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LUNAR RESOURCES: THEIR VALUE IN LUNAR AND PLANETARY EXPLORATION

BY

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OUTLINE

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ABSTRACT

This paper reviews the nature and utilization of lunar resources as a means of increasing the economy of manned lunar and planetary exploration.

Lunar resources include indigenous energy and materials which can be profitably used. The chief lunar energy source is solar radiation; in addition, geothermal steam, if available, would be valuable. Material resources, for life support, structural purposes, and rocket fuel, which can be expected to exist in the moon include oxygen, iron, magnesium, silicon, and other elements found in meteorites. The abundance and nature of lunar hydrogen, carbon, and water is uncertain. However, water, which might supply 90% of logistic requirements, should exist under any hypothesis of the moon's origin and evolution. The prognosis for usable lunar resources in general is good.

Extraction of these resources includes mining, handling, and processing. Subsurface mining is favored because it affords protection from the surface environment. Material handling can probably be done with adaptations of vehicles developed for other purposes. Processing for elements such as oxygen and hydrogen will probably be done by thermal dissociation, electrolytic reduction, or chemical reduction.

Economic analysis of lunar resource use is centered chiefly on rocket fuel, which would be the major use for lunar materials, and secondarily on life support. Parametric studies based on estimates of demand, transportation

factors and manufacturing cost, indicate that the cost of interplanetary missions can be reduced by factors of 4 to 10 with the use of lunar and planetary resources.

Human factors discussed include requirements and the efficiency of resupply, regeneration, and synthesis of life support supplies (air, water, and food). Synthesis of these from lunar materials becomes attractive for long-term bases. Further research is needed in artificial atmospheres, space suit design, water recovery, metabolic loads, and time allocation.

INTRODUCTION

Manned space flight has developed much faster than even its most optimistic supporters of a few decades ago expected, due chiefly to the pressure of international competition, the availability of large military rockets, and the general acceleration of technological progress in areas such as electronics. It appears that space flight has in fact gained irreversible momentum, and that we shall shortly attempt extensive lunar exploration and manned interplanetary flights. These will, however, be extremely expensive and complex operations if use is not made of natural resources existing on the moon and planets: consider the probable state of transoceanic aviation if each plane had had to carry all fuel and other supplies for a round trip. On the other hand, if we can discover and use extraterrestrial resources in the early stages of such exploration, we shall not only reduce its cost but speed the day when serious manned exploration of the entire solar system can begin.

The moon will of course be the real starting point for the exploration of the solar system; correspondingly, the first extraterrestrial material resources used will be lunar resources. The purpose of this paper is to summarize the state of knowledge in the utilization of lunar resources and to suggest a fruitful course for future efforts in this field.

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THE NATURE OF LUNAR RESOURCES

Indigenous Energy Sources

There are two major lunar energy sources which may be of value for lunar resource utilization: solar and geothermal energy.

Solar energy, the most predictable source, has of course been used by hundreds of solar-cell-carrying satellites, whose power requirements are very low compared to those of a lunar base. Used by systems such as the parabolic mirror of the Sunflower system,[1] solar energy has the advantages of being dependable and able to furnish extremely high temperatures if desired; in addition, small solar thermal units can be relatively light. The disadvantages of solar energy for lunar use are, first, that, except for polar locations,[2] it is intermittent, being available only 14 days per month. Second, the collector must be aimed at the sun, necessitating a tracking mechanism. Finally, and most fundamental, the solar constant (averaging 1400 watts/meter^2 on the lunar surface) is an absolute upper limit to the amount of energy which can be collected per unit area; for very high yields, therefore, the collector area must be very large.

Lunar geothermal energy in the form of volcanic gases has been evaluated as a possible power source by Austin, et al.[3] Its usefulness obviously depends on the existence of recent volcanism on the moon, a possibility now taken very seriously since the confirmation by competent astronomers of transient events, which may represent defluidization.[4] Theoretical studies[5] strongly indicate that the potential for volcanic activity does not contradict the generally accepted cold planetesimal theory of the moon's origin, since long-lived isotopes would dominate the current heat flow. Geothermal power has several characteristics which make it of potential value.[3] First, and most important, even with a relatively low water content, volcanic gases themselves are a potentially useful product. Second, the power output is continuous (although levels may decline with time from any one vent). Finally, a geothermal drilling operation would be to some extent self-supporting, as Austin, et al. point out; steam from a small well could be used to drill a bigger well, etc., whereas other power sources must have additional equipment brought in to increase yield.

Early lunar bases, such as the LESA I, would probably use a mix of power sources, including fuel cells and solar cells.[6] Nuclear power, however, (specifically the 35 kw SNAP-8 reactor) becomes attractive for operations involving only 6 men for up to 6 months in the LESA concept, with a 100 kw reactor recommended for larger bases. There is thus little requirement for solar power, and no immediate requirement for geothermal power. The material value of volcanic steam, however, could rapidly make such sources competitive should they be found.

Indigenous Raw Materials

Lunar raw materials may be conveniently classified, on the basis of function, in three major categories: life support, structural purposes, and rocket fuel.

Materials for life support--air, water, and food--are of immediate interest. Air is clearly the most important; in addition to oxygen, small quantities of the metabolically inert components, such as nitrogen, helium, or argon would be desirable for long-term operations to make up leakage. Water is of almost equal importance, because it can be electrolyzed to produce oxygen in addition to its primary uses of drinking, washing, and cooling. Food requirements will probably be met for all but the most advanced lunar installations by shipments from earth, although closed ecology agriculture or synthesis are eventual possibilities.

There are two major categories of structural uses for lunar materials, between which there is no sharp division. These are shelter construction and shielding against radiation and micrometeoroids. Material for shielding, depending in both cases primarily on mass/unit area, can have a wide range of properties as long as it can be worked. Shielding material is thus assumed to be available in LESA studies.[7] The use of lunar rock or soil for shelter construction, on the other hand, is somewhat speculative, most such proposals centering on the use of existing natural cavities. Green[2] proposed the use of lava tubes for shelter; the discovery of what might be collapse depressions on Ranger photographs of Mare Cognitum led Kuiper, et al.[8] to make the same suggestion.

Rocket fuels are the third functional group of lunar raw materials, and because of the large weights required, quantitatively the most important. Steinhoff[9] points out, in fact, that water alone might supply 90% of all lunar logistic requirements. The most desirable chemical rocket fuels at this time appear to be hydrogen and oxygen; the problem of their discovery and use is thus essentially that of water resources. In addition, hydrogen and oxygen could power fuel cells for surface vehicles, and hydrogen alone could serve as reaction mass for nuclear rockets. Fissionable fuel itself would continue to be brought from earth for the foreseeable future because of the complexity of uranium refining operations, even if ore were present.

We shall begin our discussion of the nature of materials which might be used to meet these requirements with a brief summary of the elemental abundances, since these govern the possible range of rocks and minerals. A useful tabulation is given by Ringwood[10] (Table 1).

Relative Abundances of Some Common Elements in the Sun
(Hydrogen = 10^{12})

Hydrogen	H	12.00	Sodium	Na	6.30
Helium	He	11.15	Chlorine	Cl	6.30
Neon	Ne	9.00	Aluminum	Al	6.20
Oxygen	O	8.96	Calcium	Ca	6.15
Carbon	C	8.72	Nickel	Ni	5.91
Nitrogen	N	7.98	Argon	A	5.60
Iron	Fe^{2}	7.87	Chromium	Cr	5.36
Silicon	Si	7.50	Phosphorus	P	5.34
Magnesium	Mg	7.40	Manganese	Mn	4.90
Sulphur	S	7.30	Potassium	K	4.70
Iron	Fe^{3}	7.16	Titanium	Ti	4.68
Iron	Fe	6.57	Cobalt	Co	4.64
Fluorine	F	6.50	Vanadium	V	3.70
			Scandium	Sc	2.82

The relation of the solar atmosphere to the composition of the moon is of course a difficult cosmochemical problem. However, the moon is thought by some scientists to consist at least partly of undifferentiated non-volatile solar matter; should this be true, it implies that the abundance of carbon and hydrogen may be relatively high. Urey[11] in fact estimates that the moon may contain about 7-11% by weight of carbon (graphite) and 2-3% water. Nitrogen may also be relatively abundant in the moon, judging from its solar abundance, although its mode of occurrence is difficult to predict. Carbonaceous chondrites would be a good source of combined nitrogen if abundant; other possibilities are ammonium salts in volcanic rocks and fumarolic gasses.

Specific rock types which may occur on the moon cover a wide range; the problem of predicting them is tied up with the general problems of the composition of the moon and the origin of its surface features. For convenience, they may be discussed under three categories: meteorites, igneous rocks, and rocks formed by shock metamorphism.

Meteorites are of great importance in the estimation of lunar resources for two reasons. First, some meteorites may have come from the moon. Urey[42] presents evidence for this theory, and proposes specifically that some carbonaceous chondrites may be of lunar origin. Second, meteorites provide direct evidence of the range of petrologic processes which have operated in the solar system, thus aiding attempts to infer lunar rock types.

The carbonaceous chondrites are of particular interest in this review because of their high water content. These meteorites, although rare in museum collections, occupy a central role in cosmochemical theory. Ringwood,[10] for example, considers them to be similar to the primordial material from which the planets were formed by autoreduction. The chemical compositions of analyzed carbonaceous chondrites have been tabulated in a comprehensive review by Mason:[12]

Table 2

Carbon and Hydrogen Contents of Carbonaceous Chondrites*

	Type I	Type II	Type III
SiO_2	22.56	27.57	33.58
MgO	15.21	19.18	23.74
C	3.54	2.46	0.46
H_2O	20.08	13.35	0.99
S	6.20	3.25	2.27

* Based on mean values of 11 analyses by H. B. Wiik and 3 from literature.

The water contents reported by Wiik and others must not be uncritically accepted as representing the pre-terrestrial water content: Boato[43] has shown, by isotopic analysis, that water driven off at temperatures up to 180°C is chiefly absorbed (i.e., terrestrial) water. He presents 9 analyses of Type I carbonaceous chondrites with an average combined (+ 180°C) water content of 7.3% by weight.

The minerals of the Type I and II carbonaceous chondrites (the only ones considered true members of the class by Mason) include serpentine-group minerals, magnetite-like spinel, and water-soluble salts such as epsomite ($MgSO_4$ $7H_2O$). The organic compounds are high-molecular-weight aliphatic and aromatic hydrocarbons, probably of abiogenic origin.[13]

Even if we neglect the possibility that the carbonaceous chondrites come from the moon, they have important implications for lunar resource utilization. First, they demonstrate the former existence, in an extra-terrestrial body, of liquid water by the presence of veins of hydrothermal minerals such as epsomite.[44] Second, they indicate, in conjunction with the studies of Watson, Murray, and Brown, that an airless body much smaller than the moon at one astronomical unit from the sun could retain water to the present time.[44] Finally, they obviously prove the existence somewhere in the solar system of an excellent water-bearing ore.

Other meteorites with implications for lunar resources are the achondrites. It has been demonstrated that most of these meteorites have been formed by crystallization of a basaltic magma.[14] Furthermore, several strong lines of evidence summarized by Wood,[45] including the shock origin of meteoritic diamond, the absence of other high-pressure phases, and thermodynamic calculations indicate that meteorites in general were formed in or from small bodies with diameters under a few hundred kilometers. It therefore appears that magma generation can take place in bodies much smaller than the moon; in view of the low pressure gradient in the moon,[5] we should expect similar magma generation to take place there. Since Rubey[46] has demonstrated the probability that igneous activity was largely responsible for the evolution of terrestrial oceans, it seems likely that a principle mechanism for the production of hydrothermal fluids in the moon has been active.

It is believed by most scientists that some volcanic activity has taken place on the moon, although most topographic features are considered to be the result of meteoritic or cometary impact. The maria in particular are generally thought to be lava flows, although the theory[15,16,17] that they are vast deposits of welded volcanic ash (welded tuff or ignimbrite) is gaining recognition. Pictures from Rangers 7, 8 and 9 and Surveyor I have largely eliminated the extreme possibilities of electrostatically-suspended dust or aa lava. Present opinions on the mare rock types favor heavily-impacted basalt or ignimbrite with an indeterminate degree of impact. The preliminary results from the gamma-ray spectrometer carried by Luna 10 indicate, according to Vinogradov,[18] that the surface has the radioactive element content of basalt. Vinogradov also pointed out, however, that these elements (uranium, thorium, and potassium-40) are enriched by only a factor of about 10 in granites relative to basalts, but by much more relative to ultrabasic rocks or chondrites. The question is thus not settled with regard to granitic vs. basaltic rocks; a lunar origin for tektites would indicate granite, if proven. The nature of highland rock types is even more uncertain, suggested possibilities ranging from chondritic meteorites to rhyolite. Other rock types which may occur include serpentine and hydrothermally altered volcanic rocks, both of which may contain several per cent water by weight. The latter are considered possibly useful for lunar water extraction by Green.[19]

Chemical compositions of potential lunar rock types have been calculated by Palm and Strom,[20] and are reproduced in Table 3.

Table 3

Elemental Abundances in Possible Lunar Rocks (Weight %)
(Modified after Palm and Strom)

Element	Granitic	Basaltic	Aerolitic (stoney meteorites)
Oxygen	47-52	43-46	33-44
Silicon	31-38	21-24	17-25
Alumimum	5-10	3.5-9	1-6
Iron	1-6	6.5-10	12-22
Magnesium	0.1-2	3-14	14-18
Calcium	0.1-3	5-8	1-7
Sodium	0.2-4	1-2.5	0.6-0.8
Potassium	1-5	0.2-1.5	0.1-0.2
Nickel			0.1-1.7
Sulfur			0.2-2
Hydrogen	0.7-0.2	0.1-1	0.03-0.1

An important point not generally considered in discussions of lunar petrography is the possibility that all the rock types may have been shock-metamorphosed by the impact of meteorites or comets. If the vast hierarchy of circular depressions which make up the moon's surface are primarily due to impact,[21] the effects of shock-metamorphism might dominate those of volcanic or other factors. A comprehensive collection of papers on shock metamorphism presented at Goddard Space Flight Center in April, 1966 is in preparation by B. M. French.[47] The major effects of shock on rocks appear to be, in order of importance: intense brecciation and mixing, fracturing of rocks and crystals down to an atomic scale, shock-vitrification of crystals, and thermal melting. Compositional changes appear to be slight, with the possible exception of tektites. If these prove to represent the highest facies of impact metamorphism, they may be depleted in water, relative to the parent material.

The physical properties of the materials comprising the moon's surface are appropriately mentioned here, although a complete discussion would be far beyond the scope of this paper.

Pre-Ranger data, from radar, thermal, and optical studies of the moon indicated that most of the surface, except for the vicinity of ray craters and a few other anomalous regions,[22] was covered with a relatively under-dense blanket of non-consolidated material (as contrasted with solid rock).[23] Ranger and Surveyor pictures have tended to confirm this picture in the areas they cover. Although it is not yet possible to distinguish between heavily impacted terrain and pyroclastic material (such as volcanic ash), it seems safe to conclude that the earlier interpretation was essentially correct, and that much of the moon is covered with a soil-like, unconsolidated layer. It should be stressed that "unconsolidated" does not imply low bearing strength; dry sand is unconsolidated but trafficable.[24] The successful landing and operation of Luna 9 and Surveyor I implies sufficient bearing strength over much of the lunar surface.

Prognosis for Lunar Material Resources

It is possible to make very approximate predictions as to the occurrence of several useful types of material on the moon. This is of course risky in the light of rapid advances of our knowledge of the moon; however, firm information on the materials mentioned probably will not be available until much more elaborate unmanned lunar probes have landed, or possibly until manned landings.

Oxygen: It is essentially certain that there is abundant combined oxygen in lunar rocks. This follows, *a priori*, from the fact that all silicate minerals are composed of SiO_4 tetrahedra in various structures, combined with other elements; and the moon's low density (3.34 grams/cm^3) precludes a large metallic fraction. The oxygen content probably ranges from about that of meteoritic matter, averaging about 33% (by weight)[14] to that of the earth's crust, about 47%.[25] Comparable values for other elements are also presented by Mason in the two works cited.

Water: The most conservative estimates of lunar water content are based on the assumption that there has been extensive defluidization of the moon by means of vulcanism. In that event, Green[19] estimates that we could expect large quantities of unaltered volcanic rock with a water content of 1% by weight (H_2O+). Occasional deposits of altered volcanics with 2-3% H_2O+ might also be found. Large quantities of type I and II carbonaceous chondrites or comparable rock would be a more favorable water source, containing 13-20%. Near-surface permafrost would be by far the best source, since lenses of essentially pure ice might occur. Ice deposits on the surface in permanently shaded areas are possible[26] but large quantities are improbable.

Hydrocarbons: If carbonaceous chondrites or the equivalent occur, material with an organic matter content on the order of 5-10% by weight might be expected, consisting chiefly of hydrocarbons.

Sulfur: Green[2] points out that sulfur is the most abundant non-silicate mineral in volcanic terrains; entire craters occasionally become filled with sulfur. Accordingly, if abundant vulcanism has occurred on the moon, usable quantities of sulfur should be found. Green suggests that it might be used as a sealer, a cement, and a working fluid in power plants, among other things. Sulfur also occurs in chondrites (averaging 2.1%) chiefly as FeS and carbonaceous chondrites (up to 6.6%).[14]

Shielding material: Assuming that the chemical composition of material for radiation and micrometeoroid shielding is not critical, it seems safe to expect sufficient quantities of workable loose material for almost any purpose, for reasons mentioned in the discussion of physical properties.

Miscellaneous: Basalt is used in Czechoslovakia for cast pipes and similar items requiring high resistance to abrasion and corrosion.[41] Green[2] has accordingly proposed a variety of lunar uses for basalt in a lunar base. However, the technical requirements for such utilization would be beyond all but the most elaborate and well-equipped installation. Other substances which might be found in usable quantities in a volcanic terrain include various salts and volcanic sublimates (chiefly halides), zeolites, and metallic nickel-iron.

Discovery and Evaluation of Lunar Resources

There are three major stages in the discovery and evaluation of lunar material resources.

Earth-based studies of meteorites and terrestrial analogues of lunar and planetary rock types are the basis for much of this discussion, and clearly should be continued and expanded. Additional investigations of oxygen and hydrogen extraction from such materials should be pursued because of the primitive state of technology in this area. Definite determination of the rock types existing on the moon should be rapidly followed by pilot-plant design if the compositions warrant it.

Orbital sensing will be the next step in evaluation of lunar resources. Westhusing and Crowe[27] present the results of a comprehensive study of techniques which might be applied to lunar water detection from orbiting vehicles, and recommend the following: photo-television, infrared surveys, radar altimeter, and magnetic measurements. It is hardly necessary to mention that any successful lunar orbiter, even though not designed specifically for resource detection, will provide valuable information for this purpose.

Surface and subsurface lunar exploration will be the ultimate stage of resource discovery and evaluation. Again, it will be difficult to separate economic investigations from basic geological and geophysical mapping. However, some special techniques might be used. In the same report referenced above, Westhusing and Crowe recommend the following methods for lunar water exploration during surface missions: gamma ray surveys, television, infrared surveys, gravity measurements, magnetic field measurements, and electromagnetic methods.

EXTRACTION OF LUNAR RESOURCES

The process of extracting lunar resources and converting them into usable form are discussed under three headings: mining, material handling and transportation, and processing.

Mining

There are two major categories of mining methods: surface and sub-surface. Surface methods, typified by open cutting and stripping, are generally much lower in cost on earth. For the moon, however, they have the obvious disadvantage that they must be done in the open, exposed to near-space conditions of vacuum, radiation, and micrometeoroid flux. Plans have been developed for surface excavation as part of the LESA studies,[6, 7] and such methods will probably be used for materials such as loose rubble for shielding. Because of the disadvantage of space exposure, however, most investigations have centered on subsurface methods.

Subsurface mining has the following major advantages:

1. Operators and equipment are protected from radiation, micrometeoroids, and extreme temperatures;
2. Operations can be conducted, with suitable locks, in an atmosphere of some sort, thus easing problems such as drill-bit cooling and lubrication of moving parts;
3. Shelter and mining sites can be close together, and former stopes and tunnels may be used for shelter or storage.

The actual subsurface technique used will depend largely on the type of material being mined. A large low-grade deposit of water-bearing rock, for example, would probably be extracted by some sort of caving. More specific choices will depend on the size, shape, and grade of the ore body, as well as on other factors, such as possible grain adhesion.

From a cost-effectiveness viewpoint, nuclear explosives are greatly to be preferred for large volume mining operations because of their low weight, and because they may lend themselves to in situ extraction processes.[28] However, development of nuclear mining methods has been hampered on earth by the test-ban treaty, and might encounter similar difficulties for lunar use if nuclear explosives are included under a treaty banning weapons of mass destruction from the moon. Nuclear explosives may in fact already be effectively ruled out for lunar use by the existing test-ban treaty. The practical outlook for such methods then, is not promising.

Material Handling

Transportation and handling of materials on the moon is part of the larger problem of lunar surface transportation. Although flying vehicles for personnel transportation are under development, they would not be economical for use in mining operations. It is presumed that mining will be done near the base site, thus suggesting the desirability of using wheeled or tracked surface vehicles.

Studies done as part of the LESA concept[7, 10] indicate that adaptations of the basic wheeled surface vehicles can be used for surface mining and material handling, with the aid of attachments. For some purposes, a portable monorail might be used. Large-volume subsurface mining would probably require the development of moon-adapted conveyor belts, whose operation would be helped by the atmosphere of sealed mines.

Material Processing

The type of material processing to be done depends of course on the end-product desired. For processing purposes, lunar resources can be divided into three main classes: elements (e.g., sulfur, nickel-iron), compounds which are potential sources of desired elements (e.g., ice, hydrated silicates), and materials used essentially "as is," such as loose soil for radiation shielding of a shelter. Attention has been chiefly focussed on the processing of the second class, i.e., on the extraction of elements such as oxygen and hydrogen from rocks and minerals.

Assuming the desired materials to exist in usable quantities, four major considerations govern the choice of processing method: energy requirements, availability of necessary catalytic materials, compatibility of the processing equipment with space vehicles, and concentration of the desired elements. Three major methods are under consideration:

1. Ore dissociation by heat--This category would apply to hydrous silicate ores with loosely bound hydroxy groups, such as serpentine, chlorite, and zeolites. Water is easily driven off from such material by temperatures of a few hundred degrees centigrade. Such extraction might be done with direct infrared radiation, rotation of the powdered ore through electrically-heated fluidized beds or kilns, or detonation of nuclear devices in the ore body. (The last-named method might produce problems of radioactive contamination of the water, which would have to be taken into account.) Underground storage of the water thus produced would be easy because low and stable temperatures are reached a few feet below the surface.

2. Electrolytic reduction--Electrolytic methods have an important advantage in requiring neither water nor other catalytic material. Silicates have been successfully electrolyzed to produce molecular oxygen. Studies are in progress[29] to investigate the application of such techniques. Considerable development is necessary because there is no comparable terrestrial process with the objective of producing oxygen rather than metal.

3. <u>Chemical reduction</u>--This technique is of particular potential value for the extraction of oxygen from lunar silicates, and can draw on considerable knowledge of the chemistry of reduction processes. A promising system[31] would use methane to reduce silicates, the product being water, which would then be electrolyzed if elemental oxygen and hydrogen were desired. A comparable system[32] would use hydrogen as the reducing agent. In both systems, initial quantities of reactant would be carried to the moon, with small periodic make-up shipments to supply reactant lost in recycling.

ECONOMIC ANALYSIS OF EXTRATERRESTRIAL RESOURCES

Early studies of the use of extraterrestrial resources were essentially qualitative, and based on the intuitive judgment that such use would be economically justifiable. However, the time is clearly approaching when decisions as to the actual feasibility of exploiting these resources, and the best methods for doing so, must be made. To furnish a firm base for such decisions, several organizations have developed techniques for quantitative economic study of extraterrestrial resource utilization.

Before discussing these techniques, several basic assumptions must be clarified.

First, there are four major classes of requirements for extraterrestrial resources:

1. Life support (including shelter, shielding, and structured materials)
2. Surface mobility fuel
3. Moon-earth return fuel
4. Planetary mission fuel.

Despite popular belief, life support requirements are relatively less important in the total resources demand picture than fuel, partly because of the small absolute quantities involved and partly because regeneration is known to be feasible. Surface mobility requirements are presently considered small for essentially the same reasons, although if extensive use is made of flying vehicles on the moon or Mars this requirement would increase because reaction motors would be necessary.

The major requirements, therefore, are rocket fuel either for return to the earth from the moon, or for manned planetary flights.

A second assumption is that the Saturn V will be the basic launch vehicle through 1980 and possibly 1990. Various other assumptions have been described in papers presented at the third and fourth annual WGER meeting[33,34]; they concern launch costs, mission modes, and types of fuel resource.

The method of economic analysis described by the WGER involves three separate analyses: a resource demand estimate, a resource transport cost estimate, and a resource manufacture cost estimate (the last referring to manufacture on the moon).

Resource Demand Estimate

The most important factor in forming a demand estimate is the extent of the lunar program. It was assumed that a quasi-permanent lunar scientific station will be established by 1975, and maintained by crew rotation and logistic support through 1985. Complements of 6 to 12 men were assumed. The most complete cost analysis done by the WGER assumes a launch rate of 8 Saturn V's per year for a 20 year period (1970-90).

Resource Transport Estimate

The option treated in this estimate is that of bringing all fuel from earth; i.e., that of no extraterrestrial material utilization. Variables treated in this estimate include launch vehicle cost, vehicle reliability, mission reliability, and vehicle availability. The estimate itself is the product of the weight transported from the earth to the moon and the cost per unit weight.

Resource Manufacture Cost Estimate

This is defined as the resupply of a consumable resource at a lunar base by means of a lunar material processing plant. The two major phases of manufacture are resource acquisition (i.e., discovery and evaluation) and resource exploitation.

Items which together determine the final cost figure include:

1. Cost of shipping equipment
2. Electrical power requirements
3. Manpower requirements.

The analysis of the manufacturing costs was done on the basis of extraction of water from lunar subsurface ice deposits. Although an optimistic model, it is easily analyzed. The transport and manufacture options were then compared by performing parametric analyses of each. Plots were constructed showing, for the years 1970, 1975, 1980, 1990, the cost of each method as a function of resource demand in pounds per month delivered to the moon. Studies are still in progress, and of course will be repeated as costs and other variables change. Some preliminary results, however, can be mentioned.

A six-man lunar base, gradually increasing to a 12-man complement, would amortize the cost of a lunar manufacturing plant (for water extraction) within six to eight years, depending on the chemical process used and the starting material (ice vs. permafrost).

Cost analyses have been performed by Gillespie[35] on the use of lunar propellants to retanking spacecraft for interplanetary missions. Four to six-fold reductions in launch mass are possible when leaving the surface of Mars on conjunction-class and Venus-swingby trips to earth. In some cases, even a ten-fold reduction is possible. Departures from the surface of Venus are possible if lunar retanking is used; without it, only departure from a Venus parking orbit is within our engineering capability. It is believed that eventually the cost of interplanetary transportation can be reduced a full order of magnitude.

In summary, these preliminary studies demonstrate that major reductions in the cost of lunar and interplanetary flights may be achieved with the use of extraterrestrial fuel resources, eventually permitting space flight to advance from the stage of small reconnaissance missions to regular, payload-carrying trips without major engineering breakthroughs.

HUMAN FACTORS IN LUNAR RESOURCE UTILIZATION

Life Support Requirements

A major factor in any study of lunar resource utilization is the amount of material (chiefly food, water, and oxygen) required for life support. Estimation of these requirements is difficult, since they depend not only on obvious variables such as metabolic rate but also on regeneration effectiveness. Nevertheless, numerous estimates are available; a typical one, presented in Table 4, served as the basis for the LESA Life Support Systems study.[36]

Table 4[36]

Material Requirements as a Function of Metabolic Rate

Material (lb/man-day)	Average Metabolic Rate (BTU/hr) 350	500	650
Food	1.16	1.50	1.83
Minimum water intake	4.73	4.77	4.80
Oxygen	1.37	1.96	2.55
TOTAL material intake	7.26	8.23	9.18

The average metabolic rate of men operating a semi-permanent lunar base is hard to judge. Activities inside the shelter would probably, on the basis of terrestrial experience, involve rates on the order of 500 BTU/hr. Outside work in space suits, however, would involve rates two or three times higher.[37] It is clear that these figures are only approximations.

The relation between life support requirements and refueling requirements is not generally appreciated. Lunar resources are frequently cited as being valuable primarily for life support, but the weight of material such as water which would be used for rocket fuel production is considerably greater. For example, using the figures in Table 4, we can easily see that to support 3 men in a LESA I module on the moon for 3 months, at an average metabolic rate of 650 BTU/hr, about 8300 pounds of material would be needed. (This ignores the possibility of recycling air and water, but also ignores the weight of equipment for such recycling, and so is probably a valid first approximation.) By contrast, the fuel required to return these three men to earth by direct flight, as estimated by Segal,[38] is about 34,000 pounds. The disparity between life support and fuel requirements becomes greater for longer stay times and larger bases, when regeneration of air and water becomes practical, because regeneration of rocket fuel is difficult or impossible.

Resupply, Regeneration, and Synthesis

Life support supplies can in principle be provided to a lunar base in three ways: resupply from earth (including initial stores on single-landing missions), regeneration of available material, and synthesis from lunar deposits. Any plan to use lunar resources for life support must compete with the other two methods.

A detailed comparison of the effectiveness of these methods would be beyond the scope of this paper. However, existing studies of the problem indicate that the choice depends strongly on the mission length and the size of the lunar base complex. For a minimum lunar base, typified by the LESA model 1 (3 men for 3 months), all supplies would be carried from earth, with no regeneration, resupply, or synthesis.[6] For more advanced bases, regeneration becomes attractive and would certainly be used to a considerable extent for any feasible advanced base.

If life support material is the only product of the operation, synthesis of life support materials does not become economically attractive until relatively large, semi-permanent bases are established, because of the probable efficiency of regeneration processes. This judgement would, of course, be reversed if large quantities of very easily processed ore--such as high-grade permafrost--were found near the base. Nevertheless, it seems clear that the use of lunar resources is not easily justified for human requirements alone.

Human Participation in Resource Utilization

The degree of automation desirable in the extraction, processing, and handling of lunar resources depends on the interaction of many factors. Human dexterity, mobility, and visual ability would certainly be useful in setting up equipment for resource utilization. On the other hand, the high cost per man hour of lunar stay time, and the fact that prime mission objectives would probably be scientific, require the maximum degree of automatic operation. The probable variability in composition, texture, and concentration of solid material resources will present numerous problems in design of equipment for such untended operation, as will the conditions on the lunar surface.

Areas for Further Research

The utilization of lunar resources is obviously inseparable from manned space missions in general, and consequently shares many problems of the latter. However, several particular areas closely related to resource utilization need further development, including the following:

Artificial atmospheres: The nature of the inert component of the lunar base atmosphere must be taken into account in life support material synthesis plans, even though it is not consumed. The two most likely choices are nitrogen and helium; helium should be difficult to obtain on the moon in usable quantities, while the outlook for nitrogen is more favorable though uncertain. The availability of the diluent is a minor factor in planning preliminary bases, but should be kept in mind if large, semi-permanent bases depending partly on lunar gas sources are planned.

Space suit design: Early studies of lunar bases, such as the Initial Concept of LESA, immediately focussed on the need for a durable, easy-to-use space suit in long-term surface operations. Fortunately, recent developments in constant-volume ("hard") suits are most promising.[18] In addition to being more flexible, such suits provide better resistance to damage than do soft suits--a definite advantage in lunar operations such as mining. Development of constant volume suits should be continued. A useful review of the suit problem is presented by Roth.[37]

Water recovery techniques: Because of the number of non-drinking uses for water in a lunar base, such as washing and cooling, a clear requirement for water recovery can be foreseen. As Malcolm[39] points out, a number of different processes are feasible, but almost all are still in the development stage. In particular, the problem of water recovery from solid waste remains essentially unsolved. Since the efficiency of such recovery systems will have considerable logistic effect, concentrated development in this area is needed.

Metabolic loads under lunar operating conditions: The amount of energy expended by the personnel of a lunar base has implications for such questions as the amount of food and drinking water needed, the amount of heat which must be dissipated (and hence, possibly, the supply of cooling water), and of course the effectiveness of man in setting up and operating complex establishments on the moon. An especially difficult problem is the effect of reduced gravity on metabolic load. It is not certain that the load will be reduced; Roth[37] points out that it may be increased. The experience of Astronaut E. A. Cernan during the Gemini 9 EVA tends to confirm this opinion. Closely related is the effect of space suits on both metabolic load and mobility. Because of continuing developments in suit design, this problem must be kept under constant study.

<u>Time allocation in lunar base operations</u>: Antarctic experience demonstrates that a surprisingly high proportion of the base personnel's time in hostile, remote environments is taken up by maintenance and personal tasks.[40,49] Continuing estimates of the time requirements of various operations, including resource utilization activities, must be made to insure that enough time is available to accomplish the primary objectives. Every effort should be made to take advantage of actual operating experience in situations analogous to lunar basing, such as Antarctic exploration, underwater stations, and prolonged orbital flights.

CONCLUSIONS AND RECOMMENDATIONS

Several major conclusions as to the utilization of lunar material resources may be reached on the basis of the foregoing discussion:

1. Usable material resources, containing oxygen, hydrogen, and various metals in combined form exist on the moon under any reasonable hypothesis of its origin and evolution.
2. Numerous techniques exist, or can be developed, to extract and use these resources.
3. The use of rocket fuel manufactured on the moon can greatly reduce the cost of projected manned interplanetary missions. Furthermore, it may permit the early achievement of missions not currently feasible.
4. The use of lunar resources for life support can substantially reduce the cost of maintaining long-term scientific lunar bases, and can produce a considerable degree of logistic independence.

It is recommended that research in the areas described here be continued and expanded, so that action may be taken immediately when firm information on the geology of the moon becomes available. In particular, continuing parametric studies on the economics of lunar resource utilization should be made to take advantage of advances in space science and technology.

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