466.	0.887	NA
62	Electrometallurgical Products	0.345	447.	1.295	24.0
63	Iron & Steel Foundries	0.285	4,639.	16.291	46.2
64	Aircraft Equipment - NEC	NA	3,102.	NA	NA
Totals			104,979 M\$	65.0 10^9 kg	384.0 10^9 kw-hr

VI - 29

Total Value-added in SIC's 60,000 M\$

Table II

CONVERSION OF SEQUENCE NUMBERS IN TABLE I
(MORE LIKELY PRODUCTS)
TO COMMERCE, 1967 SIC AND 1972 SIC CODES

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
1	130100	1925	3761	14	620200	3821	3823
2	380400	3334	3334				3824
3	490400	3565	3565				3829
4	130400	1941	3662	15	620701	3871	3873
	560400	3662	3832		620702	3872	
	630100	3831		16	530500	3622	3622
5	570200	3674	3674	17	630200	3851	3851
6	560300	3661	3661	18	620300	3822	3822
7	360800	3264	3264	19	130500	1951	3484
8	510102	3574	3574	20	362100	3297	3297
	510400	3579	3579	21	640102	3912	3915
					640103	3913	
9	600200	3722	3724	22	580300	3693	3693
10	510101	3573	3573	23	361600	3291	3291
11	360701	3262	3262	24	560100	3651	3651
12	380800	3352	3353	25	360702	3263	3263
			3354	26	570300	3679	3675
			3355				3676
13	620100	3811	3811				3677

Table II - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
			3678	43	580400	3694	3694
			3679	44	130200	1929	3483
27	380500	3339	3339	45	640501	3951	3951
28*	470100	3541	3541		640503	3953	3953
29	620500	3842	3842	46	490500	3566	3566
30	420202	3425	3425				3568
31	570100	3671	3671	47	640702	3964	3964
32	470300	3544	3544	48	430200	3519	3519
		3545	3545	49	470 00	3542	3542
33	420100	3421	3421	50	420300	3429	3429
34	640105	3961	3961	51*	610500	3751	3751
35	490100	3561	3561	52	381300	3369	3369
36	381100	3361	3361	53	530600	3623	3623
37	520400	3586	3586	54	640301	3941	3944
38	380900	3356	3356		640303	3943	
39	420201	3423	3423	55	540100	3631	3631
40	130700	1911	3489	56	420600	3492	3499
41	620400	3841	3841		420900	3496	
42*	490200	3562	3562		421100	3499	

Table II - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
57	590302	3714	3714	62	370102	3313	3313
58	421000	3497	3497	63	370200	3321	3321
59	510200	3572	3572			3322	3322
60	350100	3211	3211			3323	3324
		3229	3229				3325
		3231	3231	64	600300	3723	3728
61	400800	3446	3446		600400	3729	3769

Table III
 SIC'S LESS 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	Plating & Polishing	16.39	845.	0.052	NA
2	Pleating & Stitching	15.14	249.	0.016	NA
3	Schiffli Machine Embroideries	14.49	98.	0.007	NA
4	Metal Coatings & Allied Services	9.28	570.	0.061	NA
5	Steel Pipes & Tubes	8.16	1,049.	0.129	4.1
6	Cut Stone & Stone Products	7.79	120.	0.015	1.5
7	Cold Finishing of Steel Shapes	7.53	1,328.	0.176	4.7
8	Jewelry - Precious Metals	7.26	913.	0.126	0.7
9	Aircraft	6.99	7,129.	1.020	9.8
10	Cement - Hydraulic	6.68	1,450.	0.219	134.4
11	Structural Clay Products - NEC	6.34	147.	0.023	7.4
12	Brick & Structural Clay Tile	6.28	417.	0.066	23.2
13	Steel Wires & Related Products	6.21	1,007	0.162	4.5

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
14	Photographic Equipment & Supplies	6.12	4,530.	0.741	10.2
15	Ceramic Wall and Floor Tile	5.99	142.	0.024	1.8
16	Non-metallic Mineral Products - NEC	5.40	135.	0.025	NA
17	Chemical Preps. - NEC (SIC 2891 OUT)	5.33	1,788.	0.335	13.8
18	Pottery Products - NEC	4.98	52.	0.010	NA
19	Womens Hosiery (Exc. Socks)	4.96	800.	0.161	2.6
20	Floor Covering	4.94	2,560.	0.518	9.6
21	Knit Outerwear Mills	4.93	1,384.	0.281	3.3
22	Lace Goods	4.87	38.	0.008	NA
23	Vitreous Plumbing Fixtures	4.44	219.	0.049	2.6
24	Hosiery - NEC	4.42	488.	0.110	NA
25	Luggage	4.34	296.	0.068	NA
25	Dental Equipment & Supplies	4.23	332.	0.079	0.3

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁺⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
27	Printing Ink	4.23	413.	0.098	NA
28	Clay Refractories	4.09	274.	0.067	7.9
29	Morticians Goods	4.03	318.	0.079	1.6
30	Apparel made from Purchased Materials	3.98	18,468.	4.641	NA
31	Drugs	3.75	6,511.	1.735	NA
32	Knitting Mills - NEC	3.75	59.	0.016	NA
33	Primary Batteries - Dry & Wet	3.73	283.	0.076	0.4
34	Silverware & Plated Wire	3.68	296.	0.081	1.0
35	Knit Underwear Mills	3.66	442.	0.121	NA
36	Carbon & Graphite Products	3.65	306.	0.084	4.9
37	Machinery (Exc. Electrical) - NEC	3.65	3,576.	0.980	8.6 (1)
38	Sewing Machines	3.64	130.	0.036	0.3
39	Printing Trades Machinery	3.63	669.	0.184	1.0

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw=hr
40	Misc. Plastics Products (SIC - 3021)	3.60	9,520.	2.643	44.0 (1)
41	Hard Surface Floor Coverings	3.27	278.	0.085	1.2
42	Thread Mills	3.22	281.	0.087	1.4
43	Mineral Wool	3.18	613.	0.193	13.0
44	Canvas Products	3.16	224.	0.071	NA
45	Phonograph Records	3.08	461.	0.150	1.3
46	Electric Lamps	3.04	884.	0.291	2.1
47	Rubber Footwear	2.95	487.	0.165	NA
48	Switch Gear & Switchboards	2.84	1,717.	0.604	1.9
49	Scales & Balances	2.78	161.	0.058	0.2
50	Boat Building & Repairing	2.78	956.	0.307	1.3
51	Food Products Machinery	2.73	812.	0.298	1.5
52	Minerals Ground or Treated	2.71	337.	0.124	9.5

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁺⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
53	Automotive & Apparel Trimmings	2.70	920.	0.341	NA
54	Electrical Measuring Instr. & Transformers	2.68	2,400.	0.897	NA
55	Woodworking Machinery	2.67	396.	0.148	0.7
56	Musical Instruments	2.62	501.	0.191	0.8
57	Felt Goods - NEC	2.61	119.	0.046	NA
58	Textile Machinery	2.57	668.	0.260	1.9
59	Fabricated Textiles Products - NEC	2.57	588.	0.229	NA
60	Primary Metal Products - NEC	2.54	666.	0.262	10.1
61	Metal Working Machinery NEC - (SIC 3541)	2.52	1,207.	0.477	NA
62	Adhesives & Gelatins (SIC - 2899 OUT)	2.48	754.	0.304	4.4
63	Electrical Equipment - NEC	2.45	422.	0.172	NA
64	Sporting & Athletic Goods - NEC	2.43	1,410.	0.580	1.8
65	Surface Active Agents	2.42	376.	0.155	3.3

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^6 \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
66	Fabricated Rubber Products (Missing SICs)	2.42	2,299.	0.951	15.7
67	Dolls	2.31	162.	0.070	0.2
68	Cordage & Twine	2.31	155.	0.067	NA
69	Service Industry Machines - NEC	2.26	731.	0.324	1.4
70	Textiles & Plants - NEC	2.24	491.	0.220	NA
71	Signs & Advertizing Displays	2.23	973.	0.435	NA
72	Elevators & Moving Stairways	2.23	393.	0.176	0.6
73	Special Industrial Machinery - NEC	2.21	2,114.	0.957	3.3
74	Agricultural Chemicals - NEC	2.20	934.	0.425	4.0
75	General Industrial Machinery - NEC	2.19	950.	0.434	1.7
76	Paper Industries Machinery	2.16	364.	0.168	1.1
77	Electrical Industrial Apparatus - NEC	2.10	366.	0.174	0.8
78	Narrow Fabric Mills	2.04	460.	0.225	1.4
79	Curtains & Draperies	2.03	619.	0.304	1.7

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
80	Household Vacuum Cleaners	2.02	380.	0.188	0.5
81	Industrial Furnaces & Ovens	1.99	360.	0.181	0.4
82	Steam Engines and Turbines	1.97	1,778.	0.903	2.8
83	Yarns Mills & Finishings - NEC	1.96	3,687.	1.883	13.1
84	Lead Pencils & Art Goods	1.79	161.	0.090	0.5
85	Blowers & Fans	1.78	654.	0.367	1.3
86*	Misc, Products - NEC	1.77	1,250.	0.708	2.5
87	Lighting Fixtures	1.75	1,987	1.135	4.2
88	Automatic Merchandising Machines	1.73	263.	0.152	0.6
89	Secondary Non-ferrous Metals	1.73	1,703.	0.987	8.0
90	Organic Fibers Non-cellulosic	1.68	2,924.	1.740	43.4
91	Tanks & Tank Components	1.67	221.	0.132	NA
92	Pipe & Valves & Pipe Fittings	1.65	2,960.	1.794	NA

Table III - Contined

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
93	Electric Housewares & Fans	1.59	1,310.	0.823	2.2
94	Conveyors & Conveying Equipment	1.59	788.	0.495	1.2
95	Refrigeration Machinery	1.58	5,405.	3.425	8.0 (1)
96	Shipbuilding & Repair	1.57	2,664.	1.693	4.7
97	Industrial Moving Equipment	1.57	1,269.	0.810	2.2
98	Buttons	1.56	76.	0.049	NA
99	Small Arms Ammunition	1.55	356.	0.230	NA
100	Plumbing Fittings & Brass Goods	1.55	575.	0.372	1.0
101	Broad Fabrics Mills & Finishing Plants	1.51	7,278.	4.811	54.9
102	Motors & Generators	1.50	2,043.	1.361	6.0
103	Motor Vehicles	1.48	34,839.	23.517	33.0
104	Polishes & Sanitation Goods	1.47	1,517.	1.032	NA
105	Household Refrigerators & Freezers	1.47	1,396.	0.951	2.9

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
106	Non-ferrous Wire Drawing & Insulating	1.46	3,582.	2.461	7.4
107	Construction and Oil Field Machinery	1.44	5,926.	4.113	13.3
108	Tire Cord & Fabric	1.43	556.	0.390	1.4
109	Wiring Services	1.41	1,708.	1.208	3.3
110	House Furnishings - NEC	1.39	1,233.	0.887	NA
111	Metal Doors & Sash & Trim	1.38	1,687.	1.221	3.2
112	Brass & Bronze & Copper Castings	1.38	378.	0.274	2.1
113	Artificial Flowers	1.31	88.	0.068	0.1
114	Mining Machinery	1.30	626.	0.480	1.5
115	Screw Machine Products, Bolts, etc.	1.28	2,526.	1.962	6.9
116	Trailer Coaches	1.22	3,734.	3.061	NA
117	Laundry Equipment	1.22	1,229	1.009	2.9
118	Truck & Bus Bodies & Truck Trailers	1.15	2,182	1.897	3.6

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
119	Farm Machinery	1.15	4,358.	3.789	9.9 (1)
120	Copper Rolling & Drawing	1.10	2,514.	2.292	9.5
121	Toilet Preparations	1.06	3,295.	3.096	2.2
122	Storage Batteries	1.00	789.	0.785	2.5
123	Household Appliances - NEC	0.945	554.	0.586	1.4
124	Non-ferrous Forging	0.937	181.	0.193	3.2
125	Tires & Inner Tubes	0.907	3,043.	3.355	23.7
126	Misc. Fabricating Wire Products	0.862	1,275.	1.480	2.9
127	Sheet Metal Work	0.855	2,176.	2.547	4.3
128	Transportation Equipment (NEC, SIC 3523,3792)	0.809	724.	0.894	NA
129	Heating Equipment (Exc. Electrical)	0.795	859.	1.081	2.7
130	Locomotives, Railroad, Street Cars & Parts	0.791	1,986.	2.511	4.3
131	Fabricated Plate Work (Boiler Shops)	0.778	2,711.	3.485	7.7

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
132	Processed Textile Waste	0.721	109.	0.151	NA
133	Padding & Upholstery Filling	0.707	109.	0.155	NA
134	Metal Sanitary Ware	0.681	300.	0.441	2.3
135	Textile Bags	0.602	207.	0.344	NA
136	Coated Fabrics not rubberized	0.598	291.	0.487	2.9
137	Metal Stampings	0.595	6,742.	11.336	15.1
138	Knit Fabric Mills	0.568	3,083.	5.425	8.5
139	Iron & Steel Forgings	0.562	1,150.	2.048	14.4
140	Asbestos Products	0.545	620.	1.137	NA
141	Explosives	0.542	332.	0.612	8.4
142	Steel Springs	0.528	269.	0.510	1.4
143	Fabricated Structural Steel	0.519	3,183.	6.130	5.3
144	Metal Cans	0.503	3,563.	7.284	8.7
145	Misc. Metal Work	0.401	1,302.	3.242	2.8

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10 ⁺⁶ \$ of SIC	Total Mass 10 ⁹ Kg	Sector Energy Consumption 10 ⁹ kw-hr
145	Synthetic Rubber	0.376	885.	2.352	19.2
147	Metal Barrels & Drums & Pails	0.362	375.	1.034	1.6
148	Primary Copper	0.348	2,250.	6.461	21.0
149	Plastic Materials & Resins	0.348	3,638.	10.450	45.7
150	Primary Lead	0.333	374.	1.124	4.1
151	Fertilizers - Mixing Only	0.256	650.	2.538	1.9
152	Primary Zinc	0.208	306.	1.473	13.9
153	Glass Containers	0.163	1,727.	10.595	41.6
154	Carbon Black	0.162	184.	1.140	6.3
155	Blast Furnaces & Steel Mills	0.073	19,445.	266.181	408.2
156	Reclaimed Rubber	0.0646	24.	.373	NA
157	Concrete Products - NEC	0.0549	1,593.	29.013	8.1
158	Gypsum Products	0.0461	520.	11.265	12.1

Table III - Continued

Sequence Number	Description	\$/Kg	Total Shipped Value 10^{+6} \$ of SIC	Total Mass 10^9 Kg	Sector Energy Consumption 10^9 kw-hr
159	Fertilizers	0.0415	1,614.	38.881	NA
160	Paints & Petroleum & Related Products	0.0355	24,836.	699.013	NA
161	Lime	0.0326	193.	5.937	27.0
162	Concrete Block & Brick	0.0221	695.	31.420	4.0
163	Paving Mixtures & Blocks	0.0146	749.	51.238	11.3
164	Ready-mixed Concrete	0.0132	3,289.	248.404	24.5
165	Industrial Inorganic & Organic Chemicals	NA	NA	NA	0.1
166	Gaskets & Insulation (SIC 3292)	NA	NA	NA	NA
Totals			310,406. M\$	1,577. 10^9 kg	1,419.0 B kw-hr

Note: Total Value-added in 1972 was 144,139 M\$
by these industrial operations.

Table IV
 CONVERSION OF SEQUENCE NUMBERS IN TABLE III
 (LESS LIKELY PRODUCTS)
 TO COMMERCE, 1967 SIC AND 1972 SIC CODES

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
1	420401	3471	3471	19	180101	2251	2251
2	190303	2395	2395	20	170100	2271	2271
3	190305	2397	2397			2272	2272
4	420402	3479	3479			2279	2279
5	370105	3317	3317	21	180201	2253	2253
6	361500	3281	3281	22	170300	2292	2292
7	370104	3316	3316	23	360600	3261	3261
8	640101	3911	3911	24	180102	2252	2252
9	600100	3721	3721	25	340302	3161	3161
10	360100	3241	3241	26	620600	3843	3843
11	360500	3259	3259	27	270404	2893	2893
12	360200	3251	3251	28	360400	3255	3255
13	370103	3315	3315	29*	641000	3994	3995
14	630300	3861	3861	30	180400	2300	2300
15	360300	3253	3253	31	290100	2831	2831
16	362200	3299	3299			2833	2833
17*	270406	2899	2899			2834	2834
18	360900	3269	3269	32	180203	2259	2259

Table IV - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
33	580200	3692	3692	53	190304	2396	2396
34	640104	3914	3914	54	530100	3611	3612
35	150202	2254	2254		530200	3612	3825
36	530700	3624	3624	55	480300	3553	3553
37*	500000	3599	3592	56	640200	3931	3931
			3599	57	170200	2291	2291
38	540600	3636	3636	58	480200	3552	3552
39	480500	3555	3555	59	190306	2399	2399
40*	320400	3079	3041	60	370400	3399	3398
			3079				3399
41	640900	3996	3996	61*	470400	3548	3546
42	160400	2284	2284				3547
43	362000	3296	3296				3549
44	190302	2334	2394	62*	270402	2891	2891
45	560200	3652	3652	63	580500	3699	3699
46	550100	3641	3641	64	640400	3949	3949
47*	320200	3021	3021	65	290203	2843	2843
48	530300	3613	3613	66*	320302	3069	3069
49	510300	3576	3576	67	640302	3942	3942
50	610200	3732	3732	68	170900	2298	2298
51	480100	3551	3551	69	520500	3589	3589
52*	361900	3295	3295	70	170800	2297	2297

Table IV - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
	171000	2299	2299				3646
71	641100	3993	3993				3647
72	450100	3534	3534				3648
73	490600	3559	3559	88	520100	3581	3581
74	270300	2879	2879	89	380600	3341	3341
75	490700	3569	3569	90	280400	2824	2824
76	420400	3554	3554	91	130300	1931	3795
77	53.300	3629	3629	92	420800	3494	3494
78	160200	2241	2241			3498	3498
79	150100	2391	2391	93	540400	3634	3634
80	540500	3635	3635	94	460200	3535	3535
81	490600	3567	3567	95*	520300	3585	3585
82	430100	3511	3511	96	610100	3731	3731
83	160300	2269	2269	97	460300	3536	3536
		2281	2281			3537	3537
		2282	2282	98	640701	3963	3963
		2283	2283	99	130600	1961	3482
84	640502	3952	3952	100	400200	3432	3432
85	490300	3564	3564	101	160100	2211	2211
86*	641200	3999	3999			2221	2221
87	550200	3642	3642			2231	2231

Table IV - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
		2261	2261	117	520200	3582	3582
		2262	2262		540300	3633	3633
102	530400	3621	3621	118	590100	3713	3713
103	590301	3711	3711		590200	3715	3715
104*	290202	2842	2842	119	440000	3522	3523
105	540200	3632	3632				3524
106	381000	3357	3357	120	380700	3351	3351
107	450100	3531	3531	121	290300	2844	2844
	450300	3533	3533	122	580100	3691	3691
108	170700	2296	2296	123	540700	3639	3639
109	550300	3643	3643	124	381400	3392	3463
		3644	3544	125	320100	3011	3011
110	190200	2392	2392	126	420500	3481	3495
111	400500	3442	3442				3496
112	381200	3362	3362	127	400700	3444	3444
113	640600	3962	3962	128*	610700	3799	3799
114	450200	3532	3532	129*	400300	3433	3433
115	410100	3451	3451	130	610300	3741	3743
		3452	3452		610400	3742	
116	610600	3791	2451	131	400600	3443	3443
			3792	132	170500	2294	2294

Table IV - Continued

Sequence Number	Commerce	1967 SIC	1972 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
133	170400	2293	2293	150	380200	3332	3332
134	400100	3431	3431	151	270202	2872	2875
135	190301	2393	2393	152	380300	3333	3333
136	170600	2295	2295	153	350200	3221	3221
137	410200	3461	3465	154	270405	2895	2895
			3466	155	370101	3312	3312
			3469	156	320301	3031	3031
138	180300	2256	2257	157	361100	3272	3272
			2258	158	361400	3275	3275
139	370300	3391	3462	159	270201	2871	2873
140*	361700	3292	3292				2874
141	270403	2892	2892	160	300000	2851	2851
142	420700	3493	3493		310100	2911	2911
143	400400	3441	3441			2992	2992
144	390100	3411	3411			2999	2999
145	400900	3449	3448	161	361300	3274	3274
			3449	162	361000	3271	3271
146	280200	2822	2822	163	310200	2951	2951
147	390200	3491	3412	164	361200	3273	3273
148	380100	3331	3331	165	270100	2812	2812
149	280100	2821	2821			2813	2813

Table IV - Continued

Sequence Number	Commerce	1967 SIC	1968 SIC	Sequence Number	Commerce	1967 SIC	1972 SIC
		2815	2816			2819	2869
		2816	2819	166*	361800	3293	3293
		2818	2865				

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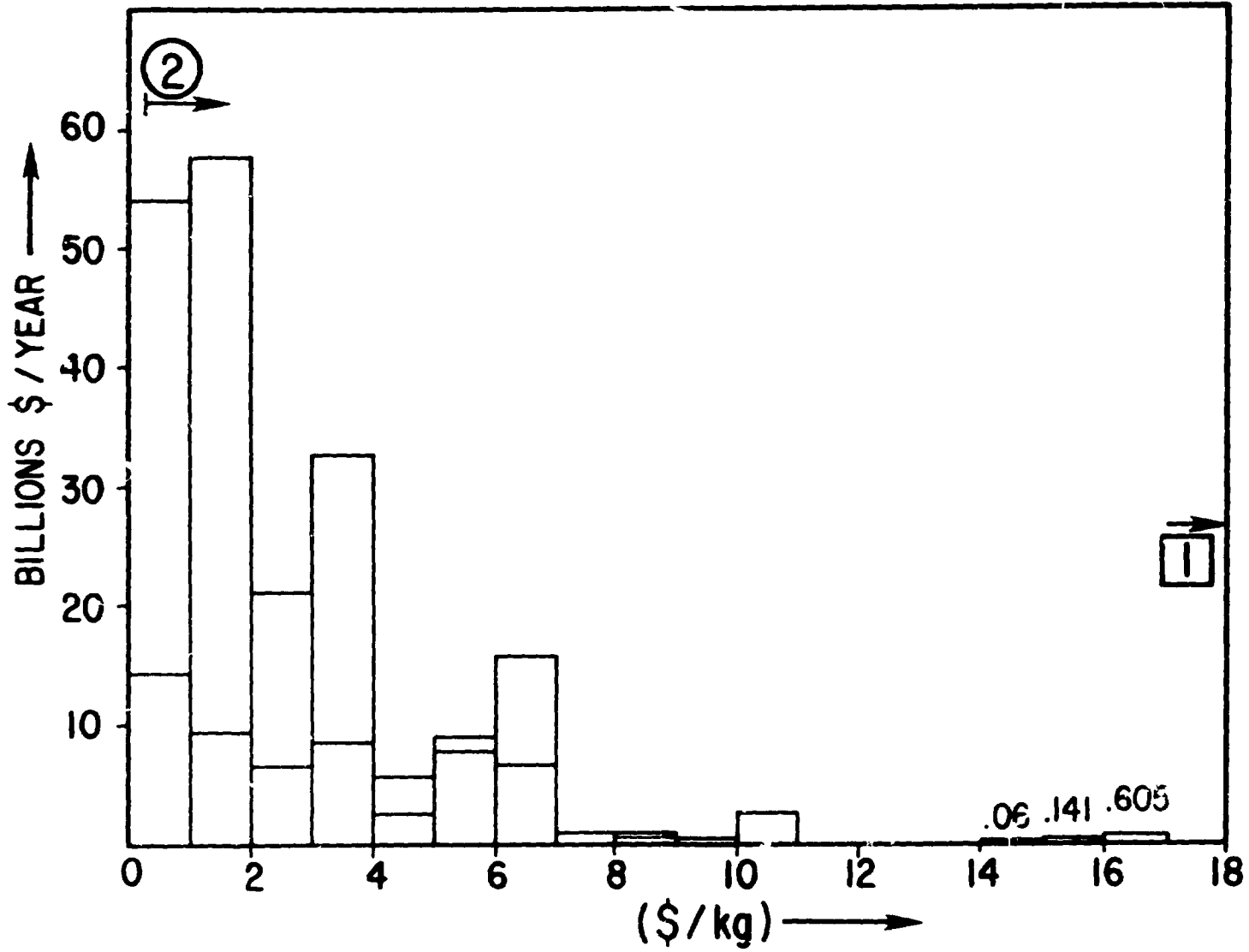


Figure VI-1