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ASTRONAUTICS INFORMATION: UTILIZATION OF EXTRATERRESTRIAL RESOURCES

JET PROPULSION LABORATORY
PASADENA, CA

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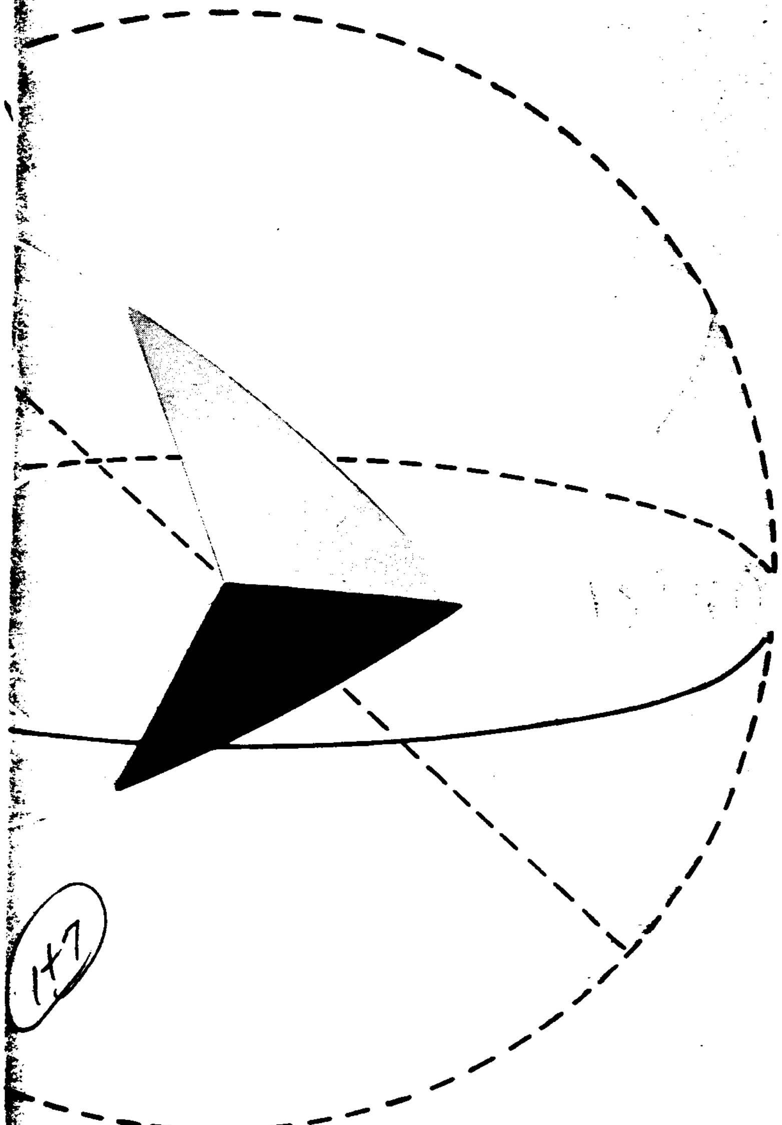

UTILIZATION OF EXTRATERRESTRIAL RESOURCES

SEMINAR PROCEEDINGS

SEPTEMBER 25–26, 1962

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA

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FOREWORD

Eight state-of-the-art briefings intended to bring members of the Working Group up to date in technical areas relating to future manned expeditions to the Moon and planets were presented at the Meeting of the Working Group on Extraterrestrial Resources held in Washington, D. C., September 25–26, 1962 by recognized authorities in their respective fields. Since it was felt that the material presented at the meeting would be useful for reference purposes, most of the speakers submitted summaries of their remarks for publication. This document is a collection of the material submitted.

The speakers and their subjects were:

Mr. P. H. Bliss of The RAND Corporation, Santa Monica, California, on current lunar surface vehicle concepts.

Dr. H. D. Chapman of the University of California, Riverside, California on hydroponic gardening in extraterrestrial environments.

Mr. A. A. Fowle of the Arthur D. Little Co., Cambridge, Massachusetts, on water dissociation and product gas liquefaction and storage.

Lt. Col. G. W. Johnson of the Jet Propulsion Laboratory, Pasadena, California, on extraterrestrial base housing and facilities.

Dr. H. G. Poole of the Colorado School of Mines, Golden, Colorado, on lunar rocks as a source of oxygen.

Dr. R. C. Speed of the Jet Propulsion Laboratory, Pasadena, California, on the possible occurrence of water on the Moon and water extraction from lunar and planetary materials.

Mr. W. B. Taylor of the National Aeronautics and Space Administration, Washington, D. C., on the objectives and current studies for the NASA Lunar Logistics Systems program.

Mr. W. H. Woodward of the National Aeronautics and Space Administration, Washington, D. C., on the status of power supplies for manned extraterrestrial bases.

N 67-83320

Status of Designs of Lunar Surface Vehicles

P. H. BLISS

The RAND Corporation

I. INTRODUCTION

This report is made for the purpose of summarizing the activities of the various organizations that have been giving some thought and design effort to producing a lunar surface traversing vehicle. It is a state-of-the-art rather than a technical report, intended to see where we are in this effort and to survey the trend of the various designers.

The different types of vehicles being proposed are discussed, with some details of their size, type of traction, and motive power used. A description of the body styles and accessory provisions of the various vehicles will be presented. Where available, performance details will be given.

Because this report is unclassified and some of the most pertinent material on the Moon vehicles is classified Secret, details on some of the vehicles will necessarily be sketchy.

II. GENERAL PROBLEM

A. Statement of Problem

The problem is to design a vehicle for travel on the Moon's surface that will be entirely dependable, yet compact enough to be transported in a spacecraft to the Moon. This problem is increased by the lack of information on the surface conditions on the Moon and the fact that the first vehicle landed must work. Besides traversing the surface, the vehicle must be capable of performing all tasks required, including the provision of life-support features for the operator or crew.

B. Some Desirable Attributes of Lunar Surface Vehicles

The most desirable attribute of a lunar surface vehicle would be absolute dependability. Speed is not considered a primary requirement, but trafficability over any surface conditions encountered is extremely important. The vehicle must either have a pressurized and air-conditioned compartment for the operator which is shielded against micrometeorites, or the operator will have to wear his space suit while moving around.

The motive power to propel the vehicle should be dependable and capable of covering the range of travel expected of it before having to return to the base for refueling or recharging. A backup source of motive power would be very desirable, especially if batteries are used for the primary power.

Mechanical arms or material-handling cranes would be desirable, with some cargo-handling space on the vehicle to transport payloads. The movement of materials around the lunar base will be of great importance.

The closed-cab vehicles should have some provision for life support for the crew for a minimum number of days as dictated by the mission. This would mean oxygen and air locks for ingress and egress of the operators, with sufficient stored air to permit several openings of the lock. Recirculation methods should be able to salvage part of the air prior to opening the lock.

C. *Some of the Difficulties Confronting Designers*

1. Lack of Data on Soils or Rock Surface of the Moon

Theories exist on the composition of the Moon's surface ranging from fine lunar dust to hard igneous boulders, with indeterminate roughness or size of the boulders. Without knowledge of the type of surface on the Moon, it is most difficult to design a vehicle that will be best suited for the operation. It is planned that some of the present exploration programs will sample the materials on the surface of the Moon; if these plans are successful, we will be able to proceed more logically on one type of design. Until this happens, it appears to be most useful to devote our time to considering several alternate surface conditions and design several vehicles, with one or more types for each assumed terrain condition. Then, if data are obtained from *Surveyor* or *Prospector* Programs, we can concentrate on one of the preliminary designs and refine this design prior to final development.

A design procedure exists for off-the-road vehicles which was proffered by M. G. Bekker (Refs. 1, 2, 3) several years ago. To use it, the stress-strain characteristics of the soil must be known. In order to obtain these data on the Moon, the General Motors designed Bevameter will be soft-landed in the *Surveyor* Program, and readings of the penetration and shear value of the Moon's surface will be radioed back to Earth.

2. Vacuum-Caused Problems

The hard vacuum on the surface of the Moon causes several problems for lunar surface vehicle designers. Basic is the necessity for providing life-support facilities on any vehicles that are operated by a man not wearing a space suit. Considerable weight is necessarily involved in making a pressurized cabin provided with an air lock and the air tanks and pumps needed to handle the operation of the lock.

All lubricants in use today will boil away in a vacuum, leaving the metal-bearing surfaces bone dry. This means that bearing seals will have to withstand the vacuum condition as well as the temperature range of around 500°F if ordinary lubricants are used. Some metals sublimate in a vacuum and erode, which could cause rapid deterioration of these parts, especially at the higher temperatures. With inorganic compounds, both decomposition and evaporation are possible hazards. Some researchers are considering the use of pairs of metals in bearing and shaft surfaces that have the least tendency to seize when rubbing against each other. It will be difficult to design electrical motor bearings of these metals, however, for continuous operation.

3. Temperature Range, −244 to 260°F

Numerous problems exist due to this extreme temperature range. Hydraulic fluids in use today will not operate in such low temperature without becoming too viscous. The fluids designed for extremely low temperatures (−65°F being the lowest tested) are unsatisfactory at high temperatures.

The operation of many items of electronic equipment would be adversely affected at temperatures above 210°F. The strength of materials decreases appreciably with increase in temperature. At the extreme low temperatures, materials will have a higher yield point but will be so brittle that fatigue failures will occur rapidly.

Unequal expansion and contraction of dissimilar metals in equipment would have to be considered in design; otherwise, parts would get out of alignment. Liquid propellant stored on the vehicle would have to be insulated against the temperature change, or most of the propellant would be lost. Radiators and heat-dissipating devices will be critically affected by the temperature extremes on the Moon and would have to be oriented properly at all times. Different metals would be required on radiation devices, with one metal exposed for removing and the other for absorbing heat.

4. Meteorites and Micrometeorites

Meteorites hitting the vehicle would either penetrate the shell, causing loss of air pressure and possible explosion of the oxygen content, or cause chipping of the vehicle surface. Repeated chipping could also result in progressive thinning of the shell or cracking, causing failure by leaks. One answer to this problem is to use double walls, with highly resistant metals, such as molybdenum or beryllium, forming one or both of the walls. The best would be beryllium because of its high elastic modulus-to-density ratio. Some automatic method of detecting and sealing punctures would have to be provided, since the operator could only survive for about 15 sec if the pressure dropped to 3.0 psi of air.

Micrometeorites would not be as dangerous as the larger meteorites, but continual bombardment would give rise to problems. Also, they might damage the space suits with their lighter shielding.

5. Lack of Oxygen

The lack of air or oxygen on the surface of the Moon limits the type of motive power that can be employed. The internal combustion engine could not be used without a supply of oxygen. The lack of oxygen also makes the design of a vehicle more complicated, since the operator must wear a space suit or be provided with a pressurized cabin with the life-sustaining environment. This life-support requirement alone accounts for almost half the bulk and weight of the vehicle.

6. Solar Flares

The extremely large flux of high-energy protons following a solar flare is of great danger to man and necessitates constant shielding. The radiation dose would be about ten times the lethal amount for man but can be reduced to allowable tolerances by carbon shielding.

Solar flares vary in frequency from year to year and from month to month. Predictions have been made that as many as 180 flares of significant intensities will occur in 1968 (Ref. 4), with the years just preceding and following being almost as bad. Low-frequency years are 1964, 1972, and 1973. The frequency of solar flares appears to be at a minimum during the months of December and January. This suggests the possibility of scheduling lunar flights having personnel aboard during the periods of lowest occurrence of solar flares. Manned expeditions could also be working on the dark side of the Moon during flares, or the personnel could retire to heavily shielded storm shelters when such flares were expected.

The shielding on a lunar surface vehicle required for protection against meteorite bombardment would also protect the operator against solar flares of limited magnitude, thus making it possible for the vehicle to be out and operating during such flares.

7. Galactic Cosmic Rays

The intensity of these cosmic rays is of such a low value that the human body can tolerate many hours of exposure. The shielding which would be required to eliminate these rays would be extremely thick and impractical, since the galactic cosmic rays have a very high penetration ability.

8. Van Allen Belt Radiation and Natural Radiation

Shielding required to reduce the danger from the high-energy Van Allen Belt protons, if found near the surface of the Moon, would have to be excessively thick, because the damage is done in the low-energy range. The probable dosage is not too significant, however, because personnel could tolerate the rays without shielding for periods of 250 hr or more, and thus would have to be limited only in the number of missions per year or the hours per mission.

Natural radiation from the surface of the Moon could be very hazardous and, unfortunately, very little is known about the presence or intensity of such radiation. If surface radiation is intense and universally distributed over the surface of the Moon, it could mean that habitation of the Moon is impossible; a Moon roving vehicle would then be unnecessary. On the other hand, the radiation may be low enough to permit shielding the personnel from its effects in the design of the vehicle without increasing its weight beyond that permissible.

9. Weight and Size Limitations of Vehicle Due to Limited Transport

One of the first parameters confronting the designer of a lunar surface vehicle is the weight and size limitations imposed by the cargo space and capacity of the space missile that transports the vehicle to the Moon. Integration of facilities and components is one way to save both space and weight. Some designers are proposing the use of the hull of the missile as the body of the lunar surface vehicle, with the communications facilities built into the vehicle that will be used both during flight to the Moon and later, while roving on the surface. Others are building collapsible components for their vehicles that can be expanded after landing.

The payload available for the vehicle that will traverse the Moon is now generally assumed as being 20,000 lb or less. This weight could increase if larger boosters become available.

III. SPECIFIC DESIGNS

The lunar surface vehicle designs will be discussed by the companies proposing them. Not all of the companies working on these vehicles are included, but the majority are represented. At least, a sufficient number are cited to give a good sampling of the trends in design.

A. General Motors Corp.

The research into lunar surface vehicles in General Motors is headed by M. G. Bekker, formerly Chief, Land Locomotion Research Laboratories, U. S. Army, in Detroit, Michigan. Mr. Bekker is the author of authoritative texts on the design of vehicles for off-the-road travel (*The Theory of Land Locomotion*, 1956, and *Off-The-Road Locomotion*, 1960). He has also written several papers on the subject of lunar transportation within the last year (Refs. 1, 2, 3). Under his direction, several types of lunar vehicles have been constructed in scale-model sizes and tested in the laboratory over several different materials, such as large boulders, coarse gravel in an uneven pile, and coarsely ground wheat flour.

One type of model tested was the articulated, flexibly connected, spiral screw vehicle (Fig. 1). This vehicle

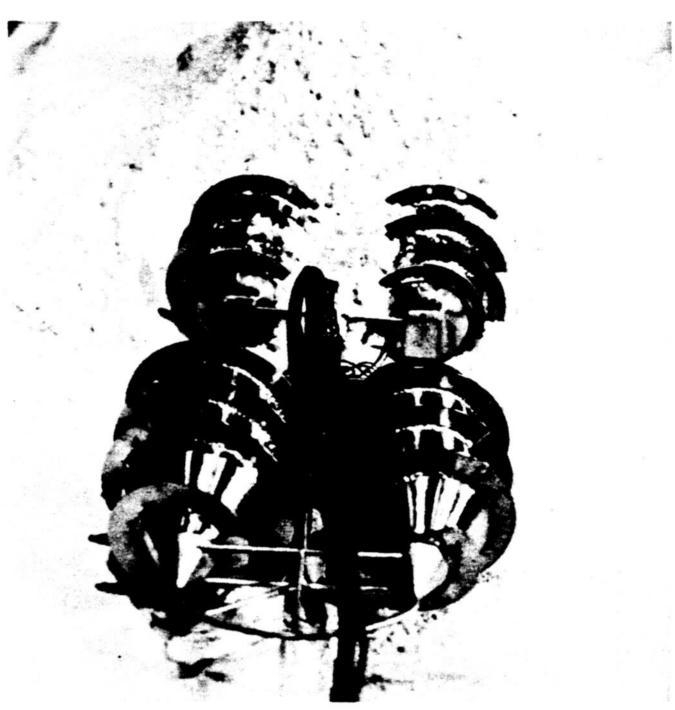

Fig. 1. Spiral screw vehicle proposed by General Motors Corp., traversing simulated lunar dust

consists of two parallel pairs of rotors, mounted in tandem, with each rotor separately powered and the pairs of rotors connected with a flexible spring connection which allows considerable independent motion of each half of the vehicle. This permits each half to follow the contour of the ground surface quite closely, maintaining its tractive force at all times.

The spiral rotor machine was tested particularly in the flour, which might simulate the lunar dust (if there is any dust), and it performed quite well. The photograph (Fig. 1) shows it operating in this medium. This type of vehicle would not be proposed for operating on hard surfaces.

The second type of vehicle model was made with 4, 6, and 8 pairs of individually powered donut wheels. Each axle was connected to the next by a flexible coupling made of spring wires which allowed a specific but limited amount of twist between the axles and considerable longitudinal motion between the axles (Fig. 2). The unit would climb straight up a wall, with the forward motion stopped when the last pair of wheels at the foot of the wall were spinning. Because of its low bearing pressure, this vehicle would go over the soft flour with only a slight depression in the surface. It would climb over the boulder and over the large rockstrewn hill (Fig. 3). The mobility of this vehicle was the best of all tested and indicates that the design would probably work equally well in lunar dust as over rough boulders. The train concept makes the load-carrying capacity a matter of how many wheels are hooked together. The sets of wheels could be added, one pair at a time. The more wheels, the more mobility the vehicle would have in varied terrain because some of the wheels would always have traction, while others might be suspended clear of the ground. The longer trains could also climb the higher vertical rises, since the front wheels would have a chance to drop over the top and gain a foothold on the top of the plateau.

The third vehicle proposed had spaced link tracks, supported and driven by a connection in the center (Fig. 4). Being made of spring steel, the ends of the track could be bent in any direction and were extremely flexible. In addition, spring cleats that could retract entirely on hard surfaces were evenly spaced across the track, with only the spring action gripping the surface.

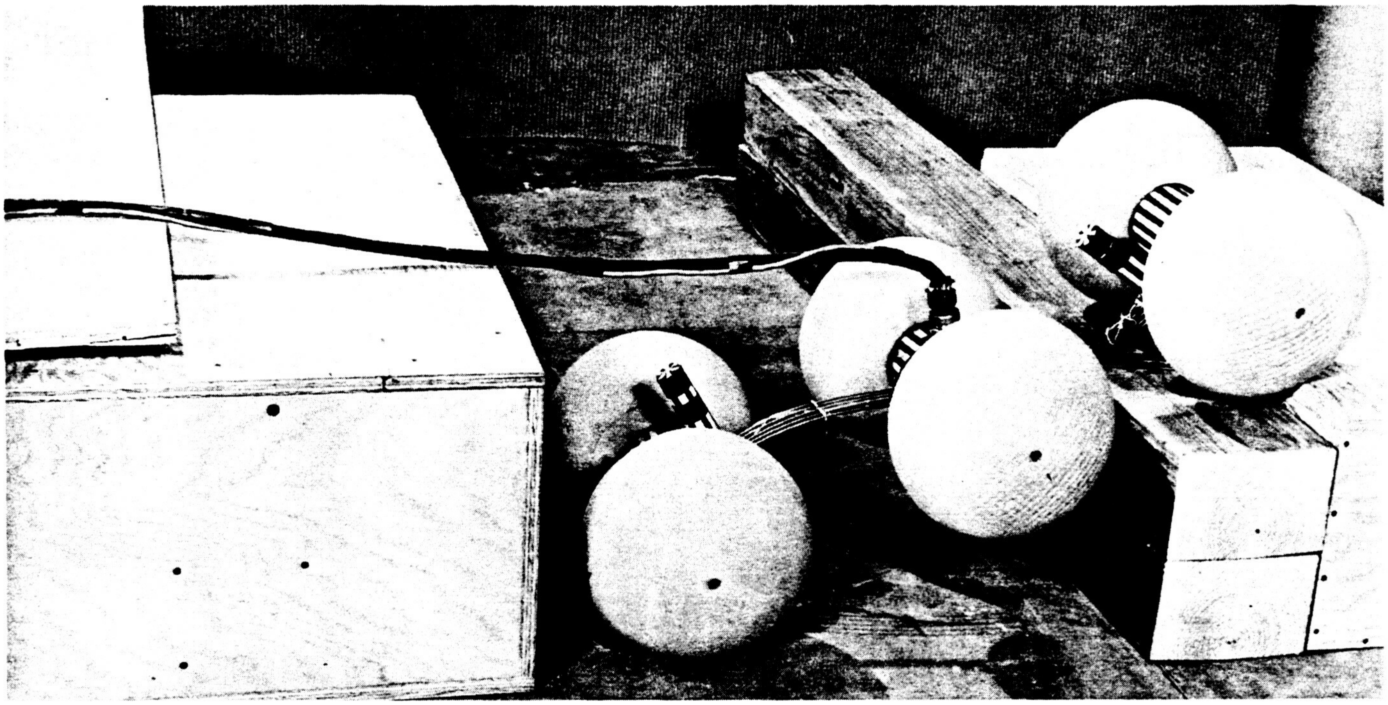

Fig. 2. Flexibly connected donut-wheeled vehicle proposed by General Motors Corp., traversing blocks of wood

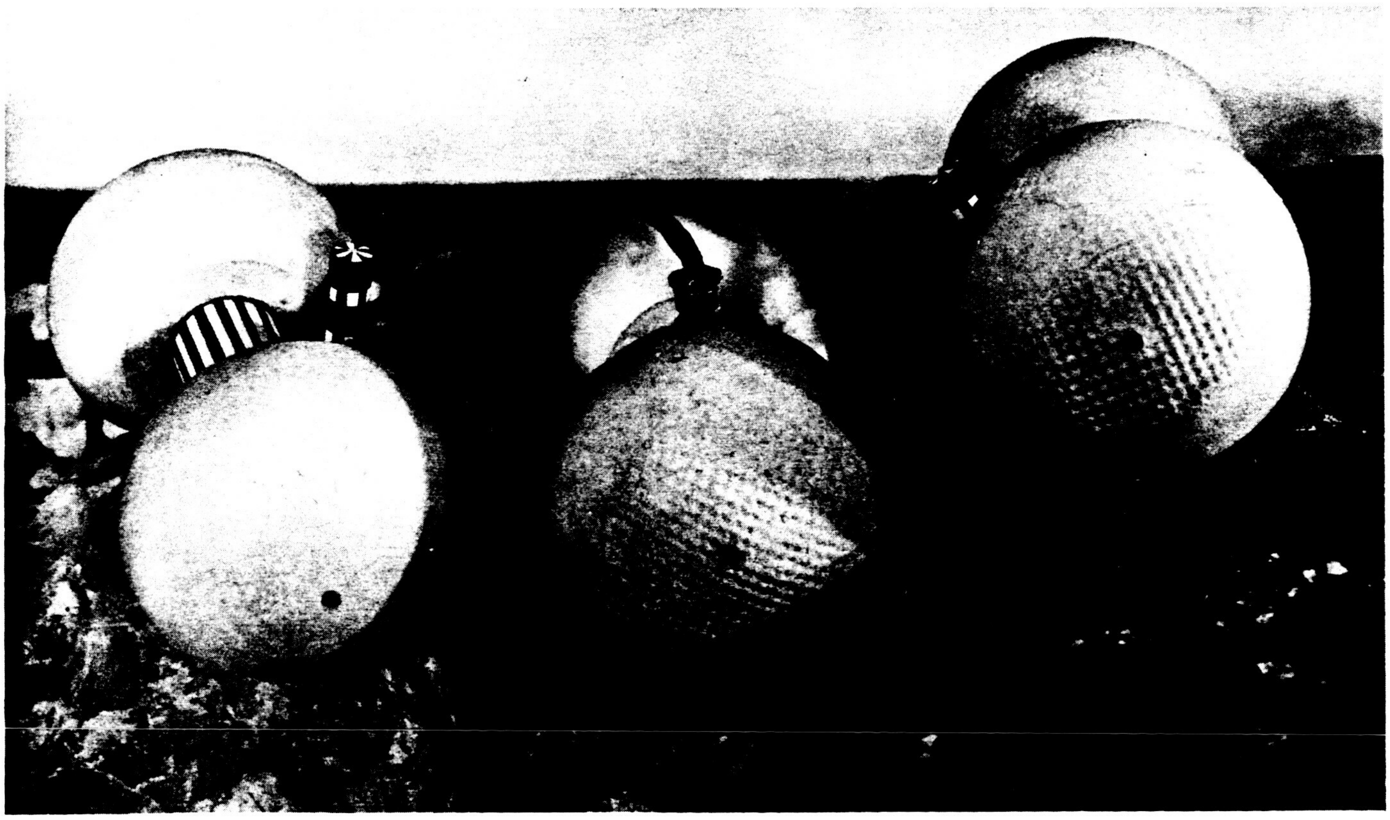

Fig. 3. Flexibly connected donut-wheeled vehicle proposed by General Motors Corp., traversing boulders and gravel

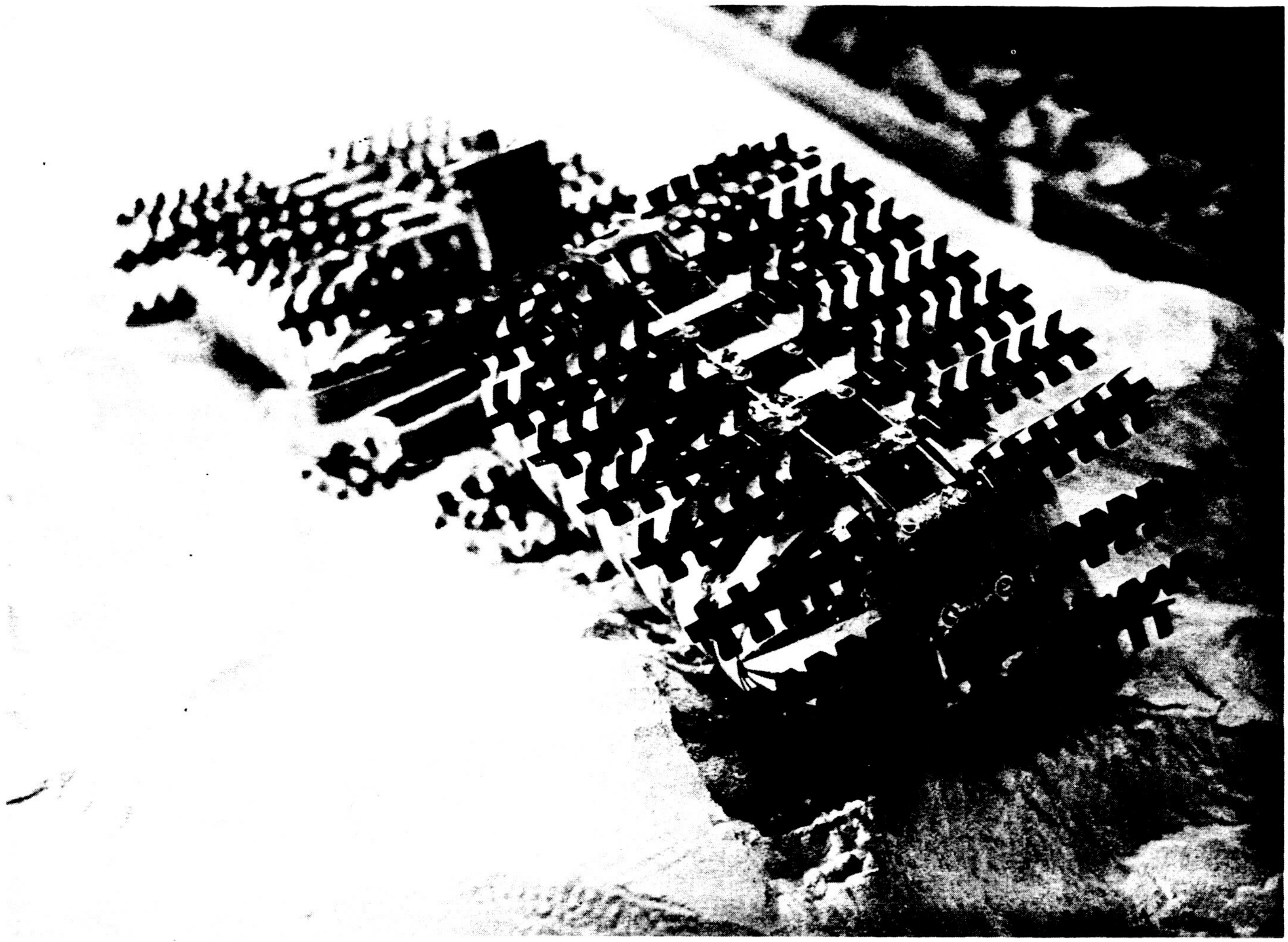

Fig. 4. Spaced-link flexible-tracked vehicle proposed by General Motors Corp., traversing lunar dust

In soft material, the entire area of the cleat would be used for gaining traction. This vehicle was also articulated and performed quite well in the flour or gravel pile but was not as agile over the large boulders as the previous model. For shipping, the tracks are curved around the body and clamped, making a cylindrical load of much smaller diameter than when they are extended.

B. Martin Co.

The Martin Co. analyzed various types of vehicles for a series of performance characteristics. Considered were wheeled, unicycle, tracked, reaction, amoeboid, walking, pogo-stick, leap-frog, and jumping platform vehicles. According to the analysis, the tracked rated first, followed by the wheeled, and then the reaction type. The tracked vehicle is called a Manned Lunar Surface Vehicle (MLSV). The vehicle body is a sealed capsule protecting the operator from the lunar environment, with 12-hr occupancy proposed before refueling. The vehicle may be remotely controlled or operated from the capsule. Fabric-reinforced belting with aluminum bars is suggested for the MLSV.

The power source proposed is batteries and a low-temperature liquid hydrogen turbine engine with a peak of about 30 hp.

C. Hughes Aircraft Co.

The Hughes concept of vehicles for traversing the Moon is called the Lunar Roving Vehicle (LRV). Several configurations are proposed. One has wheels made like an umbrella that fold up in a cylindrical shape and can be projected out of the capsule upon landing. The umbrellas expand and lift the vehicle up on its wheels automatically (Fig. 5). The space required for the flight to the Moon is thereby conserved. The bodies of the vehicles consist of two sections of cylindrical shape, one topped by the operator's dome. The vehicle has been named TREEL (Tractive Regulation for Extreme Environmental Location). One of its space-saving features is that the radio used in flight to the Moon is the same one that will be used on the Moon by the LRV for local and Earth transmissions. The LRV has a crane and several manipulators that are operated with a TV camera control.

Another configuration proposed by Hughes has roller drums, which propel a belt track. This motivation is attached to a life-support cylinder and to utility vehicles.

A third configuration makes use of large, inflated donut tires or wire-formed tires. Here, wire ribs hold the load, and the rubber cover acts to tie them together and provide flotation. The covering is loose over the wire so that, in soft material, the cover depresses between the wires to give better traction.

Power sources proposed for these vehicles are not definitely selected, but under consideration are solar-energy engines or chemical, battery, and nuclear engines and fuel cells. Of these, nuclear energy is best for long duration and high power requirements; the chemical battery is best for simplicity and short duration; and solar-energy engines are best for long duration and up to 50 kw maximum power requirements. In addition to weight considerations, reliability, cost, vehicle integration, mission integration, and personnel safety should be the most important considerations in power system selection.

D. American Machine and Foundry Co.

The Lunar Traversing Device (LTD), proposed by the American Machine and Foundry Co., is a large rubber-tired vehicle with a cylindrical body. Each tire is driven by an individual DC motor powered by fuel cells. The 20-hp model weight is estimated at 6000 lb and the 40-hp model at 7000 lb.

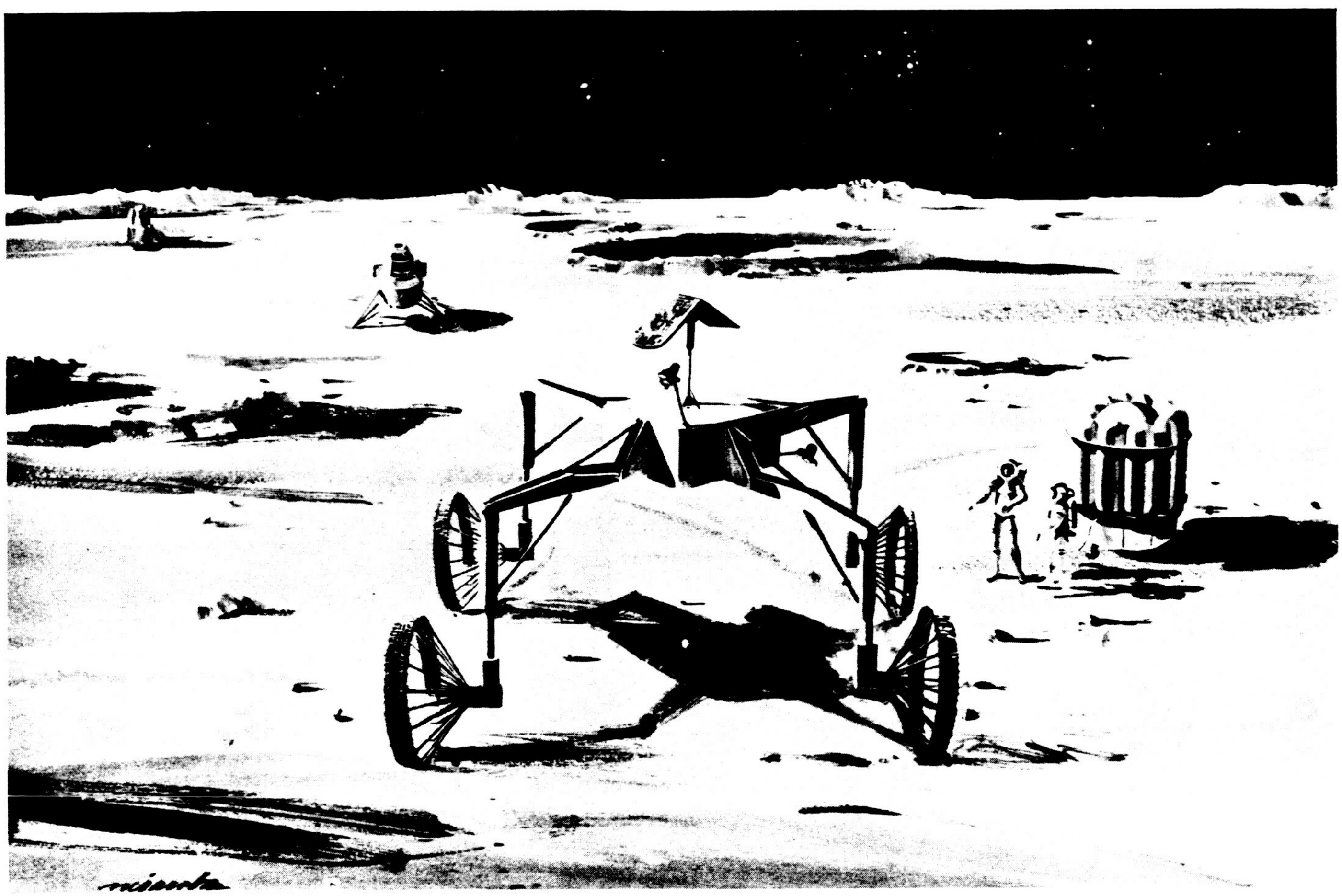

Fig. 5. TREEL wheeled vehicle proposed by Hughes Aircraft Co.

Three types of engines were studied: solar, nuclear, and chemical. The final selection was a combination fuel-cell–solar-collector device. Since the solar device could power the vehicle for one Moon day (13.6 Earth days), this would conserve fuel. The fuel cell has the byproduct of H_2O, which can be used as water or reconverted to hydrogen and oxygen.

E. Ralph M. Parsons and General Electric Co.

Proposed is a compact vehicle to operate as a lunar surface material mover, personnel–cargo carrier, crane/boom, conveyor, winch, and surface auger. Preference is for tracks, based on Earth experience, but wheels might be used under certain conditions. Such a vehicle, called a UET (Universal Engineer Tractor), has been built by International Harvester for the Army. The power source proposed is a 40-kw fuel cell.

F. Bendix Corp.

The Bendix design incorporates a folding vehicle that emerges from the missile and moves around on flexible wheels. It could be powered by fuel cells and solar engines.

G. Grumman Aircraft Engineering Corp.

The Grumman design uses Metalastic wheels made with a flexible 60-deg cone for a hub which supports the rim. Under load, the cone becomes elliptical in shape, elongating the ground contact surface of the rim, thus giving greater tractive effort. A second wheel tested was made with a series of spiral spokes, connected by a rim. This elastic wheel performed as a very efficient structural member, with good load distribution throughout the entire wheel. The report did not treat the shape of the vehicle body nor the source of power.

H. Space-General Corp.

The Space General Moon Rover was propelled by three pairs of legs and powered by solar batteries attached to a roof. The machine had a TV camera and a mechanical hand for picking up and moving objects.

Space General also has proposed a wheeled vehicle made with a basic chassis which can accommodate attachments for functional purposes. Provision has been made for earth-moving and bulldozing, hauling materials and personnel, and for handling materials and life-support features. The bare chassis can be operated by a man in a space suit. With the life-support capsule added, the operator can be in shirt sleeves while operating. Upon return to the base, the door of the space vehicle is latched to the door of the living quarters, so that no loss of air will be sustained. This vehicle would weigh around 8000 lb with the life-sustaining capsule and would have a maximum diameter of 12 ft. The length is under 20 ft, so that two would fit into a 14 $\times$ 40 ft cargo missile.

Motive power considered for this vehicle was heat engine, fuel cell, battery, and solar engine, to be determined by the mission of the unit. For bulldozing, the company proposes the use of tracks to obtain greater tractive effort.

I. Radio Corp. of America

RCA has studied two walking machines and one balloon vehicle. One six-legged walker proposed had a drill on the end of its manipulator arm for taking samples of the surface materials. The other walker was four-legged, with rubber-connected joints. The balloon vehicle was to be powered by a solar battery connected to a flat roof. The bag would be inflated after landing on the Moon and could roll around on its one plastic bag like a large rubber ball, rotated by the motors turning an axle through its center.

J. Northrop Corp.

The Northrop concept uses tracked crawlers that are internally powered and can be placed under any pipe-shaped tank or body, one at each end, to make the object mobile. These crawlers look like a pair of conventional tracks and rollers removed from a caterpillar tractor. Several configurations of this vehicle were proposed for different uses, such as personnel housing, cargo carrying, and general utility. One other smaller vehicle, with a single pair of tracks resembling a truncated jeep, was proposed for hauling one man wearing a space suit.

IV. CONCLUSIONS

Because of the lack of knowledge of the composition of the Moon's surface and environment, lunar vehicle design concepts are necessarily based on assumptions. The choice of surface contact between the vehicle and the Moon seems to tend toward conventional wheels and tracks. However, spiral screw devices, walking machines, and large rubber-ball machines are cropping up among the unconventional types.

The best recommendation for the final design of a lunar surface vehicle is to continue the study of various types of vehicles, based on certain assumptions of conditions on the Moon. When more data are available concerning lunar surface conditions, the most suitable design can be modified and refined toward a final design.

The unconventional types of vehicles should be thoroughly tested, with prototype models being built of each and an extensive program of testing instituted to determine exactly what each type is capable of doing in the different types of Earth terrain. This performance can then be matched with the type of soil and terrain found on the Moon, and the best vehicle selected. Considerable testing has been done on the conventional vehicles, and the performance of wheels and tracks is quite well established.

Since dependability of these Moon surface vehicles is the most important requirement, the cost of experimenting with various proposed vehicles in a scientific and systematic manner will be small compared to the cost of the mission. And if the success of the mission depends upon the surface vehicle, it is even more obvious that a very elaborate and thorough design and prototype testing program should be instituted, as expediently as possible, so as to be ready with the surface vehicle when the manned Moon exploration trips are made. Considering that it may cost a billion dollars or more to put a man on the Moon, it should not be out of line to spend 100 million dollars in lunar surface vehicle research and development.

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N 67-86321

Hydroponics or Soilless Culture

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Historically, hydroponics is not a new field; plant physiologists have known and used it for some 100 years. (Knop is credited with having originated the method around 1860.) During the late 1930's, a great upsurge of interest in soilless culture took place. Inevitably, some enthusiasts got carried away. Claims were made of enormous potential yields; skyscraper tops were said to be capable of producing enough food for all of their occupants; and closets, basements, garages, etc. were wishfully converted into fields for hydroponic culture. Numerous publications on the subject appeared during this period (see Bibliography).

Although, in fact, the yields obtained with soilless culture can be excellent (see Table 1), they are generally no greater than those obtainable in good soil without the addition of similar chemicals. It is probably easier in terms of effort involved to get high yields with hydroponics; the quality of the foodstuffs is satisfactory; and the seed produced is viable. Where no soil is available, such as in rocky areas, on steep hillsides and mountains, and on water and marsh surfaces, soilless culture is definitely advantageous (see Table 2). Where good soil and water are available, on the other hand, there are at present no special advantages to the use of hydroponics. Problems of insects and plant disease are no less, and the construction, control, and operations costs exceed those incurred with standard agricultural methods. In the future, with increasing pressure of population, the soilless culture of foodstuffs will in all probability come into much wider commercial use. (See Table 3 for locations in which hydroponics has been used commercially to date.)

Table 1. Comparative yields — agriculture vs hydroponics

Crop	Comparative yield			Location
	Agriculture[c]	Hydroponics	per ft^2	
Tomato	12 lb/plant	27.4 lb/plant	—	California
	10 lb/plant	22.5 lb/plant	—	India
Rice[a]	3000 lb/acre	9000 lb/acre	0.20	India
Potato	60,000 lb/acre	130,000 lb/acre	2.98	California
		140,000 lb/acre	3.20	India
Corn[b]	2000 lb grain/acre	6000 lb grain/acre	0.14	India
Lettuce	9000 lb/acre	21,000 lb/acre	0.48	India
Beet root	9000 lb/acre	20,000 lb/acre	0.46	India
French bean	210 lb/1000 ft^2	588 lb/1000 ft^2	0.58	India
Cauliflower	15,000 lb/acre	32,000 lb/acre	0.73	India

[a]Yields of rice up to 14,400 lb/acre have recently been reported under agricultural conditions.
[b]Yields of corn up to 304 bushels of grain/acre have been reported recently under agricultural conditions.
[c]Under average agricultural conditions.

Table 2. Advantages of soilless culture

Maximal yields (more research needed)
Use in areas where soil unavailable; steep hillsides, mountains, rocky, gravelly areas, unused paved areas, roofs, basements (light necessary), window boxes, verandas, etc.
Freedom from weed problem
Better control of diseases?
Better control of insects?
Elimination of salinity problems
Elimination of drainage problems

Table 3. Some locations where soilless culture has been used commercially

Location	Probable purpose or reason for use	Present position
Iwo Jima and Wake Island	Lack of good soil, economics (war)	?
Curacão	Lack of good soil	Not used now; fresh fruit and vegetables flown in
Bahrein	Lack of good soil	?
Iraq (Habbiniyah)	Lack of soil	?
India	Lack of good soil, shipping, economics, population density	Still underway in 1955
Japan	U.S. Army personnel food supply	Discontinued
	Substitute for soil	In use and interest increasing
United States	Cultivation of specialty crops, such as tomatoes, flowers, etc.	Many discontinued
England	Growing of carnations	?

Table 4. Methods of supplying nutrients[a]

Concentrated stock solutions of various salts
Packets of dry chemicals to known amounts of solution or sprinkled on top of bed
Compressed tablets
Synthetic resins, anion- and cation-saturated
Iron, as finely divided magnetite; also chelates
Frits, for Zn, Mn, B, Cu, and Fe
Perforated, plastic-coated chemical packets a possibility

[a]Fertilizer and technical grade salts can be used.

Table 5. Example of hydroponics nutrient solution

Compound	Mg/l	Nutrient supplied[a]	Total concentration in final solution[b] ppm	Satisfactory variations ppm
KNO_3	707.7	N	N 198	50–400
		K	K 273	50–400
$Ca(NO_3)_2 \cdot 4H_2O$	708.5	N	Ca 120	50–400
		Ca	Mg 24	12–120
$MgSO_4 \cdot 7H_2O$	246.5	Mg	S 32	10–500
		S	P 31	10–200
$NH_4H_2PO_4$	196.0	N	Cl 3.50	1–50
		P		
KCl	7.4	K		
		Cl		
H_3BO_3	1.54	B	B 0.27	0.1–0.5
$MnSO_4 \cdot H_2O$	0.93	Mn	Mn 0.27	0.1–1.0
$FeSO_4 \cdot 7H_2O$	1.11	Fe	Fe 0.22	0.1–1.0
$ZnSO_4 \cdot 7H_2O$	0.72	Zn	Zn 0.16	0.1–0.5
$CuSO_4 \cdot 5H_2O$	0.12	Cu	Cu 0.03	0.01–0.2
H_2MoO_4	0.016	Mo	Mo 0.009	0.01–0.1
Total	1870.4	13 elements	682.46	

[a]Thirteen elements are essential in variable amounts.
[b]Final solution contains about 2 g of total salts per liter.

The basic requirements for the growing of plants by the soilless culture method are as follows:

1. *Substrate*—gravel, sand, cinders, haydite, vermiculite, water.
2. *Nutrient solutions* (see Table 4 and example, Table 5)—chemicals in salt, tablet, or solution form (Table 6); synthetic resins; possibly fertilizer salts [KNO_3, $MgSO_4$, $CaH_4(PO_4)_2$, etc.].
3. *Water* (see Table 7).
4. *Air*—carbon dioxide and oxygen (Table 8).
5. *Light*—minimum, 2000 ft-c; optimum, 4000 ft-c (Table 9).
6. *Temperature*—acceptable range, 32-120°F; optimum range, 60-100°F (Table 10).
7. *Humidity*—25–90% preferred but not essential.

In addition to these basic requirements, protection must be provided against weather extremes, air pollution, and excessive radiation, as well as insects and disease. Also, some means must be devised of checking the nutrient solution periodically for conductivity, pH, etc., and of making appropriate adjustments. Table 11 presents a list of the types of containers that may be used for hydroponic plantings.

Table 6. Chemical mixture[a]

Major salt	Weight
Sodium nitrate ($NaNO_3$)	5 oz
Ammonium sulfate ($[NH_4]_2SO_4$)	3 oz
Calcium sulfate ($CaSO_4 \cdot 2H_2O$)	1.5 oz
Superphosphate ($CaH_4[PO_4]_2$)	3.0 oz
Potassium sulfate (K_2SO_4)	4.0 oz
Magnesium sulfate ($MgSO_4 \cdot 7H_2O$)	2.5 oz
Trace element mixture	0.5 g
Zinc sulfate	5.3 g
Manganese chloride	16.0 g
Boric acid	12.0 g
Copper sulfate	5.3 g
Iron sulfate	17.0 g

[a]Applied at rate of 2.0 oz per week to 9 ft² of trough space will provide sufficient nutrients.

Table 7. Water requirements of plants grown in open air[a]

Plant	Water transpired per lb dry matter[b] lb	Relative requirement[c]
Millet	187–367	1.00
Sorghum	272–303	1.14
Corn	253–495	1.31
Barley		1.94
Wheat	394–639	2.09
Oats		2.18
Rye		2.37
Legumes		2.81
Grasses		3.10

[a]In a closed system, water could be recycled.
[b]From Miller, *Plant Physiology*, 1938, p. 49.
[c]Affected by humidity, fertility (less water required for excellent than for poor ground), soil moisture (good moisture supply reduces water requirement), and diseases (leaf rusts increase water requirement). Under optimum conditions of humidity, fertility, etc., at least 100-150 lb of water would probably be required per pound of dry matter.

Research in hydroponics is currently being conducted quite vigorously. At Scripps, Drs. W. H. Thomas, F. T. Haxo, K. A. Clendenning, Ralph Lewin, and Joyce Lewin are culturing algae. The following are also reported to be doing work on algal culture:

Dr. Mary Belle Allen
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Table 8. Carbon dioxide requirements of plants[a] for photosynthesis

Normal content of air on Earth: 3 parts CO_2 in 10,000 of air (by volume) = 0.03%; higher in industrial areas, close to soil, and in soil (e.g., 5 to 10 times higher in soil).

Source of CO_2: respiration of plants and animals, organisms, combustion of wood, coal, petroleum, disintegration of rocks (e.g., $CaCO_3$), volcanoes, water in streams, oceans, etc.

10,000 l of air contain 1.7 g of carbon.

One acre of corn would need the CO_2 out of 20,000 tons of air where concentration of CO_2 is 3 parts in 10,000.

There is evidence that roots can absorb some carbon from dissolved CO_2 in the soil solution.

Photosynthesis can be increased by increasing the CO_2 of the air. (Warburg, using chlorella, obtained a proportional increase from 0.05 to 10% CO_2 in the air. Toxicity and other limiting factors come into play (i.e., light, stomata numbers, etc.).

When CO_2 is 10 to 15% in air, it inhibits growth.

For 610 lb dry matter, assuming 50% carbon content, 1,120 lb CO_2 would be required.

[a]In a closed system in equilibrium with man, CO_2 would be reused continually.

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Table 9. Light requirements of plants[a]

Midday intensity on clear day in temperate zone is 10,000 to 12,000 ft-c. (2,000 to 3,000 ft-c are sufficient for many plants.)
There is greater photosynthesis with intermittent light.
Light intensity, temperature, and CO_2 are all interrelated.
Wavelength: blue and red important—730 mμ upper limit; ultraviolet not important—390 mμ lower limit; green not important.
Ultraviolet beyond wavelength of 290 mμ is injurious.

[a]Photosynthesis $CO_2 + H_2O \rightarrow 1/6\ (C_6H_{12}O_6) + O_2\ \Delta H = 112{,}000$ calories.

Table 10. Temperature

For photosynthesis	Threshold temperature, −6 to −20°C. O_2 evolution ceases at 0 to 2°C for warm, temperate plants. O_2 evolution ceases at 4 to 8°C for subtropical and tropical plants. Photosynthesis, with no other factor limiting, increases up to 25°C.
For plant growth	Varies with plant, but optimum region is generally 70 to 90°F.

Higher plants are being investigated in Japan, at the University of California at Riverside, and in many other places, but mostly from a plant nutrition point of view.

Table 11. Types of containers

Redwood tanks or troughs
Concrete tanks or beds (asphalt coated)
Iron tanks or troughs (asphalt coated)
Plastic tanks, troughs, or containers
Brick structures
Puddled clay
Stones laid in pattern, outlined, and coated with nonerodible mud plaster, 4 ft wide and up to 100 ft long
Asbestos sheeting

Research is still needed to determine what combination of crops will produce maximum digestible nutrients per unit area and meet the necessary protein, carbohydrate, fat, etc., needs of man (see Appendix). Other problems requiring further study are those concerned with securing the maximum yields of usable crops per unit area (combination of nutrient levels, moisture, substrate character, light, temperature, CO_2, humidity, aeration, etc.; mechanical arrangements—stacking or layering to reduce space requirement); plant breeding to produce desired yield and quality; control of diseases and insects; and finding the simplest and best means of renewing and controlling nutrient levels, resins, coated nitrogen sources, etc. In addition, experiments should be performed under simulated Moon conditions on the recycling of CO_2, oxygen, and water; the effects of reduced gravity; radiation control; and on enclosure materials which will screen out harmful radiation but not useful wavelengths.

APPENDIX

Food Requirements of Man

The initial basic requirements for starting a hydroponics setup to support one man are as follows (see Table 1):

1. *Plant beds*—500–1000 ft^2, made of suitable plastic or other material. (Layering arrangements might decrease this area.)

2. *Substrate*—gravel, sand, soil-dust mixture.

3. *Water*—roughly 1000–2000 gal for 500–1000 ft^3 of gravel and sand.

4. *Chemicals*—20—40 lb for 1000—2000 gal of nutrient solution.

5. *Carbon dioxide*—303 g carbon per day for 756 g food = 1,102 lb carbon dioxide in enough air to give concentration that man can tolerate.

6. *Oxygen*—sufficient for man will supply plant root needs.

7. *Light source*—to provide 3000–4000 ft-c intensity if setup is underground.

8. *Heat source*—to maintain temperatures at 70–85°F if setup is underground.

9. *Enclosure material*—must be strong and permit transmission of useful light while screening out harmful radiation.

Table A-1. Basic dietary needs of man (154 lb or 70 kg; physically active)

Item[a]	Amount
Calories	3000
Protein	70 g
Calcium	1 g
Iron	12.0 mg
Vitamin A	5,000 I.U.
Thiamine	1.5 mg
Riboflavin	1.8 mg
Niacin	15.0 mg
Ascorbic acid	75.0 mg
Vitamin D	6.0 I.U.
Water	2.5 l
Salt	5 g
Iodine	0.15 to 0.30 mg
Phosphorus	Not in normal food
Copper	1 to 2 mg
Carbohydrates	595 g
Fat	77 g

[a]Total dry food: 756 g = 1.62 lb per day (610 lb per year). 0.10 to 0.60 lb dry corn can be produced per square foot. Assuming optimum, 610/0.60 ≐ 1000 ft^2 of hydroponic surface per person, or about 1/40 acre, ≐ plot 4 × 250 ft or 10 plots 4 × 25 ft. By appropriate layering or use of algae, the area occupied can be decreased.

In summary, the needs per man are: (1) 500–1000 ft^2 of plant surface to absorb carbon dioxide and fix food at 1.62 lb per day, (2) 1000–2000 gal water to provide 25% saturation of planting bed, (3) 3,636,000 lb air to supply 1,102 lb carbon dioxide at 0.03%, and (4) 20–40 lb chemicals (assuming reuse) to make up 1000–2000 gal nutrient solution.

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N 67-86522

Processing of Water on the Moon

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A. Electrolysis

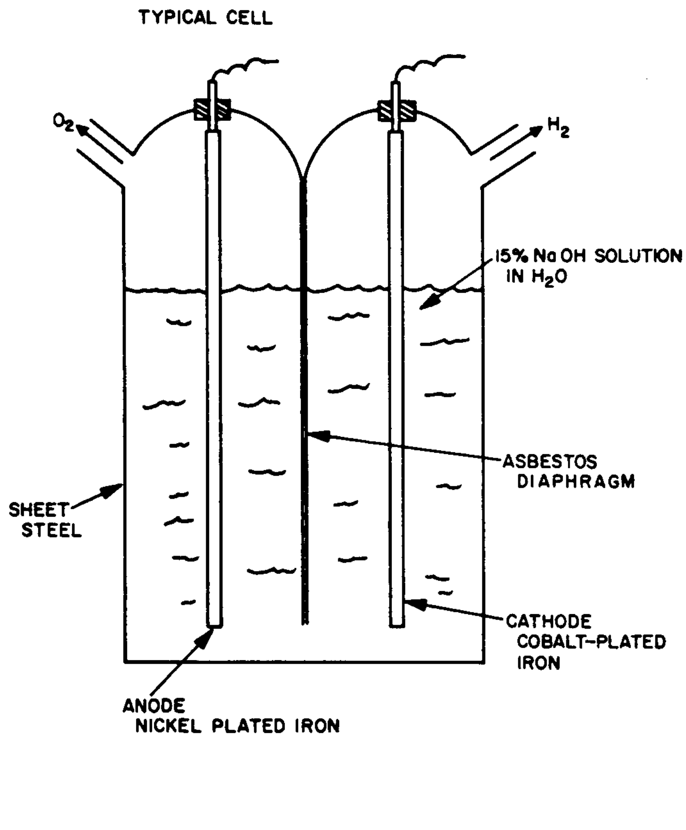
The electrolytic dissociation of water into gaseous forms of hydrogen and oxygen is a well known process that can quickly be summarized in a series of illustrations. Table 1 presents some physical properties of hydrogen and oxygen for purposes of reference. Figure 1 illustrates the chemical process and the equipment used in the industrial production of hydrogen and oxygen by the electrolysis of water. Table 2 summarizes the characteristics of electrolytic H_2-O_2 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.

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.

Table 1. Some physical properties of hydrogen and oxygen

	Fluid	
	H_2	O_2
Density of gas @ NTP, lb/ft³	0.0056	0.0892
Density of liquid @ NBP, lb/ft³	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 @ NBP, Btu/lb	194.5	91.5
Pre-cool temperature for practical J-T process, °K	65	300



$2H_2O \rightarrow 2H_2 + O_2$

$\Delta H = +2(68{,}317)$ cal/g formula wt

Fig. 1. Electrolytic hydrogen and oxygen production reactions

Table 2. Characteristics of typical electrolytic H_2-O_2 cells

Basis	9 lb $H_2O(l) \rightarrow$ 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 ft³

Figure 2 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 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.

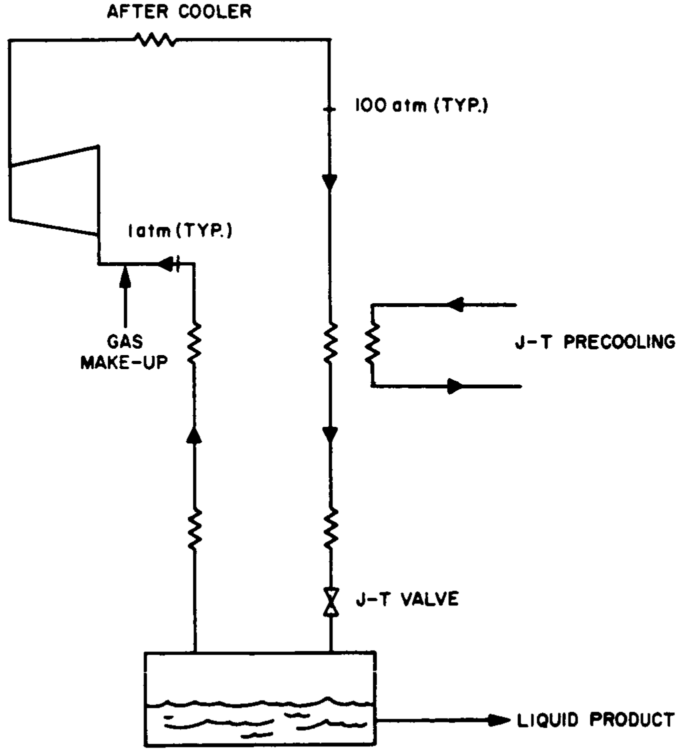


Fig. 2. Schematic representation of Joule-Thomson gas liquefier

Figure 3 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, making possible more efficient operation at lower pressure levels. This is translated in terms of power and weight savings.

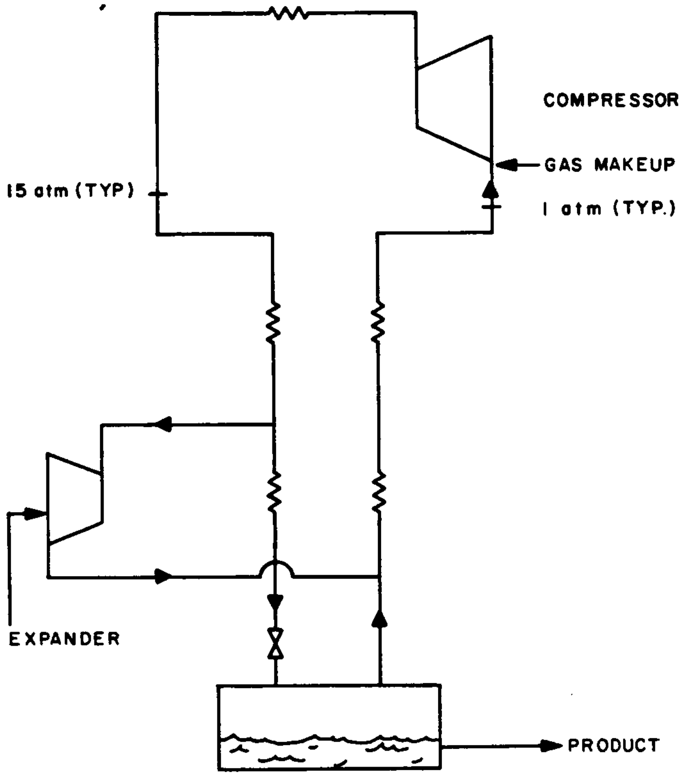


Fig. 3. Schematic representation of gas liquefier using expansion engines

Typical characteristics of an oxygen liquefier operating on the Claude cycle are shown in Table 3. Table 4 shows typical characteristics of a hydrogen liquefier. These Tables indicate a rather substantial power requirement for liquefaction, although it is lower than

Table 3. Typical characteristics of oxygen liquefier (expansion engine cycle)

Reversible work requirement	0.08 kw-hr/lb
Actual shaft work requirement	0.32-0.40 kw-hr/lb
Ratio of shaft work to heat extraction	10:1
Weight of industrial plant (exclusive of power supply and buildings)	250–500 lb/kw
Estimated weight of lunar plant (exclusive of power supply and buildings)	50–100 lb/kw

Table 4. Typical characteristics of hydrogen liquefier (expansion engine cycle)

Reversible work requirements	2 kw-hr/lb
Actual shaft work requirements	8-10 kw-hr/lb
Ratio of shaft work to heat extraction	70:1
Weight of industrial plant (exclusive of power supply and buildings)	300–600 lb/kw
Estimated weight of lunar plant (exclusive of power supply and buildings)	70–140 lb/kw

that for separation. In addition, a fairly substantial plant weight requirement can be noted. The estimated weights of lunar plants are derived from studies of space-borne refrigeration systems.

Tables 3 and 4 do not show requirements for plant maintenance. The maintenance requirements for liquefaction plants now in operation are incompatible with the needs of 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 5, 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 light-weight, 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.

Table 5. 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}

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Lunar Base Construction

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The possibility of establishing a permanently manned lunar base was considered seriously as soon as early studies indicated that it was technically feasible to put men on the Moon and return them to Earth. Such studies were conducted by industry, the Air Force, and the Army. The greatest difficulty in giving credence to results from lunar base studies lies in the fact that very little is known about the physical and chemical properties of the surface. Of course, this situation is expected to change when television pictures taken from an impacting *Ranger* spacecraft are transmitted back to Earth. Additional information will be obtained within the subsequent two years from the *Surveyor* program, which is designed to soft-land a spacecraft containing instruments to measure and photograph the physical features of the lunar surface at the landing site.

Notwithstanding the present dearth of information, it has been possible to make meaningful studies of lunar bases. This was accomplished by making a wide range of assumptions regarding the nature of the lunar surface. Then, by designing a base that is insensitive to surface features over the range of assumed conditions, feasible base designs could be obtained.

An important factor influencing the base design is the sequence of events and equipment available before man can have extended stay times on the Moon. It is, therefore, necessary to review briefly the planned approach to these problems. The first two men to land on the Moon in a lunar excursion module will have an intended stay time of only 6 hr but life-support provisions for approximately 48 hr. Subsequent flights may provide a stay time of several days for the two men landed but will be limited by two factors: (1) the length of time the third man can stay in lunar orbit waiting for the landed crew to return and (2) the amount of life-support provisions that can be carried in the landed spacecraft. This second limitation can be overcome if a one-way (Earth-to-Moon) lunar-logistics supply vehicle can be landed shortly before or soon after the men land and provided the supply vehicle can be landed in close proximity to the manned landing.

Since the foregoing supply vehicle can be of substantial size, it can be designed as a shelter for the men. It would undoubtedly be more adequate than the lunar excursion module, which the men must use otherwise. Subsequent supply vehicles would possibly contain a manned surface vehicle, landing aids, power supplies, surface measurement equipment, or base building equipment. Such items will probably be combined in any one supply vehicle payload.

It must be assumed that for stay times on the order of weeks, the man left in lunar orbit will return to Earth after the lunar excursion module has landed. A separate one-man flight to the Moon at a later date will be required to pick up the two men remaining there. By proper scheduling of the foregoing events, it is possible to have several men on the Moon at all times. (The numbers being discussed vary between six and twenty.) An example of proper scheduling would be to rotate two-man crews by using the lunar orbiting spacecraft that had just brought two men to the Moon to return two men that had been placed on the Moon in an earlier mission.

From the foregoing, it should be obvious that the supply vehicle will be required before a permanent base can be constructed. The supply vehicle will provide shelter for the men while they construct a more permanent base. The number of men available for construction work will depend upon the size of the supply-vehicle shelter and the number of shelters landed. However, a safe assumption at this time is that at least one shelter will be available and that this should house four men.

All studies to date indicate that a permanent base should be underground or consist of surface modules covered with lunar soil. Using surface soil for cover, if possible, would be an economical means of providing protection from solar and cosmic radiation, decreasing the thermal control problem, and providing protection from meteorites.

It is during this phase of the lunar base development that possible use can begin to be made of indigenous materials. It is not considered necessary at this point to prove mathematically that it is more economical to use natural resources found on the lunar surface than to transport them from the Earth. If, for example, water could be found or obtained by processing lunar soils, a heavy transportation burden from the Earth to the Moon would be obviated. The water could be separated by electrolysis into H_2 and O_2, a rocket fuel. Another example would be a means of processing lunar soils to obtain building blocks, or the use of lunar soil as an ingredient in a slurry that would "set up" in a vacuum.

If fairly simple means can be found to utilize lunar materials for shelter construction, a series of such bases can be visualized. These would have similarities to oases in the desert; i.e., surface parties traveling in a lunar surface vehicle would proceed from one shelter to another and remain at a shelter while operating in the local area.

The foregoing concept appears to be a logical sequence of events based on present plans. It means that permanently manned lunar bases are possible within this decade.

N 67-86524

Lunar Rocks as a Source of Oxygen

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A thermodynamic study of the thermal stability of conventional terrestrial minerals in a hypothetical lunar atmosphere has opened some interesting speculation.

Much of the Earth's crust is composed of oxides of silicon, aluminum, magnesium, and related compounds. These crust components may be as much a product of the Earth's atmosphere as vegetation and animal life. Though inanimate and long considered imperishable, these materials are stable under conditions of an atmosphere equivalent to 34 ft of water at sea level and persist under adverse conditions of moisture and temperature to altitudes of roughly 29,000 ft above sea level. The oxygen content averages 21%, and the oxygen partial pressure would be roughly 1/5 atm.

The question is posed as to the behavior of these minerals under varying temperatures and at 10^{-13} atm. A profusion of data on the thermal dissociation of many metal oxides and other compounds exists in the literature. These data have been concerned mainly with extrapolated free-energy–temperature diagrams based on formations from the elements.

In recent years, accumulated data on high-temperature stable suboxides, which often exist only in the gaseous phase, have been presented in the literature, with free-energy values based on spectroscopic measurements and calculation. These products, which are more familiar to technical personnel concerned with high-temperature vacuum installations, serve in effect to lower the dissociation temperature of many materials, as for example, quartz:

$$SiO_2 \rightarrow Si + O_2$$

$$SiO_2 \rightarrow SiO + \tfrac{1}{2} O_2$$

With the first dissociation, 1 atm of oxygen would be obtained at temperatures above 3900°K. The latter reaction provides 1 atm of oxygen at roughly 3100°K, about five times the oxygen pressure in the Earth's atmosphere. Under conditions of vacuum of upwards of 10^{-13} atm, quartz could dissociate at temperatures as low as 1000°K.

The first question becomes: What happens to quartz or other silicates exposed to high vacuums and moderate temperatures over geologic periods of time?

One answer would expect the lunar crust to be deprived of silica and silicates and be composed of spinels and other alumina-bearing materials. Magnesia could also be lost. This crust could be superficial and not persist to any great depth.

The second question might be of critical significance. If quartz persists at moderate depths, can it be mined, introduced into solar furnaces, gases compressed, and used as a source of oxygen to support life in the lunar environment?

Again, one answer would be a qualified yes, without consideration of the competitive cost of shipping liquid oxygen around the universe in tank cars. Other oxides might be added to silica as potential oxygen source material.

The real question still to be answered would be related to the Moon's origin. Are the Earth's crust minerals a product of the atmosphere and is the Moon a fragment of the Earth?

If the Moon was once part of the Earth, perhaps the odds in favor of oxygen mines on the Moon would be improved.

Perhaps the metallic meteorites are in a more stable form for high-vacuum space travel and the silicate forms are created during atmosphere traverse.

Figs. 1–7 illustrate the behaviors and properties of various compounds and present other information pertinent to answering the question asked by the title of this paper.

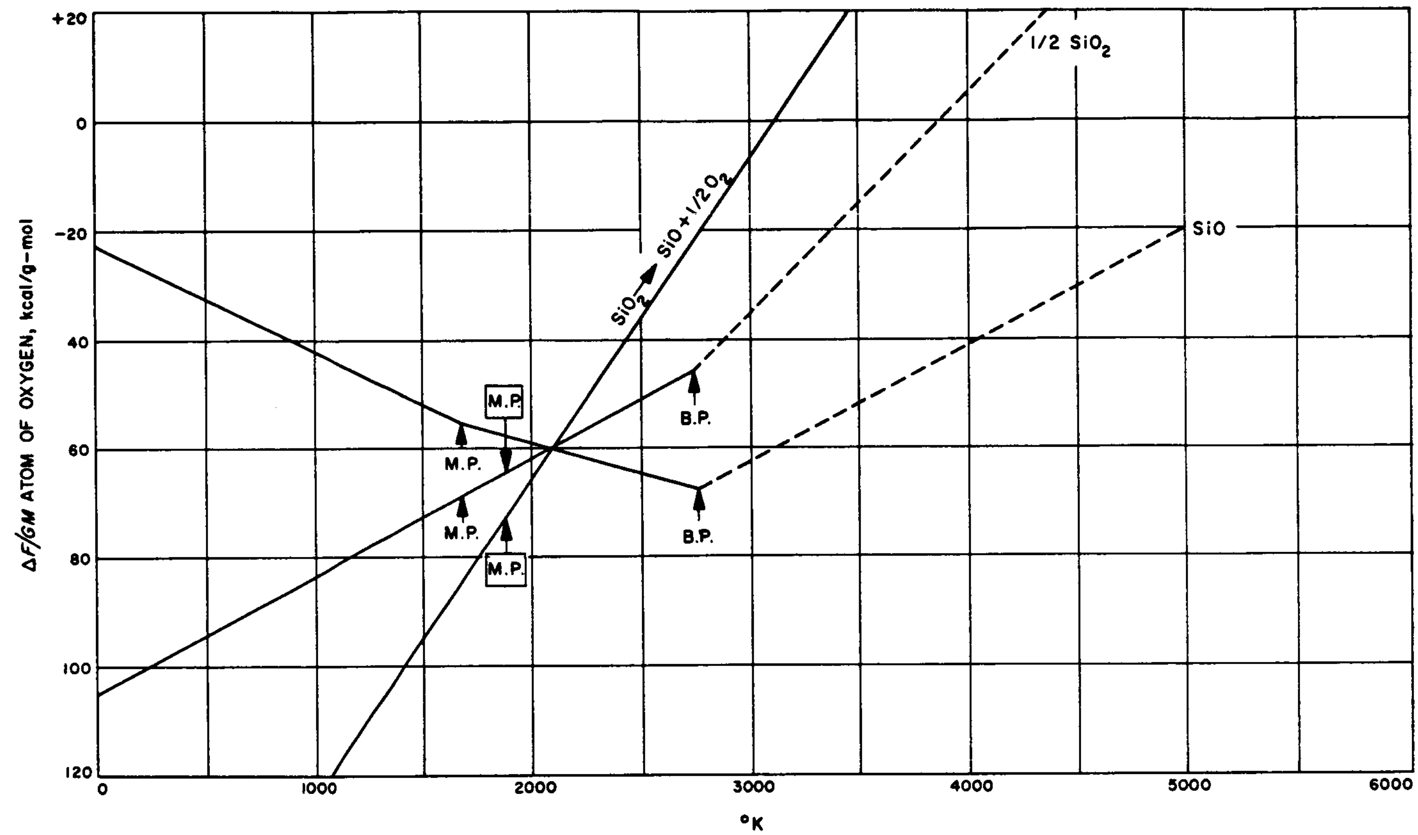

Fig. 1. Thermal stability of silicon oxides

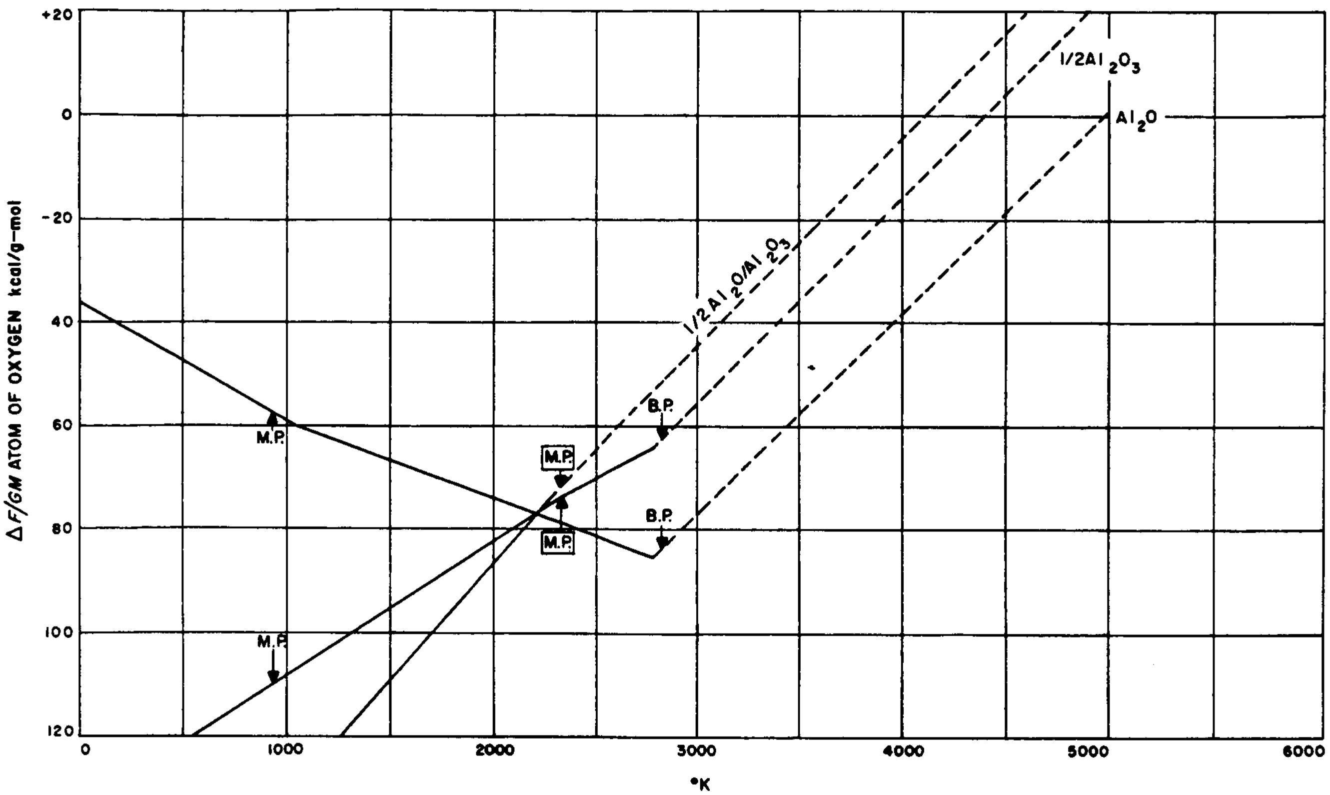

Fig. 2. Thermal stability of aluminum oxides

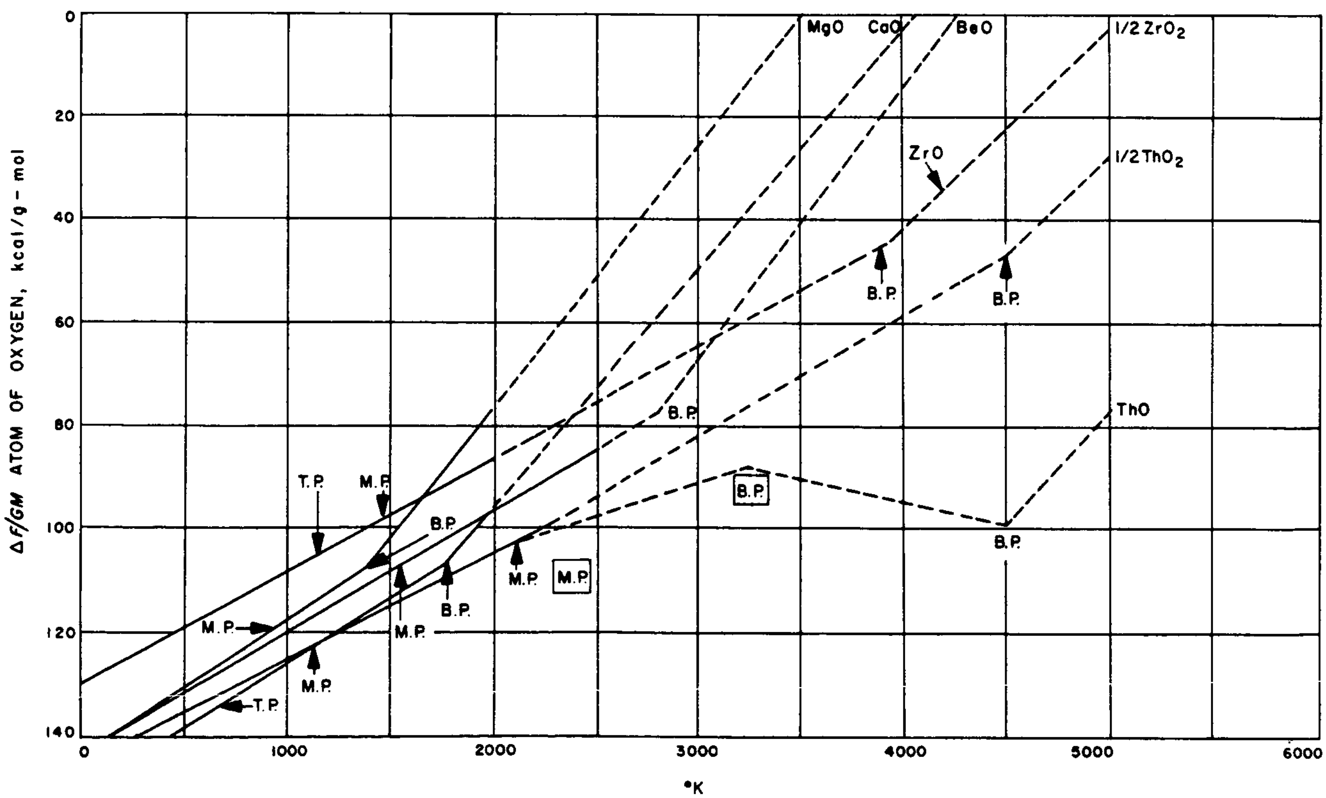

Fig. 3. Thermal stability of refractory oxides

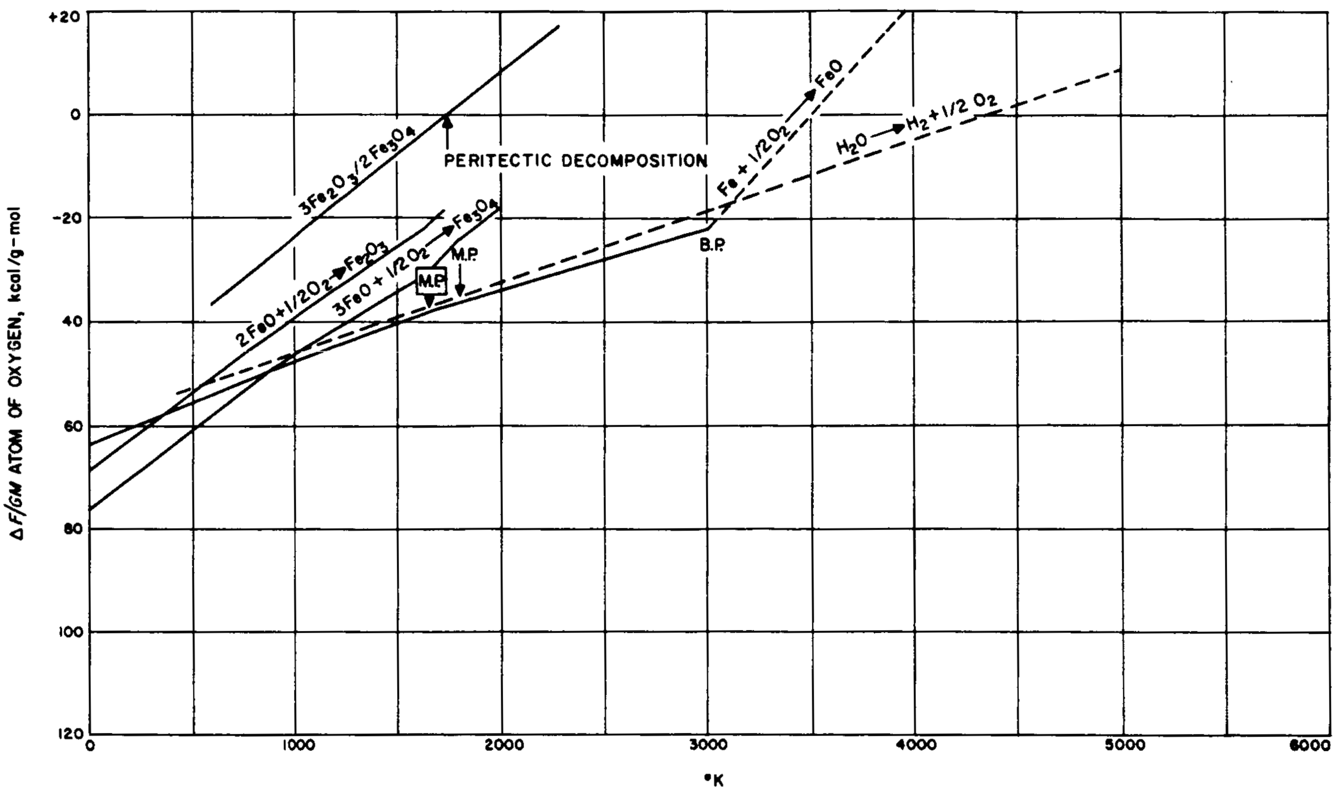

Fig. 4. Thermal stability of iron oxides

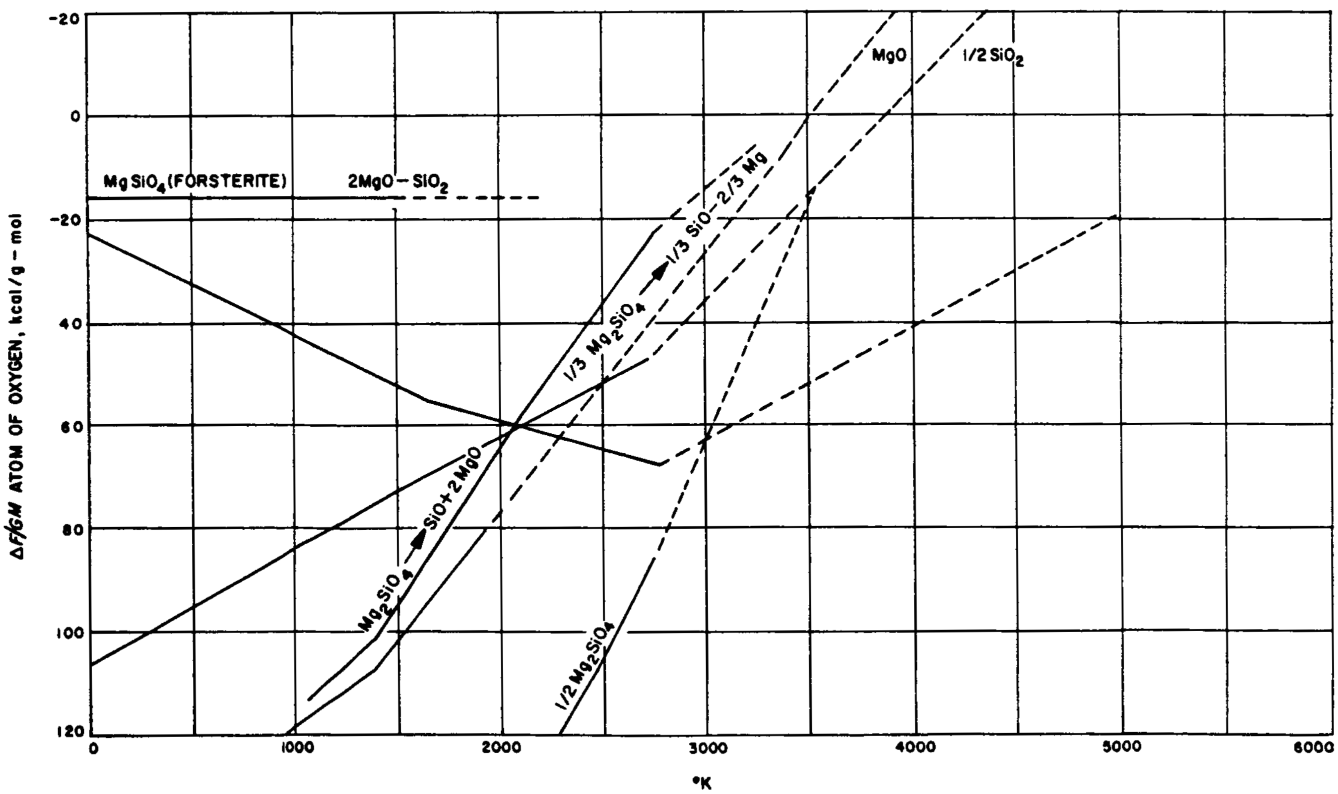

Fig. 5. Thermal stability of forsterite

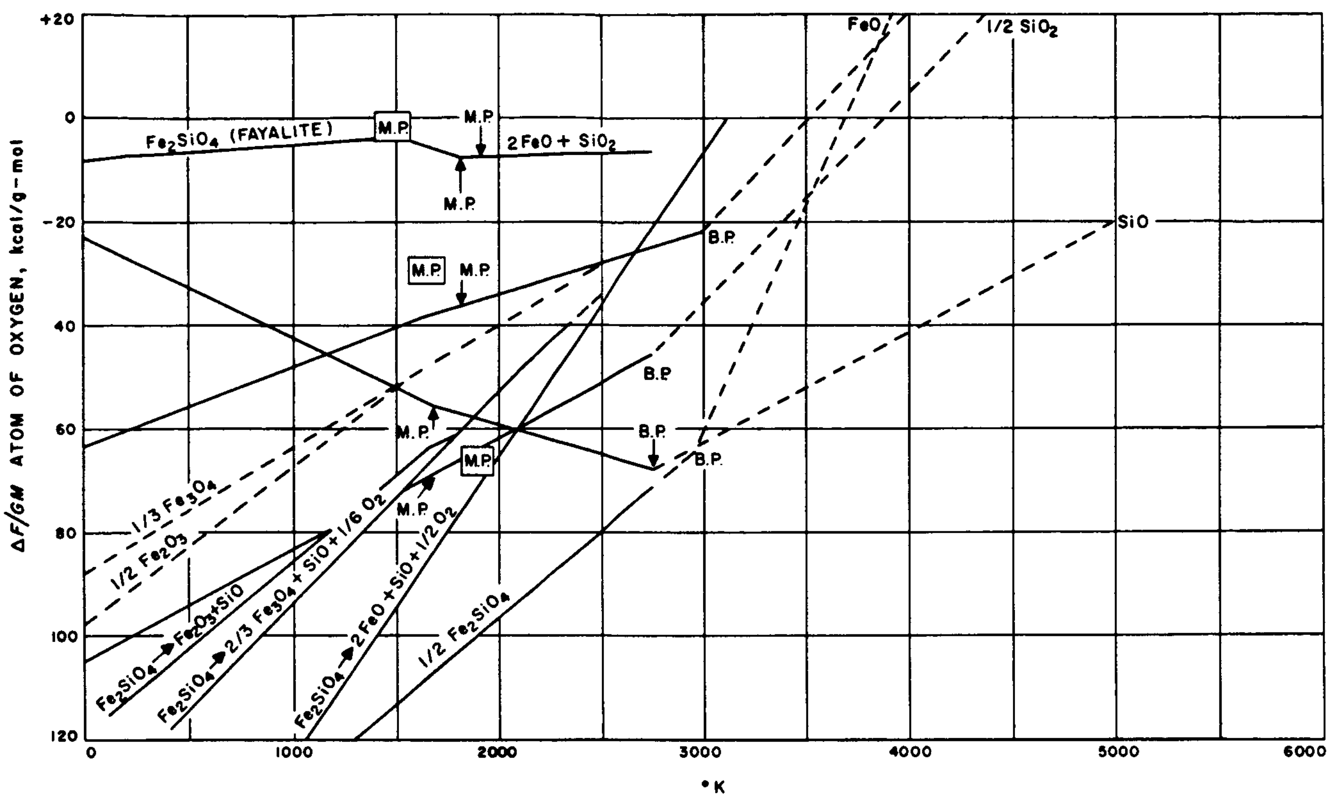

Fig. 6. Thermal stability of fayalite

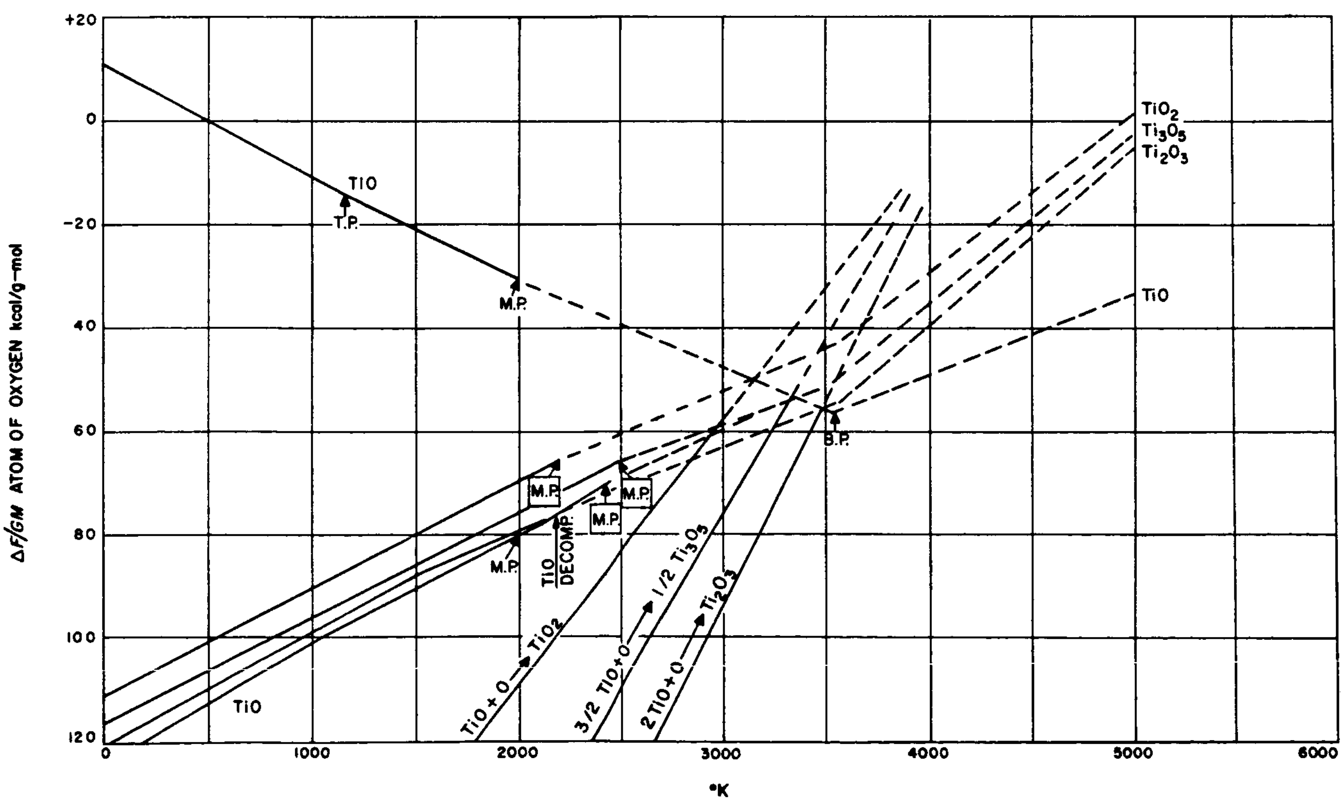

Fig. 7. Thermal stability of titanium oxides

Water in Lunar Materials

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N 67-86525

I. THEORY

Two lines of evidence, as follows, suggest independently that materials which formed the Moon were not anhydrous:

1. Meteorites, our only sample of extraterrestrial material, contain water in varying amounts. Chondrites average about 0.25% water by weight. Carbonaceous chondrites, however, contain up to 20% water; and, although much of this water may be adsorbed atmospheric and surface water, the abundance of silicate hydrates in these objects indicates that considerable water existed in these meteorites before Earth impact.
2. The gas emission from Alphonsus observed by Kosyrev (Ref. 1) indicates that volatiles are diffusing out of the Moon. The observed emission was a C_2 band. Analyses of presumably juvenile gases reaching the Earth's surface show that water generally composes 95% or more of the gas. By analogy, it is suggested that water must be reaching the lunar surface.

Consequently, it is reasonable to conclude that water existed in the materials which formed the Moon as well as those which formed the Earth or meteorites (or their source object). An estimate of the water content of the primordial Earth is 0.03% (Ref. 2).

Water originally uniformly distributed throughout an accreted Moon would diffuse radially outward until a chemical potential gradient was established with lunar pressure and temperature gradients under which further flow of water would cease. This zero flow gradient may be expressed by

$$\frac{d\mu_{H_2O}}{dz} = M_{H_2O}g - \left(S_{H_2O} + \frac{Q^*}{T}\right)\frac{dT}{dz}$$

where lateral gradients are zero and M is the mass of a mole of water, g is gravitational acceleration, z is depth, S is molar entropy of water, and $Q^* \equiv Q - H_1$; Q is the energy transported per mole of H_2O, H_1 is the partial molar enthalpy of water, and μ_{H_2O} is the chemical potential of water. This problem is extended by a number of possible complicating factors: i.e., convection of rock masses in the Moon, fusion in the lunar interior, strength of lunar interior and depth of fracture, and degree of nonideality of diffusing fluids.

Diffusion of water radially outward in the Moon should continue until a zone is reached in which hydration and absorption can occur. Neglecting the latter, it can be estimated that hydrous silicates are unstable below 250–300 km depth in the Moon where pressure is around 12–14 kbar. The temperature at this level would be around 1000°C if the Moon is assumed to have a uniform distribution of a chondritic abundance of K^{40}, U^{238}, U^{235}, and Th^{232}. The upper surface of this hydration zone will be either the lunar surface or, in the case of some hydrous silicates which partially to totally dehydrate in vacuum, some shallow depth down to 20 m, where the load pressure has increased to 1 bar. Greater depths would be required if water is completely mobile in the surface materials. Within the zone of hydration, assemblages of hydrous silicates will change vertically in accordance with the temperature, pressure, rock composition, and water diffusivity gradients in the zone. In general, however, successive silicate assemblages should be progressively more hydrous as the exterior of the hydration zone is approached. As water enters this zone, a partition will occur between hydration and continued diffusion to the surface. If very deep fissures are absent in the Moon, it seems unlikely that much water could have reached the surface, considering the great thickness of the hydration zone through which the diffusing water had to pass, unless the Moon contained an unusually large amount of primeval water. It should be emphasized that, because of the complete uncertainty of flow rates, it is not clear whether all water over the equilibrium amount has reached the zone of hydration in 4.5×10^9 years. Table 1 shows bulk water contents of the hydration zone as a function of original lunar water content, assuming complete degassing of the interior and no loss of water at the surface.

Table 1. Bulk water contents of the hydration zone

Bulk lunar water wt. %	Hydration-zone water wt. %
0.03	0.067
0.3	0.67
3.0	6.7

II. OCCURRENCES OF WATER

Possible occurrences of water on the Moon are as follows:

a. Crystalline Hydrates. Table 2 lists crystalline hydrates and their water contents by the most prominent natural chemical systems. The temperatures of dehydration given in the Table were obtained by differential thermal analysis (Fig. 1), and the temperatures so derived depend upon the rate of heating and environmental gas pressure. This is not a reversible process, and the temperatures are not equilibrium dehydration temperatures. Heating rates for most of these runs were 5–10°/min. For lower heating rates, dehydration temperatures would be a little lower.

Heat requirements H for dehydration of these phases are given by

$$H = \int_0^{T_D} C_{PdT} + \Delta H_D$$

where the subscript D = dehydration. Calculated results specified in calories per gram of H_2O derived are given in the last column of Table 2 for phases in which heat capacity as a function of temperature and heat of dehydration data are known. For phases in which data do not exist, energy requirements are guessed, and categorized on the basis of other mineralogical considerations. As a result, it is clear that energy requirements for water extraction from minerals are widely varied. Consequently, the need for exploration for hydrous mineral assemblages with lowest dehydration energy requirements is indicated.

b. Glasses. Volcanic glasses on Earth contain up to 0.5% by weight juvenile water. Secondary water, the source of which is chiefly groundwater, occurs in partly to wholly devitrified glasses in amounts from 2–6%. Dehydration temperatures for water in volcanic glasses are generally less than 300°C.

c. Adsorbed Water. Adsorbed water occurs in rocks with widely different adsorption bond strengths. The amount of adsorbed water will differ greatly with composition of the adsorber. For instance, powdered olivine and SiO_2 glass were both exposed to the atmosphere for several days. Adsorbed water was not detected on the olivine, whereas the SiO_2 glass adsorbed 4% water.

Table 2. Prominent hydrous phases, temperatures of their dehydration peaks, and energy requirements for dehydration

Mineral	Composition	H_2O wt. %	T (at 1 atm) °C	H_2O* cal/g
	MgO-SiO_2-H_2O			
Brucite	$Mg(OH)_2$	31.0	410	1075
Chrysolite and lizardite	$Mg_6Si_4O_{10}(OH)_8$	13.0	637–715	~ 2200
Antigorite	$Mg_6Si_4O_{10}(OH)_8$	13.0	790–802	2550
Anthophyllite	$Mg_7Si_8O_{22}(OH)_2$	3.4	1020	> 700
Sepiolite	$Mg_3Si_4O_{11} \cdot 5(H_2O)$	12.0	775	B
Talc	$Mg_3Si_4O_{10} \cdot (OH)_2$	4.5	970	7000
Stevensite	$2xM \pm Mg_{3-x}Si_4O_{10}(OH)_2 \cdot nH_2O$	17.5	830	B
	$MgO(FeO)$-Al_2O_3-SiO_2-H_2O			
Chlorite	$Mg_4Al_2(Al_2Si_2)O_{10}(OH)_8$	12.9	680, 840	~ 3100
	$Fe_4Al_2(Al_2Si_2)O_{10}(OH)_8$	11.4		
	Al_2O_3-SiO_2-H_2O			
Gibbsite	$Al(OH)_3$	34.6	350, 500	832
Montmorillonite	$X_4(Al, Si)_8O_{20}(OH)$	14.0	125, 650, 850	B
Kaolinite	$Al_4Si_4O_{10}(OH)_8$	14.0	600	1983
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	5.0	630–850	6800
	Alkali-Al_2O_3-SiO_2-H_2O			
Paragonite	$NaAl_2(AlSi_3)O_{10}(OH)_2$	4.7	700–900	C
Muscovite	$KAl_2(AlSi_3)O_{10}(OH)_2$	4.5	700–900	5100
Biotite	$K(Mg, Fe)_3(Al, Si_3)O_{10}(OH)_2$	2.2 to 4.3	1100	D
Analcite	$NaAlSi_2O_6 \cdot H_2O$	8.2	300–400	B
Thomsonite	$Na_3CaAl_3Si_3O_{12}CO_3, OH_2$	3.9	400	C
Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$	9.5	420	B
Many other zeolites		8–28 (most around 15)		BC
	CaO-Al_2O_3-SiO_2-H_2O			
Amphiboles	$Ca_2(MgFe)_5(Al, Si)O_{22}(OH)_2$	2.2	1000–1100	D
Zoisite	$Ca_2Al_3Si_3O_{12}(OH)_2$	2.0	1000	D
Prebnite	$Ca_2Al_2Si_3O_{10}(OH)_2$	4.4	825	CD
Laumontite	$Ca_7Al_{14}Si_{28}O_{80}25H_2O$	14.5	270, 450	B
Many zeolites		Around 15	Up to 400	BC
	Others			
Gypsum	$CaSO_4 \cdot 2H_2O$	20.9	200	A
Alums	e.g., $KAl(SO_4)_2 \cdot 12H_2O$	45.6	550, 850	A
Opal	$SiO_2 \cdot n(H_2O)$	1 to 28	100–400	A
Geothite	$Fe(OH)_3$		300	932

*A < 1500 cal/g H_2O
B = 1500–3000 cal/g H_2O
C = 3000–7500 cal/g H_2O
D > 7500 cal/g H_2O

De-adsorption in the latter material occurred at around 150°C.

d. Pore Water. Liquid or solid water may occur in pore spaces in near-surface lunar rocks in which water permeability is very low.

e. Surface Condensates. Some water which reaches the lunar surface will be concentrated in cold traps in shadowed parts of the lunar surface. Surface ice will probably be most prevalent at high latitudes. This problem has been discussed by Vestine (Ref. 4) and Watson (Ref. 2).

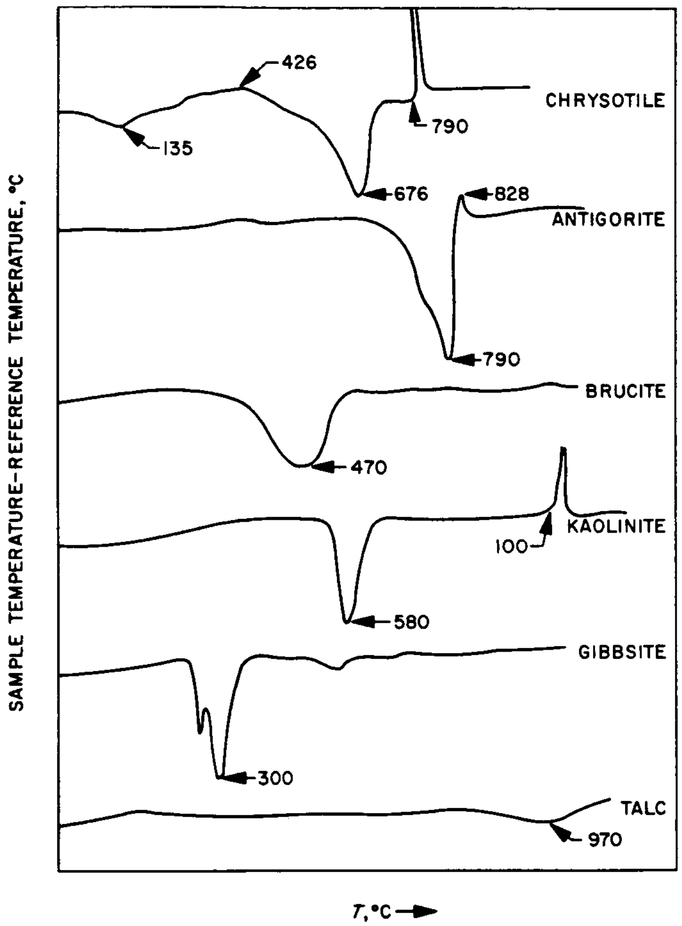

Fig. 1. Differential thermal analysis curves for selected hydrous minerals (reference: α Al_2O_3)

III. METHODS OF EXPLORATION FOR LUNAR WATER

A number of methods could possibly be used from unmanned and manned spacecraft for delineating the water content of surface or near-surface lunar rocks.

A. *Spectral Analysis of the Lunar Thermal Emission From an Orbiting Vehicle*

Hydroxyl (2.6 to 3μ) or molecular water (6.1μ) emission (or adsorption) minima may be detectable, and variations in the strength of these bands would be indicative of water abundance in the surface materials if variations in surface geometry on the spectra are understood (Ref. 5). Furthermore, spectral emittance at higher wavelengths (9 to 25 μ) is in many cases diagnostic of hydrous silicates. Figure 2 shows adsorption spectra of four magnesium silicates in which adsorption bands from 8–11 μ differ in the hydrous and anhydrous ones.

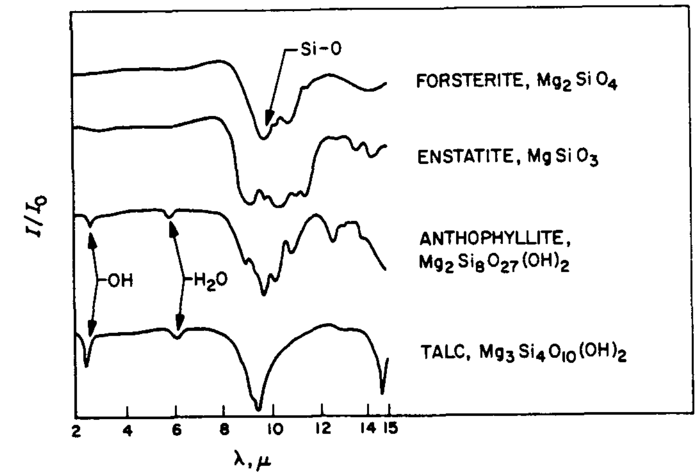

Fig. 2. Spectra of some silicates in the system MgO-SiO_2-H_2O

B. *Ground-Based Geophysical Surveys*

Combined magnetic, gravity, and possibly, seismic surveys in certain rock types can delineate variations in the degree of hydration in these rocks. Figure 3 shows a magnetic traverse across a serpentinite near San Luis Obispo, California. Chemical composition and mineralogical changes across the body indicate that hydration in this rock mass has proceeded generally according to the reaction

$$\underset{\text{olivine}}{Mg_{24}Fe_6Si_{15}O_{60}} + 16H_2O + SiO_2 + O_2 \rightarrow \underset{\text{magnetite}}{2Fe_3O_4} + \underset{\text{antigorite}}{4[Mg_6Si_4O_{10}(OH)_8]}$$

Textural evidence, however, indicates that the reaction took place with volume-for-volume replacement of the left-hand assemblage by the right-hand one rather than maintaining a closed chemical system. Figure 3 shows that the degree of oxidation of the iron and the magnetic susceptibility vary sympathetically across the body with water content; density varies antipathetically with water content. Consequently, the above reaction has gone furthest along the borders and least far in the center. The magnetic profile may be interpreted as superimposed anomalies across three adjacent dike-shaped bodies. The exterior bodies have greater magnetic field intensities than the inner one, and this difference may be correlated with their higher water content.

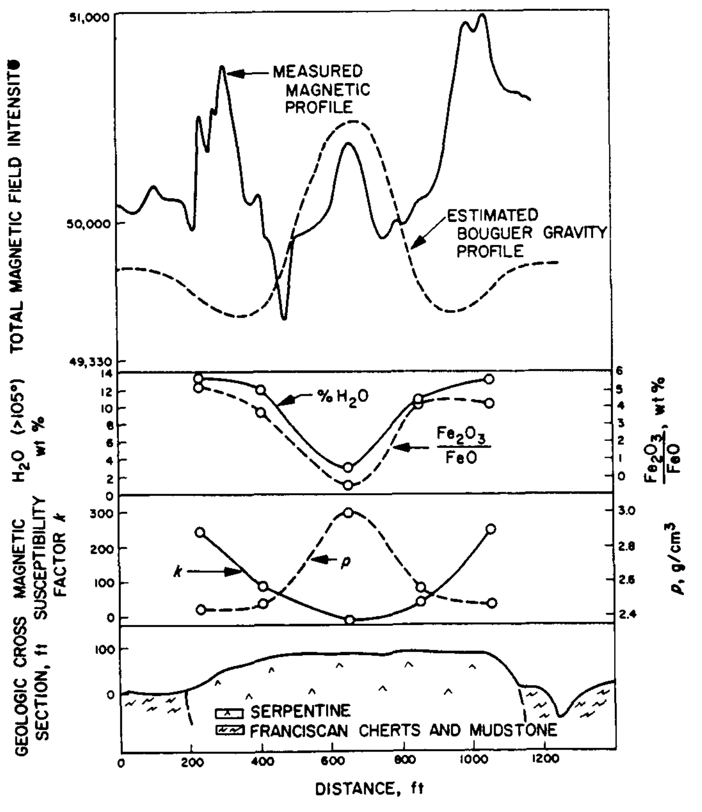

Fig. 3. Correlation of magnetic and gravity anomalies with content across a serpentine near San Luis Obispo, California

A gravity profile across this serpentinite has not yet been measured, but the variation in density is shown in Fig. 3d. Bouguer gravity anomalies of 1 to 7 milligal are calculated for the density variations in this body for various assumed configurations and depths of the body. If topographic corrections are very small, gravity anomalies might be useful in delineating zones of maximum hydration in ultrabasic rocks on the Moon.

Seismic velocities may also provide information on areas of maximum hydration in ultrabasic rocks. Compressional wave velocity in dunite (an anhydrous equivalent of serpentinite) is 8.6 km/sec, whereas compressional velocity of pure serpentine is 5.6 km/sec.

C. Neutron Albedo

The high thermal neutron cross-section of hydrogen may be a key to mapping zones of hydrous lunar rocks. Lingenfelter *et al.* (Ref. 6) have shown that ratios of thermal to fast neutrons leaking out of the lunar surface could provide information on the hydrogen content of lunar surface rocks. The utility of this method is not clear, however, since potentially high-spallation hydrogen content of surface rocks may provide an excessive background for measurement of amounts of hydrogen as water.

D. Possible Qualitative Indicators of Hydrous Rocks

1. Structures

Certain geologic structures may indicate paths of preferred movement of water in the peripheral part of the zone of lunar hydration. In the zone in which lunar rocks have sufficient strength to fracture, water would preferentially move out of these open spaces, since the chemical potential would be governed by hydrostatic rather than lithostatic pressure gradients. Rocks on the walls of these fissures may be highly hydrated. In particular, faults, fractures, fracture intersections, and other numerous linear features on the lunar surface might be zones of intense hydration. Furthermore, craters with observed activity (e.g., Alphonsus) should be examined.

2. Chemical Indicators

Anomalies in surface concentration of K^{40} and the uranium isotopes which could be mapped by an orbiting gamma-ray spectrometer may be indicative of zones of hydration. Both K and U are geochemically lithophyllic and may be dissolved in water moving toward the lunar surface. Precipitation of these materials during surface evaporation of water or incorporation in phases formed by hydration would concentrate these elements at places where the most water has reached the lunar surface.

In a similar manner, surface deposits of soluble salts may be indicative of places where water has preferentially reached the surface and at which hydration may have been widespread.

In the reaction involving hydration of ultrabasic rocks discussed in Section IIIB, it was mentioned that petrographic evidence indicates that the hydration proceeded volume-for-volume in an apparently open chemical system. This mode of hydration appears to be widespread on Earth, and the volume of the resulting lower-density hydrate assemblage is the same as that of the original anhydrous material. Consequently, some components must leave the system during the reaction. In the case of ultrabasic hydration, MgO must be given off. Consequently, concentrations of surficial magnesian salts may be indicative of hydration of ultrabasic rocks below. These minerals could possibly be detected by their thermal emission spectra.

E. Other

Lunar surface and subsurface materials would be analyzed for water during the course of general scientific exploration of the Moon. Ostensibly, lunar rocks will be investigated by unmanned and manned expeditions using conventional petrologic instrumentation such as x-ray diffraction, infrared adsorption, differential thermal analysis, and various methods of direct chemical analysis. Numerous simple methods of quantitative water analysis exist and could be used in conjunction with the foregoing experiments.

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Summary of *Apollo* and Lunar Logistics System Plans

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The basic mission objective of Project *Apollo* is to land men on the Moon and return them to Earth at the earliest practicable date. The *Apollo* crew will consist of three men, two of whom will land on the surface of the Moon, conduct surface operations for up to 24 hr, and then rejoin the third crew member in lunar orbit for return to Earth. Initial *Apollo* spacecraft capabilities will require the early landings to be within $\pm 10°$ of the lunar equator on the visible side of the Moon, with preference for landing sites in the leading quadrant (between 270 and 360° lunar longitude). As presently planned, the *Apollo* spacecraft will be capable of carrying approximately 200 lb of scientific equipment to the lunar surface and of bringing approximately 80 lb of lunar material back to Earth. A detailed plan for utilization of crew capabilities while on the lunar surface is not expected to be complete for some time. The first *Apollo* lunar mission is now scheduled for the late 60's, with additional launches planned at reasonable intervals.

The following objectives of a Lunar Logistic System (LLS) were established as a basis for the studies of possible LLS configurations:

1. To provide essential support to *Apollo* by acquiring lunar surface data not otherwise obtainable prior to the first *Apollo* flight and by soft-landing equipment and supplies at the intended manned landing site in order to give maximum assurance of *Apollo* mission success and to provide the maximum capability for extending the scope and value of the limited *Apollo* crew stay-time on the lunar surface.

2. To provide the capability for delivering equipment, materials, and supplies to the lunar surface in the quantities required to establish and maintain semipermanent and (later) permanent bases for extended exploration and exploitation of the Moon.

The LLS studies were based on the use of *Saturn*-class launch vehicles to provide the capability of delivering payloads in three weight classes (approximately 2000, 7000, and 30,000 lb) to points within 1 mile of intended *Apollo* landing sites. Payload functions now being considered for the LLS include: provisions for extending stay-times of men and landed, manned spacecraft; crew shelter and scientific laboratory facilities; lunar roving capability; surface modification; power; communications; lunar data acquisition; and crew rescue. Pre-*Apollo* LLS flights could begin several months prior to the first manned landing, with flights scheduled at approximately 3-month intervals and extending through the planned period of early *Apollo* flights. Early LLS missions may use a three-stage *Saturn 1B* launch vehicle to carry 2000-lb payloads, while post-*Apollo* LLS missions could use *Saturn V* launch vehicles to deliver either 7000-lb payloads with an unmanned LEM in the basic *Apollo* configuration or 30,000-lb payloads in a fully automatic, cryogenically fueled unmanned spacecraft.