

Astronautics Information

**RECOMMENDATIONS FOR UTILIZATION
OF LUNAR RESOURCES**

SEMINAR PROCEEDINGS

**A REPORT OF THE
WORKING GROUP ON EXTRATERRESTRIAL RESOURCES,
MARCH 8, 1963**

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Foreword

This Report contains the recommendations of the Working Group on Extraterrestrial Resources (WGER) for a program of research and development toward the utilization of extraterrestrial resources in supporting and enhancing the economy of manual lunar and planetary missions.

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

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

The Chairman of the Working Group is Dr. E. A. Steinhoff of the Rand Corporation, with Dr. J. B. Edson, NASA, as Vice-Chairman, and Mr. S. H. Dole, Rand Corporation, as Secretary. The Working Group is presently organized into the following subgroups with membership as shown:

Steering and Planning Committee

Dr. J. B. Edson, NASA Hq.-OART, Chairman
 Mr. S. H. Dole, Rand Corporation, Secretary
 Maj. T. C. Evans, NASA Hq.-OMSF
 Dr. M. Eimer, Jet Propulsion Laboratory
 Dr. V. E. Fryklund, NASA Hq.-OSS
 Mr. J. J. Gangler, NASA Hq.-OART
 Lt. Col. G. W. S. Johnson, Jet Propulsion Laboratory
 Dr. E. B. Konecci, NASA Hq.-OART
 Dr. J. W. Salisbury, Air Force Cambridge Research Laboratory
 Dr. R. Speed, Jet Propulsion Laboratory
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Subgroup on Environments and Resources

Dr. R. Speed, Jet Propulsion Laboratory, Chairman
 Mr. R. P. Bryson, NASA Hq.-OSS
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 Dr. J. B. Edson, NASA Hq.-OART
 Dr. M. Eimer, Jet Propulsion Laboratory
 Dr. D. Gault, NASA-Ames Research Center

Mr. B. Hall, U. S. Army-Office of Chief of Engineers
 Dr. F. Hoehndorf, Holloman Air Force Base
 Dr. J. W. Salisbury, Air Force Cambridge Research Laboratory

Subgroup on Biotechnology

Dr. E. B. Konecci, NASA Hq.-OART, Chairman
 (No members; inactive)

Subgroup on Facilities Construction, Operation, and Maintenance

Lt. Col. G. W. S. Johnson, Jet Propulsion Laboratory, Chairman
 Mr. P. H. Bliss, Rand Corporation
 Dr. M. Eimer, Jet Propulsion Laboratory
 Maj. T. C. Evans, NASA Hq.-OMSF
 Mr. J. J. Gangler, NASA Hq.-OART
 Mr. R. Geye, NASA-Lewis Research Center
 Mr. W. Gillespie, NASA-Manned Spacecraft Center
 Mr. B. Hall, Army-Office of Chief of Engineers
 Capt. R. D. Hensley, NASA-Marshall Space Flight Center
 Dr. L. D. Jaffe, Jet Propulsion Laboratory
 Mr. F. C. Littleton, NASA-Manned Spacecraft Center
 Mr. D. R. Lord, NASA Hq.-OMSF
 Mr. W. R. Peterson, U.S. Army
 Mr. W. Robinson, NASA-Marshall Space Flight Center
 Mr. E. L. Schriver, NASA-Marshall Space Flight Center

Subgroup on Mining and Processing

Dr. J. W. Salisbury, Air Force Cambridge Research Laboratory, Chairman
 Lt. Col. W. C. Athas, Air Force Office of Scientific Research
 Mr. F. M. Baumgardner, U.S. Army
 Mr. P. H. Bliss, Rand Corporation
 1st Lt. R. T. Dodd, Jr., Air Force Cambridge Research Laboratory
 Mr. J. J. Gangler, NASA Hq.-OART
 Dr. R. McCutchan, NASA-Manned Spacecraft Center
 Mr. H. M. Schurmeier, Jet Propulsion Laboratory

All subgroups have industrial participants who are not listed because of their varying degree of participation.

In accordance with its function the Working Group has prepared, as its first task, this Report of its preliminary studies, recommendations, and conclusions.

Recommendations for Utilization of Lunar Resources

I. INTRODUCTION

The purposes of this Report are:

- a. To identify and describe the opportunities for early use of lunar materials and environment in the support of lunar and other astronautic operations.
- b. To recommend research that leads toward timely exploration of those opportunities and which should be initiated now.
- c. To recommend advance technology work on those processes and required developments for which adequate operational boundary conditions have been established, including the power supplies to operate them.

We find that an aggressive program, based on our recommendations and implemented by the appropriate agencies, can open the way to the economical achievement of national leadership in lunar utilization in the time frame of the 1970's. Significant work in some of these areas is now going on with NASA and Department of Defense support. We are confident that this work will provide a sound base for the necessary additional effort.

We observe that a program of scientific and exploratory work on the Moon is the rational sequel to and virtually implicit in the present national commitment to manned lunar landing. We find, on the basis of our studies, that the economy and effectiveness of such a program will depend to a major degree upon effective utilization of lunar materials for the construction, supply, and operation of the required bases. Skill in this use of local resources could, as noted above, become the deciding factor in any international contest for leadership in lunar operations.

We also observe that, over the foreseeable future, a most promising use of lunar substance is in the manufacture of rocket propellants, particularly of oxygen and hydrogen, for astronautic vehicles in traffic between the Earth, the Moon, and the planets. The advantage is due to the low lunar escape velocity. This and other factors make it likely, in our opinion, that the Moon will become a permanent site of manned operations. From this conclusion follows the prospect for numerous other, long-term requirements for use of lunar materials.

In Section III, Conclusions and Recommendations, are listed the most important kinds of lunar materials, their prospective uses and sources, and the recommended research regarding each.

Our studies have identified certain factors which are of critical importance to the full and timely exploitation of lunar resources. These are:

- a. Accelerated investigations of the physics and chemistry of the lunar surface.
- b. Study and development of suitable power sources and sinks.
- c. Development of suitable methods and equipment for the extraction, processing, handling and storage of lunar substances.
- d. Development of methods, equipment, and vehicles for lunar prospecting; that is, for locating useful materials.

Brief discussions and suitable recommendations about these areas are included in the following Sections. More extensive discussions of many of these topics will be found in the Reports of the subgroups which are in the Appendixes.

II. LUNAR BASE DEVELOPMENT SCHEDULE

The exact course of lunar surface exploration and exploitation cannot be predicted at present. However, most probable missions will require support by lunar surface facilities. Although the size, lifetime, and purpose of these facilities will vary with the specific missions, all must perform the fundamental functions of providing shelter, life support, power, communications, and surface mobility. An acceptable lunar base concept must capitalize on the similarities which are certain to exist among various possible types of lunar facilities and yet retain sufficient flexibility to accommodate many uncertainties of mission and environment.

To meet the potential need it is anticipated that a modular lunar base system will be developed. The system will probably consist of a family of prefabricated modules which can be assembled on the lunar surface in a variety of arrays to support a wide range of missions. The design must facilitate expansion of installations both to increase capacity and to decrease dependence on resupply from Earth. The demands of economy and operational effectiveness will require maximum practicable use of lunar resources. This consideration must be given early and continuing emphasis in the activities charted in Fig. 1.

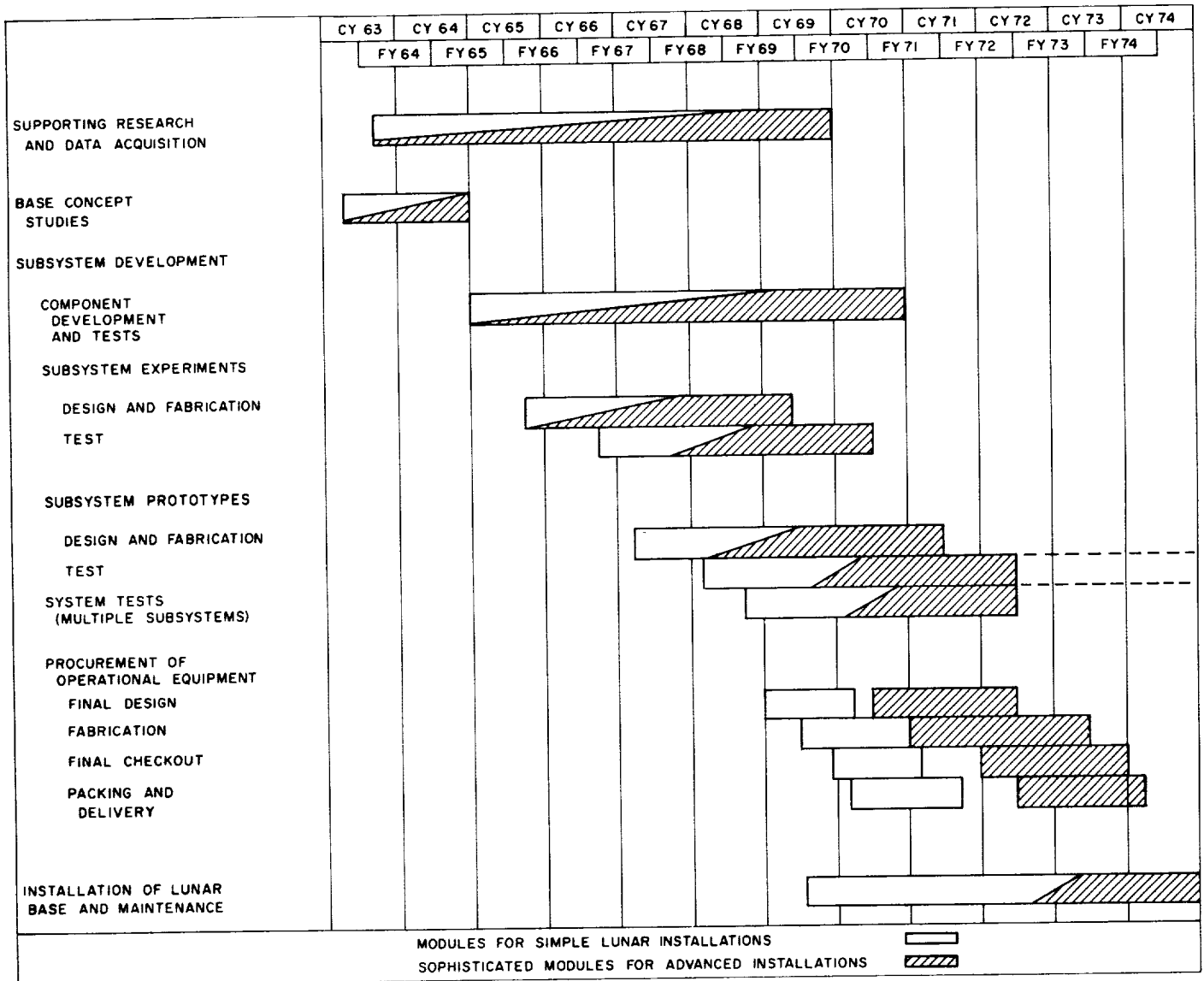


Fig. 1. Possible schedule for lunar base development

Figure 1 outlines the type of research and development program necessary to provide a lunar base system in a timely manner. The schedule covers two broad categories of lunar base equipment: first, the basic modules required in all installations, including the simplest and earliest; and second, more sophisticated modules needed

to supplement the basic equipment in later installations having a high degree of independence of Earth logistics.

The point of importance illustrated by the schedule is that time is short. Supporting research must begin in the near future.

III. CONCLUSIONS AND RECOMMENDATIONS

A. Lunar Resources

Any lunar substance that can be utilized economically in base construction or interplanetary exploration is a resource which must be exploited at the earliest opportunity. There may be many such lunar substances of which we have no knowledge, but there are certain useful substances which are likely to be present. Chief among these is water.

1. Water

Water is needed for life support, and as a general reagent and catalyst. Electrolysis of water can provide hydrogen and oxygen for rocket propellants, combustion engine fuel and oxidizer, and fuel cell reagents. By providing a lunar refueling capability, which is the most economical use of lunar water, the direct cost of many astronautic operations may be reduced, lunar base construction and interplanetary exploration can be accelerated, and minimum-time trajectories can replace minimum-energy Hohmann trajectories. The use of lunar hydrogen and oxygen to power fuel cells and as general reagents or catalysts will reduce the logistics burden of a lunar base, as will the use of water and oxygen for life support.

2. Oxygen

Oxygen may be the only economically available lunar resource if water is not present in particularly favorable locations or forms. If hydrogen is supplied from Earth, oxygen can be utilized as outlined in Section A1.

Oxygen alone is, however, still needed for life support and as a reagent.

3. Hydrogen

Hydrogen is clearly most useful where oxygen can be supplied (see Section A1), but it also can be used as a reagent or catalyst should a convenient source of hydrogen be found in lunar hydrocarbons. Hydrocarbons themselves would be of great advantage in the food synthesis aspect of life support.

4. Soil

Soil, which includes both coarse and fine debris on the lunar surface, will be needed in many phases of base construction. In view of the typically great mass and volume of base components, wherever the lunar surface materials can be used to substitute for prefabricated terrestrial parts, a great logistical advantage will have been attained.

5. Recommendations

Recommendations for research are as follows:

1. A detailed systems analysis of the savings in time and money gained from the utilization of various probable lunar resources, taking into account the several forms in which these resources may be present.

2. A study of the most efficient manner in which lunar resources may be utilized, aimed primarily at originating new uses for lunar materials.

B. Chemistry and Physics of Lunar Surface

Water, oxygen, and hydrogen are the substances of most immediate concern in investigations of lunar resources. Chief sources of lunar water appear to be hydrated silicate minerals, and surface and pore ice. The partition of water between these two forms and the uniformity of distribution of water over the lunar surface and near-surface is probably a function of the lunar thermal history. If fusion and tectonic activity have been common in the Moon's history, it is likely that hydrated materials are concentrated in zones of fracture and volcanic activity. In this case, much of the Moon's water will have reached the surface, and some of it may have survived as ice in shadowed zones, particularly at high latitudes. If the Moon has remained a "cold" body, more uniform distribution of water of hydration in lunar rocks might be expected.

Present knowledge of the Moon's density and the known composition of the Earth and meteorites strongly indicate that oxygen is the most abundant element in the Moon. Nearly all the oxygen is probably associated with silicate radicals, though some oxygen is likely bound with hydrogen as molecular water or as hydroxyl radicals. Silicate rocks are probably uniformly distributed over the lunar surface.

The most probable source of lunar hydrogen is water. Hydrocarbons (primitive or from cometary impact) or some volcanic gases (HCl, NH₄, etc.) constitute possible but less likely sources of lunar hydrogen.

Appendix A gives estimates of possible lunar concentrations and forms of these substances as well as for metals and non-metals of possible early interest on the Moon. Dust and broken rock constitute the most important of the latter category. Large fragment sizes are probably most abundant near fresh craters. It is not yet certain where very fine material is concentrated on the lunar surface, though topographic lows are the present best guess. The widespread existence of lunar dust, however, seems clear.

Appendix A lists the parameters presently considered to form the physical nature of the lunar surface. Values for some parameters are fairly well known; other parameters are represented, however, by numbers which are of limited application, as they are integrated over very large areas of the Moon or the whole lunar surface and so do not provide a true picture of the surface at specific places. Factors which appear most vital to lunar surface operations are (1) the effect of meteorite bombardment

on the lunar surface and the flux of meteorite secondaries, (2) the surface geometry (relief and slopes) on the scale of a spacecraft, (3) the electrostatic field at the surface, (4) the dominant processes of erosion and deposition on the Moon, and (5) the degree of internal activity on the Moon.

Recommendations

Recommendations for research to further our knowledge of the subject presented in this Section are grouped in major categories, as follows:

1. Probe missions and early preparation of additional experiments for measurements from spacecraft which will make possible the better utilization of lunar materials.
2. Spectroscopic and photographic observations of the Moon from Earth by balloon-borne (or ground-based) telescopes at all wavelengths.
3. Theoretical and laboratory studies of simulated lunar materials and processes. Some examples are:
 - a. Studies in a simulated lunar environment on homogeneous and layered models of granulated materials for their mechanical, thermal, electrodynamic, and acoustic properties.
 - b. Further investigation of the physical and chemical effects of impact on solid and granular material.
 - c. Equilibrium in pertinent petrological systems in vacuum at high (1000°C) and low (0°C) temperatures.
4. Studies of pertinent geological relations on Earth to obtain a better understanding of lunar processes. Some examples are:
 - a. Modes of evolution of juvenile water and other gases on Earth.
 - b. Impact crater studies.
 - c. Radar studies of known Earth terrain to assist evaluation of lunar radar data.

C. Power Sources

Substantial power sources are required to construct a lunar base, extract substances from lunar materials, and to explore the lunar surface (see Appendixes B and C). Power sources for these various functions can be divided into two basic types: stationary and mobile. Several stationary power plants are required for the general operation of a manned base; mobile power sources are required for vehicles and portable life-support systems.

It has been concluded from several independent studies that nuclear power plants are the most suitable for large permanent stationary energy sources. Fuel cells, batteries, and turbines would probably be the most satisfactory power sources for mobile applications. For emergency back-up and auxiliary power sources, solar energy should be considered. Solar furnaces, solar cells, and thermoelectric solar devices are examples of solar power sources.

Recommendations

Recommendations for immediate research and development are as follows:

1. Initiate development and testing of a nuclear power plant to serve as the basic energy reservoir for construction and operation of a lunar base. This stationary plant would also supply energy to a surface vehicle for exploration. This power plant should be designed to obtain maximum extractable energy within a weight limitation of 25,000 pounds. It should be a self-contained module capable of being launched on a *Saturn 5* booster and landed on the Moon as a unit from which a man can receive power by merely connecting a power line. (Present and planned reactors, such as the *SNAP-8*, are not suitable for operation in the lunar environment where temperatures vary from -240 to $+250^{\circ}\text{F}$.)

2. Initiate system development and testing of propulsion power sources for a manned lunar-surface traversing vehicle. Several approaches should be undertaken concurrently and component development should be accelerated (fuel cells, rotating machinery, batteries, solar collectors, and generators).

3. Initiate studies of a second, larger nuclear power source of several megawatts. This will be required at a later date to process large quantities of lunar materials.

4. Develop heat-rejection devices for lunar power systems. In the absence of an atmosphere, the use of space radiators or the Moon itself as a heat sink will have to be considered as possible ways to dissipate waste heat. It is therefore recommended that this problem be emphasized in any development of power sources.

D. Base Construction and Surface Transportation

There are problems concerned with the construction of a manned lunar base and surface transportation which can be solved with laboratory research and analytical studies here on the Earth. (See Appendix B.)

Recommendations

Recommendations for research and development are as follows:

1. Initiate analysis of the base design and construction procedures as they concern lunar surface modification. This analysis should include definition of required equipment. Specific items to include in this study are:

- a. Use of explosives.
- b. Excavation, transportation, and placement of materials by mechanical means.
- c. Processing surface and excavated materials.
- d. Foundation and surface preparation.
- e. Stabilization procedures.
- f. Construction planning.

2. Select and test materials to build a manned surface-traversing vehicle. Materials to consider are metals, plastics, shielding materials, seals, bearing materials, and lubricants.

3. Develop accessory subsystems for a manned surface-traversing vehicle: life-support packages; television and communication packages; manipulators.

The recommendations in the following list are considered necessary, but development could possibly be deferred until the foregoing items are well under way.

1. Develop lightweight, compact drilling and coring equipment. Such equipment may be used for scientific investigations and as a tool in constructing a permanent base.

2. Develop an antenna concept for use on the lunar surface.

3. Develop both portable and fixed equipment for identification of lunar materials.

4. Develop and test a prototype manned surface-traversing vehicle.

5. Formulate base and equipment maintenance concepts.

6. Coordinate research of soil mechanics problems.

E. Mining and Processing

Utilization of lunar resources will require the mining and processing of surface or subsurface materials. In view

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RECOMMENDATIONS FOR UTILIZATION OF LUNAR RESOURCES

of the uncertainties concerning form and mode of occurrence of useful materials, final designs for equipment can obviously not be arrived at. Several broad areas of research are recommended, however, to provide the necessary foundation for equipment development when the physics and chemistry of the Moon are better known. (Specific problem areas are delineated in Appendix C.)

Recommendations

Recommendations for research and development are as follows:

1. Investigate lunar excavation techniques, giving emphasis to possibly unique lunar possibilities.
2. Study practicability of all possible resource extraction techniques and the relation of each to power sources, including:
 - a. Low-weight, high-reliability electrolysis and liquefaction equipment.
 - b. Thermal dissociation processes.
3. Investigate physical chemistry of oxygen reduction, dehydration, and ice-melting in the lunar environment.
4. Study the effect of the lunar environment on the physical properties of probable lunar surface materials.

APPENDIX A

**REPORT OF THE SUBGROUP ON ENVIRONMENT
AND RESOURCES**

R. C. SPEED, CHAIRMAN

MEMBERS OF THE SUBGROUP

**R. P. Bryson
J. Dornbach
J. B. Edson
M. Eimer
D. Gault
B. Hall
F. Hoehndorf
J. W. Salisbury**

**Submitted
to the
Working Group on Extraterrestrial Resources
February 1963**

I. ESTIMATES OF LUNAR RESOURCES

Resource	Concentration (all wt. %)			Natural Forms	Lunar Distribution	Technical Approach
	Maximum	Minimum	Average			
H ₂ O	~15	0	Probably <2	Mineral water Adsorbed water Water in volcanic glass	May be low (<1%) concentration if distributed uniformly in surface rocks. More hydrous minerals may exist near fractures.	a. Thermodynamics of dehydration b. Probe exploration methods c. Balloon-borne photography and spectroscopy See above
	4-5 10	0 0	0.5 0.5-4 on Earth			
H	—	—	—	Pore water (or ice) in lunar rocks Surface ice	Rocks between ~20 m and 2 km deep Externally shadowed areas, mostly at high latitudes	Model experiments
	—	—	—	Solar protons		
	—	—	—	Spallation protons in lunar surface	Function of latitude and phase	
	~1.0 H ₂	0	—	Water, hydroxyl in lunar rocks		
	—	0	—	Hydrocarbons (natural or cometary impact)	Impact sites (e.g., Aristarchus) fractures, craters, fumaroles	Telescopic and spectroscopic observation
	—	0	—	Volcanic gases (HCl, NH ₄ , H ₂ S, H ₂ O)		
	0	40	48	Rock-forming silicates	Uniform	
	70	30	—	Other oxidized inorganic salts (SO ₄ , CO ₃ , BO ₄ , NO ₃ , oxides)	Fractures, craters, fumaroles	Telescopic, spectroscopic observations and probe experiments
	—	—	—	Water		
	88	0	—	Volcanic gases (SO ₂ , H ₂ O, CO ₂)	Fractures, craters, fumaroles	

Metals									
Mg	~30 -30 40	<1 20 0	2 - 20 25	Silicate rocks Meteoritic debris Deposits of salts on surface	Search for peridotites Impact craters Fractures, craters, fumaroles	} Probe exploration techniques and geologic studies			
Fe	15 90 15	<1 5 <1	3 - 8 5 - 10	Silicate rocks Meteoritic debris Rocks	Search for ferrogabbros Impact craters Search for anorthosites, syenites, high-Al basalts Impact craters				
Al									
Ni	12	<1	2	Meteoritic debris					
Non-Metals									
Refractories									
MgO									
Al ₂ O ₃ TiO ₂									
High-Density Native Fe Ba SO ₄									
Pb SO ₄									
Cement Various salts Sulphur Light Aggregate Dust— volcanic ash and Lapilli									
Biological Materials									
Potassium	6	0.5	0.5-3						
Phosphorus	2	10 ⁻²	0.3						
Calcium Nitrogen	10 —	1 —	2-7 —						

II. FACTORS IN PHYSICAL NATURE OF LUNAR SURFACE

Factor	Technical Approach
A. Fields and Particles <ol style="list-style-type: none"> 1. Magnetic field 2. Gravity 3. Electromagnetic flux 4. Particulate flux 5. Secondary flux 6. Meteorite flux 7. Meteorite secondaries 8. Electrostatic field 	Spacecraft to make measurements and development of good experiments
B. Surface Geometry <ol style="list-style-type: none"> 1. Relief on all scales 2. Slopes on all scales 	
C. Physical Properties of Surface Materials <ol style="list-style-type: none"> 1. Thermal conductivity and heat capacity 2. Electrical conductivity and dielectric constant 3. Magnetic susceptibility 4. Density 5. Porosities and permeabilities to a variety of fluids 6. Compressibility and shear strength 7. Particle size frequency distribution and particle shapes 8. Spectral reflectivity 	Improved radar reflection measurements Spacecraft photography Balloon photography on Moon New telescopic work
	Spacecraft measurements and model studies

D. Surface Processes

1. Modes of erosion
2. Modes of deposition
3. Sintering
4. Compaction
5. Mass movements
6. Volcanic phenomena
 - a. Gas emission
 - b. Land form construction by lava and ash emission
 - c. Seismic activation
 - d. Collapse and subsidence
7. Impact phenomena
 - a. Crater and ejecta blanket formation
 - b. Degradation of Moon by escape of secondaries
 - c. Seismic and heat-energy generation
8. Tectonic phenomena
 - a. Faulting and doming as land-forming processes
 - b. Seismic activation

Spacecraft measurements and photography
 Photogeologic studies
 Experimental work (hypervelocity impact, electrostatic transport, etc.)
 Experimental studies
 Experimental studies
 Experimental (stability of slope loads in vacuum under spectrum of disturbance)

Telescopic and spectroscopic observation

Spacecraft observation and telescope work

Telescope and spacecraft

Experimental

Spacecraft observation and seismology

Spacecraft measurements

Need to measure nighttime temperature

Spacecraft measurements

E. Atmosphere

F. Temperatures

- a. Surface thermal radiation flux
- b. Depth of diurnal heating
- c. Subsurface temperature gradient

G. Subsurface Structure

APPENDIX B

**REPORT OF THE SUBGROUP ON FACILITY
CONSTRUCTION, OPERATION
AND MAINTENANCE**

GEORGE W. S. JOHNSON, CHAIRMAN

Submitted
to the
Working Group on Extraterrestrial Resources
February 1963

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Panel on Construction Techniques and Equipment	23
Panel on Operations Support	27
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Preface

This Report is submitted in response to a request for recommendations regarding the research that should be undertaken immediately to later enable men on the lunar surface to utilize natural resources, thus reducing their dependence on Earth supplies.

The subgroup held a meeting on November 1, 1962, to organize their efforts and exchange information. This was followed by a second meeting on January 17 and 18, 1963, to integrate the various recommendations into one Report which was agreed to unanimously by all members of the subgroup.

The subgroup was organized into panels of two or three people each at the first meeting, and this Report contains their consolidated recommendations and a compilation of results from the various panels. A lunar base concept was considered necessary to provide guidance to the other panels. However, because of the concurrent efforts of the panels, the base concept was unable to influence the other panels to the degree desired.

Surface transportation and both mobile and stationary power systems have been considered by the subgroup because they are an integral part of any lunar exploration concept and their designs are influenced by the processing and utilization of lunar resources.

The following excerpt from the minutes of the first subgroup meeting provide an understanding of the responsibilities of each panel:

1. The Requirements and Uses

The intent here is to examine possible functions of a permanent lunar base and determine its general character, its size, and the number of bases required. This can also be considered as an over-all mission integration study. It is thought that this portion of the work must precede the activity of the other members of the subgroup, because they need this type of guidance, or goals, to determine power requirements, and so forth. The three members of the subgroup responsible for this activity are D. R. Lord, G. W. S. Johnson, and W. Gillespie.

2. Construction Techniques and Equipment

This includes the development of load-carrying vehicles and digging and construction equipment necessary

for making mortar from lunar soil. The subgroup members responsible for this area of activity are B. M. Hall and J. J. Gangler.

3. Operational Support

This includes the support activities necessary to keep the base operational, such as the power plant, the storage of fuel, the operation of a facility to obtain water, the maintenance of the houses or shelters, and the maintenance of all support equipment. The subgroup members responsible for this activity are R. Gey and R. D. Hensley.

4. Mission Equipment

This includes the operation of such equipment as telescopes, computer centers, tracking, communications. This group will determine their size and complexity, and the protection required from the environment, with emphasis on special features which would affect the construction of the base. The subgroup members responsible for this activity are M. Eimer and W. R. Peterson.

5. Surface and Flying Vehicles

This group will examine the various means of transportation on the lunar surface, including the type of vehicle and its power plant. Special construction equipment is excluded. The subgroup members responsible for this activity are P. H. Bliss and L. D. Jaffe.

Included in the initial request for this Report was a requirement for a list of people or organizations conducting research applicable to this subgroup. An attempt has been made herein to comply where applicable by including such information at the end of each panel's Report.

The following is a list of subgroup members. Only those who were present at the first meeting worked on the panels. However, almost all members participated in the deliberations at the second meeting where the recommendations were finalized.

Subgroup Members

Dr. P. H. Bliss, Rand Corporation
 Dr. M. Eimer, Jet Propulsion Laboratory
 Maj. T. C. Evans, NASA Hq.

SUBGROUP MEMBERS (Cont'd)

Mr. J. J. Gangler, NASA Hq.
Mr. R. Geye, Lewis Research Center
Mr. W. Gillespie, Manned Spacecraft Center
Mr. B. M. Hall, U.S. Army
Capt. R. D. Hensley, Marshall Space Flight Center
Dr. L. D. Jaffe, Jet Propulsion Laboratory

Lt. Col. G. W. S. Johnson, Jet Propulsion Laboratory
Mr. F. C. Littleton, Manned Spacecraft Center
Mr. D. R. Lord, NASA Hq.
Mr. W. R. Peterson, U.S. Army
Mr. W. Robinson, Marshall Space Flight Center
Mr. E. L. Schriver, Marshall Space Flight Center

Research Recommendations

It is recommended that the following research be undertaken immediately to support a manned lunar base. The list is arranged in order of priority.

1. Initiate development and testing of a nuclear power plant to serve as the basic energy reservoir for construction and operation of a lunar base. This stationary plant would also supply energy to a surface vehicle for exploration. This power plant should be designed to obtain maximum power within a weight limitation of 25,000 lb. It should be a self-contained module capable of being launched on a *Saturn 5* booster and landed on the Moon as a unit which a man can start up and receive power from by merely connecting a line to it.

2. Initiate system development and testing of propulsion power sources for a manned lunar-surface traversing vehicle. Several approaches should be undertaken concurrently. Component development should be accelerated (fuel cells, rotating machinery, batteries, solar collectors and generators).

3. Determine design and construction procedures as they concern lunar surface modification. This analysis should include definition of required equipment. Specific items to include in this study are:

- a. Use of explosives.
- b. Excavation, transportation, and placement of materials by mechanical means.
- c. Processing surface and excavated materials.
- d. Foundation and surface preparation.

e. Stabilization procedures.

f. Construction planning.

4. Develop accessory subsystems for a manned surface-traversing vehicle: life-support packages; television and communication packages; manipulators.

5. Selection and testing of materials to build a manned surface-traversing vehicle: metals, plastics, shielding materials, seals, bearing materials, and lubricants.

The recommendations in the following list are considered necessary, but development could possibly be deferred until the foregoing items are well under way. This list is not arranged in order of priority.

1. Develop lightweight and compact drilling and core-boring equipment. Such equipment may be used for scientific investigations and as a tool in constructing a permanent base.

2. Develop an antenna concept for use on the lunar surface.

3. Develop both portable and fixed equipment for identification of lunar materials.

4. Develop and test a prototype manned surface-traversing vehicle.

5. Formulate base and equipment maintenance concepts.

6. Coordinate research of soil mechanics problems.

Panel on
REQUIREMENTS AND USES

Subgroup on Facility Construction,
Operation and Maintenance

G. W. S. Johnson
D. R. Lord
W. Gillespie

January 18, 1963

Concept of a Permanent Lunar Base

A permanent lunar base is a logical follow-on to a temporary base which is transported to the Moon as a module on the lunar logistics vehicle. A permanent base would utilize lunar material to the maximum extent possible to decrease the dependence on logistical supplies from Earth. This means that in choosing a site for a permanent base the mineral supply or possibility of obtaining water should be given very serious consideration.

Since some development items require many years to produce a usable device, the base concept or plan must be finalized as soon as possible. If required information is delayed, the base build-up will be postponed correspondingly. Therefore, there is an urgent need for information about the lunar surface. Lunar photographic orbiters and unmanned soft-landed spacecraft capable of returning a soil sample to Earth should be undertaken immediately.

The present lack of definitive knowledge of the lunar surface composition, texture, and topography precludes the formulation at this time of specific base concepts. An exploration program for manned landings subsequent to the first landing has not been formulated. The lack of such a plan also inhibits the formulation of specific base concepts. It is anticipated that a detailed exploration program can be agreed upon as soon as more knowledge is obtained about the lunar surface from the unmanned lunar programs: *Ranger* and *Surveyor*.

Any lunar base concept stipulated at this time must be adaptable to as varied a surface condition as possible. Present assumptions about the lunar surface may be completely erroneous. In addition, there are other restraints caused by trajectory and booster size considerations that influence the concept of a lunar base. The tendency will be for the first landing sites of unmanned spacecraft to become the sites for manned landings and for the same sites to later become lunar bases whether best suited or not. Therefore, one of the constraints in choosing the initial landing sites for unmanned spacecraft should be their possible abundance in natural resources.

The present manned and unmanned lunar program will have a direct influence upon the design of a lunar base. Possible landing areas using presently programmed *Apollo* equipment are restricted by many trajectory and rendezvous considerations. However, intentions are that future lunar-landing spacecraft will have more flexibility,

permitting landings at any point on the lunar surface. Conservative planning dictates that such improvements not be mandatory for the establishment of an early base. Thus, the early base site will most likely be located in the area where manned landings occur under the *Apollo* program. The available area is roughly bounded by 10 deg north latitude and 10 deg south latitude on the visible face of the Moon. The longitude limits are approximately 45 deg west and 30 deg east.

It is assumed that the temporary base will be continuously occupied while the permanent base is being constructed. It is also assumed that the permanent base would be located adjacent to the temporary base. Therefore, it is important that the prime consideration for location of a temporary base be availability of resources for a permanent base. An examination of the aforementioned large available landing area indicates that it includes a sufficient variety of lunar topography to assume that a desirable site for a permanent base will probably be available.

Thus, the most probable area in which a permanent base would be constructed will be subjected to the maximum extremes of diurnal temperature variation. This is an important design parameter that is compounded by the rapid rate of cooling or heating that occurs on the lunar surface.

Present knowledge of the lunar environment suggests that a permanent base should be underground. Such a design would economically provide protection from micro-meteoroids, solar radiation, and extreme temperature changes. However, surface conditions may make it impossible, or very expensive, to construct such a base. Therefore, present concepts must be flexible enough to construct a permanent base either underground or on the surface.

One of the major considerations for any base either above or below ground is its power source. Studies have concluded that a nuclear power plant transported from Earth as a unit is the most desirable. Since the power requirements continually increase as more ambitious projects are undertaken, the size cannot be determined by stating "requirements." The size will be limited by the weight of the power unit. Thus, the measure of efficiency will be kilowatts per pound of weight. Present and fore-

seeable boosters will limit the weight of the power unit to approximately 25,000 lb.

Solar power has been suggested, but because of the long nights—14 Earth days—it does not appear satisfactory as the main source of power. It may have application in an emergency or on a mobile vehicle. Solar cells have also been considered but because of the high power requirements and long duration, they do not appear as satisfactory as a nuclear power plant. Other possibilities have also been ruled out on the same arguments.

A logical progression of lunar base development is already becoming apparent. First, two men will land at a preselected site and explore the surface in the immediate vicinity for a few hours before returning to Earth. Special supplies may have already been landed at the site to aid the men in their tasks. Several months later, two more men will land at the same site, if supplies are already there, and these men will live in the Lunar Excursion Module (LEM) for approximately a week while they perform various tasks to enhance their probability of survival and to obtain more information about the lunar surface. If a power supply and Lunar Logistics Vehicle (LLV) are already at the site, the men may live in the LLV instead of the LEM. It is presumed that the LLV is more spacious than the LEM, and can be designed to provide some shielding from solar radiation. The factor limiting the stay time will be the endurance ability of the man remaining in lunar orbit in the Command Module. It is assumed at present that one week will be about the limit of his endurance. Using the same site as the original landing party seems logical in order to use old supplies or equipment and perhaps use parts of old spacecraft to enhance survival.

Several months later, if previous missions provide sufficient confidence, two men will remain on the lunar surface for several weeks, while the man in the Command Module returns to Earth. Later another man will be put into a lunar orbit in a Command Module from which he can retrieve the two men in the LEM. It will not be until this extended stay time that serious consideration will be given to initiating any activity leading to a permanent base constructed from lunar materials. Thus, there will only be two men available to undertake the early activities associated with construction of a permanent base. Because of the dangerous environment, the functions the men perform while exposed only in lunar suits must be held to a minimum.

By this time the men should be provided with some type of surface transportation vehicle transported to the Moon in an LLV. Such a vehicle should be compatible with the stationary base power supply so that it can be recharged within a reasonable time period. Mechanical manipulators will enable the men to perform many simple tasks without exposing themselves to the environment in a lunar suit. The initial vehicle should provide at least a 25-mi radius of action from the stationary power source.

Assuming highly successful missions through the foregoing extended stay time, the subsequent objective will be to perform two or three similar missions that overlap so that at least four men will be on the Moon at all times. These men could then devote considerable time to construction of a permanent base. Since their number is small, construction equipment will have to be highly automated. The cost of transporting men to the Moon and supplying them with the necessities of life is obviously so enormous that a special construction crew does not appear to be justifiable.

The main responsibility of the astronauts in the temporary base will be to operate the life-support and scientific equipment and perform surface exploration. Because of the high cost of transportation to the Moon, the number of astronauts will be small, and very elaborate training efforts are justified to cross-train each man in several disciplines. They will have to operate communications equipment and provide assistance during landing and departure of fellow astronauts. In addition, they will have to set up and operate the special construction equipment to process materials and build a permanent base.

The permanent construction will, therefore, proceed slowly until the base becomes somewhat self-sustaining and capable of supporting additional men. The permanent construction may progress more rapidly if the cost of transporting supplies and equipment to the Moon is greatly reduced—a possibility when nuclear upper stages or a *Nova* booster becomes available. If it turns out, as many suspect, that rocket fuel can be obtained from lunar resources, the Moon then becomes an attractive place from which to launch interplanetary expeditions. Then the cost of the build-up of a lunar base could easily be justified and its rate of build-up would be much more rapid than depicted above. However, there are so many uncertainties at this time associated with possible functions of a lunar base and the possibility of utilizing the lunar resources that a more conservative approach is warranted for present planning.

When considering the problems associated with construction of a permanent base, it appears obvious that not more than one such base can be justified at this time. Certain restraints already described limit its location. Therefore, it must be assumed that surface exploration parties will radiate from the base. The extent of their travels will be limited by their power supply and life-support equipment. Perhaps a simple portable power supply can be developed to permit recycling and processing of oxygen and water to extend the radius of the surface expedition. The possibility of prepositioning caches of supplies from lunar-orbiting spacecraft may be considered as a possible method of extending the range of the surface exploration party. If rocket fuel can be obtained from natural resources, manned flying vehicles using rocket engines may be a possibility for transportation between points on the lunar surface. Another possibility for trips of several hundred miles is to land another LEM at a preselected site where exploration is desired.

Since men will probably be existing on the Moon continuously before a permanent base is constructed from lunar resources, the functions of a permanent base must be examined. These can be listed as follows:

1. Provide the men more adequate protection from solar radiation, micrometeoroids, and extremes of temperature.
2. Increase the mission capabilities of the base—vehicle maintenance garage, fuel storage, additional life-support equipment so more men can exist and operate scientific equipment, communication equipment, and computers in conjunction with research laboratories.

As presently visualized the permanent base should be constructed in a design which could be continually expanded as the early portions are completed and occupied. The early modules should provide increased life-support capability and additional laboratory space. One of the early modules of a permanent base should be designed to be utilized as a maintenance garage for the construction equipment and special lunar surface vehicles. It will also inherently serve the functions of providing increased protection from solar radiation. Thus, a large volume and large entrance and airlock are required.

The men should have a "shirt sleeve" environment in which to perform maintenance. This means that an integral part of the first portion of the permanent base must be devoted to life-support equipment (air purification and power). The internal size of this first portion is estimated to require a volume in the order of 30 feet wide by 50 feet long and 15 feet high. The cross-sectional area may be circular in shape, if sufficient floor space is provided.

As the permanent base is expanded, another module should be devoted to operation of equipment used to process lunar material. Processing equipment to obtain water would have the highest priority, but other processes may be feasible and desirable; i.e., obtaining oxygen from silicon oxides. The actual processing plant may be at a remote location where ore-bearing soil is abundant. The volume requirements of the facilities necessary for this activity are difficult to estimate at this time because both the processes and equipment are unknown. However, if a rough approximation must be made for other planning purposes, the volume can be estimated to equal the volume required for the maintenance activity. Under this concept, each cavity or module of the permanent base would be the same size.

When the early portions of a permanent base are completed, the base will be continually expanded to provide additional capabilities, the extension consisting of additional modules which could be used to house more personnel and equipment. Suggested uses for additional modules are hydroponic farming, computational center, tracking center, living quarters, laboratory. Other uses will become apparent in the future.

In summary, a single permanent base is visualized located near the lunar equator on the visible face of the Moon. The permanent base may be underground and powered with nuclear power and consist of a series of connected cavities or modules constructed one at a time and each occupied as soon as completed. The first module would be used as a maintenance facility for construction equipment and lunar surface vehicles. Subsequent modules would contain more life-support equipment and processing equipment as well as living quarters. Lunar exploration will be carried out with a manned surface vehicle performing sorties in various directions from the permanent base.

Panel on
CONSTRUCTION TECHNIQUES AND EQUIPMENT

**Subgroup on Facility Construction,
Operation and Maintenance**

**James J. Gangler
Bruce M. Hall**

January 18, 1963

Construction Techniques and Equipment

I. INTRODUCTION

The following project treatment is controlled in scope by the concept outlined in the subgroup letter-directive dated January 3, 1963. Stated briefly, the thought is directed toward surface modification and materials utilization. Techniques and equipment for construction or erection of structures and support facilities are not included.

II. DISCUSSION

In consideration of each identified element of extraterrestrial construction, a decision must be made as to priority of the several elements of the construction task. This is a necessary and controlling factor in establishing priority for the research and development which precedes. Specifically, as applied to this project, an early commencement of investigation is indicated. Reasons for this early initiation are:

1. In any base construction program, terrestrial or extraterrestrial, the ability to loosen, handle, reshape and replace surface materials is an essential and basic element of a construction capability. These are capabilities of initial concern in developing design of structures and in determining the requisite capabilities of construction equipment.

2. A prime factor in the logistics problem is the use of indigenous materials in construction to the maximum practical extent. Knowing how they will be utilized and by what equipment techniques is a prerequisite in any logistics plan.

Development of a capability for excavation and surface modification rests on a comprehensive development of soil mechanics relative to extraterrestrial materials in an alien environment. During early lunar or planetary occupancy this capability will not necessarily be on the full range of materials that can be conceivably encountered on the exotic surface. However, a concept for design and methods of construction for all conceivable conditions is necessary to assure that site selection will not be controlled by excavation and surface modification restrictions any more than is realistically necessary.

III. DEVELOPMENT

A. Planetary Models

Of primary interest is a continued effort to apply all known surface facts and factors to the development of a lunar or planetary "model." These models should be spe-

cifically constructed to reflect physical condition effective in construction where soil mechanics are a factor. Some of this work, as concerns the lunar surface, is presently in progress. Armour Research Foundation, the Jet Propul-

sion Laboratory, Hughes Aircraft Company, General Motors Corporation (the latter two under Jet Propulsion Laboratory contracts), and Space Sciences Laboratory, North American Aviation, under contract to NASA, are investigating basic soil properties. To be determined are internal strengths, bearing strengths, penetration resistance, compressibility, shear strength, angle of repose, internal friction, apparent cohesion, and stress-strain behavior. Compound soil properties will be developed relative to excavation and drilling resistance, work of removal, tunneling problems and others. It is important that these efforts be continued and the derived information be utilized in preparing a continuously updated model for use in projects where indigenous materials are to be utilized. Further, soil mechanics models should be prepared for each of the planets considered as soon as meaningful information is obtained. A study should be instituted which would consider all the available data on each planetary site and should list all requisite data not on hand. Efforts should be made to include this requirement in the planetary probes as they become available.

B. Design Methods

1. Objectives

- a. To study procedures for the design of lunar excavation and surface modification.
- b. To provide complete engineering information and investigational program guidance for the design of extraterrestrial surface modification.

2. Program

Each of the generalized concepts for extraterrestrial facilities will be reviewed carefully to identify applicable elements of soils design in surface modification. The procedures for terrestrial design of a similar element will be reviewed, and controlling assumptions in the theoretical and empirical procedures will be identified and compared to conditions anticipated at specific locations on the lunar or planetary surface. Need for laboratory and field testing to evaluate effects of the alien materials and alien environment will be defined. When necessary, new theoretical and empirical design methods will be developed.

As interim design procedures become available, example designs will be developed. This information will then be available for estimating quantities for structural design of buried structures and for construction operations. Design of the most likely facilities will be developed into computer programs. This will permit studying of all variables and identifying those most significant for

assured construction. The results will be used in identifying needed information to be obtained from lunar and planetary probes and early manned landings.

Methods for validating design procedures will be established. Adequacy of critical design will be demonstrated first in environmental chambers and then on the lunar or planetary surface.

The presently identifiable elements of design are:

- a. Stability of the existing surface with respect to slope angle.
- b. Resistance of unmodified surface to penetration.
- c. Limits of surface modification that can be made to the lunar or planetary surface without loss of stability.
- d. Effort required to excavate.
- e. Lateral pressures developed on buried structures.
- f. Depth of cover over buried structures required to support live loads during construction and operation.
- g. Sorting or processing surface and fill material to provide satisfactory surface smoothness or fill stabilization.
- h. Trafficability parameters, especially related to traction and smoothness.
- i. Surface stabilization techniques to improve efficiency of equipment and/or men. This will include compaction, control of gradation of materials, and chemicals or other stabilization procedures as required.

C. Construction Operations

1. Objective

To provide construction procedures and equipment design parameters for accomplishing excavation and surface modification on lunar and planetary surfaces.

2. Program

This operation can be conceived as supplementing and applying design concepts in field application. To meet this objective, it will be necessary to subdivide these operations into a coherent series of tasks which cover all elements of extraterrestrial construction. These tasks are: (a) explosives; (b) excavation, transportation, and placement of materials; (c) processing surface and excavated materials; (d) foundation and surface preparation; (e) stabilization procedures; and (f) construction planning.

The construction subprojects will be carefully reviewed to identify individual elements of construction methods and procedures. Terrestrially developed capabilities will be reviewed and controlling assumptions in the theoretical and empirical procedures will be identified. These operational factors will receive field and environmental

testing in exercises controlled by elements of the lunar or planetary environment. Where necessary, new construction procedures will be developed. Methods of evaluation and validation of the developed extraterrestrial construction procedures will be established for future manned landings.

Panel on
OPERATIONS SUPPORT

**Subgroup on Facility Construction,
Operation and Maintenance**

R. D. Hensley

January 18, 1963

Operations Support Projects

I. NUCLEAR POWER SUPPLIES

There will be a definite need for a source of power on the lunar surface in order to construct, operate, and maintain a temporary or permanent base. Because nuclear energy provides a source of electrical energy in a compact form capable of yielding over 1000 times the energy of a chemical source which is equal in weight, and owing to the susceptibility of solar cells or thermionic emissions to the lunar environment, it will receive preferential treatment as a lunar power source.

A study should be initiated to examine the power requirements for all phases of lunar exploration and base

build-up and to evaluate the capabilities of *SNAP* systems to satisfy these requirements within the proper time frame. The results of this study should serve as the basis for identifying and defining the limitations of current systems under development, and indicating the research and development necessary to produce a reactor and power conversion equipment for use at a permanently installed lunar base. If so indicated by the study, work on the power supply should begin immediately in order to be available during the period of permanent base installation.

II. LUNAR STORAGE OF LIQUID PROPELLANTS

Because the Moon is situated in a thermal environment quite different from that of Earth, a need exists to study the storage requirements for liquid propellants. The temperature of the lunar surface and objects located on it depends primarily on the laws and mechanisms of radiation and conduction heat transfer. The temperature rise of liquid propellants, for a variety of insulations, within a storage tank above ground with respect to latitude

location, tank geometry, and tank surface properties, should be studied. Included in the study should be an analysis of the thermal environment of a tank situated beneath the lunar surface and the alteration of the lunar surface necessary to achieve complete or partial burial. A comparison of the storage times available for a specific propellant such as liquid hydrogen above ground and below ground should be made.

III. SPACE MAINTENANCE

A considerable amount of detailed study effort has been directed toward evaluating man's capabilities in space for performance of maintenance and repair tasks. Work should be undertaken to establish maintenance techniques in reduced Earth gravity, repair techniques

for systems components which would be utilized at a lunar base, and the development of tooling and systems compatible with man's predicted capabilities on the Moon. Tool design, remote manipulator, and future hardware design criteria should be established.

IV. CURRENT STUDY PROJECTS

People or organizations known to be performing work in these areas are listed as follows:

Surface modification techniques in lunar construction.

- (1) Lunar construction capability study for NASA (OMSF) by Corps of Engineers, U.S. Army.

Investigations into soil mechanics as applied to the lunar surface materials and lunar environment.

- (1) Armour Research Foundation, Illinois Institute of Technology. Engaged in a three-year study for OART, NASA, entitled "Studies of Lunar Soil Mechanics."
- (2) Arthur D. Little Co., Cambridge, Mass. Engaged in an in-house study on lunar soil mechanics.
- (3) Chrysler Corporation. Lunar surface properties. Mr. L. Lawrence, Jr.
- (4) Center for Radiophysics and Space Research, Cornell University. NASA contracted study entitled "Laboratory Experiments Relating to the Lunar Surface."
- (5) Douglas Aircraft Co., Inc., Missiles and Space Systems Div. In-house study on lunar surface characteristics headed by Dr. J. A. Ryan.
- (6) General Electric, Missile and Space Vehicle Dept. In-house study of lunar surface materials and possible methods of soil stabilization.
- (7) General Motors Corporation, Santa Barbara, California. Engaged in lunar soil studies in connection with Surveyor and other lunar landers. Supported by NASA-JPL. Dr. M. G. Bekker.
- (8) Geophysics Research Directorate, AFRD, Air Research and Development Command, USAF. In-house study on lunar soil mechanics headed by Dr. John W. Salisbury.
- (9) Grumman Aircraft Corporation. Lunar soil properties. Mr. J. D. Halajian.
- (10) Hughes Aircraft Corporation, Culver City, California. Engaged in lunar soil studies as part of the Surveyor program under NASA-Jet Propulsion Laboratory sponsorship.
- (11) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. In-house laboratory studies of lunar soil mechanical and thermal properties. Drs. Carl Thorman and L. D. Jaffe.
- (12) Langley Research Center, NASA. In-house study on lunar soil, Dr. George Brooks.
- (13) North American Aviation, Inc., Space Sciences Laboratory. NASA contract on lunar soil mechanics, Dr. Jack Green.
- (14) Southwest Research Institute. Studies on construction techniques utilizing lunar surface materials.



Panel on
MISSION EQUIPMENT

**Subgroup on Facility Construction,
Operation and Maintenance**

W. R. Peterson

January 18, 1963

Mission Equipment

I. DRILLING AND CORE-BORING EQUIPMENT

Early knowledge of the subsurface composition of the Moon will depend to a large degree on the availability of appropriate equipment which can penetrate the surface and extract samples of the material.

A. Performance Requirements

It would appear that the first objective is the development of drilling capability. The production of core samples is highly desirable and may be mandatory for certain analyses, but much more difficult to achieve. The size of the hole is not greatly important for exploration purposes, except as it affects power consumption and mass of equipment. However, a capability for large (4 in. or more) diameter holes will increase the versatility of the equipment, making it useful for other operations such as drilling holes for posts, masts, and guy wire anchors and for the burial of small items such as electric power supplies.

Drilling and core-boring requirements will grow with the advance in size of lunar base operations. There will be an immediate need for small portable equipment for the production of shallow exploration holes. For advanced stages of lunar resources exploitation, deep drilling to a depth of several thousand feet with fixed installations is envisioned.

B. Restraints

1. Conventional drilling or boring equipment depends on air, water, or other viscous media for removal of chips and cooling of the bit. Neither liquid nor gas will be available.

2. Drilling and core-boring operations are heavy consumers of power.

3. The usual drilling and boring operation requires relatively heavy axial loading of the bit in order to effect penetration of the cutting edges. Lunar equipment will necessarily be designed as light as practicable for logistical reasons. Reduced gravity will further reduce by a factor of six the available mass for loading the tool.

4. Ambient atmosphere or a cooling medium normally acts as a lubricant between the tool and the soil material. The effect of this operation in a hard vacuum may be excessive friction, galling, or cold welding.

C. Design Approach

1. The most likely concept for the cutting tool will be an impact type with a mechanical-type device for removing the chips.

2. High efficiency with low power consumption will be a critical design requirement.

3. Supplementary means may be required for loading the cutting tool as the mass of the equipment may be insufficient for this purpose. Lunar soil may be used for ballasting or the equipment may be secured with soil anchors.

4. Tests must be made in ultrahigh vacuums to determine the interaction of cutting-tool material with various simulated soil types. Results of these experiments will dictate tool material and design parameters.

D. Development Capabilities

Hughes Aircraft Co. is probably the only firm which has successfully built and tested drilling equipment for the Moon. This equipment was designed for use on the *Surveyor* and has a capacity of 1¼-in. holes to a depth of 5 ft with a relatively high efficiency. The performance of this device is described in a paper by Dr. H. Carl Thorman of the Jet Propulsion Laboratory entitled "Review of Techniques for Measuring Rock and Soil Strength Properties of the Moon."

Hughes Tool Co. is one of the foremost designers and builders of drilling tools. They have engaged in several studies related to extraterrestrial drilling operations, among them ASTIA Document AD258661, "Final Technical Report on Feasibility Study of Drilling a Hole on the Moon," and a proposal to NASA for development of a lunar tunnel driver.

Texaco, Inc. has also studied the subject of lunar surface drilling and no doubt has a capability for a complete design effort.

The U.S. Army Engineer Research and Development Laboratories have done extensive work on development of lightweight, high-speed drilling equipment for tactical

use. This equipment possesses some unusual innovations which should be considered in the design of the lunar device.

Armour Research Foundation, Battelle Memorial Institute, and Midwest Research Foundation have been performing research on drilling of holes on the Moon.

II. RADIO TELESCOPES

A. Existing Installations

A convenient listing of some of the world's major radio telescopes is contained in *Time*, December 14, 1962.

- (1) Jodrell Bank, England: a 250-foot-diameter dish
- (2) Parkes, New South Wales, Australia: a 210-foot-diameter dish.
- (3) National Radio Astronomy Observatory, Green Bank, West Virginia: a 300-foot-diameter dish.
- (4) University of Illinois: a 600-foot cylindrical trough.
- (5) University of California, Hat Creek, California: a fully steerable 85-foot-diameter dish.
- (6) Stanford University: a tree farm type of antenna consisting of elements mounted on 40-foot booms.
- (7) Caltech Owens Valley Station: two dish antennas rigged in tandem.
- (8) Nancy, France: a large mattress-shaped antenna.

B. Performance Requirements

It would appear that for maximum effectiveness a lunar radio telescope would be located on the far side of the Moon to avoid as far as possible stray signals from the Earth. The size of the installation will be limited primarily by logistics and construction capability. Steerable parabolic dishes are the most useful and versatile, but require an extreme mass of complex machinery. By virtue of their large size, immovable reflectors such as the trough at the University of Illinois are extremely sensitive and are capable of receiving useful data from distances of

billions of light years. Perhaps satisfactory data can be obtained by just laying out simple wires (many kilometers long) on the surface of the Moon.

C. Construction of Lunar Antennas

Construction of large antennas, particularly on the far side of the Moon, would appear at best to be a formidable task. However, several elements of the lunar environment favor the design and construction of this type of installation. The reduction in gravity and complete absence of atmospheric disturbance will reduce by a large factor the mass of supporting structure. Fixed antennas may be constructed directly on the surface without the need for supporting structures. A favorable site selection which exploits the natural contour of the local lunar surface will reduce the excavation task.

D. Research and Development

1. The first effort appears to be a detailed study of the design and performance of existing equipment.
2. The second phase of study should be the translation of existing designs into those compatible with the lunar environment and with the limitations of logistics and construction capability.
3. The third phase of the study would consider the results of the lunar probes and exploration to ascertain which local resources could be utilized in the construction of large antennas. Hopefully, metallic elements or other suitable reflective material may exist in suitable form and quantity on the lunar surface for processing into antenna components.

Panel on
LUNAR SURFACE AND FLYING VEHICLES

Subgroup on Facility Construction
Operation and Maintenance

P. H. Bliss
L. D. Jaffe

January 18, 1963

Lunar Surface and Flying Vehicles

I. INTRODUCTION

In considering the construction, operation, and maintenance of a lunar manned base utilizing extraterrestrial resources, it seems clear that there will be need for transportation of men, equipment, and materials on and across the lunar surface. This Report is concerned with vehicles for this purpose. Vehicles will also be needed for construction: "earth"-moving vehicles, cranes, etc., which are covered in another Panel Report. A considerable degree of overlap may occur, however, and it may well turn out to be desirable to utilize the same basic vehicle for both construction and transportation.

A large number of reports, papers, and proposals have been written on the subject of lunar surface vehicles — both manned and unmanned. Some of the more interesting documents are listed in the bibliography. As some of the documents are classified and many are proprietary in nature, this Report will not attempt to review them in detail. It will, however, mention some of the concepts common to many of the documents and some of the problems which appear to emerge from these studies. Emphasis will be upon concepts and problem areas where supporting research and technology effort may be warranted during the next few years.

II. CONCEPTS

A. *Manned and Unmanned Vehicles*

Manned vehicles are obviously required for transportation of humans and may be highly desirable for a number of other operations such as exploration, some maintenance, etc. On the other hand, transportation of freight, some maintenance, some scientific investigations, etc., might well be done without operators in the vehicles by the use of remote control. Thus both manned and unmanned vehicles need to be considered. To reduce the number of different vehicles it has also been suggested that vehicles should be capable of operation either with a man aboard or by remote control.

B. *Power*

Power will be needed for movement of the vehicle, for communications, for guidance, for life support, for manipulation, and for temperature control. Primary power sources which have been suggested include chemical energy, solar energy, and nuclear energy.

Nuclear energy sources should utilize turbogenerator or thermionic conversion to produce electricity. For manned vehicles carrying reactors, shielding from nuclear radiation would impose very heavy weight penalties. Other problems would include disturbance of sensors by nuclear radiation, radioactivation of the soil by neutrons, and heating of the soil by waste heat, thus complicating temperature control. Small secondary power sources fueled by radioisotopes could be more easily shielded and could provide emergency or auxiliary heating and power.

Solar power seems attractive for daytime use. Solar turbogenerators and thermionic generators require high degrees of solar energy concentration and therefore well-oriented reflectors; these are difficult though not impossible to incorporate in surface vehicles. Solar thermoelectric or photoemissive devices do not as yet seem promising in size or weight in comparison to photovoltaic cells. The latter were proposed by many writers. A serious

problem with solar power sources is the large area required: only 1.4 kw/m² are available from the Sun. A 300 ft² (30 m²) array, which seems large for a surface vehicle, receives 40 kw and at 15% efficiency will produce 6 kw—probably not adequate for a vehicle of such size.

The chemical energy sources discussed were storage batteries for auxiliary or emergency use and hydrogen-oxygen reactors for larger amounts of power. The hydrogen-oxygen reactors could take the form of piston engines, gas turbines, or fuel cells; all three have been seriously considered and are being investigated experimentally at the present time. The mechanical converters have the disadvantage of requiring that the mixture ratio be far from stoichiometric to keep temperatures within limits that solid materials can stand. With all three systems the water produced can be retained and either recovered for life support or electrolyzed back to oxygen and hydrogen using nuclear or solar power at the lunar base or perhaps solar power on the vehicle itself. Fuel weights will probably limit the operating radius, without refueling, to a few hundred kilometers.

For unmanned vehicles, then, it appears that hydrogen-oxygen fuel can be used for short- and moderate-range vehicles, solar power for vehicles that need run only in daytime (if these vehicles are small and economical of power), and nuclear power for vehicles of any range. For manned vehicles, which require additional power for life support as well as additional weight and shielding, the matter is not so simple. Hydrogen-oxygen fuel is apparently suitable for moderate ranges. For long-range travel (more than a few hundred kilometers) surface-to-surface rockets may well prove best. For long-range manned surface vehicles, refueling might be necessary, using fuel dumps or power stations emplaced en route by rockets or unmanned surface vehicles. An alternative might be to bring the power stations along, either as a very large and very light foldable solar array that could be spread out when the vehicle stops to recharge, or, if night operation is needed, as an accompanying unmanned nuclear-powered surface vehicle, which could recharge the manned vehicle at intervals but would not come close to the men while its reactor was on.

C. Drives and Traction

Electric and hydraulic drives have been considered by many authors. Essentially all have come to the conclusion that electric drives are preferable because of the difficulties with hydraulic fluids at very high and low tem-

peratures and the very serious consequence of a hydraulic leak. Both exposed and sealed drive mechanisms have been considered. Most of those who have studied the problem carefully have concluded that sealed mechanisms protected from lunar environment are preferable.

Traction devices have been discussed at length. These include conventional wheels with pneumatic tires, with metallic tires, with metallic tires plus grousers, elastic metallic wheels, tracks, walking legs, jumping devices, rolling vehicles, spiral screws, ballistic rockets, and rockets sustaining the vehicles at moderate altitudes. Despite all consideration of non-conventional traction devices, the overwhelming agreement is that they have little advantage and that metal-rimmed wheels are probably the method of choice. These might be either rigid or elastic, in configuration ranging from tricycles to four wheels to multiwheel trucks or trains. The consensus seems to favor the tricycle only when an extreme weight limitation is imposed. Normal four-wheel construction is generally favored with some interest in multiwheeled trains for transporting heavy loads.

Tracks are favored by a few people. Their chief advantage under anticipated lunar conditions would seem to be the ability to bridge possible crevasses or other holes.

Ballistic rockets may be of some use for long-distance surface-to-surface transportation or for emergency rescue operations.

The traction element design depends very heavily on the nature of the lunar surface to be encountered. The information on this is unfortunately scant and likely to remain so until vehicles have been landed on the Moon and make better measurements.

D. Vehicle Dynamics

Also related to the nature of the lunar surface is the vehicle suspension to be used. The types suggested are generally conventional.

The speeds proposed are generally in the 1 to 5 mph range for surface vehicles. There seems little likelihood that high speeds will be practical over the expected types of lunar terrain unless roads or rails are built. Added limitation on speed arises from the probable need for remote control with a time lag of several seconds in the control loop, as discussed in Section C. The lower lunar gravity reduces the restoring force available to balance inertial forces on a vehicle that is tipped, and so would

considerably reduce operating speed over obstacles or during turns.

E. Communications

Communications between lunar surface or flying vehicles and their main lunar base are limited by short lines of sight on the Moon and the lack of a lunar ionosphere. Ground-wave communications may be possible at distances of 50 to 150 km but at low frequencies. These frequencies would permit voice communication and normal telemetry, but no television. Since television from the vehicle appears highly desirable (see Section F), this is a serious limitation, but it might be permissible for manned vehicles. Almost all of the authors conclude that relay via Earth will be the best means of communication between vehicle and lunar base even though this means tying up large antennas on Earth and introducing a 1½-sec time delay each way in communications. For vehicles on the far side of the Moon, a lunar-orbiting communications satellite would presumably be needed. It is possible that for operations within a few kilometers of the main base, line-of-sight transmission might be used, particularly if the area is relatively smooth and there are no large obstacles or hills which would shadow surface vehicles from the base.

F. Remote Control

Unmanned vehicles must be controlled remotely from the lunar base or from the Earth. Even for manned vehicles, capability for remote control seems desirable for emergency situations and to relieve the load on the men. There seems almost universal agreement that remote control should be carried out by means of stereotelevision from the surface vehicle to the manned base or to the Earth; the operator could be located in either place and would direct the vehicle by radio commands. Terrain-feeling devices and terrain-scanning radar carried by the vehicle have been suggested as additional aids. For surface-to-surface flying vehicles, techniques similar to those used for manned ballistic rockets on Earth would presumably be applicable.

G. Navigation

Whether the vehicle be manned or unmanned, it is clearly necessary that its location be known. Navigation systems proposed include dead reckoning, celestial, radio from lunar base, radio from Earth, and inertial. Methods outlined are generally conventional.

H. Life Support

Concepts of life-support systems within the lunar surface or flying vehicle range from a "shirt-sleeve environment," through men in pressure suits within a pressurized cabin, to each man within his own individual hard-shell walking cabin. Ability of the men to leave the vehicle in suits and walk across the surface for short distances seems desirable. Thus, space suits for use on the surface and methods of entering and leaving the vehicle in a suit are needed. Provision for supply of oxygen, water, food, removal of wastes, and control of temperature, humidity, and other factors are generally suggested along the lines of those currently used or considered for manned space vehicles. The suit itself, because of the need for surface capabilities, would have to be different.

I. Manipulators

Manipulators for handling objects outside of the vehicle seem highly desirable. For unmanned vehicles, these would have to be controlled from the manned base or from Earth by radio command. For manned vehicles, they could be controlled from within the vehicle. Manipulators on individual space suits have also been suggested. The concepts seem to center around manipulators, generally electrically driven, of the kind used in handling radioactive components, but presumably much lighter.

J. Temperature Control

For surface-to-surface flying vehicles, temperature control, during flight at least, can be along the lines normally used or considered for space vehicles. For lunar surface vehicles, problems are more severe because of the presence of extremely hot or extremely cold lunar surface, and more complex schemes have therefore been suggested. These center around multiple-layer insulations and shadowing, together with active temperature control. Suggested techniques include circulating fluids around the individual assemblies and then passing them through a heat exchanger. On-board heat is considered necessary during the lunar night even if the vehicle is unmanned and shut down.

K. Simulation

A number of concepts for Earth simulation have been suggested. These range from tests of components in vacuum to tests of complete vehicles in large Moon simulators containing simulated lunar surfaces. One suggestion is that the desert or arctic areas of the Earth might provide reasonable test grounds.

III. PROBLEM AREAS

A survey suggests that the most important problem areas, and those where lead time before design of lunar surface vehicles is most important, relate to the nature of the Moon itself. The present NASA program contemplates measurements of this kind. However, since these measurements will probably be the pacing items, it seems that effort on measuring lunar surface properties should be heavily emphasized. This might mean attempts to get more surface data in the present *Ranger* program.

A. Lunar Environment

Important facets of lunar environment on which better information is needed are:

1. Geometry of the Lunar Surface

To design a surface vehicle, the first requirement is a knowledge of the geometry of the surface. This includes characteristics on a scale ranging from many kilometers to microns. Information is needed on slopes, crevasses, boulders, holes, rock roughness and size, presence or absence of soil, particle size of the soil, its depth, etc. Some of these data can be obtained visually. For others, measurements will be needed. Quantitative techniques are sometimes used on Earth for measurement of the terrain features of size varying from centimeters to tens of meters. These consist of slope or elevation detectors which are moved across the surface; they may be of use on the Moon.

A major problem in measuring both geometric and other properties of the lunar surface is that of getting an adequate sample. Measurements at one or a few points may be highly misleading. It will be necessary to obtain data, in advance, on areas which can be considered representative of the terrain to be traversed by the surface vehicles.

2. Lunar Surface Mechanical Properties

If the lunar surface turns out to be essentially a continuous sheet of hard rock, further data on its mechanical properties are probably not necessary for surface vehicle design. If, however, something that might be termed soil or sand is present, or if the "rocks" are not solid but porous, data on their bearing capacity will be needed. Measurements of shear properties may also be desirable.

The sampling problem is again present. Even small areas of very low bearing capacity might serve as traps for vehicles.

The *Surveyor* program is planned to give data on lunar soil mechanical properties. It would be highly desirable to get this information earlier, if at all possible, and to increase the area of sampling quickly.

3. Lunar Surface Electrical Properties

To determine the extent to which ground-wave communications will be possible on the Moon, information is needed as to the dielectric constant and electrical conductivity of the lunar surface. This need not be determined on areas of a few square centimeters but measurements of areas of some square kilometers would be desirable, as are measurements of properties vs depth to some meters. Measurements of these properties from Earth seem limited to considerably larger areas. Measurements at a few points are planned for *Surveyor*.

4. Lunar Surface Thermal Properties

To design vehicles and suits with proper temperature control, a better knowledge of thermal properties of the lunar surface is needed. Measurements on the scale of a meter or so would be desirable. Again, sampling presents a problem. The advanced *Surveyor* payloads, if these are carried through, are intended to provide some information.

5. Meteoroid Environment at the Moon

Design of surface and flying vehicles, and especially of space suits, for use on the lunar surface will be heavily influenced by requirements for protection from meteoroids. There are major uncertainties in the primary flux of meteoritic particles striking the Moon. The meteoroid flux close to the Earth is very different from that away from the Earth. Since the cause of the concentration around the Earth is still not clear, there is no way to judge the extent of concentration at the Moon. Measurements close to or at the surface of the Moon are needed to fix the distribution of meteoroids in flux, mass, velocity, density, and perhaps composition.

In addition to the primary flux, it seems clear that there must be a very much larger flux of secondary particles of somewhat lower velocity, produced by the hyper-

velocity impact of the primary particles on the lunar surface. Again, measurements of the flux, mass, velocity, and density distribution of the secondary particles are needed. Some work on Earth, either experimental or theoretical, to determine the relation between a given primary flux and the resulting secondary flux would be worthwhile.

6. Solar Flares

Shielding of men in vehicles and in space suits from solar-flare particles will probably be very difficult. It does not seem that the shadow of the Moon will provide protection from high-energy solar particle emissions though it may cause a time delay before they reach the night side. More data are needed concerning solar energetic particle emissions, particularly as to the directionality of the particles as a function of time during each event. This would give a much better idea of how long men on the Moon would have to take shelter after a major flare occurs. Better techniques for predicting flares would also be of great value.

7. Solar Plasma and Electromagnetic Radiation

Low-energy solar plasma particles, as well as solar X-ray and extreme ultraviolet radiation, may damage optical surfaces, both windows and temperature control surfaces. This would be serious both on the Moon and for space vehicles. More complete measurements of these emissions would be helpful.

B. Investigations on Earth

Among the problem areas where experimental or analytical work on Earth appears desirable are:

1. Materials

Suitable materials for use in vacuum under the temperature range of the lunar surface (-150 to $+150^{\circ}\text{C}$), and perhaps higher for certain parts, require evaluation and perhaps development. Most of these materials are organic polymers. They include seals, adhesives, and perhaps fabrics and elastomers. Insulating materials may also need some attention.

2. Dust Behavior

There is some suggestion that rock dusts in vacuum will tend to adhere electrostatically to surfaces and interfere with proper operation. Some laboratory work on this point seems warranted. If problems exist, some materials development may be indicated, particularly on optical materials, to insure that dust will not adhere.

3. Lubrication

Though techniques of sealing moving parts in pressurized containers may be widely applicable, there are probably some parts which need to run in the vacuum unpressurized. Because of the tendency of most bearing and gear materials to seize in high vacuum, some additional work on lubrication techniques for high-vacuum operation at both high and low temperatures seems warranted. There are several groups associated with the space program working in this field.

4. Electromechanical Components

Again, it would be highly desirable to have some components that could operate in vacuum, preferably at both high and low temperatures, and would not have to be sealed in pressurized enclosures. Among these are DC and AC motors, relays, and switches. Some development along this line seems worthwhile.

5. Power Sources

Some work is under way on sources using hydrogen-oxygen fuel for production of electricity. These sources include fuel cells, gas turbines, and piston engines. This work should be continued, as should work on solar and nuclear power sources. It will be useful for lunar surface vehicles as well as in other parts of the space program.

6. Suspension Dynamics

There are a number of problems involved in design of suspensions of vehicles to move over rough terrain. Perhaps not too much can be done until the terrain is better known and functional specifications for the vehicle set down. However, some advanced development may be warranted, in particular in developing analytical and possibly modeling techniques.

7. Soil-Vehicle Interactions

The principles of soil-vehicle interactions are known and the primary need now appears to be knowledge of the lunar surface, rather than immediate studies of traction devices. When the geometry and mechanical properties of the surface are determined, work on traction devices should proceed at an accelerated rate.

8. Control

Several companies have been working on the problems of remote control of a moving vehicle in the presence of a $1\frac{1}{2}$ -sec time lag. Further investigations along this line seem warranted, including use of a $2\frac{3}{4}$ -sec time lag to

simulate vehicle-to-lunar-base communications via Earth. Performance of systems which can be controlled either from on-board a vehicle or remotely may warrant some attention.

9. Guidance, Navigation, and Communication

Problems in these areas seem to lie primarily in specific design and in knowledge of the Moon. It does not seem that much worthwhile work could be done in the way of advanced development.

10. Life Support

Problems in this area are being considered in another subgroup Report.

11. Manipulators

General purpose manipulators, some of which are suitable for remote control, are commercially available and some of these have been evaluated for use in vacuum.

Additional work seems warranted in assuring vacuum capability, in investigating problems of remote operation with a time lag, and particularly in reducing weight from that appropriate to Earth equipment to that appropriate for lunar missions.

12. Temperature Control

Work under way is concerned primarily with temperature-control problems in space. Problems of temperature control on the lunar surface warrant special attention and advanced development of techniques and concepts required for lunar surface vehicles should be encouraged.

13. Meteoroid Effects

Better information is needed on the effects of meteoroids in penetrating and spalling vehicle and suit materials, on meteoroid "bumpers," and on self-sealing materials for use over wide temperature ranges. Efforts in this field should be continued and perhaps expanded.

IV. RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

The research which is most urgently needed concerns the lunar surface: its geometry and its mechanical, electrical, and thermal properties. Experimental and theoretical work on the meteoroid environment at the lunar surface and measurements of solar flare emissions are also needed. Some research on meteoroid effects and on electrostatic adherence of rock dust in vacuum seems warranted.

Advanced development is justified on organic, optical, and insulating materials, vacuum lubrication, electro-mechanical components for use in vacuum, unsealed lightweight manipulators, and design techniques for temperature-control systems and perhaps for suspensions. Work should be continued on devices to produce electricity from hydrogen-oxygen fuel and on remote control of a surface vehicle with a time lag.

Once data on the nature of the lunar surface have been obtained, advanced development on traction and suspen-

sion techniques should be considerably expanded, and studies of the various types of vehicles resumed. In addition, careful studies should then be made of techniques and required facilities which will be necessary for thorough and exhaustive testing of the surface vehicles on Earth.

With adequate data on the lunar surface, development of a vehicle can be started when mission objectives and constraints are set. An essential attribute of such a vehicle must surely be dependability; this should be given primary attention in both design and testing.

Specific recommendations are as follows:

Bearing Materials. Basic research is urgently needed to find metals, alloys, plastics or other new bearing materials that will operate without lubrication, in a vacuum at temperatures of -244 and $+260^{\circ}\text{F}$.

Lubricants. Failing to find suitable bearing materials which will run dry, basic research should be conducted to find lubricants that will work under above conditions.

Seals. Shaft seals that will withstand the above temperatures with a vacuum on one side and atmospheric or 14.7 psi or less pressure on the other side may be needed in many machines.

Rubber. A rubber material, synthetic or natural, that will retain its flexibility under the above conditions should be developed for use as tires, seals, or other parts of machines.

Power Sources. Development and testing of engines for propelling vehicles, whether solar engines, fuel cells, or battery-operated electric motors are used should be programmed.

Life-Support Units. In order to provide life-support units in vehicles which are light and compact, research should be made with a goal of building the most compact sealed unit possible.

Hydraulic Fluids. In anticipation of needing hydraulic drives on some of the equipment, research should be made on fluids that will operate under the above temperature and pressure conditions.

Structural Materials. Since the temperature range affects the strength of almost all structural materials, it would be appropriate to find materials which will operate most effectively under these conditions.

Electric Motors and Wiring. Since most investigators are recommending use of individual wheel electric drive motors on vehicles, research is needed to develop electric motors that will operate under these conditions of temperature and vacuum.

Shielding Materials. The lunar vehicle must be shielded to protect the operator from radiation and micrometeoroids. Basic research should be conducted to find the best shell materials for resisting these effects and the best design for the cabs. Double or triple walls may be indicated, for example, with air space between.

Wheels. If metal wheels are required because rubber tires do not prove capable of withstanding the rigors of the Moon's environment, research should be conducted to find ways of designing a wheel that will be flexible or provide a suspension system which will smooth out the riding qualities of the wheel.

TV Controls. To operate efficiently, the vehicle should have TV viewing of all its operations relayed to the base station. Research should be started on TV units that will operate under these extremes of temperature and vacuum.

Communications. Research in two-way radio communications units should be made which will provide dependable communications for the operator and base controller, with consideration of both line-of-sight communications and greater than line-of-sight distances.

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APPENDIX C

**MINING AND PROCESSING OF
LUNAR WATER DEPOSITS**

**A Preliminary Report of the Subgroup on
Mining and Processing**

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Mining and Processing of Lunar Water Deposits

I. INTRODUCTION

The Mining and Processing Subgroup of the Working Group for Extraterrestrial Resources met for the first time on November 15, 1962 at the Air Force Cambridge Research Laboratories in Bedford, Massachusetts. The purpose of this meeting was to make a preliminary examination of the feasibility of mining and processing techniques on the lunar surface, and to define the major problem areas requiring further research. The draft report which followed this meeting has subsequently been revised on the basis of material submitted to the chairman, resulting in this Preliminary Report. In each case, every effort has been made to give credit to those attendees who contributed ideas. The reader need hardly be cautioned that those who have ideas generally feel a proprietary interest in them. Permission to use or work on concepts new to the reader should be obtained directly from the originator.

II. TYPES OF DEPOSITS CONSIDERED

Dr. Salisbury reviewed possible types of lunar water deposits, so that mining and processing techniques could be evaluated in the light of possible deposit locations and configurations. Four types of deposits were considered:

A. Surface

Among those present, Dr. Green had pointed out in 1960 that water might persist as ice in permanently shadowed zones because of its very low vapor pressure at low temperatures. Thus, relatively large surface deposits of ice may be present in crater bottoms near the lunar poles.

The subgroup did not think that such deposits could be economically mined, due to their unfavorable location, but still considered them in the event that no more favorable type of deposit exists on the Moon.

B. Subsurface Blanket

It is possible that layers of ice or hydrated minerals may exist in the upper few meters of the lunar surface

materials, especially around suspected sites of extensive gas release such as the chain craters. This type of subsurface deposit, which would be mined by open pit methods, was defined as a subsurface blanket deposit.

C. Subsurface Massive

It is also possible that such deposits of ice or hydrated minerals could extend to sufficient depth to require the use of underground mining techniques. This type of deposit was defined as a subsurface massive deposit.

D. Bare Rock

Unenriched rock was the final source of water that the subgroup considered. Realizing that water extraction from bare rock may or may not prove economical, the subgroup nevertheless accepted the possibility that it may be the only source available. Dr. Green pointed out the rather wide variability of water content in igneous rocks, and subsequent discussions with Dr. Green and Mr. Segal have indicated that the "juvenile" or initial magmatic water content of igneous rocks is probably much less than 1%.

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III. MINING AND TRANSPORT

A. Surface

The subgroup recognized the extreme difficulty of performing any operations on the lunar surface, and favored simplified mining or processing techniques. Because surface or subsurface blanket types of water deposits might require surface mining and transport, however, the group discussed possible techniques.

Lt. Colonel Athas suggested that a high-temperature laser beam could be used as a cutting and pulverizing tool on or under the lunar surface, and Dr. Glaser suggested the plasma jet for the same purpose. Because such tools require considerable advance of the present state of the art, these suggestions were difficult to evaluate, but the subgroup felt that they definitely merited further study. The major advantage of laser or plasma jet tools would be their reusability, in contrast to such expendable tools as explosives.

Mr. Baumgardner pointed out, on the other hand, certain advantages of explosives in mining. First, they may be made to lift as well as cut, thus placing pulverized ore in an advantageous location for loading and transport. Second, charges may be placed so as to reduce the ore to a size range favorable for loading or processing. Third, modern explosives are light, and require no heavy support equipment. Fourth, explosives are simple and reliable.

Surface mining by means of a scraping vehicle was discussed by Mr. Segal, who displayed a design on which he had been working. Mr. Baumgardner pointed out the unusual difficulty of designing a workable scraper for use in a $\frac{1}{6}$ -g environment, and that it was not adaptable to deposits of solid material or to rubble deposits containing large blocks.

Surface transport of lunar materials was briefly discussed, and Mr. Bliss submitted a written report on this subject. Because the transportation problem is considered in detail by the Base Construction Subgroup, however, it is not covered here. Suffice it to say that both mining and transport on the lunar surface pose many special problems, and are to be avoided or minimized if possible.

B. Subsurface

It is clear that subsurface mining and transport are greatly to be preferred on the Moon to surface operations. Creation of a shirtsleeve environment for both men and machines almost appears necessary for any extensive mining project. The problem of what cutting tools and transport vehicles are most economical and most suited to the underground lunar environment remains to be solved, however, as it is certain that terrestrial mining techniques are not directly transferrable.

IV. EXTRACTION

Given a water extraction requirement of 9 lb per hour, which was suggested by Dr. Steinhoff as a minimum desirable production rate, the subgroup examined every extraction technique that those present could think of.

A. Solar Furnace—Simple

As discussed in the previous Section, the most desirable extraction technique is one which requires little or no mining and transport. It appeared to the subgroup that a simple solar furnace was conceivable which would ful-

fill this requirement in the case of surface deposits of ice in permanently shadowed zones. None present had given serious thought to such a concept but, with the help of various subgroup members (principally Dr. Glaser, Dr. Green, and Dr. McCutchan), Dr. Salisbury developed a schematic diagram of such a system (see Fig. C-1). Ideally, a solar-energy collector perched on the rim of a polar crater would be able to continuously vaporize ice on the crater floor. This vapor would then be collected and processed on the spot without the necessity for mining or transport.

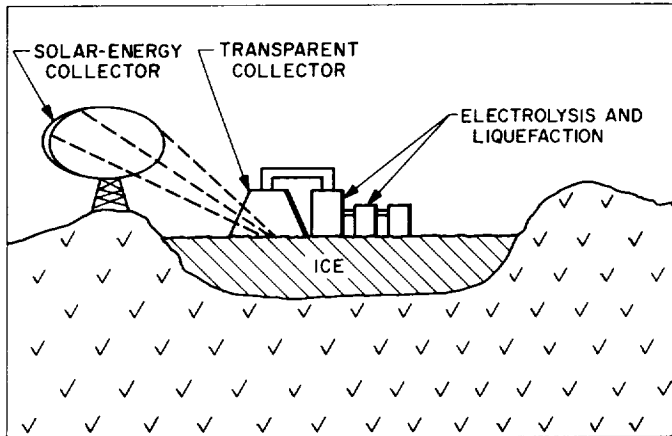


Fig. C-1. Solar furnace—simple: melting and processing of ice in a permanently shadowed zone at the bottom of a polar crater

Such a scheme has several advantages: (1) no mining or transport; (2) surface activity and manpower requirement low for automatic system; and (3) low power requirement.

Disadvantages are: (1) a closed system with pressure and temperature control is essential, and it is unlikely that an irregular and probably porous ice deposit would permit a good seal with the vapor collector; (2) impurities and meteoroidal debris that must be present in the ice would quickly form an insulating cover over the surface being vaporized; and (3) necessary polar location makes it of doubtful value.

The subgroup concluded that it was unlikely that such a system was either workable or practical in view of its serious disadvantages, but, in view of the great desirability of simple *in situ* extraction, did not discard the idea completely.

B. Solar Furnace—Complex

Several members of the subgroup (Dr. Glaser, Dr. Green, and Mr. Segal) had worked on more or less sophisticated solar furnace designs depending on the batch principle. Subsequent to the meeting, Dr. Glaser submitted a preliminary analysis of complex solar furnace techniques which is reproduced as follows:

“The solar furnace extraction technique applies best to deposits of rock containing water as a hydrate. For example, a typical serpentine on the lunar surface might contain 10% water of hydration. Other rocks might con-

tain one or two percent water of hydration. Heating this material to 800°C may be necessary for removal of the water of hydration. Several different types of heating devices and furnaces have been proposed.

“In order to consider the requirements of such a process, let us assume recovery of 8 or 16 lbs per hour of water from the subsurface material. Considering spherical kiln systems as shown in the diagram of Fig. C-2 typical power requirements, reflector sizes, and kiln size are shown in Table C-1 for various moisture contents of the subsurface rock. Also shown in the Table are the heat requirements for the kiln, i.e., the heat that must be transferred into the rock directly. The difference between total power and the kiln requirements are the heat losses. (The relation of power output to diameter of reflector is given in Fig. C-3.)

“For the first case listed in Table C-1, 8 lb per hour of water with a moisture content of the rock being 2%, the distribution of heat is as follows: Radiation and heat losses from uninsulated portions of the kiln, 27 kw; heat required to vaporize the water from the rock, 2.4 kw; heat required to raise the temperature of the rock from -40 to 800°C, approximately 35 kw. Thus, the major portion of the heat must be used as sensible heat in heating the rock from the lunar temperature to the temperature at which the water of crystallization can be removed. This total quantity of heat must be transferred through

Table C-1. Typical requirements for lunar water recovery system (solar furnace spherical kiln system)

Conditions		Total Power Required kw	Kiln Power Requirements kw	Typical Reflector Size ft
Capacity lb/hr	% H ₂ O in Rock			
8	2	64 ^a	38	35
16	2	102 ^a	76	44
8	2	67 ^b	41	36
16	2	107 ^b	81	46
8	1	100 ^a	73	44
16	1	173 ^a	146	58
8	1	102 ^b	75	44
16	1	177 ^b	150	59
8	10	36 ^a	9	27
16	10	46 ^a	19	30
8	10	38 ^b	12	27
16	10	50 ^b	24	31

^aValues of power requirements calculated using estimated heat of vaporization of water from rock as 575 cal/g.

^bValues of power requirements calculated using heat of vaporization of water from chrysolite (measured values) of 1110 cal/g.

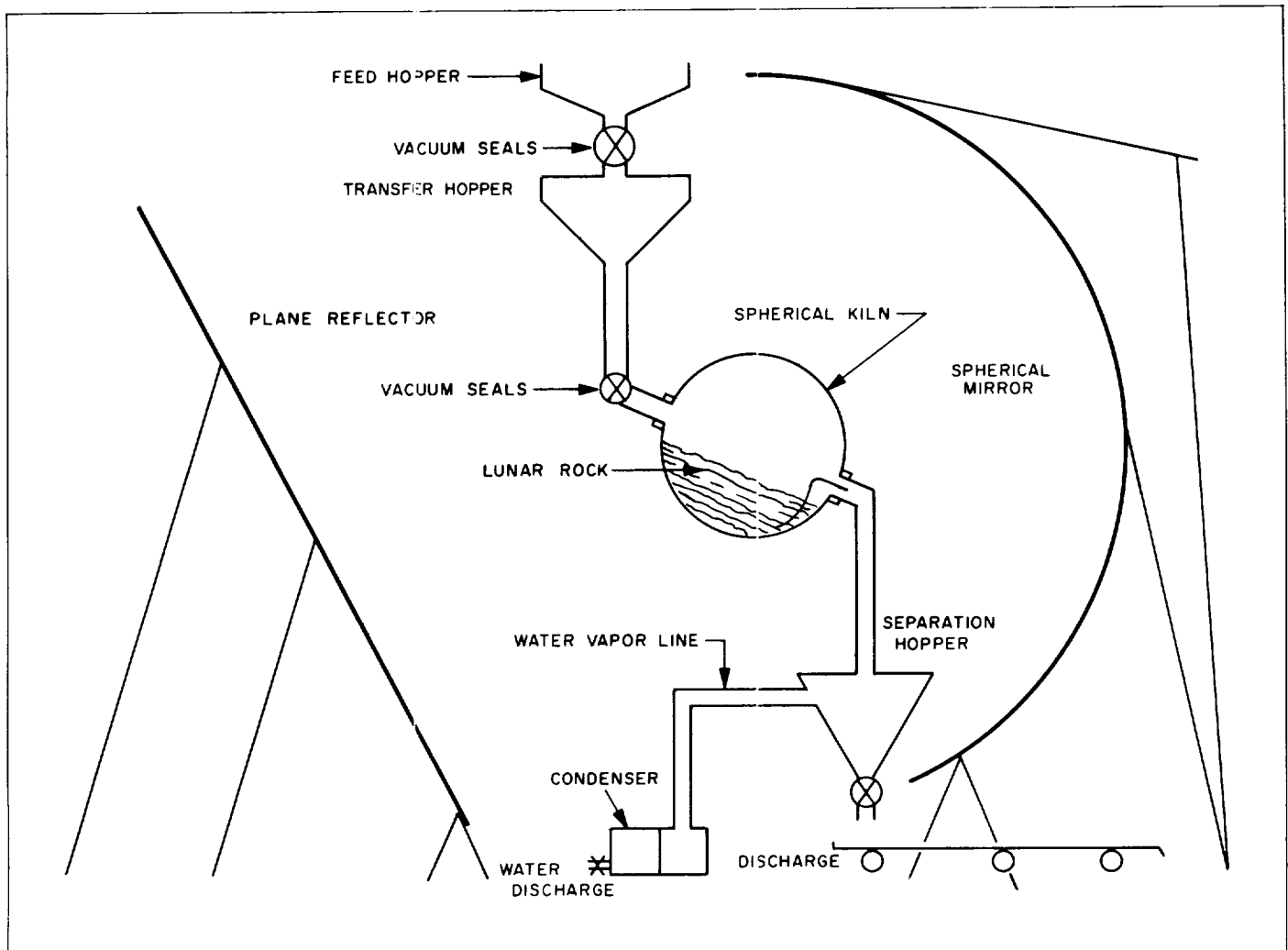


Fig. C-2. Schematic diagram of a complex solar-furnace water-production system

the kiln wall to the rock contained. This heat transfer occurs by two principal mechanisms; radiation from the uncovered portion of the kiln surface to the rock bed and conduction from the hot kiln wall to the rock surface. Preliminary calculations indicate that a temperature rise of several hundred degrees centigrade of a kiln wall above the temperature of the rock are necessary for the required rates of heat transfer. Even under these conditions, heat transfer will be primarily by radiation from the hot kiln wall to the solid, rather than by conduction from the kiln wall to the solid. Typical heat transfer coefficients in this type of system are one to five Btu/hr-ft²°F by the conduction type of heat transfer from the solid wall to the rotating solid and effective radiation heat transfer coefficient of 20 to 100 Btu/hr-sq ft°F for the radiation heat transfer coefficient. Increasing the speed of rotation of a kiln of the type depicted in Fig. C-2 would increase

the conduction coefficient. However, this could lower the average wall temperature and thus also decrease the effective radiation heat transfer coefficient. A balance between the two mechanisms must be obtained. Even with rapid kiln rotation, however, it is difficult to envision a conduction or convection heat transfer coefficient greater than ten Btu/hr-sq ft°F. Limited heat transfer to rock contained within the kiln and the fact that the majority of the heat required for the operation must be used as sensible heat of the rock are the two principal limitations to this process.

“Considering the heat transfer limitation, several solutions are available. Modification of the spherical kiln shown in Fig. C-2 to a cylindrical kiln with a window through which the radiation can be directly passed may reduce losses in transmission of heat to the kiln wall and

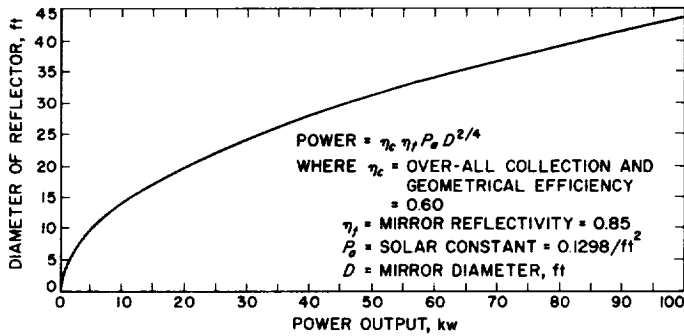


Fig. C-3. Power output from solar reflectors on lunar surfaces as a function of diameter

lower the total power requirement, and correspondingly, the total reflector size. Windows for such a device, however, are not simple to construct and a mechanical problem as well as material problems may exist. This

type of kiln shown in Fig C-4 does, however, have the advantage of a more direct heating of the charge by solar energy. Rapid rotation of the cylindrical kiln would in effect produce a semifluidized bed, thus providing more surface for the radiant energy to impinge upon. Vacuum seals would be necessary in the rotating kiln of any type.

“Another type of kiln system can use a fluidized or partially fluidized bed. For example, water vapor could be used as the fluidizing substance, pulverized rock would be suspended in a stream of superheated steam for at least part of the process. Steam used for heating could be recycled so that only the original requirement is needed. By using a fluidized system both sensible heat recovery and rapid heat transfer rates can be achieved.

“A study of the kiln method of water extraction might include such topics as:

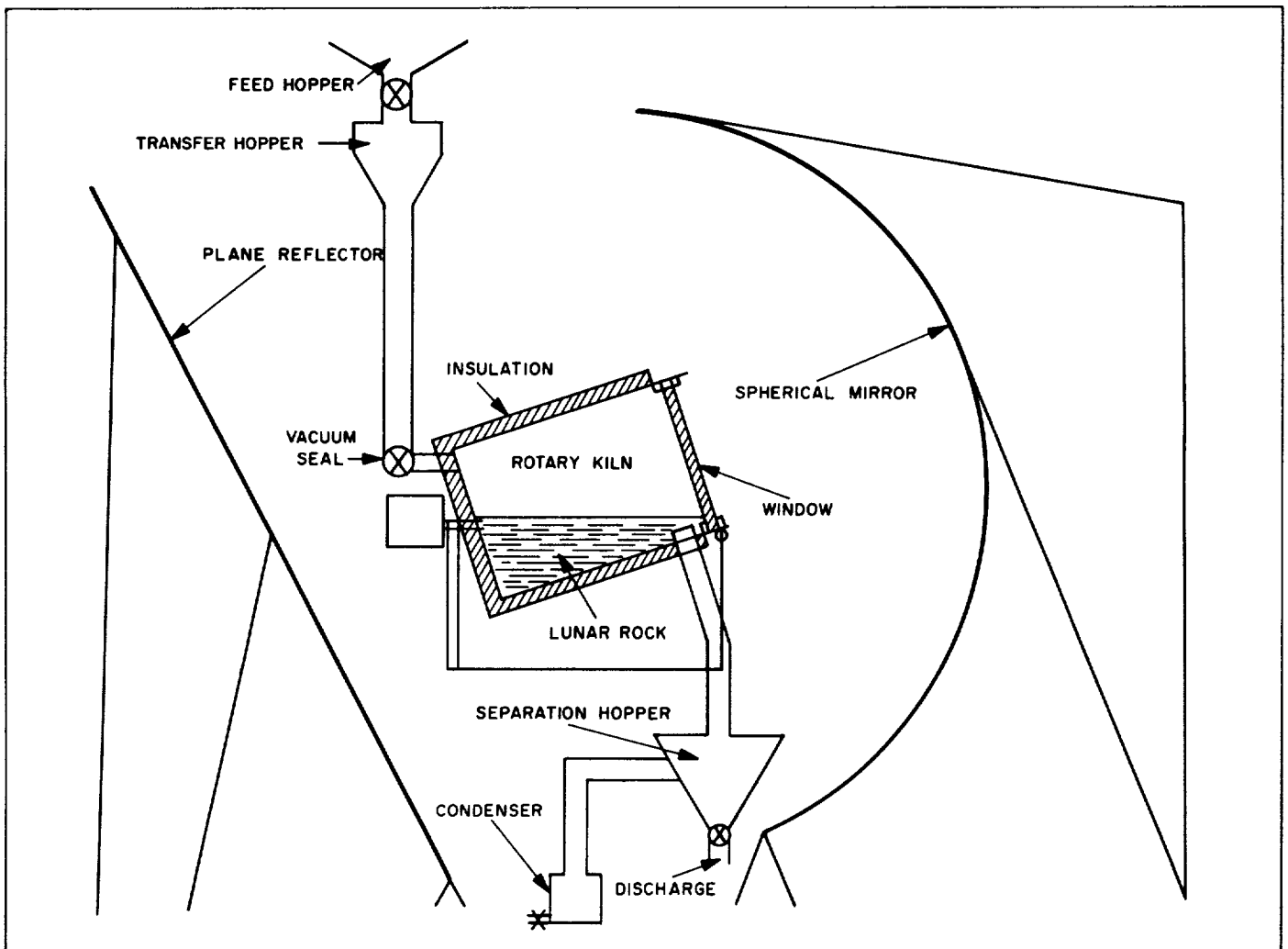


Fig. C-4. Diagram of complex solar-furnace water-production system using kiln with optical window

1. Kiln design using several alternative heating methods, i.e., heat transfer through the brick wall vs direct heat transfer through a radiant energy window.

2. Evaluation and possible economic appraisal of a closed steam recycle system.

3. Over-all process economic evaluation including material requirements, design criteria, transportation requirements and other factors.

4. Estimation of the requirements for heat rejection, materials, and apparatus for the condensation cycle for the extraction scheme.

5. Estimates of the reliability of the kiln extraction method, i.e., consideration must be given to the effects of meteorites, optimum locations on the lunar surface, storage requirements for operation during the lunar night time.

"The complex solar furnace has several advantages: (1) Low power requirement with respect to all extraction techniques except the simple solar furnace and possibly the nuclear Frasch process. (2) It is independent of the geometry of the deposit or type of ore.

"Disadvantages are: (1) Necessity for mining and transport of ore means weight, power, and personnel penalties. (2) Such a system will be able to operate only 14 days out of 28 in the most desirable locations for a lunar base, i.e., near the lunar equator. (3) It requires a Sun-tracking system to operate on the lunar surface."

The subgroup concluded that the complex solar furnace would probably be the most practical extraction technique for use on thin ice deposits at the lunar poles, but of doubtful value in areas of periodic sunlight because of the power storage problem and the necessity for mining and transport of the ore. It can, however, by no means be ruled out as a practical extraction technique at any location, and further study is warranted.

C. Laser Furnace

A laser furnace powered by solar and/or nuclear energy was suggested by Lt. Colonel Athas as a substitute for the solar furnace.

A laser furnace has three advantages over solar furnaces: (1) It is independent of the Sun when necessary and can operate above or below ground. (2) It can be mobile with power transmission from a central power

source like the solar furnace. (3) It is independent of the geometry of the deposit or type of ore.

Disadvantages are: (1) Low efficiency means large power loss. (2) Large power losses automatically lead to a heat dissipation problem. (3) Additional weight is required for laser and transmission lines. (4) As in the case of the complex solar furnace, it requires mining and transport.

The subgroup had difficulty in evaluating the laser furnace concept because so many parameters depend upon future development. Pending such development it appeared, however, that the use of laser techniques is an unnecessary complication of the extraction process unless very high temperatures are required.

D. Electric Arc Furnace

Dr. Glaser suggested the use of an electric arc furnace powered by a nuclear reactor and/or solar energy as an alternate to the laser furnace and solar furnace.

The electric furnace has the same advantages and disadvantages as the laser furnace in comparison with solar furnaces. In contrast, it is available and less complex than the laser.

The subgroup concluded that, pending future developments, the electric arc furnace was a strong possibility for underground and nonpolar water extraction.

E. Nuclear Frasch Process

Dr. Salisbury suggested an extraction technique that is patterned after the Frasch process for extracting sulfur on Earth. With this technique, water is extracted from the ore *in situ* by supplying a source of heat at the bottom of a drill hole (see Fig. C-5). There is some doubt as to the best method of heat transfer, but radiant heat was considered in the diagram. Thus, radiant heat from an unshielded nuclear reactor at point A is used to vaporize ice or to drive off water of hydration, depending upon the type of ore deposit considered. The steam so generated rises through the drill hole to run a turbine generator B, and then is condensed to liquid water in radiation panel C. This water may be stored directly, or electrolyzed and liquefied at points D and E. Subsequent discussions with Dr. Lenedahl, a nuclear engineer, have led to the conclusion that it may be more practical to transfer the rejected heat from the base nuclear thermionic power plant to the bottom of the drill hole by means of liquid sodium or some other working fluid. This would have

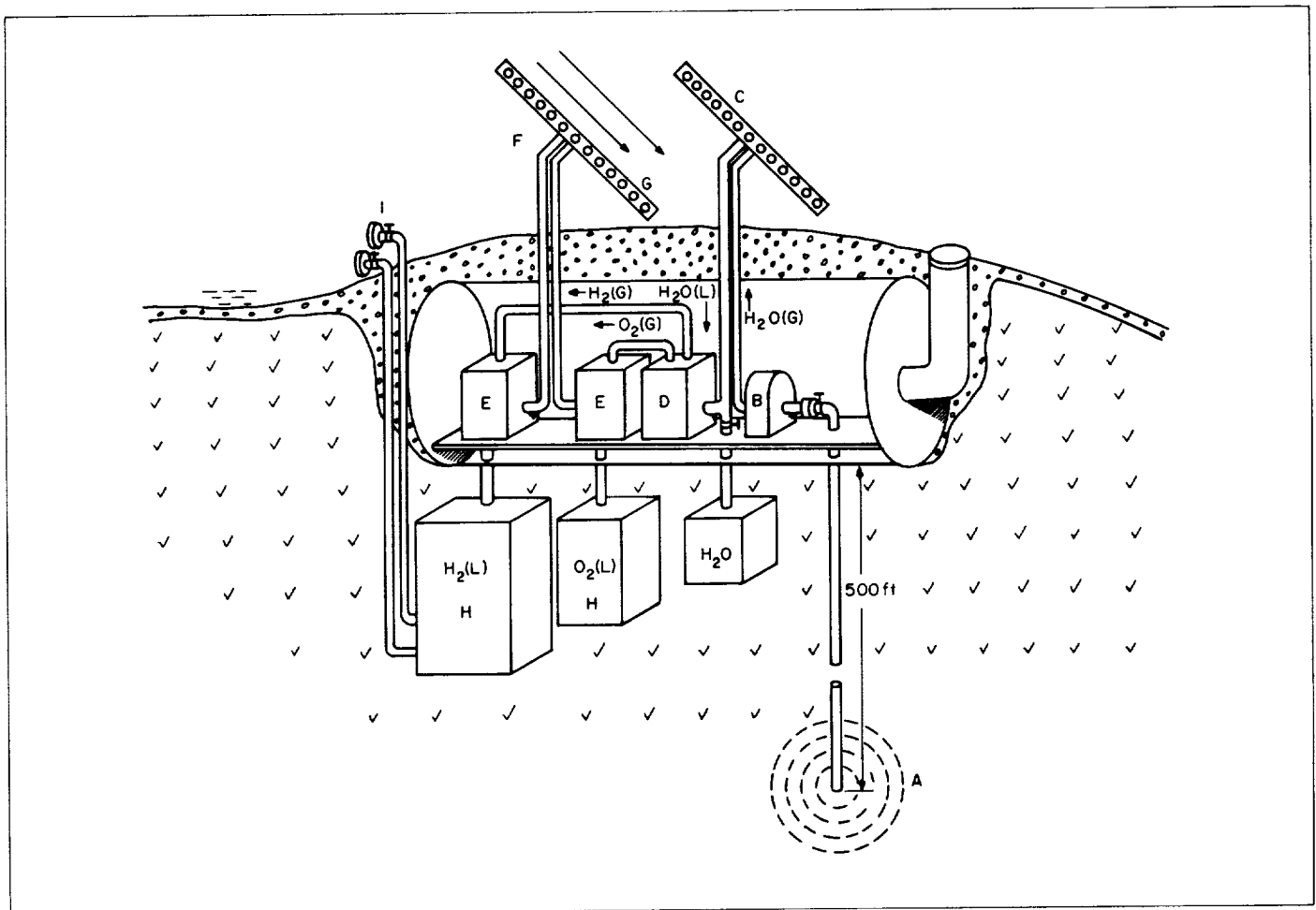


Fig. C-5. Nuclear Frasch process of water extraction

the advantage of economically attacking the heat dissipation problem for the base power plant and of eliminating the radioactive hazard. A great disadvantage is the low temperature (less than 1000°C) of reactor heat rejection. Clearly, a great deal of scientific and engineering study will be required before a firm design can be discussed, but preliminary calculations indicate that this technique should be feasible with ice deposits, and probably so with hydrated mineral deposits. It is unlikely, however, that this extraction technique could be used with bare rock because of the relatively large volume of rock that must be brought to the high temperatures required for extraction.

The advantages of the general principle are: (1) No mining or transport is required. (2) Automatic extraction and processing presents little manpower drain. (3) It is independent of the Sun. (4) It may be adapted to either surface or subsurface deposits, as long as they are thick.

(5) It has a low power requirement if rejected power plant heat is used.

Disadvantages are: (1) The process is ore-dependent. (2) The process is also geometry-limited in that it requires a thick deposit to be practical. (3) If direct radiation of heat from a buried reactor is used to extract the water, impurities will be highly radioactive.

The subgroup concluded that the nuclear Frasch process was a promising one for massive subsurface or thick surface deposits, because of the very desirable advantages of no surface mining and transport and automatic operation. Dr. Salisbury and Dr. Glaser are continuing their study of this extraction technique.

F. Chemical Extraction

Extraction of subsurface ice by adding chemicals to lower its melting point was a suggestion for *in situ* extrac-

tion made by Dr. Glaser. With a lunar subsurface temperature of -20 to -50°C , such an extraction technique appeared possible, but rate of production was again considered questionable. Dr. Glaser made an analysis of the possibilities and problems involved in chemical extraction, and his report is as follows:

"The depression of the freezing point of a solvent by the addition of a solute is well known in both theory and application. The addition of inorganic salts to lower the freezing point of water for the production of brine solutions as well as melting of ice is the most common example. In the production of brines the usual limitation is the solubility of the salt. In melting applications the principal limitation is the eutectic point of the mixture, the point at which solid water, salt, and solution coexist. For example, the minimum liquidus temperature of a mixture of calcium chloride and water is approximately -51°C (-59°F). Other salts lower the freezing point of water to a greater or lesser degree depending on the molecular weight of the material and the solubility of the salt in water. Other materials such as inorganic acids, organic alcohols, glycols and ethers are equally effective in lowering the freezing point or melting point. For terrestrial uses where weight limitations are not restricting, the lower the eutectic temperature the more versatile will be the solute. In lunar applications where weight is a prime consideration, the quantity of solutes necessary to lower the freezing point is of great importance. The possibility of producing the solute or finding the solute on the lunar surface must also be explored. Since the lunar subsurface temperature is approximately -30°C (-22°F), many possible additives and solutes must be eliminated. Typical prospective solutes, however, are hydrogen chloride, calcium chloride, and lithium bromide.

"The process which we are considering is one in which a brine solution is circulated in the ground to an ice deposit. As the brine diffuses through the ice formation, some of the ice melts and is brought to the surface with the brine solution. On the surface the brine is concentrated; part of the water is removed and remainder recirculated after heat exchange at surface conditions.

"The process has several inherent limitations. The viscosity of concentrated low-temperature brine solutions is quite high. This increases the power requirement for pumping of the brine solutions and makes the brine difficult to handle. In addition, apparatus must be available for the removal, by distillation or evaporation, of water which has diluted the brine. Several methods of separation are available and an optimization study would be necessary to lead to the best method. Another problem is the rate of solution of ice deposits in the brine. This

depends, of course, on the temperature of the brine and the ice, the concentration of the brine in contact with the material, flow properties of the fluid as it passes over the ice and other factors which usually affect the rates of mass transfer. Sufficient laboratory data of the rates of mass and heat transfer to a dissolving substance from a fluid are available to enable prediction of the rates of dissolution if the solid material can be properly characterized. The characterization of the deposit, however, presents a problem, because the geology of the subsurface is still at a speculative stage. In addition to these limitations a more serious limitation may be the transportation of a considerable amount of chemical to the lunar surface for the initiation of such a melting process. Even hydrogen chloride which forms one of the lowest eutectic mixtures and requires a very small amount of solute will be of substantial weight. For example let us consider a subsurface deposit of material occupying a volume of 100,000 cu ft (100 ft square and 10 ft deep). If ice existed at even as low a concentration as 5% by volume basis, approximately 120,000 lb of ice could be extracted from this deposit using a hydrogen chloride (or inorganic salt) mixture and operating in the temperature limits between the assumed subsurface temperature of -40°C and a surface temperature of 0°C , for example. The quantity of hydrogen chloride required on a "one-shot" basis would be approximately 60,000 lb. Recirculation of hydrogen chloride (or salt) could reduce the chemical requirements by a factor of ten or more depending on the rate of production and characteristics of the deposit. However, with increase in recirculation more power is required to separate the water from the resultant solution. The use of calcium chloride would require transportation of a greater weight compared to hydrogen chloride. Although the weights are very high the advantage or appeal of *in situ* extraction technique is very great, so that the possibility of using locally occurring lunar material for the solute may make this plan attractive. Figure C-6 shows a flow sheet of a chemical extraction process.

"A more complete study of a chemical extraction technique is required to point out potential application and to determine the necessary parameters for economic evaluation. A study might include the following points:

1. Evaluation of potential solutes and their possible availability on the lunar surface.
2. Power vs rate required for brine pumping based upon a variety of deposit types.
3. Power requirements for extraction of water from brine solutions.
4. Materials requirements for the process."

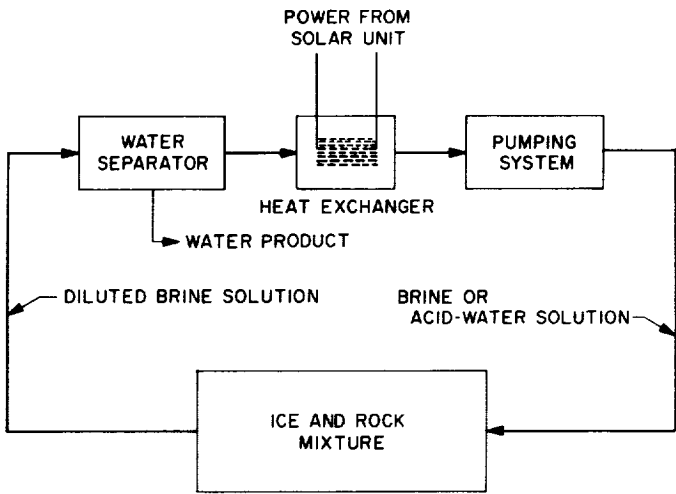


Fig. C-6. Flow sheet for chemical extraction process

G. Direct Hydrolysis

In an effort to examine every possibility, Professor Shotts suggested that direct hydrolysis of surface or sub-

surface ice might be a technique which would provide *in situ* extraction and processing (see Fig. C-7). Neither Professor Shotts nor any of the subgroup believed that the rate of such a reaction, even if salts were present in the ice, would be great enough to make it practical. Because of the obvious advantages of automatic *in situ* mining brought out in previous discussions, however, Professor Shotts pursued the concept further. He found that all references do not agree, but that the specific resistivity of pure ice is on the order of 10^{10} ohm/cm at lunar subsurface temperatures. It is, therefore, difficult to envision the successful operation of this extraction technique unless the ice has been melted and/or had salts added to it, which amounts to the use of a different method of extraction. Dr. Salisbury suggested in view of this that direct hydrolysis may be most useful in conjunction with some other extraction technique, such as the chemical extraction process suggested by Dr. Glaser. It is possible that direct hydrolysis could be controlled so as to automatically maintain the salinity of the brine, thus eliminating much of the need for brine pumping, as well as the brine concentration step in processing.

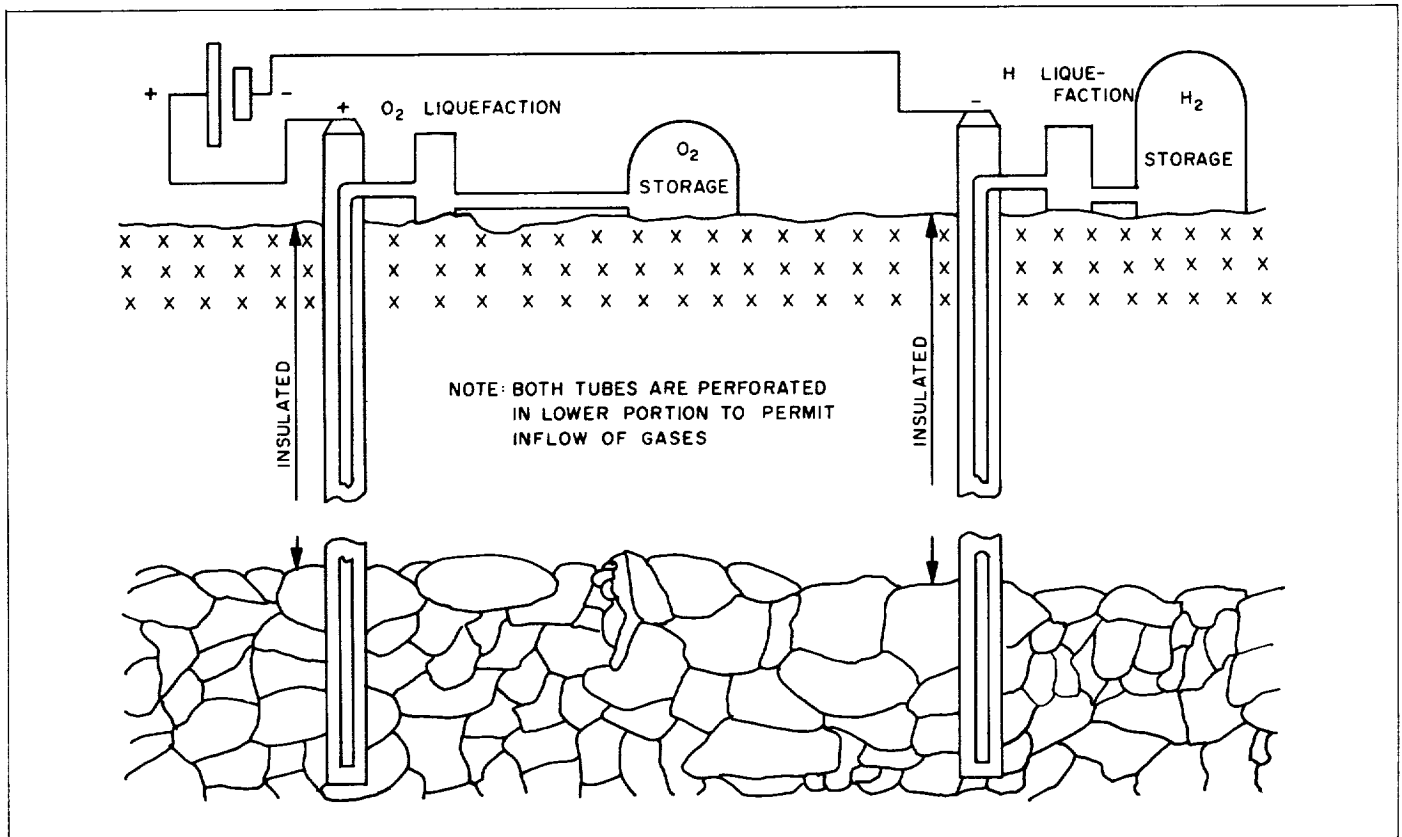


Fig. C-7. Water extraction by direct electrolysis

V. PROCESSING

The processing of water on the Moon was discussed in a written submission by Mr. Fowle, and is presented below:

A. Electrolysis

"The electrolytic dissociation of water into gaseous forms of hydrogen and oxygen is a well-known process that can quickly be summarized in a series of illustrations. Table C-2 illustrates some physical properties of hydrogen and oxygen provided for purposes of reference. Figure C-8 illustrates the chemical process and the equipment used in the industrial production of hydrogen and oxygen by the electrolysis of water. Table C-3 summarizes the characteristics of electrolytic H₂-O₂ cells used in industrial practice. It is of interest to note that substantial amounts of power are required for the process and that rather heavy equipments are common to the land-based systems now in use. Very little can be done to reduce the power requirements, for the process as now carried out is relatively efficient, but undoubtedly great savings in weight can be realized.

Table C-2. Some physical properties of hydrogen and oxygen

	Fluid	
	H ₂	O ₂
Density of Gas at NTP, lb/ft ³	0.0056	0.0892
Density of Liquid at NBP, lb/ft ³	4.43	71.5
Normal Boiling Point, °K	20.4 (-422.9°F)	90.1 (-297.4°F)
Critical Point Temperature, °K	33.3	155
Critical Point Pressure, psia	188	730
Latent Heat at NBP, Btu/lb	194.5	91.5
Pre-cool Temperature for Practical Joule-Thompson Process, °K	65	300

Table C-3. Characteristics of typical electrolytic H₂-O₂ cells

Basis: 9 lb H ₂ O (l) → 1 lb H ₂ (g) + 8 lb O ₂ (g)
Power = 27.7 kw-hr
Volts/Cell = 2.1
Amps/Cell = 250-14,000
Efficiency = 65%
Dry Weight = 6500 lb
Volume = 121 ft ³

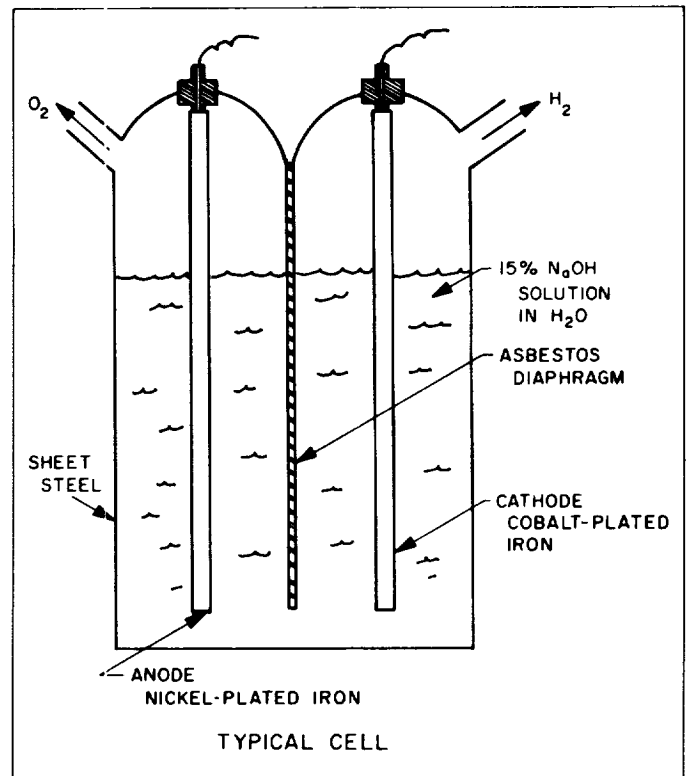


Fig. C-8. Electrolytic hydrogen and oxygen production reactions: $2\text{H}_2\text{O}(\text{l}) \rightarrow 2\text{H}_2(\text{g}) + \text{O}_2(\text{g}); \Delta H = +2(68,317)$ cal/g formula wt.

B. Liquefaction

"Having reduced water to gaseous hydrogen and oxygen, the next step in the process considered is to reduce them to their liquid forms for convenient storage and use. Two basic systems for liquefying hydrogen and oxygen are now in use. These systems are based on the so-called Joule-Thomson and Claude liquefaction cycles.

"Figure C-9 is a schematic representation of a Joule-Thomson gas liquefier. This system was the first to be applied to the liquefaction of gases, primarily because of the simple nature of the equipment required. This system could be used to produce liquid oxygen on the Moon but it is very unlikely that it could be used to produce liquid hydrogen because of the unavailability of a heat sink at sufficiently low temperatures for Joule-Thomson precooling. At any rate, this process is relatively inefficient and for this reason it has been largely superseded by the Claude process. Certainly systems patterned after the Claude

process are of most interest when considering the liquefaction of gases in the lunar environment.

“Figure C-10 shows a schematic representation of a gas liquefier operating on the Claude cycle. The use of low-temperature expansion engines is fundamental to this cycle. The use of expansion engines make possible more efficient operation at lower pressure levels. This is translated in terms of power and weight savings.

“Typical characteristics of an oxygen liquefier operating on the Claude cycle are shown in Table C-4. Table C-5 shows typical characteristics of a hydrogen liquefier. From these Tables we note a rather substantial power requirement for liquefaction, but one less than that required for separation. In addition, we note a fairly substantial plant weight requirement. The estimated weights of lunar plants are derived from studies of space-borne refrigeration systems.

“Tables C-4 and C-5 do not show requirements for plant maintenance. The maintenance requirements for

liquefaction plants now in operation are not acceptable for lunar liquefaction operations. However, developments in progress hold promise for the realization of systems giving unattended reliable service for periods measured in many thousands of hours.

“One of the really significant technical problems associated with the processes described is the requirement to reject substantial amounts of heat to the environment. The only obvious way of rejecting this heat is with a space radiator. As can be seen in Table C-6, the radiator area (and, by inference, radiator weight) will be large.

“In summary, the processing of water to liquid hydrogen and oxygen on the Moon introduces some challenging technological problems. Certainly the need for lightweight, efficient, reliable systems is obvious. The problem of heat rejection is unusual. A careful analysis of the logistics of lunar-base operations coupled with an investigation of a creative approach to the design of systems particularly suited to the lunar environment is needed before the characteristics of near-optimum systems can be defined.”

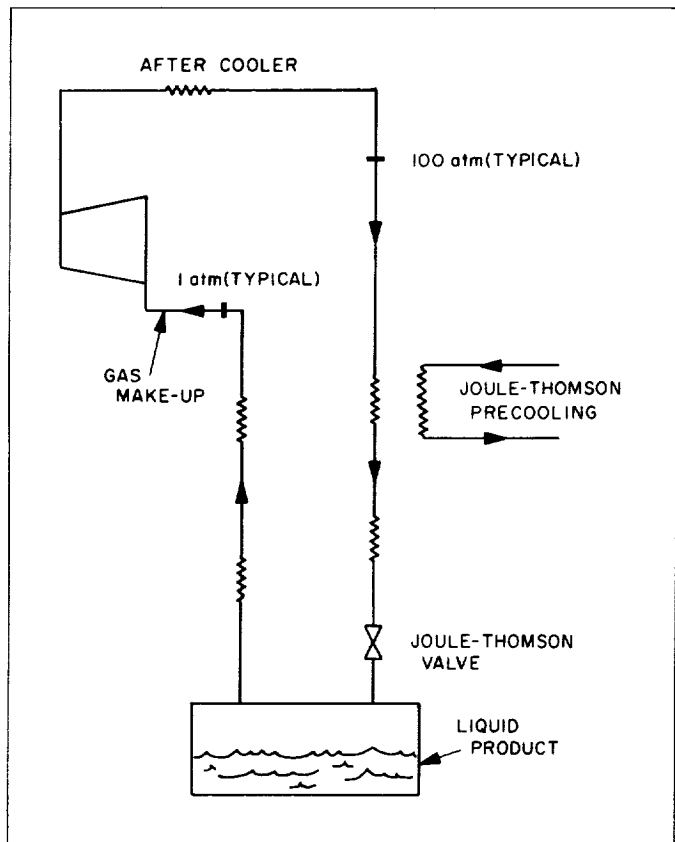


Fig. C-9. Schematic representation of Joule-Thomson gas liquefier

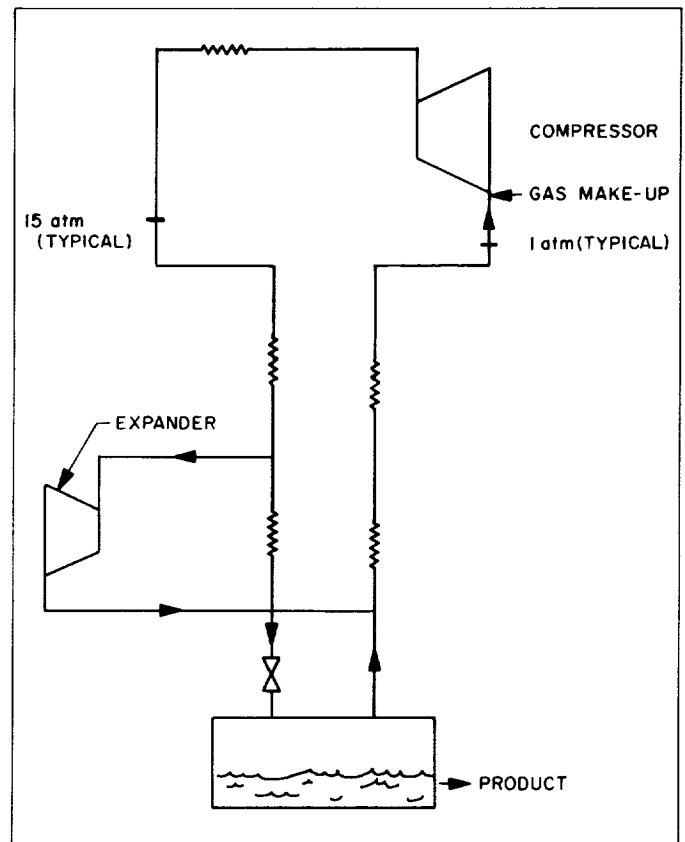


Fig. C-10. Schematic representation of gas liquefier using expansion engines

Table C-4. Typical characteristics of oxygen liquefier (expansion engine cycle)

Reversible Work Requirement \cong 0.08 kw-hr/lb
Actual Shaft Work Requirement \cong 0.32-0.40 kw-hr/lb
Ratio of Shaft Work to Heat Extraction \cong 10:1
Weight of Industrial Plant (exclusive of Power Supply and Buildings) \cong 250-500 lb/kw
Estimated Weight of Lunar Plant (exclusive of Power Supply and Buildings) \cong 50-100 lb/kw

Table C-5. Typical characteristics of hydrogen liquefier (expansion engine cycle)

Reversible Work Requirements \cong 2 kw-hr/lb
Actual Shaft Work Requirements \cong 8-10 kw-hr/lb
Ratio of Shaft Work to Heat Extraction \cong 70:1
Weight of Industrial Plant (exclusive of Power Supply and Buildings) \cong 300-600 lb/kw
Estimated Weight of Lunar Plant (exclusive of Power Supply and Buildings) \cong 70-140 lb/kw

Table C-6. Maximum heat rejection to space vs radiator area

Temperature °K	Heat rejection kw/ft ²
300	4.32×10^{-2}
90	3.58×10^{-4}
20	9.65×10^{-7}

VI. GENERAL CONCLUSIONS

It is clear that the alien environment of the Moon requires a complete re-evaluation of known mining and processing techniques, and probably the development of new ones. What is possible on the Earth may not be so on the Moon, and what is economical on Earth probably is not on the Moon. Certain generalized specifications can be listed for lunar mining and processing techniques, such as the requirements for minimum weight and power, and maximum reliability and automatic operation. Such generalizations help very little, however, in coming to quantitative grips with specific mining and processing techniques, especially in view of the little known about the lunar environment and its effect on the operations of men and machines. The subgroup felt, nevertheless, that certain very tentative conclusions could be reached concerning lunar mining and processing:

1. If lunar ore deposits cannot be processed *in situ*, underground mining and transport will probably be more feasible and economical than surface operations because of the importance of a shirtsleeve environment to both men and machines.
2. If thin, surface polar ice deposits are processed, a complex solar furnace using a batch process will probably be the most feasible and economical extraction system.
3. If shallow, nonpolar, blanket-type subsurface ice or hydrated mineral deposits are processed, an electric arc furnace powered by a nuclear reactor may be the most feasible and economical system.

4. If thick surface or subsurface ice or massive hydrated mineral deposits are processed, it may be possible to develop a nuclear Frasch process to extract water *in situ*. This, or any other extraction technique that will eliminate the need for mining and transport, is greatly to be desired.

5. If bare rock is the only source of water available on the Moon, the electric arc furnace appears to be the most promising extraction system except near the poles where sunlight is available a large portion of the time.

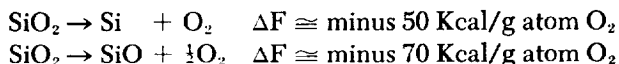
All members of the subgroup were certain that their tentative conclusions will be modified as new knowledge of the lunar environment is obtained. All hope their conclusions will be completely altered by new concepts of water extraction. This hope underlines the need for imaginative scientists and engineers to work on this problem now. Large areas of basic and applied research are clearly defined, despite our present lack of knowledge of the exact nature and location of lunar resources. Considering the long lead-time involved in the development of a lunar mining and processing system, only a large research effort will suffice.

ADDENDUM A

Additional Resources

Resources other than water may be present on the Moon. Several members of the subgroup discussed their work, or that of other research groups, concerned with extraction techniques for such substances.

Mr. Smith described his research on the manner in which oxygen may be extracted from a silicate rock by the simple addition of heat energy, the reactions taking place as follows:



These reactions proceed at 2750°K and 10⁻¹³ mm mercury, but the kinetics have not yet been studied.

Mr. Baumgardner reported that B. B. Carr of the Callery Chemical Company has been working on the use of hydrogen arc jet, a water condenser, and electrolysis to release oxygen from lunar rock (reported in *Missiles and Rockets*, November 19, 1962). The process operates by melting SiO₂ in a hydrogen stream at temperatures up to 2600°K. A chemical reaction between the two at high temperatures produces silicon and water. This process

requires the transport of hydrogen to the Moon, but is more or less independent of the rock to be found there.

Dr. Green described possible uses of sulfur, which he demonstrated might be present on and below the lunar surface in large amounts. Experiments performed in his laboratory show that sulfur makes an excellent waterless cement and, mixed with volcanic ash, it makes a good structural material or electrical insulator. Molten sulfur may even be used as a lubricant or as a working fluid in mineral dressing. The high probability of sulfur or sulfur compounds accompanying any water deposit on the Moon make these experiments of great interest.

Dr. Salisbury pointed out that one resource that will surely be utilized in base construction is the rubble ejected from the meteorite craters that must be present on the lunar surface. This rubble will be highly variable in depth and modal block size, but deposits of an appropriate nature should be available. Probably more than one sort of "earth"-moving technique will be required to utilize this resource, and research on both explosive and vehicular techniques appears warranted.

ADDENDUM B

Power Requirements

Detailed power requirements were not readily available for most mining and extraction techniques, although it is clear from processing power requirements alone that a large power supply will be required for the entire mining and processing operation.

ADDENDUM C

Problem Areas

A number of specific problem areas requiring new or continuing research efforts became apparent at the meeting. They are:

1. Heat rejection above and below the lunar surface
2. Possible lunar excavation techniques, including the laser and plasma jet
3. Surface and subsurface transport vehicles
4. Lubrication in a vacuum
5. The practicability of obtaining large amounts of electrical power from solar energy
6. Pressure, temperature and composition variables acting in dehydration
7. Efficiency of transferring heat to subsurface ore deposits by radiation or conduction
8. Weight of all equipment now developed or in the development stage, such as power supplies, electrolysis, and liquefaction equipment
9. Usefulness of "back-pack" solar furnace or other crude water-extraction systems for early *Apollo* flights
10. The practicability and design parameters of a solar furnace to operate in the lunar environment
11. The feasibility and rate vs power requirement of chemical extraction
12. Problems involved in direct electrolysis of ice and/or water in an underground environment
13. Lunar surface and subsurface geology

ADDENDUM D

Names and Addresses of Attendees

Lt. Colonel William C. Athas
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University, Alabama

Mr. Fred L. Smith
Colorado School of Mines Research Foundation
Golden, Colorado

ADDENDUM E

Names and Addresses of Organizations Known to be Competent in the Area of Lunar Mining and Processing

Aerojet General (Contact Dr. B. Keilin)
Azusa, California

Air Force Cambridge Research Laboratories
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Callery Chemical Company (Contact Mr. B. B. Carr)
Callery, Pennsylvania

College of Mineral Industries (Contact Dr. Brindley)
Pennsylvania State University
University Park, Pennsylvania

Colorado School of Mines Research Foundation
(Contact Mr. F. L. Smith)
Golden, Colorado

Martin-Marietta Corporation (Contact Mr. H. S. Zahn)
Martin Company
Space Systems Division
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Materials Technology Department
(Contact R. W. Jones, D-134)
Hughes Aircraft Company
Culver City, California

Northrop Corporation (Contact Dr. E. Azmon)
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