NASA SP-177

PROCEEDINGS OF THE WORKING GROUP ON EXTRATERRESTRIAL RESOURCES

AEROSPACE MEDICAL DIVISION

Brooks Air Force Base, Texas

February 19-21, 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA SP-177

NASA S & T Library
Washington, DC 20546

PROCEEDINGS OF THE SIXTH ANNUAL MEETING OF THE WORKING GROUP ON EXTRATERRESTRIAL RESOURCES

Aerospace Medical Division
Brooks Air Force Base, Texas
February 19–21, 1968

Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1968
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the Superintendent of Documents
U.S. Government Printing Office, Washington, D.C. 20402
Price $2.50
Library of Congress Catalog Card Number 68–62479

Foreword

The Working Group on Extraterrestrial Resources (WGER) is composed of technically trained personnel from NASA, U.S. Air Force, U.S. Navy, U.S. Bureau of Mines, U.S. Geological Survey, and the Army's Corps of Engineers, all Government agencies with active interests in the exploitation of space and space sciences. Also contributing to the Group's studies are various invited participants from industry and educational institutions. WGER was organized in 1962:

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

The WGER held its sixth annual meeting from February 19 to February 21, 1968, at Brooks Air Force Base, San Antonio, Tex. The Group was hosted by the Aerospace Medical Division of the U.S. Air Force. February 19 and 20 were devoted to technical sessions and the annual banquet. The morning of February 21 featured a guided tour of the Aerospace Medical Division installation and its activities.

The technical sessions were divided into five categories containing 19 papers. These categories were composed of invited contributions in the field of extraterrestrial studies from each of the five WGER Subgroups:

a. "Environment and Resources," Paul D. Lowman, Jr., NASA, chairman

b. "Mining and Processing," Reynold Q. Schotts, University of Alabama, chairman

c. "Biotechnology and Human Factors," Robert O. Matthern, U.S. Army, chairman

d. "Facility Design, Construction and Operation," Rodney W. Johnson, NASA, chairman

e. "Logistic Requirements," Jay A. Salmanson, NASA, chairman

Dr. Lewis Larmore, vice president, Advanced Research Laboratories, McDonnell-Douglas, presented the sixth annual meeting keynote address.

Dr. Hubertus Strughold, Chief Scientist, Air Force Aerospace Medical Division, presented the banquet address entitled "Unorthodoxies and Controversies in Planetary and Space Science."

Dr. Ernst A. Steinhoff, Chief Scientist, Air Force Missile Development Center, Holloman AFB, presented the luncheon address entitled "Importance of the Use of Extraterrestrial Resources to the Economy of Space Flight Beyond Near Earth Orbit."

The Working Group on Extraterrestrial Resources is indebted to the Air Force and to its Aerospace Medical Division for their outstanding hospitality. This alone went far toward making the symposium an enjoyable success.

BRUCE M. HALL,
Chairman, Working Group on Extraterrestrial Resources

Page intentionally left blank

Contents

LEWIS LARMORE
Brooks Air Force Base, Tex.

Keynote Address to Working Group on Extraterrestrial Resources

I consider it a distinct honor and pleasure for me, a solar physicist, to be asked to give the keynote speech to the Working Group on Extraterrestrial Resources. The concentration of this session on lunar resources is particularly timely and should lead to significant results which will point the direction for lunar exploration and utilization.

During the past decade, both solar physicists and selenologists have been in a preferred position in our space exploration efforts. The solar physicists have arrived at this exalted status because the Sun largely controls the characteristics and physical properties of interplanetary space. The selenologists, on the other hand, have received a much belated claim to fame because of the planned lunar landings and, hopefully, subsequent exploration. It appears extremely unlikely that your group will ever consider the details of extracting valuable resources from the Sun in the same sense that you are planning for those of the Moon. We already receive a part of the solar resources in great abundance in the form of radiation, which provides most of the life-sustaining energy here on Earth. But we continue to wonder about the lunar resources and the potential for utilizing them by methods which can be adapted from those already in use on Earth.

As a solar astronomer discussing the Moon, I now come to the question posed by Gamow's fictitious philosopher of whether the Sun or the Moon is the more useful. From your standpoint I am sure the Moon takes precedence, since we hope it can provide resources of use to mankind. Surprisingly enough, Gamow's philosopher puts the Moon first also, but for a different reason. He, too, says the Moon is more useful, since it gives us light during the night when we really need it, while the Sun shines only in the daytime when it is light anyway!

Now that both lines of reasoning have put the Sun in its proper place, we can concentrate on our nearest neighbor and try to set the stage for this meeting. Most pretelescope observers of the Moon concerned themselves primarily with the lunar motions and had only vague guesses relating to the nature of its surface. The history of astronomy is fraught with much uncertainty as to the details of just who believed what and when certain fundamental concepts were first generally accepted. The early information-retrieval systems seem to have been as unsatisfactory as ours, but for different reasons. Lack of communication and interest plagued the early philosophers to a point that several centuries sometimes elapsed between significant "breakthroughs." However, the fourth century B.C. found Anaxagoras speculating on the lunar surface. He assumed its composition to be partly like the Earth's surface and partly fiery. The latter conclusion he based on the reddish appearance typical of most total lunar eclipses.

During the next century, Aristotle showed that the Moon must be spherical and based his deductions on the study of its phases. He also concluded that we always see the same face of the Moon. However, it was not until 5 centuries later (A.D. second century) that Plutarch provided the correct explanation of the fiery appearance of the eclipsed Moon; he said it was due to the refraction of the Sun's rays through the Earth's atmosphere.

This erudite explanation was, of course, based on several centuries of background studies by the Chinese, Chaldeans, Greeks, and others, who successfully predicted eclipses and at least partially understood their cause.

The availability of the telescope suddenly changed the speculative inferences characteristic of early philosophers and provided the first quantitative results published by Galileo in 1610. In his "Sidereal Message" he described the craters, high mountain chains, and the smooth plains which, unfortunately, were dubbed with the name "maria." Although recorded observations of the lunar surface were scarce during the next 200 years, we do find a few outstanding examples, among which are Hevelius' map of the Moon in 1647 and William Herschel's measurements of lunar mountain heights in the latter part of the 18th century. During these early observations the great debate began concerning the origin of the lunar topographic features: Are they impact or volcanic?

As time progressed and telescopes improved, many details became evident on the lunar surface which added fuel to the fire of the great debate. One need only mention the names of Schroeter, Beer and Mädler, and Schmidt to refresh your memory of the great selenographers of the early 19th century. Schmidt's discovery of a change in the crater Linné led many observers to seek other changes in the lunar topography with some questionable success.

Photography gave lunar observations a new spurt of interest with the 1850 photograph made by Bond by the daguerreotype process. Photographic atlases of the Moon began appearing which provided the kind of documentation necessary to prove the existence of lunar changes and gave to the "armchair" astronomers observational evidence to be studied at their leisure. One of the most famous of these atlases was produced by Loewy, Puiseux, and Le Morvan of the Paris Observatory late in the 19th century. Although photography provides us a wealth of permanent records of the lunar topography, it does not replace good visual observations. Until the flights of our Ranger, Orbiter, and Surveyor vehicles, the best photographs recorded detail only to about 1 kilometer on the lunar surface because of the "seeing" limitations of the Earth's atmosphere. Visual observations, on the other hand, frequently give a resolution five times or so better during short periods of excellent seeing.

We now have photographs, however, which show details on the lunar surface to a fraction of an inch. But the great debate still goes on. In 1941 Fred Whipple published a book entitled "Earth, Moon, and Planets" in which he compared impact and volcanic simulation to a point which seemed to lay the question to rest forever. Lunar topography appeared certain to be the result of impact. This kind of thinking convinced most astronomers that little purpose could be served by additional research which would lead to a better understanding of the lunar topography. As a matter of fact, I proposed a research program on this subject for a master's thesis at one time, but I was turned down on the basis that the impact hypothesis was so well established that we probably would learn nothing new. As a result, I became interested in stellar temperatures and solar physics.

To this day we find that most astronomers blindly accept impact from extralunar sources as being the major contributor to the appearance of the lunar surface. As most of you are aware, this picture is now changing largely because of the excellent work of geologists. The impetus provided by Spurr's four volumes and additional work by many of you here in this room have made astronomers begin to reevaluate the situation. I will admit that about 10 years ago I heard Gerard Kuiper give a lecture on the presence of cinder cones and he succeeded in convincing many of us that these formations were indeed present. As astronomers, we should take the work of geologists seriously. You may remember that during the last century most astronomers accepted Helmholtz' proposal that slow gravitational compression was responsible for keeping the Sun shining. However, under his hypothesis, the maximum age of the Sun could not be greater than 50 million years and he firmly forbade geologists to find evidence for a greater age of the Earth. But eventually the geologists, in a noncooperative spirit, proceeded to dig up indisputable evidence for an age of at least 2 billion years.

Back in 1966 the American Astronautical Society sponsored a meeting on the early lunar-probe results, and the great debate proceeded. Preliminary conclusions from the Surveyor photographs were mingled with new laboratory studies of shock phenomena and vesiculation processes. In January of this year we held a sequel to the first meeting and covered all of the Surveyor results except those of Surveyor 7. Again it was obvious that the question of impact versus volcanic origin is far from being settled. However, it appears to me, as an astronomer, that the concepts of volcanic origin are gaining much strength and the consensus favors this mechanism as accounting for upward of 80 percent of the major topographical features on the Moon.

I have spent considerable time discussing the great debate because the final outcome has direct bearing on the methods of approach to and the results of exploiting extraterrestrial resources. Onboard Surveyor experiments with magnets indicate the presence of iron. Alpha-scattering analyses show iron along with other elements: magnesium, aluminum, silicon, sodium, oxygen, and calcium at the surface. But, of course, the biggest question which needs answering is the availability of water. Impact theories provide no information, but with volcanism we have a high probability of finding water.

One of the newest, most exciting, and least believed theories presented at the recent meeting came from Dr. Don Menzel. He has reexamined Sir James Jeans' analytical work on the escape of the prehistoric lunar atmosphere and has found a couple of erroneous assumptions which change the whole picture. Jeans computed an escape time of 1000 years or less. However, Menzel's results show an escape time of more like a few hundred million years for an atmosphere of water vapor. He then pointed out the similarity between many of the lunar sinuous rills and the meandering erosions of Earth streams. Whether or not we accept this latter comparison as valid, we cannot overlook the possible erosion effects generated by an atmosphere which may have been present during a geologically significant time period.

Now let me turn our attention to future exploration, exploitation, and possible colonization of the Moon. It is inconceivable to me that the National Aeronautics and Space Administration, the National Academy of Sciences, the Congress of the United States, and the executive branch of the Government have not yet agreed in principle to the next step in our space program. We must find a worthy cause, acceptable to the public, for establishing a base of operations on the Moon. To my knowledge, not even this obvious step has been agreed upon. Our designs for lunar transportation are still in the horse-and-buggy stages and will not prove very satisfactory for exploring an area almost as large as North and South America combined.

In thinking about lunar exploration, I certainly do not intend to minimize the tremendous contributions which have been made by the Orbiter and Surveyor photography. This importance also applies to the excellent photographs made from Gemini, and I was surprised to learn from Dr. Paul Lowman a couple of months ago about the new volcanic field in Mexico and New Mexico found on these pictures. However, the followup from photographs must be done on the ground.

To an astronomer, there is only one answer as to what our next step should be. An observatory, or observatories, on the Moon would provide more spectral range and eliminate terrestrial atmospheric seeing problems. The Moon gives a firm base for telescopic observations which will eliminate the guidance mechanisms required for similar observations from Earth-orbiting vehicles. The observatory site would form the nucleus for further exploration of the Moon itself and, during the buildup phase of a colony, provide scientific data which are of unquestioned merit. I realize that these items are under consideration, along with many others. Geologists and geophysicists want to extend their earthly findings to other worlds and feel that this work should have priority. Civil and mining engineers wish to examine soils and prospect for useful resources. Is there any way to agree on a priority of research needs?

Perhaps we are dealing with a very broad maximum on our optimization curve. This kind of situation always calls for strong leadership and sometimes an arbitrary decision on the part of our policymakers. Certainly this was the case during the early part of the present decade when President Kennedy committed the United States to a manned lunar landing. We should now put aside our parochial interests and try to answer the fundamental questions: Should we establish a manned operational center on the Moon? If so, how should the priority of the various disciplines of geology, astronomy, mining, radiation chemistry and physics, civil engineering, and many others be ranked?

In looking over the program for this meeting, I notice one omission in extraterrestrial resources which could be of great importance on the Moon. I would like to point out that the existence of some kind of living organisms may be present, and, if so, they might be put to some good use as we now contemplate here on Earth. One of your illustrious members pointed out a few years ago that the possibility of fossil lunar life forms, which is usually subject to acid criticism, should be reconsidered in terms of enhanced defluidization on the Moon in spots where enormous volumes of carbon dioxide or carbon monoxide might have been released to the lunar surface. Conditions would have been favorable for the development of algae or bacteria just below the surface of the warm, moist, mineralized lunar tuff.

It is almost unbelievable how life has adapted itself to varying conditions on Earth. We find life forms from the bottom of the deepest oceans to the driest deserts, as well as in the fuel tanks of jet aircraft. In passing, I might say that the organisms in the fuel tanks live at the interface between the fuel and the small amounts of water present. They eat the hydrocarbon fuel and their excretions corrode the metal fuel tanks. This adaptiveness may not be so surprising, but the realization that over 100 different varieties of organisms with this capability have been isolated may give you cause for thought. Dr. Sidney Fox has pointed out in a recent article that dry protein, in contrast to protein in solution, withstands cathode radiation with no significant destruction of amino acids. This result indicates that primitive protein synthesized abiotically in dry, hot regions would be relatively resistant to nonthermal radiation. I am not attempting to prove or disprove the existence of life forms on the Moon; I am only calling your attention to the possibility, and in my opinion a significant probability, that we will find indigenous life already there when we arrive.

I would like to conclude my remarks by again calling your attention to the fact that the next step in our space program has not been clearly defined. It is timely for this group along with others to take a strong position and to make the necessary statements that can be used in national space program planning. Are there any oversights in the program to date? What about remote detection of water? Do you endorse manned exploration of the Moon? Finally, with the mix of disciplines present here, is it timely and possible for you to define a matrix of scientific and engineering priorities based on the establishment of a lunar colony? I hope in this meeting you will not shy away from the great debate and that you will discuss ways of survival on either an impact crater or a volcano.

PAUL D. LOWMAN, JR.
Goddard Space Flight Center, NASA

The Lunar Environment: A Reevaluation With Respect to Lunar-Base Operations

The following aspects of the lunar environment which bear on the feasibility of long manned lunar-surface missions and lunar bases are reviewed: gravity and magnetic fields, radiation, surface temperatures, atmosphere, meteoroid and secondary ejecta flux, nature of the terrain and surface materials, and concepts of lunar geology. Virtually all new information on these subjects is either favorable or, if unfavorable, predictable. It is concluded that, with respect to the lunar environment, lunar staytimes of 3 months could be scheduled at this time; 1-year missions appear feasible; and there are no obvious factors definitely preventing establishment of a permanent lunar base. More information is needed, however, on meteoroid flux, trafficability of the highlands, nature of lunar water deposits, geological hazards, hazards connected with lunar transient phenomena, and long-term biological effects of the lunar environment.

INTRODUCTION

Although the lunar-surface environment is continually being reevaluated to determine its impact on the Apollo program, there is no comparable reevaluation of the environment to determine its impact on establishment of a lunar base (considered here to be any manned lunar-surface mission significantly longer than 2 weeks). The purpose of this paper is to present a concise summary of current knowledge and opinion on all aspects of the lunar environment that could affect the success of a lunar base.

Some of the information presented here is from unpublished or personal sources. For this reason, and in the interest of clarity, formal bibliographic reference conventions are not followed; however, main sources of published information are listed as a bibliography at the end of the paper. Opinions expressed are those of the author and do not necessarily represent the views of NASA or of Goddard Space Flight Center.

I am indebted to a number of engineers and scientists from the Manned Spacecraft Center, the Jet Propulsion Laboratory, Goddard Space Flight Center, and the Boeing Co. for contributing preliminary unpublished information for this review.

GRAVITY AND MAGNETIC FIELDS

The configuration of the lunar-gravity field has been partly determined by tracking Lunar Orbiter spacecraft for periods of several months. It has been found that the gravity field is more homogeneous than it was formerly believed to be, and that perturbations are not enough to cause rapid decay of low-altitude (e.g., 50 nautical miles) circumlunar satellites. At altitudes of around 200 nautical miles, satellite lifetimes of several years could be expected. These findings are important for lunar-base operations and in confirming the feasibility of lunar-orbital rendezvous mission modes, long-term orbital observation and mapping of the lunar surface, and circumlunar communications satellites for point-to-point or Earth-Moon relays.

The surface value of the Moon's magnetic field is estimated, from Lunar Orbiter and Explorer 35 data, to be under 16 gammas, which is close to that of the Quiet Sun interplanetary field. The result, which has been expected, is in accord with the lack of evidence for lunar radiation belts. One consequence of the absence of a magnetic field, together with the absence of a detectable atmosphere, is that solar and cosmic radiation probably reach the surface directly with little attenuation or scattering.

The possible biological effects of the low lunar magnetic field are not known, but recent studies summarized by Busby indicate that they may be significant. In an experiment in which mice were raised in magnetically shielded cylinders, abnormal behavior, loss of hair, and early death were exhibited after the first generation, and reproduction stopped after the fourth generation. Other experiments on human and animal subjects (including micro-organisms) have also produced indications of significant biological effects from low-magnetic-field strength. On the other hand, men working in low-strength magnetic fields for several days at a time show no ill effects. Busby points out that much additional work in this field is needed before the possible effects of very long exposure to weak magnetic fields can be known.

RADIATION

Estimates of the Moon's surface radiation environment have not changed materially since 1965. The only direct surface measurements available at this time are those from Luna 9, which reported a total dose of 30 mrads/day, chiefly from cosmic rays. The chief potential radiation hazard continues to be solar flares. Although no event violent enough to harm a command-module crew has been observed, the current-model lunar module might not provide enough protection. An exposed man in a space suit on the surface would probably receive skin doses of a few thousand rads from a violent event. Flares cannot yet be reliably predicted, but since solar protons take several hours to reach the Moon (compared with 8 minutes for the H_α light by which the flare is seen), a lunar-surface mission crew could be given warning of dangerous radiation. Shielding equivalent to 5 g/cm^2 would protect personnel against all but one event in 1000; shielding equivalent to 40 to 50 g/cm^2 (as could easily be provided by the use of lunar soil) would protect against even a one-in-a-century event.

Studies by the Leander McCormick Observatory of the intensity of earthlight on the Moon's surface indicate that many operations could be carried out during the lunar night, since the expected full-Earth illumination will be equivalent to good city street lights. This would be bright enough to read by, for example. However, tasks requiring "quick and certain" seeing would be difficult; spacecraft landing at night might be precluded unless lights were provided.

SURFACE TEMPERATURES

The lunar-surface temperature range is of course important for the design of shelters and vehicles. The Surveyor telemetry provided the first direct temperature readings, with thermal compartments reaching temperatures of up to 400° K. These values were in general agreement with Earth-based data, although some non-Lambertian emission was apparent. An important indirect result of the Surveyor temperature readings was the implication that no significant amount of dust was sticking to the compartments. The lunar thermal environment, in summary, is severe but generally predictable.

ATMOSPHERE

No new direct information has been obtained about the lunar atmosphere, which is an extremely important environmental factor affecting the usefulness of the Moon as an astronomical base. However, the Surveyor spacecraft provided an empirical test of the atmosphere by obtaining many excellent pictures of the solar corona up to a distance of 20 solar radii above the lunar horizon; this and the homogeneity of the coronal image suggest that the lunar atmosphere, if any, is not likely to cause serious degradation of observations, at least for exposure times of around 10 minutes. The bright line along the horizon seen from Surveyor VI after sunset is generally thought to be the result of surface irregularities, although a particle atmosphere (a few tens of centimeters thick) had been suggested. To date, then, there is no evidence of a lunar atmosphere.

METEOROID AND EJECTA FLUX

The expected absence of a lunar atmosphere makes knowledge of the meteoroid environment of prime importance for long lunar missions. Probably the best recent information about the flux rate near the Moon is that from the five Lunar Orbiter spacecraft, which provided overlapping coverage for 14 months. Each spacecraft carried 20 pressurized can detectors with a total area of 2 sq ft; of this total of 100 detectors, 18 (made of 0.001-inch-thick copper) were punctured. This puncture rate is less than half that of similar detectors on the Earth satellites Explorers XVI and XXIII and is within a factor of 2 of the flux measured by the Pegasus satellites, which were also in Earth orbit. No directionality was noticed in the Lunar Orbiter results. It would appear that the meteoroid flux near the Moon is substantially less than that around the Earth. Since little if any degradation of Earth satellite performance by meteoroid damage has been detected even for satellites such as the Tiros series, some of which have operated for periods of 1 to 3 years, this finding is very encouraging for long-term lunar operations. It appears that any operation planned for close Earth orbit would be feasible for the lunar surface insofar as the meteoroid flux is concerned.

Closely related to the meteoroid flux problem is that of the flux of secondary fragments from meteoroid impacts. None of these have yet been detected by Surveyor spacecraft, which indicates that the former concept of a secondary-particle atmosphere is overly pessimistic. In addition, the velocities expected for secondaries are much lower than those of primary particles and are in the range of 150 to 200 m/sec. Consequently, the secondary problem does not appear to be a major one until stay-times of several years and very large exposed areas are achieved.

SURFACE CONDITIONS

Surface conditions that might affect lunar-base operations are now fairly well known for at least the mare areas as a result of the various American and Soviet soft-landing spacecraft.

Electrical properties of the Surveyor landing sites can, in principle, be inferred from the landing radar telemetry. Preliminary results from Surveyor I indicated that the radar cross-section values are close to those expected from Earth-based measurements and that the radar return was from the visible surface or from no deeper than 60 centimeters.

The Moon's gross topography has become fairly well known down to a scale of a few meters for much of its total area, in both highland and mare areas. A detailed discussion of this topic is beyond the scope of this paper. However, most of the preliminary Lunar Orbiter evaluations and Surveyor results point to the conclusion that the lunar surface offers few insuperable obstacles to lunar-base operations or long-distance surface traverses from a lunar base. Of particular interest were the pictures of the Surveyor VII landing site on the northern part of the Tycho ejecta blanket. The well-known thermal and radar anomaly presented by Tycho indicated that large rough areas of nearly bare rock might be found here; the Surveyor pictures indicated that the ejecta blanket, at least, is relatively smooth and trafficable, although the inside of the crater is probably not accessible to nor trafficable by surface vehicles.

Soil conditions have been thoroughly investigated by Surveyor spacecraft, and they are encouraging for lunar-surface operations in two respects. First, the bearing strength is quite high enough for spacecraft landing and surface travel, at least in the five landing sites. Second, the dominantly fine-grained fragmental nature of the lunar soil should lend itself to earthmoving operations such as shelter excavation, instrument emplacement, and use of soil for shielding. A further encouraging aspect is the relatively nonexotic behavior of the soil itself, and in particular its relatively low adhesion. This had been considered a major potential problem by some, but the normal performance of the Surveyor surface-sampler device indicates that little difficulty can be expected in handling the lunar soil. A possible hazard whose existence appears confirmed by Lunar Orbiter and Surveyor spacecraft is that of collapse depressions in mare areas; a fairly high proportion of craters in Alphonsus and elsewhere seem to have been formed by drainage of material into subsurface voids; the location and nature of these voids should be investigated.

GEOLOGIC CONCEPTS

A number of evolving geologic concepts have bearing on lunar-base operations. The most important of these is the now generally accepted belief that the Moon has had an extensive volcanic history (although most large craters are generally believed to have been formed initially by meteoritic or cometary impact). It has been recognized for several years that a volcanic terrain would offer many advantages to a lunar base, such as probable water deposits in the form of hydrothermal minerals, fumaroles, or subsurface hot springs, useful minerals such as sulfur, and perhaps usable natural caves. A corresponding disadvantage of a volcanic Moon is the possibility of damage by volcanic eruptions; in view of the growing belief that the lunar transient phenomena are internally caused, it would appear possible that there is currently active volcanism (and perhaps seismic activity) on the Moon. Possible sites of such activity, for example, Aristarchus, should be carefully certified before base operations are planned for them.

Another geologic concept with implications for lunar bases is that of mass wasting. The prevalence of bright slopes on old crater walls has for several years been interpreted as evidence that mass wasting is continually exposing fresh material. Many features seen on the Lunar Orbiter photographs reinforced this belief; a possible cause of such movement of material may be ground waves produced by internal seismic activity or major impacts. Since terrestrial experience shows that seismic damage is especially likely on unconsolidated terrain, it is clear that seismic activity or mass movements triggered by such activity is potentially a significant hazard on the Moon.

GEMINI PROGRAM

Medical experience of great potential interest for lunar-base operations has been derived from the Gemini program. As reported in the Gemini Summary Conference, the space environment has proven in almost all respects considerably less harmful than many had believed it to be before long-duration manned orbital missions. Weightlessness in particular has been found to produce few unforeseen effects for missions of up to 2 weeks. It seems reasonable to assume that, if crews in the confined Gemini spacecraft could withstand complete weightlessness for 2 weeks, staytimes of a few months under 1/6 g in what we hope to be the less confining quarters of a lunar base would have no harmful effects.

CONCLUDING REMARKS

It is clear that more knowledge about the lunar-surface environment is needed before a commitment to a permanent lunar base can be made. The main areas about which more needs to be known appear to be:

(1) Probability of serious meteoroid damage to structures with very large area-exposure-time products

(2) Noncatastrophic degradation of optical or other surfaces by low-density meteoroids, sputtering, and other causes

(3) Possible hazards connected with lunar transient phenomena, which have been observed to release large quantities of energy in some unknown way

(4) Trafficability of the lunar highlands

(5) Possible collapse hazards in mare terrain

(6) Location, structure, mineralogy, and water content of lunar water deposits

(7) Biological effects for very long staytimes with exposure to 1/6 g, primary cosmic rays, and low magnetic field strength

(8) Geological hazards; in particular, seismic activity, active volcanism, and landslides or debris flows

(9) Possible danger from lunar pathogens

Despite this list, it is true that the vast majority of new information about the lunar-surface environment obtained in the last few years has been favorable. It appears that as much is known now with respect to lunar-base operations as was known about the feasibility of simply landing on the Moon in 1961. Specifically, it is concluded that, from an environmental and medical viewpoint, lunar missions of 3-month duration could be confidently scheduled at this time. Furthermore, 1-year missions appear feasible enough to warrant detailed preliminary study. Finally, there are no known factors that would definitely prevent the establishment of a semipermanent lunar base (i.e., one of several years' duration with crew rotation).

BIBLIOGRAPHY

ANON.: Significant Achievements in Space Science 1966. NASA SP-155, 1967.

ANON.: Surveyor I Mission Report. Part II. Scientific Data and Results. Tech. Rept. no. 32-1023, Jet Propulsion Laboratory, Calif. Inst. Tech., Sept. 10, 1966.

ANON.: Surveyor III, A Preliminary Report. NASA SP-146, 1967.

ANON.: Surveyor VI, A Preliminary Report. NASA SP-166, 1968.

ANON.: Gemini Summary Conference. NASA SP-138, 1967.

SAARI, J. M.; AND SHORTHILL, R. W.: Review of Lunar Infrared Observations. Doc. D1-82-0586, Sci. Res. Lab., Boeing Aircraft Co., Dec. 1966.

BUSBY, D. E.: Biomagnetics, Considerations Relevant to Manned Space Flight. NASA CR-889, 1967.

BIRNEY, D. S., JR.; AND D. D. MEISEL: A Study of Earthlight on the Moon. Spec. Pub. SP67-201, Leander McCormick Observatory, Univ. of Virginia, May 1967.

SMITH, R. E.: Space Environment Criteria Guidelines for Use in Space Vehicle Development. NASA TM X-53273, 1965.

ANON.: Natural Environment and Physical Standards for the Apollo Program. M-D E 8020.008B, SE 015-001-1, OMSF, NASA, Apr. 1965.

Page intentionally left blank

S. W. JOHNSON, J. A. SMITH, E. G. FRANKLIN, L. K. MORASKI, and D. J. TEAL
Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

Gravity and Atmospheric Pressure Scaling Equations for Small Explosion Craters in Sand

An experimental investigation was conducted to determine the effects of varying gravity and atmospheric pressure on the size of small explosion craters formed in cohesionless sand. The explosives used were commercially available squibs and caps and a linear detonating cord. Gravity was varied by flying the test container in an aircraft through carefully controlled maneuvers aimed to simulate 0.17, 0.38, and 2.5 times terrestrial gravity. Atmospheric pressure was controlled separately by use of a ground-based vacuum chamber. The influence of aircraft vibrations, changes in sand density and moisture content, and techniques of measurement were considered and evaluated. It was concluded that both gravity and atmospheric pressure, when varied, will lead to significant changes in crater dimensions. The ratio of diameters is inversely proportional to the ratio of gravities to the power n where n increases as the depth of burst of the explosive increases. The n values are less than 0.16. Crater dimensions are less sensitive to changes in atmospheric pressure in the range from 5×10^{-4} mm Hg to about 300 mm Hg than they are in the range from about 300 to 1000 mm Hg. In the atmospheric pressure range from 300 to 1000 mm Hg, the ratio of diameters is inversely proportional to the ratio of pressures (mm Hg) to the power n where $n=0.044\pm0.004$. Diameters of craters formed at pressures between 1.0 and 5×10^{-4} mm Hg were on the average 1.10 ± 0.02 times those of craters formed at pressures near terrestrial atmospheric. Cratering in layers of colored sand was also studied to determine effects of pressure and gravity on the ejecta distribution and crater morphology.

INTRODUCTION

Explosive cratering as a means of soil and rock excavation has been of interest for many years. Numerous studies have been made in order to obtain a better understanding of the complex phenomenon of crater formation. These studies have revealed that terrestrial craters produced by detonation of buried explosions have dimensions which depend upon numerous factors, the most important being the energy of the explosion, the depth of burial of the explosive (DOB), and the physical properties of the medium in which the explosion takes place.

Manned bases may be established on the Moon in the future. If these bases include subsurface installations, there will be a need for a reliable and efficient means of excavation for the emplacement of the installation (ref. 1). Once a primitive base is established, dependence upon local resources might require that some type of mining and quarrying operations be initiated. Explosives might be used in these operations. If explosives are to be used in an extraterrestrial environment, the effects of environmental factors such as gravity and atmosphere on the performance of the explosives must be known so that the efficiency of the explosive as a means of excavation can be predicted.

Current knowledge of crater formation in other than a 1-g terrestrial gravity field is limited. (1 g is the gravity field on Earth and is equal to 980 cm/sec^2. Throughout the present paper, the varying gravity fields are expressed in terms of the terrestrial gravity field.) A few writers have discussed portions of the problem in a qualitative manner and have arrived at differing conclusions concerning the

324-954 O—69——2

probable effects of gravity (refs. 2 and 3). Two other studies have been made where the lunar environment of 0.17 g and the absence of an atmosphere were considered. These studies also resulted in conflicting conclusions (refs. 4 and 5). Viktorov and Stepenov detonated explosives in moist soils in accelerated frames and noted that as gravitational acceleration increased, crater dimensions were reduced (ref. 6). Chabai's work in dimensional analysis (ref. 7) suggests forms for equations relating gravity, atmospheric pressure, energy, and crater radii.

The purpose of this paper is to report the results of an experimental investigation into the effects of changing atmospheric pressure and gravity on the diameter, depth, and morphology of small explosion craters formed in cohesionless sand. This investigation was conducted in two phases. In the first phase, a deflagrating explosive was detonated at various DOB and various values of gravity in Ottawa sand. The results in this phase permitted us to conclude that gravity does have an effect on dimensions of craters formed by explosives.

In the second phase, a high explosive was used and the DOB was kept constant, but both gravity and atmospheric pressure effects were considered, although not simultaneously. Also in this second phase of the investigation several craters were formed in sand with colored horizontal layers. Comparison of preshot and postshot positions of the colored sand both in the vacuum chamber and at various values of gravity permitted the study of crater morphology and ejecta deposition.

This paper is based in part on two theses, one by J. A. Smith and E. G. Franklin and the other by L. K. Moraski and D. J. Teal, which were submitted in partial fulfillment of the requirements for the degree master of science at the Air Force Institute of Technology (AFIT). The support of the Zero Gravity Project Office of the Aeronautical Systems Division of AFIT and in particular of Donald Griggs, Carlain Silha, and Jack Thompson of that Office was of paramount importance to the completion of this investigation. Vernon Mangold, a research physicist in the Air Force Flight Dynamics Laboratory, made significant contributions to the investigation of atmospheric pressure effects on crater size. Dr. Shelton S. Alexander, now associate professor of geophysics at Pennsylvania State University; Dr. Donald Norris, associate professor of mathematics at AFIT; and Dr. David G. Roddy of the U.S. Geological Survey contributed to the data analysis. Photographic problems were solved after consultation with Jim Taylor, Jack Warwick, Merl Worland, and Robert Price of the Wright-Patterson Air Force Base Photographic Laboratories.

FIRST PHASE

Materials and Equipment

The cratering medium used was an air-dry, cohesionless silica sand (fig. 1) known as Flint Shot Ottawa sand (ref. 8). The unit weight of this sand as measured at 1 g was 106±2 lb/ft^3

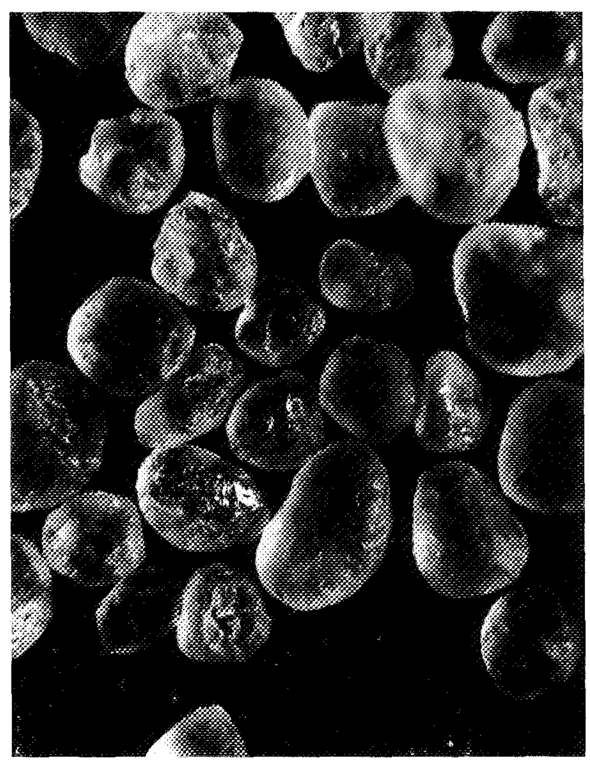


FIGURE 1.—Flint Shot Ottawa sand grains magnified. 98.8 percent by weight of this sand passes the U.S. No. 20 sieve and 92 percent is retained on the U.S. No. 40 sieve. Most particles are between 0.4 and 0.85 mm in linear dimension.

for the tests. This sand had an effective size of 0.45 millimeter and a uniformity coefficient of 1.47.

The explosive used was the electrically detonated Du Pont S–68 squib which was loaded with 6 ± 0.4 grains of Du Pont 50/25/25 mixture. This mixture is a deflagrating compound that produces a weaker shock wave than TNT and builds up pressure over a longer period of time (information received in personal communication from E. H. Cramer). The heat of the explosion was 8.3×10^9 ergs for six grains of this explosive. The heat of explosion is approximately equal to the available energy, if the explosive is adequately confined (ref. 9).

For these tests, the container used (fig. 2) was 4 feet square on its base and 5 feet high. This container was filled to a depth of 35.5 centimeters with the Ottawa sand and was flown in a twin-engine, propeller-driven C–131B airplane. The airplane is specially equipped to fly electronically programed parabolas to simulate 0.17 and 0.38 g and tight turns to simulate 2.5 g. All values of gravity were held for at least 15 seconds to within ± 0.01 g of the desired value and were recorded on an oscillographic record. Cabin pressure during the tests was 600 ± 20 mm Hg.

Photographic equipment was installed in the container to aid in recording crater depths and diameters during the tests. A high-speed camera, with a maximum rate of 2000 frames per second, was also used in the study of crater formation.

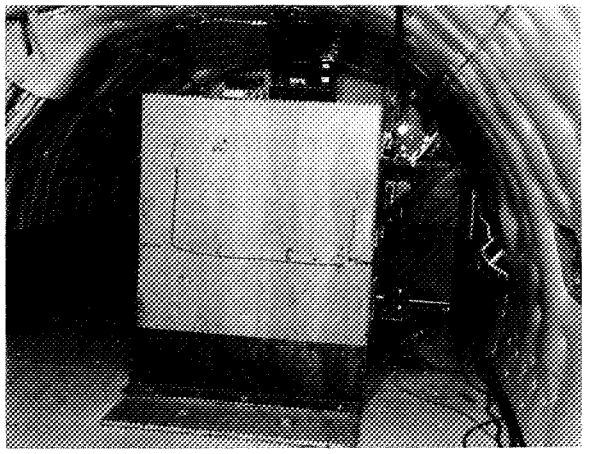


FIGURE 2.—Container used in gravity experiments. This container, shown here in the aircraft, is 4 feet wide and 5 feet high and is filled to a depth of 35.5 cm with sand. Cameras are shown mounted on the side of the container.

Procedure

Preparation for and firing of each squib involved five steps.

(1) The surface of the sand in the container was leveled.

(2) The cylindrical squib (1$\frac{3}{32}$ inches long) was placed in the sand with its axis vertical and with lead-in wires pointing upward and was then pulled up to the desired level. This desired level was determined from a mark previously painted on the lead-in wires. Experimentation showed that this technique permitted the squib to be placed to within ± 0.3 centimeter of the desired depth.

(3) Lead-in wires were then attached to the wires of the firing circuit and the container door was closed. Visual checks on the sand and wiring could then be made through the Plexiglas top of the 5-foot-high container.

(4) A single switch was then activated to start the photography and detonation sequence. In the sequence a floodlight was turned on, a movie camera started, and, finally, after a 2-second delay, the squib was fired. Motion-picture photography continued for 3 seconds after squib initiation and then terminated automatically.

(5) Crater depths and diameters were measured in the laboratory on the ground from 16-millimeter motion pictures. This procedure, which was found to give valid, accurate, and consistent measurements, was used to save time in the aircraft and permit measurements of craters before disturbance resulting from pullout of the aircraft after completion of the maneuver. Depths were measured to ± 0.65 centimeter and diameters, to ± 0.32 centimeter. Depth of the apparent crater was determined by noting the difference in the level of the sand on a thin vertical reference wire before and after firing. Crater diameter was measured from lip crest to lip crest.

Before the apparatus was flown in the airplane, many squibs were fired in order to perfect the above procedure and to ascertain the influence of boundary effects resulting from the container walls and floor and the vertical reference wire. To check the effects of boundaries, squibs were fired with 12.7, 25.4, 30.5, 33.0, and 35.5 centimeters of sand in the container. With a constant energy and DOB, craters of different sizes were formed for sand depths of 12.7, 25.4, 30.5, and 33.0 centimeters. These differences are thought to have been the result of reflections of the shock wave from the container bottom. A statistical analysis using the two-sample *t*-test (ref. 10) showed there was not a significant difference in dimensions of craters formed in 33.0 and 35.5 centimeters of sand. For that reason, 35.5 centimeters of sand was used in these tests.

Depths and diameters of craters formed with and without the reference wire showed that the presence of the wire did not have a statistically significant effect of crater size. Additional squibs were fired to check the sensitivity of crater size to small changes in DOB and to ascertain effects of aircraft vibrations on the tests. A total of 70 squibs were fired in the entire preliminary calibration part of this first phase of the experiment.

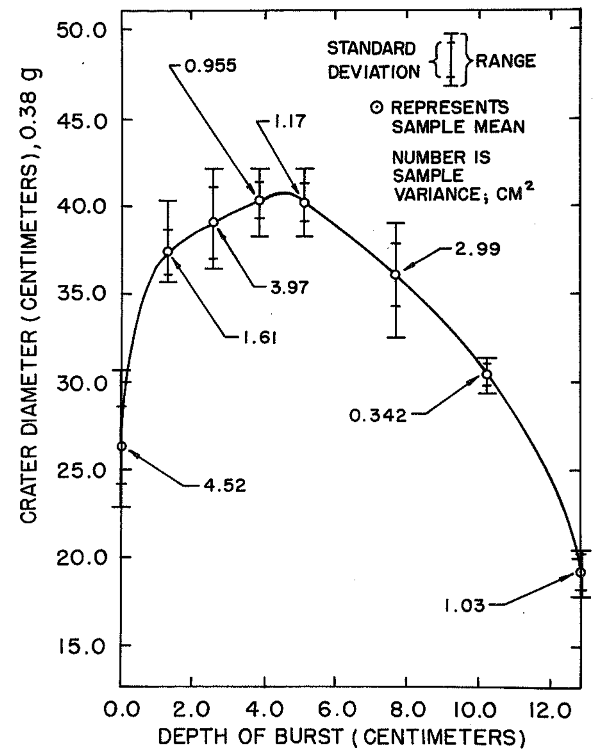


FIGURE 4.—Crater diameter versus depth of burst for 0.38 g. These craters were formed by the squib.

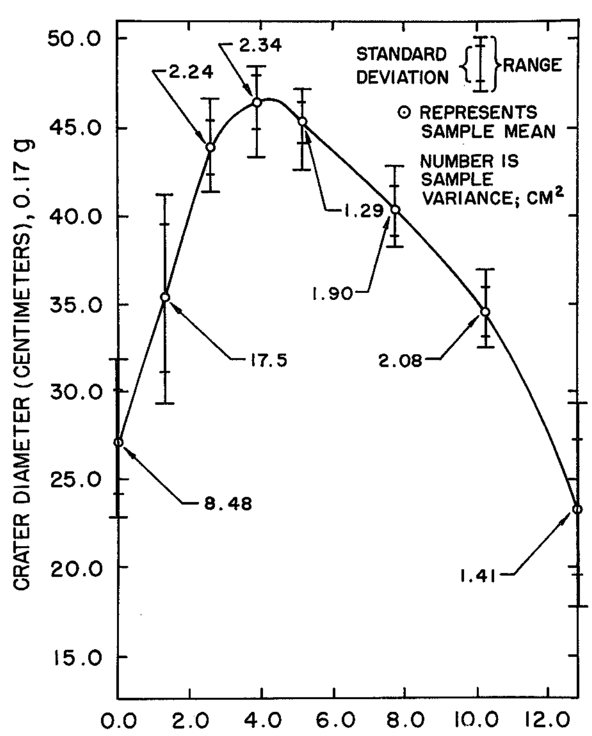


FIGURE 3.—Crater diameter versus depth of burst for 0.17 g. These craters were formed by the squib.

Finally, the squibs were fired for record. In this part of the test, 20 squibs were fired at each DOB at 1 g. Ten squibs were fired for each DOB at 0.17, 0.38, and 2.5 g in the airplane. Values of DOB used in the tests were 0, 1.27, 2.54, 3.81, 5.08, 7.62, 10.16, and 12.70 centimeters. The 370 squibs fired provided data for the necessary statistical analysis.

Presentation and Discussion of Results

Figures 3 to 6 are plots of crater diameter versus DOB for 0.17, 0.38, 1.0, and 2.5 g, respectively. In these four figures the range, standard deviation, and variance are given for each data point. In figure 7, the curves for 0.17, 0.38, 1.0, and 2.5 g are shown together for ease of comparison. It is noted that significant differences in the diameters exist for each DOB as gravity changes, optimum DOB

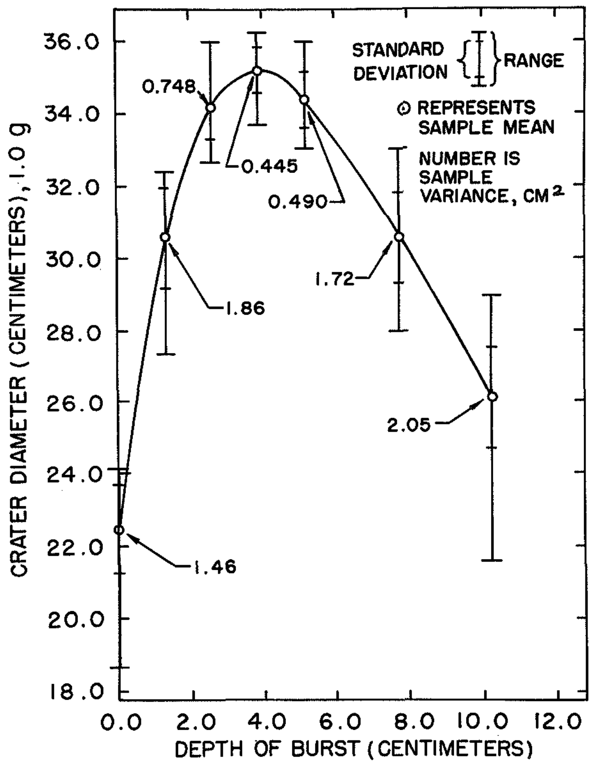


FIGURE 5.—Crater diameter versus depth of burst for 1.0 g. These craters were formed by the squib.

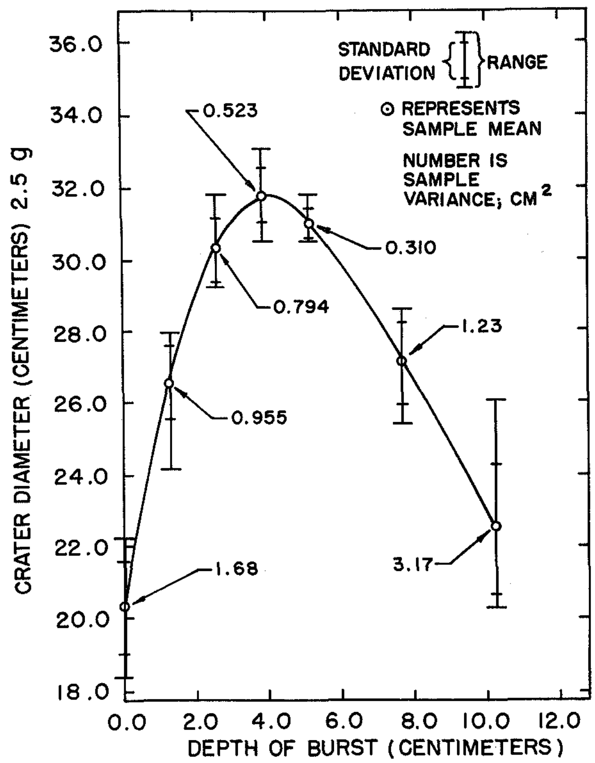


FIGURE 6.—Crater diameter versus depth of burst for 2.5 g. These craters were formed by the squib.

does not change with gravity, and the maximum DOB for which a crater is formed is a function of gravity.

That gravity effects on crater diameters are significant was confirmed by a statistical analysis of the experimental data. We compared diameters formed at the same DOB but at different values of gravity by use of the two-sample t-test. Before applying the test, we used the Kolmogorov-Smirnov test (ref. 11) to ascertain whether sample data could be assumed to be normally distributed. Once this was ascertained, the hypothesis tested with the two-sample t-test was that the mean diameters of the compared samples were equal. The alternative condition was that the sample mean for diameters formed under a given gravity field was greater than the sample mean of diameters formed under a higher gravity field. If the hypothesis that the means were equal could be rejected, gravity had an effect on crater formation. The t-test applied in this way revealed that changes in diameters vary inversely with changes in gravity with statistical significance for all comparisons except two.

One of the comparisons where the hypothesis could not be rejected was at 0.0-centimeter DOB for 0.17 and 0.38 g. At this depth, the squib was completely unconfined by the cratering medium. Lack of confining pressure on the squib can result in a large part of the charge being scattered without burning. The high-speed films taken of the cratering process showed that parts of the explosive mixture were scattered from the point of detonation for surface bursts. Such scattering resulted in a reduction in the effective yield of the explosive. The effective yield of an explosive is defined here to be that part of the available energy which contributes to crater formation. Because the reduction in the effective yield is an uncontrolled variable at this DOB, the variance of the data is increased, and the gravity effects on the cratering process for 0.17 and 0.38 g are

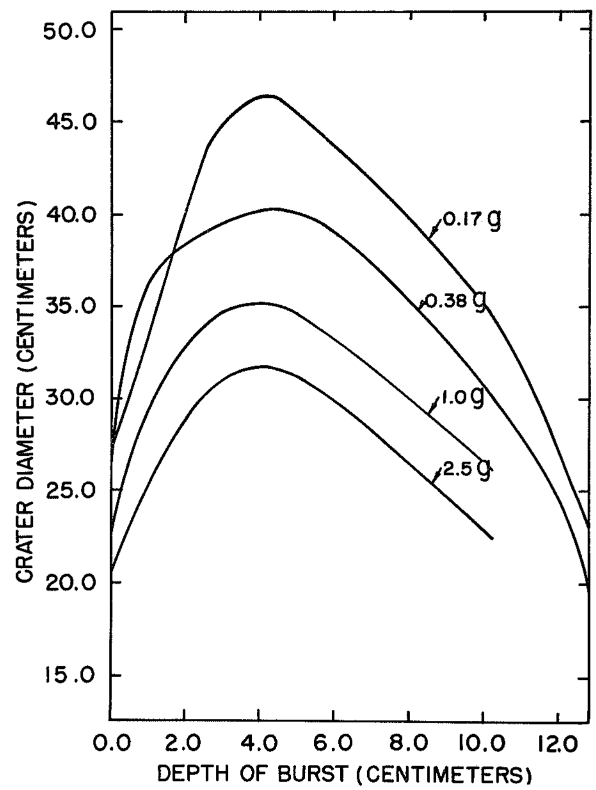


FIGURE 7.—Crater diameter versus depth of burst for 0.17, 0.38, 1.0, and 2.5 g. These craters were formed by the squib.

masked. When larger increments of gravity are taken in the *t*-test, the gravity effects on crater dimensions become apparent. In other words, for these small deflagrating explosives in dry cohesionless sand, gravity has an effect on effective yield because of the greater scattering of the explosive mixture at low values of gravity.

The other comparison for which the hypothesis cannot be rejected is between 0.17 and 0.38 g at 1.27-centimeter DOB. For this DOB, lack of adequate confining pressure on the squib is again an important factor. In this instance, the pressure of confinement is caused by the lateral pressure exerted on the squib by the medium. The minimum condition for consistency of the detonation process is that the mean confining pressure be equal to the pressure resulting when the squib is completely covered with sand in a 1.0-g field (information received in a personal communication from Mr. E. H. Cramer). This condition is achieved at 1.27-centimeter DOB for 1.0 and 2.5 g. However, for reduced gravity, the lateral pressure of the medium at a given depth is reduced because the weight of the sand is reduced. This reduction is especially critical for 0.17 g and shallow depths of burst. The gravity-dependent confining pressure affects the explosive effective yield and may be responsible for the observed crossing in the 0.17- and 0.38-g curves (fig. 7).

For all other comparisons in the *t*-test, statistically significant changes were noted for crater diameters as a function of gravity. It is observed that, as gravity increases, crater diameters decrease but not in direct proportion to gravity.

Optimum and Maximum DOB for Diameters

An important point of interest in figure 7 is the value for the optimum DOB, where the maximum crater diameter is produced from a

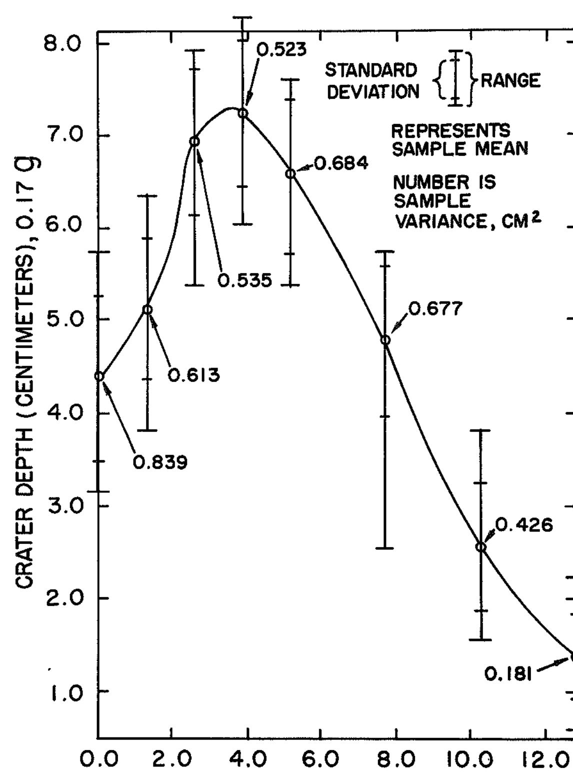


FIGURE 8.—Crater depth versus depth of burst for 0.17 g. These craters were formed by the squib.

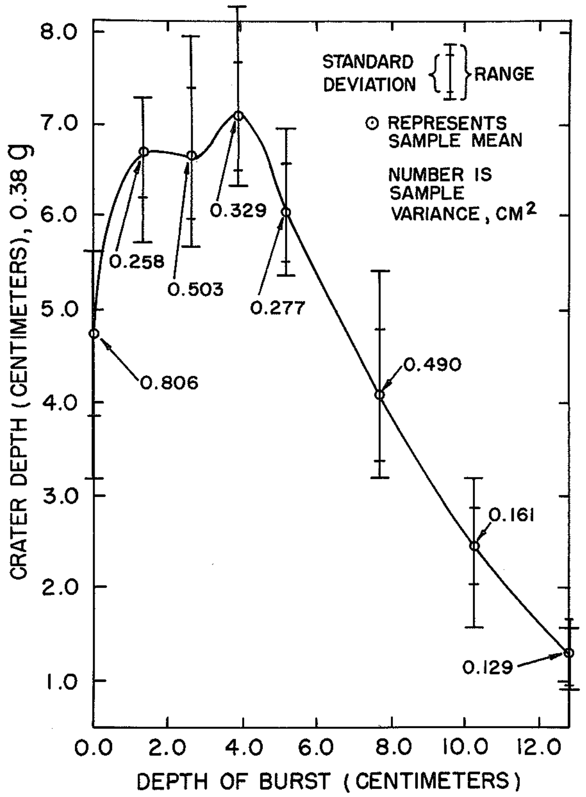


FIGURE 9.—Crater depth versus depth of burst for 0.38 g. These craters were formed by the squib.

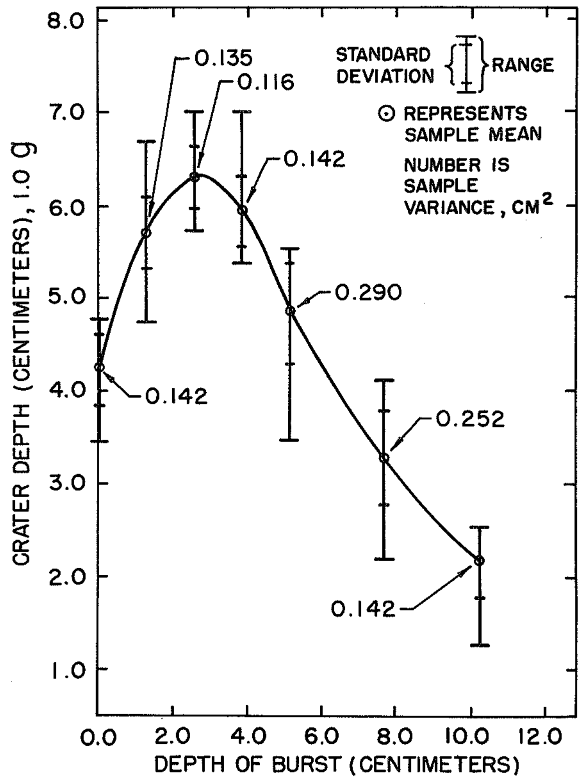


FIGURE 10.—Crater depth versus depth of burst for 1.0 g. These craters were formed by the squib.

given energy of explosive and value of gravity. A change in gravity, while changing crater diameters, does not appear to influence the DOB for maximum diameters. Also, the maximum DOB at which a crater with a measurable diameter is formed increases as gravity field strength decreases.

Depths as a Function of DOB

The depth of a crater can also be analyzed as a function of the DOB when gravity is varied. Figures 8 to 11 are plots of crater depth versus DOB for 0.17, 0.38, 1.0, and 2.5 g. These figures also give the ranges, standard deviations, and variances. Figure 12 is a consolidation of the previous four figures. The two maximum points in the 0.38-g curve are believed to be due to experimental error. Unprogramed longitudinal accelerations of the aircraft during the flight tests at 2.54-centimeter DOB and 0.38 g are thought to have caused sand to slide into the crater and reduce crater depths.

The statistical *t*-test indicates that, in most comparisons, changes in depths vary inversely with changes in gravity. Comparisons of surface bursts between 0.17 and 0.38 g and between 0.17 and 1.0 g indicate that the depths were not significantly different. This again is due to incomplete confinement of the squib. The intersection of the 0.17-g curve with the 0.38- and 1.0-g curves results from the gravity-dependent confinement of the squib at 1.27-centimeter DOB. These conclusions are based on the analysis of squib confinement for diameters as a function of DOB. Comparisons of crater depths between 0.17 and 0.38 g for 2.54-, 3.81-, 10.16-, and 12.70-centimeter DOB indicate no significant difference. Because of increased scatter in the data for these depths of burst, greater gravity increments had to be used in the comparisons of depths to bring out the significant changes. With due regard for the data at shallow depths of burst and low-g values, figure 12 shows that, as gravity increases,

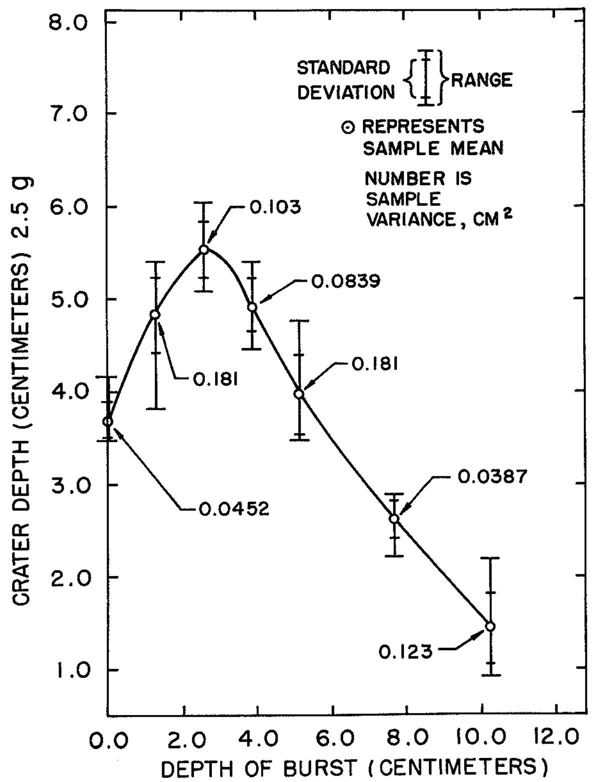


FIGURE 11.—Crater depth versus depth of burst for 2.5 g. These craters were formed by the squib.

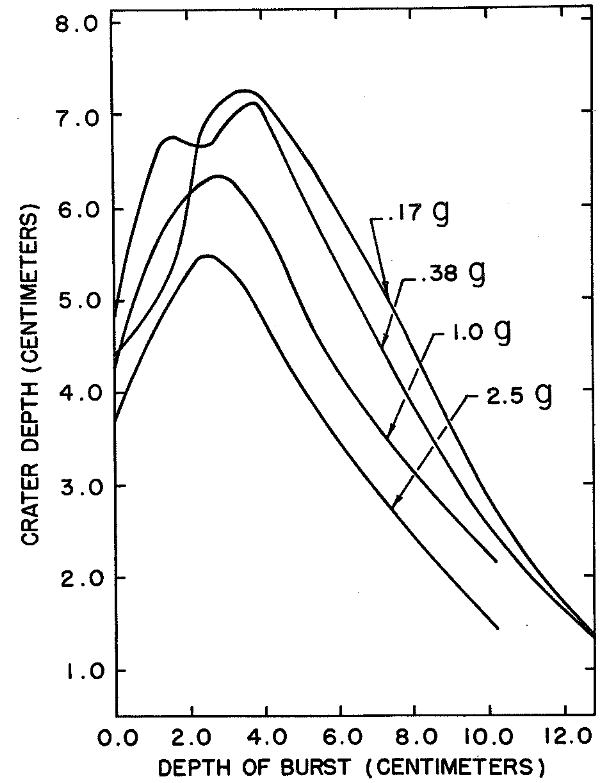


FIGURE 12.—Crater depth versus depth of burst for 0.17, 0.38, 1.0, and 2.5 g. These craters were formed by the squib.

crater depths decrease but not in direct proportion to gravity.

The optimum DOB for crater depths varies inversely with gravity (fig. 12). The maximum DOB at which a measurable crater depth is formed also varies inversely with gravity.

SECOND PHASE

Materials and Equipment

The medium used in the second phase was, as in the previous phase, Flint Shot Ottawa sand.

The explosives used in the second phase were different. Du Pont E–106 electric blasting caps containing 2 grains of lead azide, 2 grains of PETN (pentaerythritol tetranitrate), and 2.5 grains of Du Pont 50/25/25 mixture were used either alone or in combination with 2.54 centimeters of Primacord containing 2.08 ± 0.21 grains of PETN (ref. 12). The normal variation in the cap loads during manufacture is ± 3 percent. The combinations yielded a heat of explosion of either 1.2×10^{10} ergs (cap only) or 2.0×10^{10} ergs (cap and Primacord). The cap and cord are shown in figure 13.

The same container was used in this phase as in the previous phase of the experiment. Sand was once again used to a depth of 35.5 centimeters.

In this phase, the aircraft used was the KC–135A (fig. 14). With this jet-powered aircraft, vibration was minimized and the values of 0.17 and 0.38 g could be held for 25 and 30 seconds, respectively, by flying electronically programed parabolas. A 2.5-g maneuver could also be flown and held for 15 seconds. Gravity was monitored in each maneuver by accelerometers along each of the aircraft's three axes. Each airborne test shot was fired at a cabin pressure of 600 ± 20 mm Hg.

As in the first phase, photographic equipment was installed in the container on the aircraft to aid in recording crater depths and

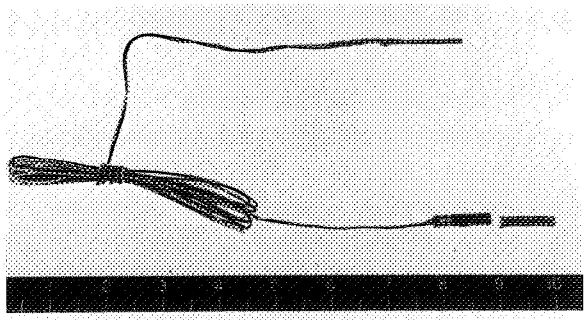


FIGURE 13.—Cap and Primacord; Primacord is 2.54 cm long. Scale shown is in inches.

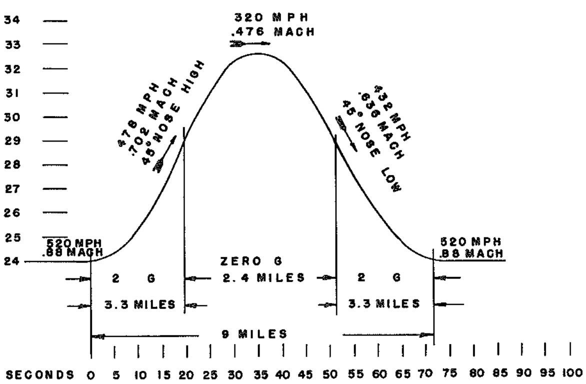


FIGURE 14.—Zero-gravity flight profile of KC–135A aircraft. The flight profiles for 0.17 and 0.38 g are similar to this profile.

diameters and for study of cratering processes.

In the second phase, a vacuum chamber (fig. 15) was used to vary atmospheric pressure. The chamber, which was used only in a ground-based laboratory, is 5 feet long and 4 feet in diameter. It was evacuated by means of a mechanical pump and an oil diffusion pump to pressures as low as 5×10^{-4} mm Hg with the sand in the chamber. Pressures were measured with either a Wallace and Tiernan gage (operating on the principle of the Bourdon tube) or an Alphatron vacuum gage, NRC type 520 B, depending on the pressure range in which the system was being operated. Pressures were recorded and temperatures were monitored during tests.

A semicircular trough 15½ inches in radius,

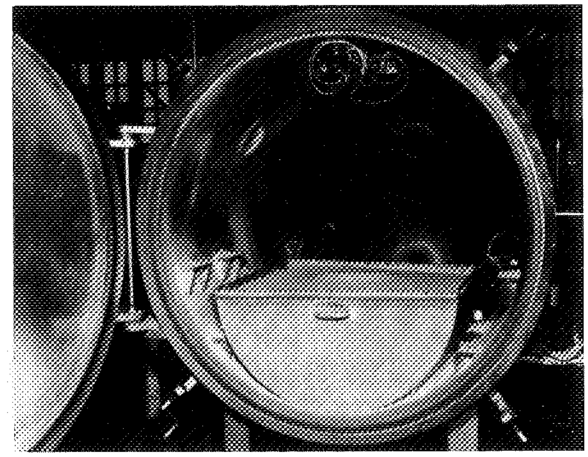


FIGURE 15.—Container for pressure experiments inside the vacuum chamber. Chamber is 5 feet long and 4 feet in diameter.

32 inches long, and constructed of sheet metal was used in the vacuum chamber to contain the sand (fig. 16). The maximum depth of sand in the trough was 36.8 centimeters.

Procedure

The procedure used in the airplane in the second phase was somewhat different from that used in the first phase. In this phase, the cap and Primacord combination was used for all shots in the gravity work. All shots were at the same DOB. The cap, with the Primacord attached, was held in a vertical position and positioned in the sand so that the

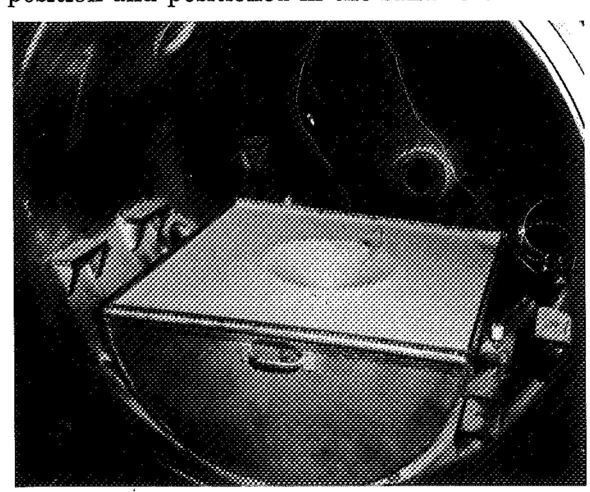


FIGURE 16.—Typical crater formed by cap in sand in the vacuum chamber.

top of the cap was level with the upper surface of the sand.

Measurements of the apparent diameter and apparent depth of the crater were made after the flight tests from photographs of a horizontal scale and a depth gage lowered into the crater after each crater was formed. This procedure eliminated the reference wire which had been used in the first phase.

In this second phase, five shots were fired at 2.5 g, 10 at 1.0 g, 10 at 0.38 g, and 10 at 0.17 g.

For study of effects of gravity on crater profiles, different-colored sands were mixed with Epibond 100-type A, a heat-sensitive adhesive powder. The sand was then placed in layers in two containers. In one of these containers a crater was formed at 0.17 g and in the other, at 2.5 g. Both were formed by detonation of the cap and Primacord combination. These two craters were preserved by heating and then cooling the sand so that the mass hardened. The hardened layered sand was then removed from the container and cut into the sections shown in figures 17, 18, and 19.

For each crater formed in the vacuum chamber, measurements were made of the apparent diameter, apparent depth, and lip height. In the sand in the vacuum chamber, 77 shots were fired with the cap only. These shots were fired at pressures ranging from 1000 mm Hg to 5×10^{-4} mm Hg.

One additional vacuum chamber shot was fired in sand with colored horizontal layers. For this shot, at 5 mm Hg, the Ottawa sand was colored with five different dyes. The layers used ranged from 3 millimeters to 2 centimeters in thickness. Results of this test are shown in figure 20.

Presentation and Discussion of Results

Figures 21(*a*) and 21(*b*) are plots of crater diameter versus atmospheric pressure (in mm Hg) in the vacuum chamber. Depth was less influenced by atmospheric pressure than was diameter. Since there were several shots fired at most values of atmospheric pressure, in these figures the sample mean is plotted and the number of shots and variance are shown. The variance (in centimeters) is shown at the

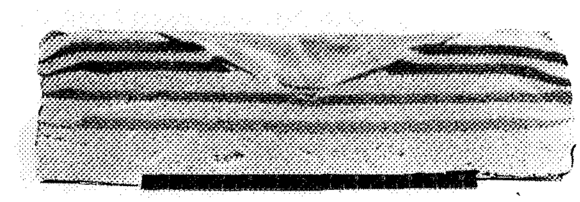


FIGURE 17.—Side view of profile of crater formed at 0.17 g by cap and Primacord. Scale is in inches.

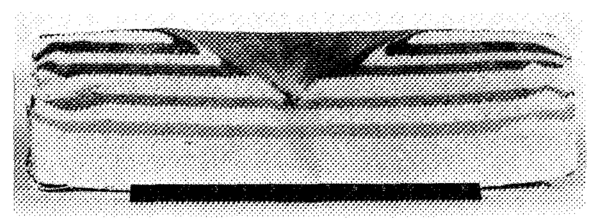


FIGURE 18.—Side view of profile of crater formed at 2.5 g by cap and Primacord. Scale is in inches.

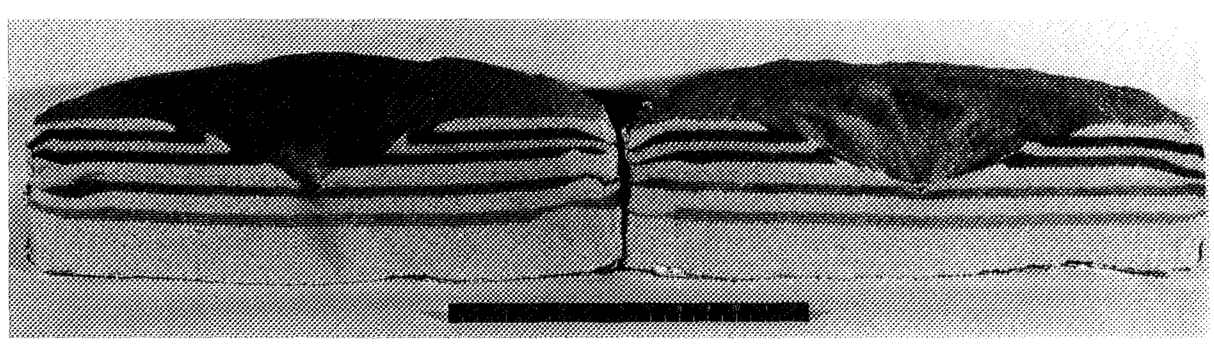


FIGURE 19.—Oblique view of profiles of craters formed at 0.17 and 2.5 g by cap and Primacord. These are the same two profiles shown in figures 17 and 18. The crater of figure 17 is shown on the right here. Scale is in inches.

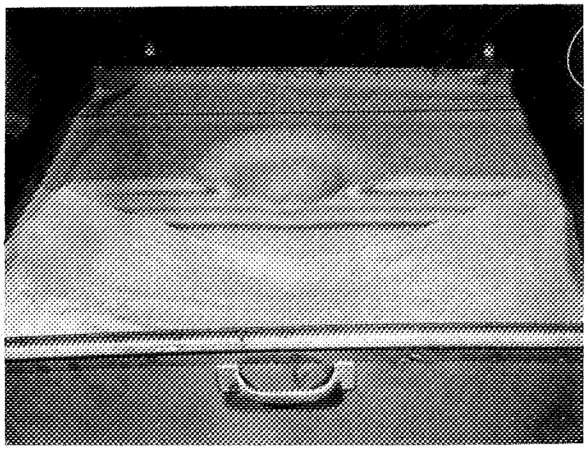


FIGURE 20.—Oblique view of cross section of crater formed by cap and atmospheric pressure of 5 mm Hg.

right of each data point along with the number of shots in parentheses. Diameter increases as pressure is decreased. The four shots fired at 5×10^{-4} mm Hg formed craters averaging 36.6 centimeters in diameter; at 1000 mm Hg pressure, the seven craters formed had a mean diameter of 32.6 centimeters. Crater lip height was essentially insensitive to changes in atmospheric pressure.

Study of the sectioned crater (fig. 20) formed in the vacuum chamber at 5 mm Hg shows that the top four layers below the surface were folded back and that a small mound was formed on the crater floor. This mound was observed only in the crater formed in layered sand. It is noted that only a very thin layer of ejecta could have rebounded off chamber walls and ceiling to fall back into the crater. This fact was verified by the absence of a multicolored mixture of sand grains on the crater floor and walls.

The results for the 35 shots fired at various values of gravity are shown in figures 22, 23, and 24. In figure 22, a plot of diameter versus gravity, the sample means are plotted and the standard deviation, range, and variance are shown. We can see here, as we saw earlier in the first phase, that crater diameter increases as gravity decreases but not linearly. Crater depth, however, does not increase monotonically with decreasing gravity. As is shown in figure 23, the crater depth begins to decrease slightly as gravity is decreased below 1.0 g. In figure 24 the crater depth divided by crater diameter is plotted against gravity. The depth-to-diameter ratio is less at 0.17 g than at 0.38 or 1.0 g.

SCALING EQUATIONS

Atmospheric Pressure

From the data in figure 25, it was calculated, using a least-squares fit, that the crater diameter varies inversely as atmospheric pressure (measured in mm Hg) to the 0.044 ± 0.004 power for the range of pressure from about 300 to 1000 mm Hg. Below 300 mm Hg and down to 5×10^{-4} mm Hg atmospheric pressure, the exponent is smaller than that above 300 mm Hg. It must nevertheless be noted that the diameters of craters formed at pressures below 1 mm Hg were on the average 1.10 ± 0.02 times those of craters formed at pressures equal to or above 740 mm Hg. (See the right-hand scales in figs. 21(*a*) and 21(*b*).)

Gravity

A hint as to the form of a gravity scaling equation is offered by Chabai (ref. 7, p. 5085) in his work in dimensional analysis. If the requirements of similitude can be satisfied, then the equation relating crater radii and gravity when DOB and energy of explosive are constant might be

$$\frac{r_1}{r_2}=\left(\frac{g_2}{g_1}\right)^{1/4}$$

Here r_1 and r_2 are crater radii and g_1 and g_2 are values of gravity. Similitude is of necessity violated in most experiments and in most practical applications because of the difficulties in scaling such parameters as strength, viscosity (a dissipation variable), sonic velocity, and either lithostatic or hydrostatic pressure (ref. 7, pp. 5081–5082).

We may take the form of the above equation and substitute for the ¼ a power n and then calculate from the previously presented data the value of n for each DOB of explosive. In the experiments the DOB's of the explosives ranged from surface to 12.7 centimeters. For all DOB's it was found that as gravity increased,

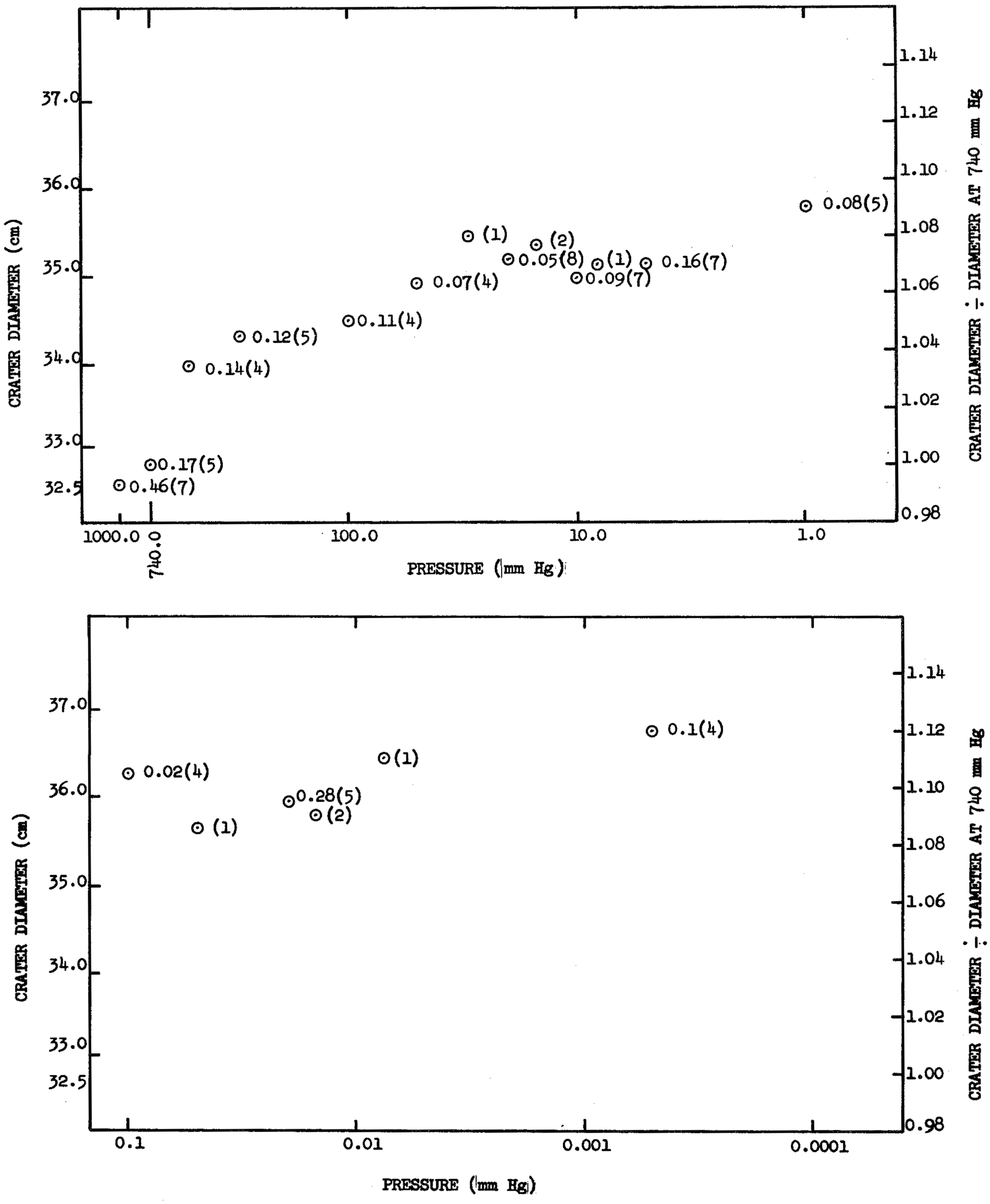


FIGURE 21.—Crater diameter versus atmospheric pressure for craters formed by cap. Variance, cm, is shown at right of each data point with number of shots in parentheses.
(*a*) Atmospheric pressure from 1000 to 1 mm Hg.
(*b*) Atmospheric pressure from 0.1 to 0.0001 mm Hg.

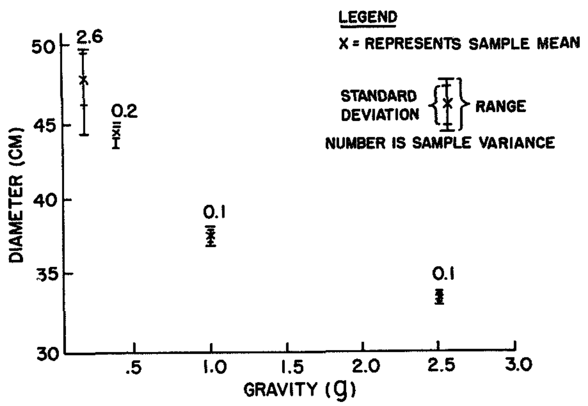


FIGURE 22.—Crater diameter versus gravity for cap and Primacord.

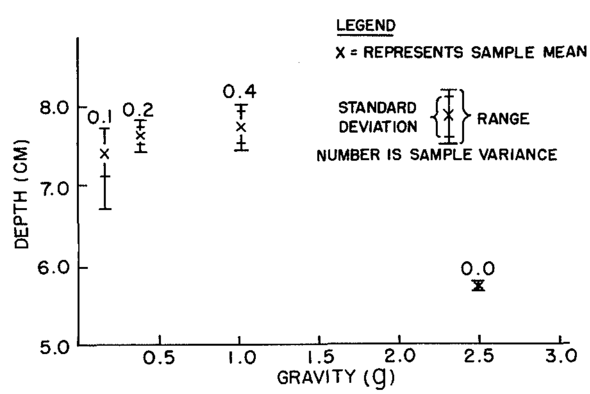


FIGURE 23.—Crater depth versus gravity for cap and Primacord.

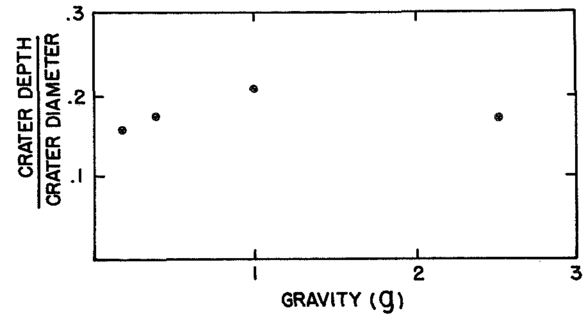


FIGURE 24.—Depth over diameter versus gravity for cap and Primacord.

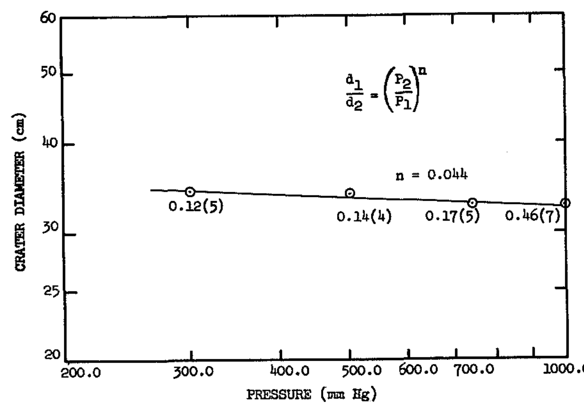


FIGURE 25.—Logarithmic plot of crater diameter versus pressure for cap. Data found in figure 21(*a*) are replotted here.

the crater diameter decreased. The results previously presented are replotted in figures 26 and 27 where crater diameter is plotted as a function of gravity on a logarithmic scale. The lines are least-squares fits to the data for each DOB. Each data point in these figures represents the arithmetic mean of diameters measured after each of 5 to 20 detonations. The number of detonations is shown in parentheses beside each data point. Variances are also given for each data point. When the results are shown as in figures 26 and 27 it is seen that the effect of gravity on diameter increases as DOB is increased. A value of n was obtained for each DOB by calculating the slope of the least-squares line. The calculated values of n are seen to be substantially less than the 0.25 obtained from dimensional analysis. If H is measured in feet and W in pounds of TNT equivalent, then it is noted that as the scaled depth of burst

$$\frac{H}{(W)^{1/3}}$$

increases from less than 0.1 to about 4.4, the value of n increases from about 0.11 to 0.16. The $H/W^{1/3}$ values are approximate because the explosives used were not spherical.

Fourth-root scaling ($n=\frac{1}{4}$) for lunar ($g_L=0.17$ g) and terrestrial ($g_T=1.0$ g) values of gravity would indicate that the radius ratios would be (refs. 13 and 14):

$$\frac{r_T}{r_L}=\frac{1}{1.569}$$

We would instead predict for shallow depths of burial approaching

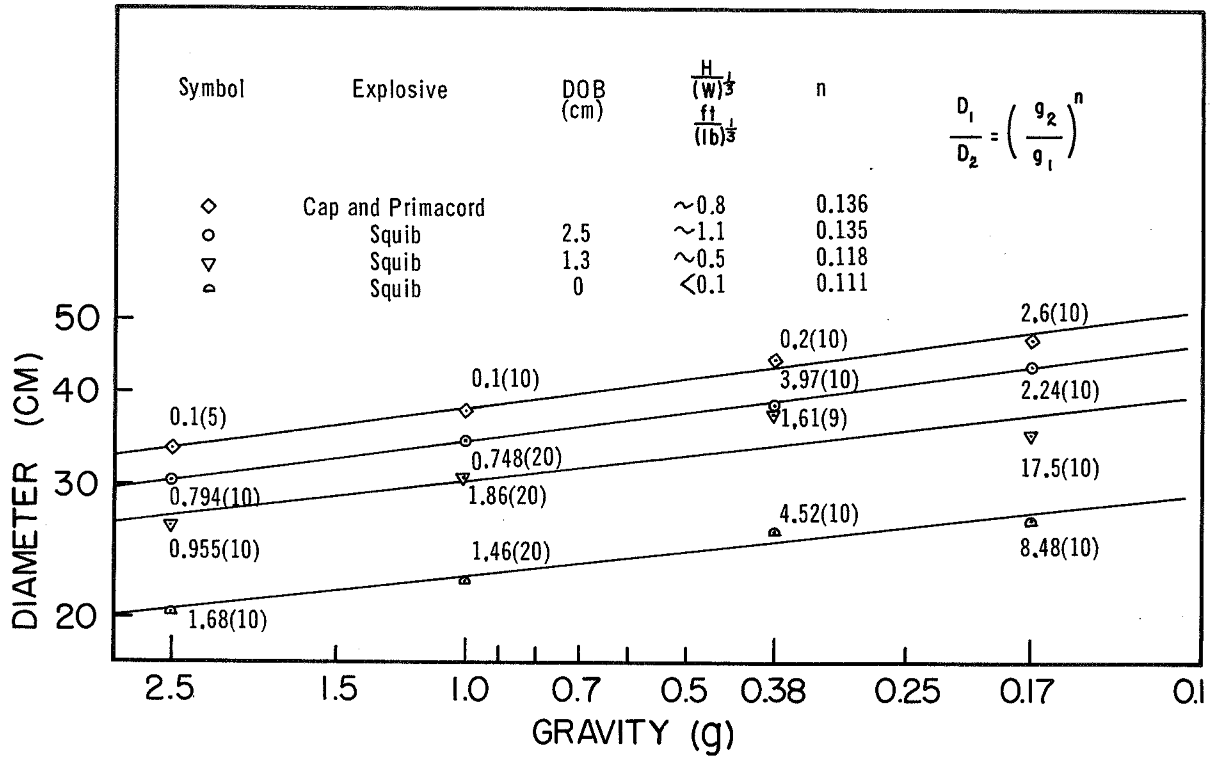


FIGURE 26.—Logarithmic plot of crater diameter versus gravity for DOB<3.8 centimeters.

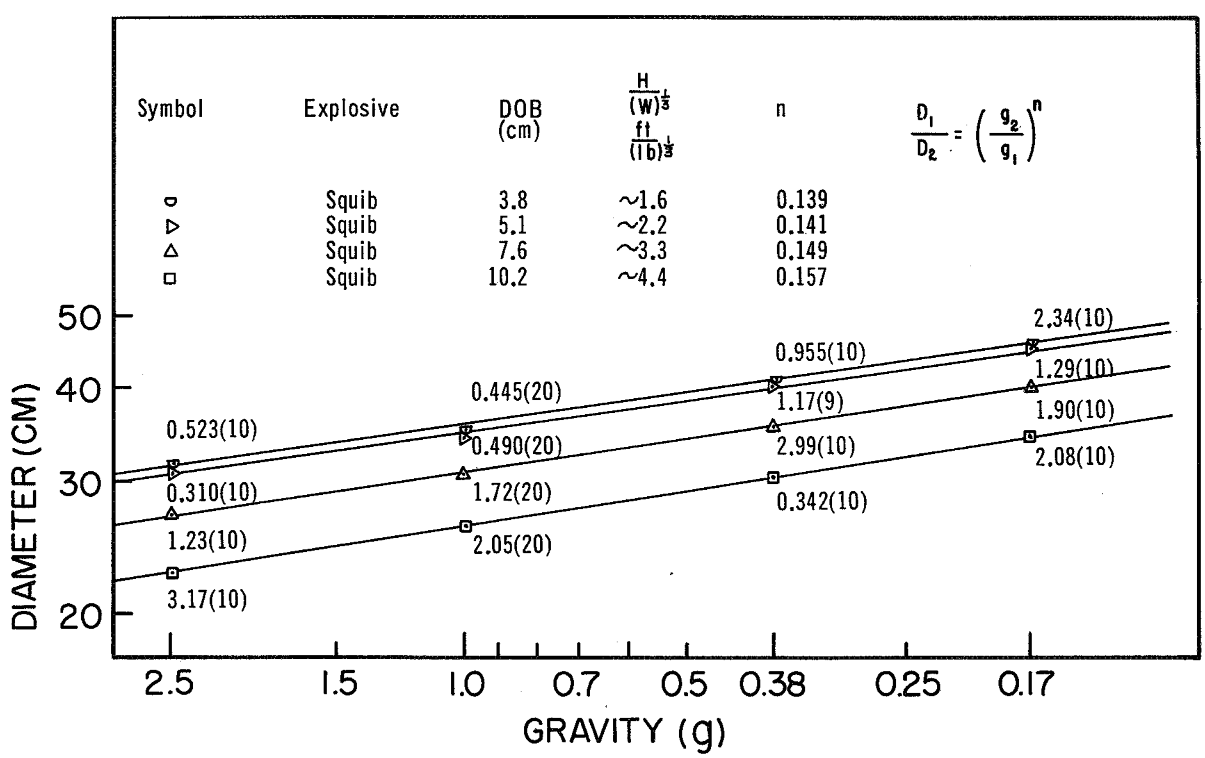


FIGURE 27.—Logarithmic plot of crater diameter versus gravity for DOB ≥3.8 centimeters.

$$\frac{H}{(W)^{1/3}} \approx 0.1$$

that

$$\frac{r_T}{r_L} = \left(\frac{g_L}{g_T}\right) 0.12 \pm 0.01$$

or

$$\frac{1}{1.22} \geq \frac{r_T}{r_L} \geq \frac{1}{1.26}$$

If atmospheric pressure effects are also taken into account, then r_T/r_L may approach 1/1.40 if it can be assumed that these effects superimpose.

The equation relating crater radii (or diameters) to gravity and the equation previously presented relating atmospheric pressure and diameters are interesting and potentially of practical significance. Caution must nevertheless be used in applying the scaling equations to craters formed in cohesive media and formed by explosives with energies greatly in excess of 10^9 to 10^{10} ergs.

REFERENCES

1. ANON.: Study of Deployment Procedures for Lunar Exploration Systems for Apollo (LESA). Vol. II. Final Rept., Lockheed Missiles & Space Co. (Sunnyvale, Calif.), Feb. 1965, p. 113.
2. MARKOV, A. V.: The Moon. Univ. of Chicago Press (Chicago), 1962, p. 325.
3. GREEN, J.: The Geology of the Lunar Base. SID 61–358, N. Am. Aviation (Downey, Calif.), May 1962, p. 12.
4. JOHNSON, S. W.: Criteria for the Design of Structures for a Permanent Lunar Base. Ph. D. Thesis, Univ. of Illinois, 1964, p. 77.
5. HESS, W. N.; AND NORDYKE, M. D.: Throwout Calculations for Explosive Craters. Geophys. Res., vol. 66, 1961, p. 3412.
6. VIKTOROV, V. V.; AND STEPENOV, R. D.: Modeling of the Action of an Explosion With Concentrated Charges in Uniform (Homogeneous) Ground. Engineering Collection of the Institute of Mechanics of the Academy of Sciences of the USSR. Vol. XXVIII. 1960, pp. 87–96. (Trans. by M. I. Weinreich, SCL–T–392, Sandia Corp. (Albuquerque, N. Mex.), 1961.)
7. CHABAI, A. J.: On Scaling Dimensions of Craters Produced by Buried Explosives. J. Geophys. Res., vol. 70, 1965, pp. 5075–5098.
8. ANON.: The Silica Sands of Ottawa. Ottawa Silica Co. (Ottawa, Ill.), 1960.
9. COOK, M. A.: The Science of High Explosives. Reinhold Publ. Corp., 1958, pp. 262–263.
10. BROWNLEE, K. A.: Statistical Theory and Methodology in Science and Engineering. John Wiley & Sons, Inc., 1960.
11. WHITNEY, D. A.: Elements of Mathematical Statistics. Holt, Rinehart & Winston, 1961.
12. ANON.: Primacord-Bickford Detonation Fuse. The Ensign-Bickford Co. (Simsbury, Conn.), 1960.
13. BALDWIN, R. B.: Ranger VIII and Gravity Scaling of Lunar Craters. Science, vol. 157, 1967, pp. 546–547.
14. MOORE, H. J.: Ranger VIII and Gravity Scaling of Lunar Craters. Science, vol. 159, 1968. pp. 333–334.

Page intentionally left blank

THOMAS R. McGETCHIN
Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

Dark Halo Craters on Crater-Chain Rilles and Volatile Flux From the Moon's Interior

Water is probably the most important natural resource that man hopes to find at or near the Moon's surface. It is unlikely that water exists as a free phase anywhere on the Moon except, perhaps, in permanently shaded areas near the poles as suggested by Watson, Murray, and Brown (ref. 1) or in a permafrost layer from a few meters to several kilometers in depth as suggested by Gold (ref. 2) and Hapke (ref. 3).

The lunar crater-chain rilles are important because they appear to be structural analogs of certain terrestrial volcanoes which characteristically contain rock bearing relatively large amounts of water in hydrous minerals and which are believed to have been emplaced by violent gaseous eruptions. Hence, by analogy, the crater-chain rilles probably imply release of volatiles, which possibly bore water, from the Moon's interior during late stages in the Moon's geologic history.

Possible terrestrial structural analogies of the crater-chain rilles include kimberlite pipes and dikes and alkali-basalt volcanoes which commonly occur as maar-type volcanoes or diatremes if eroded. Detailed investigations of the Moses Rock dike, a kimberlite-bearing diatreme in southeast Utah, have yielded the following information: (1) calcium-rich pyroxenes, which are commonly associated with pyropic garnets, are in equilibrium over a pressure range extending from the base of the crust to about 150 kilometers and well below liquidous temperatures; (2) the nature of the breccias which fill the dike suggest that they were emplaced as a solid-volatile fluidized system (no evidence of a silicate melt exists, material is particulate on all scales, debris from diverse sources is intricately mixed, and fragments have size-frequency distributions characteristic of the comminution process); (3) the relatively great abundance of hydrous phase compared with that of carbonate phases suggests that the volatile phase was mostly H_2O; and (4) minimum estimates of the upward fluid velocity based on calculations of the settling velocity of the largest upward-transported blocks in the dike yield a velocity of 10 to 60 m/sec at the present erosion surface, which was about 2 kilometers below the surface at the time of eruption. Hence, it is concluded that the Moses Rock dike was emplaced by an eruption of a volatile phase (rich in water) and solids (disrupted and physically disaggregated garnet and spinel periodotite) which flowed from a reservoir in the Earth's mantle at or near a depth of 150 kilometers to the surface in a fluidized state and which reached the surface traveling at high velocity of probably a few hundred meters per second. The inferred surface expression of the Moses Rock dike is morphologically very similar to that of the rille in the east side of Alphonsus.

The water content of an erupting medium is one important parameter in determining the surface velocity of the material ejected from volcanoes. Hydrodynamic models for the eruption at the Moses Rock dike show that the surface flow velocity is a function of water current, dike width and roughness, temperature, and gravity but is nearly independent of the length of one duct for relatively long ducts. Lower limits can be placed on the surface velocity of the ejecta erupted from the craters in the rilles from simple ballistics considerations. The width of the observable ejecta apron around the rille in Alphonsus is, for example, 8 kilometers; implying a minimum velocity of about 110 m/sec for ejection at 45°. Hence, from the observable features of the rilles, some conclusions might be drawn about the volatile content based on hydrodynamic models of their eruption.

The important conclusion is qualitative, however. The crater-chain rilles imply a type of violent gaseous volcanism produced by expansion of a volatile phase. This implies the release of volatiles from the Moon's interior to the vicinity of the surface, a necessary, although not sufficient, condition for the entrapment of water in either of the two cold traps mentioned.

324-954 O—69——3

Page intentionally left blank

J. D. HALAJIAN and H. B. HALLOCK
Grumman Aircraft Engineering Corp.
Bethpage, N.Y.

Uses of Temporal Data in Remote Sensing

The potential of complementing pictorial data with the study of the time behavior of quantified radiation from a target element is explored. To date, most studies of remote surfaces have been severely restricted to visual impressions from images, particularly in the visible wavelengths. Temporal analysis of the quantity, polarization, and spectral distribution of the electromagnetic flux from each element during a transient cycle promises information beyond the resolution of the viewing system.

Laboratory analogs and theoretical models are used to illustrate the way that lunar photometric, polarimetric, and radiometric data can be correlated with roughness, porosity, bearing strength, internal heat sources, etc. Surveyor data are used in order to verify the correlations and to resolve some ambiguities. It is shown that Earth-based, high-resolution observations of the diurnal behavior of the lunar surface at optical and infrared wavelengths could supplement Orbiter photographs and lead to the discovery of suitable landing sites and/or prime targets of exploration. The importance of prereconnaissance diagnostic research and postreconnaissance ground truth measurements as integral parts of a remote sensing strategy is stressed.

INTRODUCTION

At the present time the consensus is that orbital reconnaissance of terrestrial and extraterrestrial surfaces should be a major objective of the post-Apollo period. It is believed that high-resolution, multisensor data on a synoptic scale will help mission planners and experimenters in selecting prime targets of exploration, in laying out optimum geologic traverses, and in devising key surface measurements. In practice, this strategy will be only as effective as our ability to extract useful information from the raw remote sensor data with a minimum of ambiguity. Certainly, the vast quantity and spectral variety of orbital data will necessitate improved methods of data collection, processing, and interpretation. However, a survey of the recent literature of remote sensing shows a greater preoccupation with sensor development than with data diagnosis. While both tasks are equally important, this paper will primarily concentrate on the latter and will focus attention on an area of remote sensing concerning what are called "temporal data" in this report. Such data are simply measurements of electromagnetic radiation as a function of time, as compared, for example, with pictorial data which essentially represent the spatial distribution of the same radiation at any wavelength but at a given instant of time.

Changes in brightness and temperature of a planetary surface during a day-and-night cycle are examples of temporal data. An attempt will be made to illustrate by means of experiments, theoretical models, and qualitative discussions the way in which such data could supplement purely pictorial information. Another of the present paper is to stress the importance of prereconnaissance homework in data interpretation as an integral part of the overall strategy of remote sensing, particularly from an orbit. This preparatory analysis may well determine whether the data should be acquired in the first place and, if so, how they should be acquired in terms of choice of sensor or sensors, time of observation, geometry of viewing, etc.

TEMPORAL DATA AND THE OVERALL PICTURE IN REMOTE SENSING

Electromagnetic energy measured by remote means may be classified into pictorial, spectral, and temporal data, the designation depending on whether such data represent the distribution in space, the distribution in wavelength, or the variation with time of the energy, respectively.

Our concept of temporal data has its origin in the study of lunar astronomical data. At optical wavelengths, the temporal nature of these data emerges from the dependence of brightness on the direction of incidence (and viewing) during an insolation cycle. This cycle could also be a satellite orbital period, a season, or other natural event or even a manmade event. At infrared wavelengths, in addition to directional factors affecting radiance, cyclic heating and cooling contribute to the temporal aspect. In terrestrial remote sensing it is common to catalog into time-oriented interpretation keys the infrared response of surfaces under various meteorological conditions during a diurnal cycle. This is an example of effective utilization of temporal data. It is not an essential condition to this utilization that continuous observations over a complete temporal cycle be accomplished in the actual reconnaissance of the surface. More frequently it is expedient to match discontinuously recorded responses with an interpretation key which itself represents continuity of observation over a temporal cycle. In other words, the field data could represent a few points on the complete temporal function of known models.

The need for similar interpretation keys for the optical photometric and polarimetric responses is not equally obvious because temporal changes at optical wavelengths are less dramatic than those at the infrared ones, but nevertheless these changes could be of diagnostic value provided that they are measured with high fidelity. Extensive time-oriented interpretation keys at optical wavelengths eventually may prove very valuable as sensor gray-tone resolution is improved. Consequently, advantage can be taken from the time-varying parameters to extract more information than would appear possible by the use of pictorial interpretation only. The advantages can be realized only by very accurate preservation of gray-tone values. This, however, would involve improvement in sensor capability which is beyond the scope of the present report.

To date, most studies of remote surfaces have been restricted to visual impressions from photographs. A concept that deserves emphasis is the idea that photographs are necessary as visual, synoptic records of the size and location of surface features or gray tones, but they are not sufficient in all cases for a positive identification of these features. This inadequacy stems from the fact that many factors, such as albedo, slope, and shadowing by unresolved features, could contribute to the gray-tone values. It is not always possible to disentangle these factors without a quantitative analysis of the spectral and temporal signatures of the features in question. At longer-than-visual wavelengths there are additional factors which may cause ambiguities, such as the mechanical, thermal, and electrical properties of the surface layers, all of which tend to modify pictorial gray tones.

Generally, the coarser the resolution of imagery, the greater is the need for quantitative data on an object's spectral and temporal tone signatures and the less is the reliance that can be placed on the object's spatial configuration. Since spectral and temporal tone signatures of rocks, soils, and vegetation types quite often may indicate their composition and structure, tone signatures assume considerable importance in the interpretation of many features that are of interest in Earth resources and planetary exploration.

Those data usually referred to as photometric, polarimetric, and radiometric in the lunar literature are classic examples of temporal data. These data have received considerable attention in recent years, but more as isolated areas of scientific inquiry than as contributory clues to the overall picture in remote sensing. Figure 1 shows the major components and subcomponents of this picture. In the three-step process outlined, the first two steps

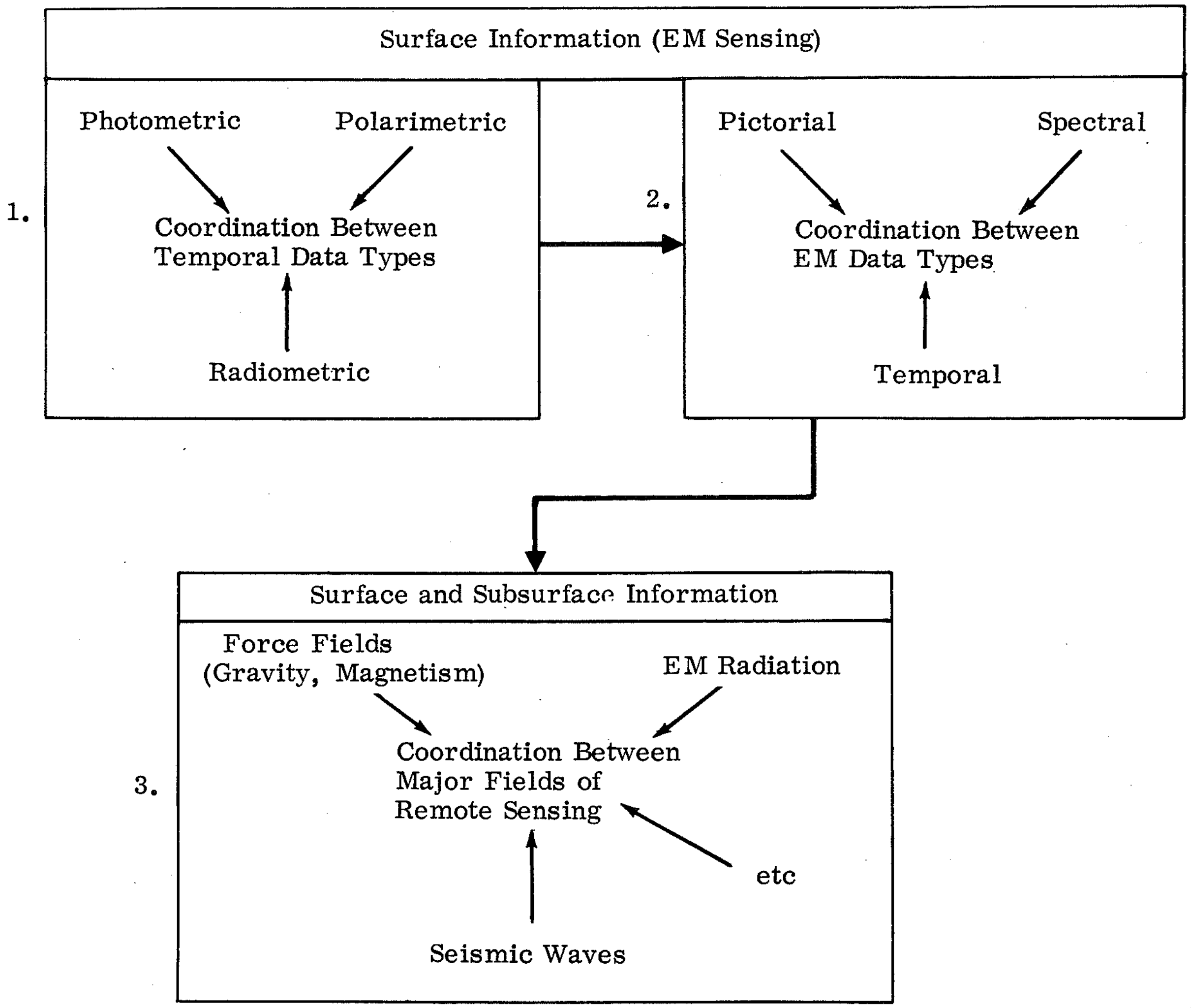


FIGURE 1.—Steps in coordinating temporal and other forms of remote sensor data.

involve electromagnetic (EM) methods of sensing. These methods provide information about the surface and near-surface material. In the first step temporal data are cross-correlated at visible and longer wavelengths. In the second step this information is used to supplement pictorial and spectral data. Step 3 gives a third dimension to the picture; it consists of combining the surface information obtained in steps 1 and 2 with subsurface data obtained by means of seismic and force-field surveys.

Since few temporal data on terrestrial surfaces currently exist, the lunar astronomical and Surveyor data are used to illustrate the techniques of cross-correlating temporal and pictorial data as outlined in steps 1 and 2 of figure 1. Spectral data (also in step 2) are not used, since such data and their correlation with material composition have been extensively investigated in the laboratory and the field by Adams (ref. 1), Hovis (ref. 2), Lyon (ref. 3), and others. As to step 3, there are no case studies at our disposal to show how it may be implemented. However, it is reasonable to predict that extraterrestrial targets, which will be explored by onsite geophysical techniques, will be selected by sifting orbital data obtained by electromagnetic means.

TYPES OF LUNAR TEMPORAL DATA

Figure 2 shows three well-known, typical "signatures" of the lunar surface. The curves are qualitative in nature and are meant to show general trends with time. The curve in figure 2(*a*) is known as the photometric function. It represents the change in the visible brightness of the lunar surface between sunrise and sunset (ref. 4). It is characterized by rapid increase in brightness at full moon and a continuous drop in brightness after full moon at all phase and viewing angles (phase angle is the angle between light rays incident on the Moon and the reflected rays as seen by an observer on Earth). This signature is called a backscattering type and is indicative of a rough surface.

A similar measurement of the percent polarization of the visible brightness (ref. 5) results in the curve shown in figure 2(*b*). It is characterized by negative polarization (about 1.5 percent) at small phase angles near full moon, a reversal to positive polarization at phase angles of about 23°, and a maximum positive polarization at large phase angles generally not exceeding 20 percent. The counterpart of the photometric and polarimetric curves at near-infrared wavelengths (0.8 to 3μ) is not known, hence the question mark in figure 2(*c*).

Radiation from the lunar surface in the infrared (mostly 8 to 14μ) has been measured by numerous investigators (refs. 6, 7, and 8) both during a lunation and an eclipse. The results can be represented as effective surface temperature variation with time, as shown in figure 2(*d*). Notice that the daytime portion of the temperature curve, unlike that of the photometric curve, is convex, and the nighttime or eclipse portion is nearly a straight line.

By assuming that the curves of figure 2 represent the norm for the lunar surface, we shall discuss successively the manner in which these temporal signatures could deviate from the norm and what these deviations may

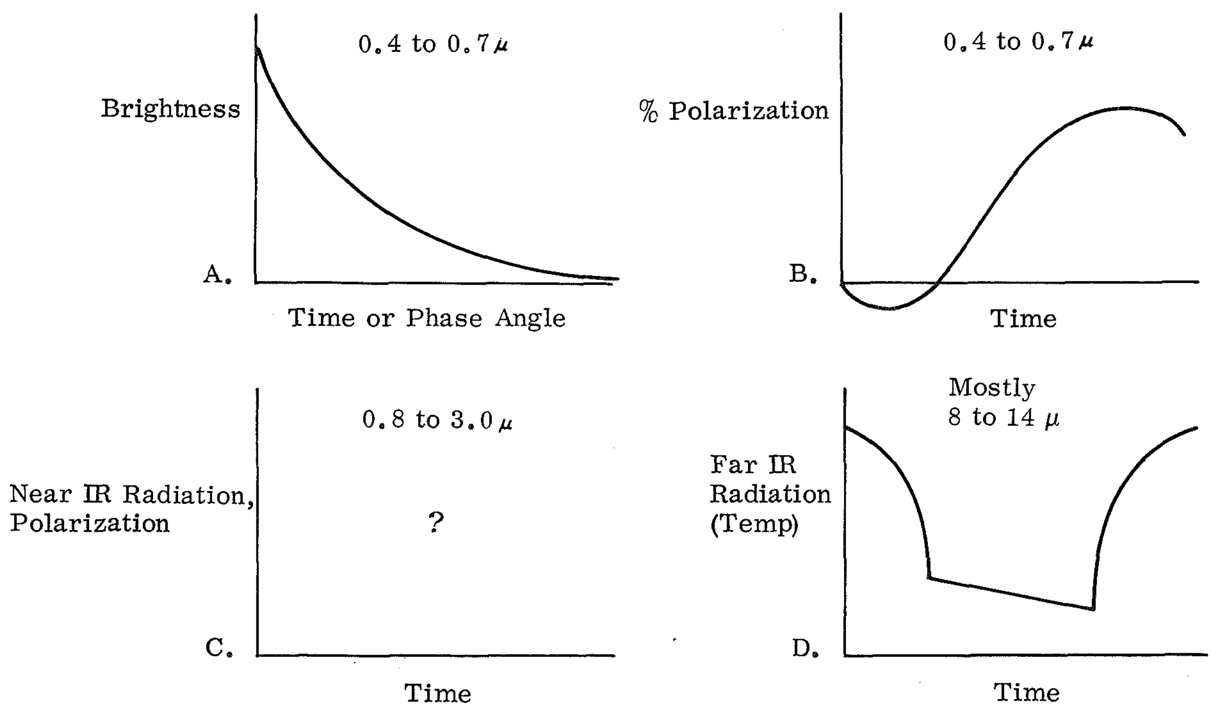


FIGURE 2.—Types of lunar temporal signatures.
(*a*) Photometric curve, 0.4 to 0.7 μ.
(*b*) Polarimetric curve, 0.4 to 0.7 μ.
(*c*) Polarimetric curve at 0.8 to 3.0 μ.
(*d*) Temperature curve, 8 to 14 μ.

mean in terms of the physical properties of the terrain.

PHOTOMETRIC ANOMALIES AND THEIR MEANING

Correlation Between Surface Roughness and Shape of Photometric Curve

There are a number of factors that perturb the lunar photometric curve. The most important of these factors is shadowing. Indeed, it is commonly recognized that a cause-and-effect relationship exists between surface roughness and the shape of the photometric curve. It has been believed, for instance, that a complex microstructure is primarily responsible for the peculiar photometric properties of the lunar surface. However, no attempts have been made, to our knowledge, to isolate the effect of this microstructure on the photometric signature and, in addition, to determine whether information on large-scale structures beyond the resolution of the viewing system could be extracted from this signature. We now propose to investigate this problem.

First, to appreciate why photometric data can supplement photographs in providing information about roughness beyond the resolution of the particular viewing system that is being used, it is necessary to recall some essential characteristics of photometry and photography. A photograph is a qualitative record of the spatial distribution of brightness. The same record properly calibrated and controlled can become the basis for the quantitative study of this distribution, known as photometry. The expression "lunar photometry" is the study of the directional properties of reflected sunlight and as such it may be considered to be the temporal extension of photography. It consists of the measurement of the total flux from each or all resolution elements in the field of view and of the change with time of this flux during a complete insolation. Thus, one may conceive of the photometric curve as a motion picture of shadowing and of a photograph as a frame in that picture. Photographic observations differentiate between gray tones within the resolution capability of the viewing system. Photometric reduction integrates all these effects over any chosen field of view within the photograph. If the integration is done on one element of resolution and expressed as a function of phase angle, then the resulting photometric curve reveals the temporal behavior of shadows cast by features smaller than the resolution of the system. Thus, it is in the quantitative analysis of the temporal and directional changes of the reflected flux from a discrete area that photometry can complement photography in the assessment of unresolved roughness.

The most accurate photometric data on the lunar surface presently are taken with photoelectric sensors of excellent linearity and calibration rather than through direct film photography. The resolution of a photoelectric system usually is taken to be the field of view of any one sensor element. Unresolved shadows would fall within this field.

In figure 2(*a*) the following features of the photometric curve are selected for their diagnostic values: (1) the area under the normalized curve, (2) the slope of the curve near its peak (i.e., the region of opposition), and (3) the curvature and ordinate value of the tail end of the curve (i.e., the region of specularity at oblique viewing). We propose that these features are clues to terrain properties which will now be discussed.

Total Roughness

Total roughness is defined as an index of the integrated effect of all unresolved shadow-casting protrusions in the field of view, which could include features ranging from particles of dust to mountains. For a given viewing angle, the area under the normalized back-scattering photometric curve is a function of the cumulative shadowing effect of all these irregularities. This correlation of photometry with surface structure has been demonstrated satisfactorily in numerous experiments in which specimens ranging from solid rocks to very rough, dendritic sea corals were examined with a photometer having a large area-viewing capability (ref. 9).

A slight variation of previously reported

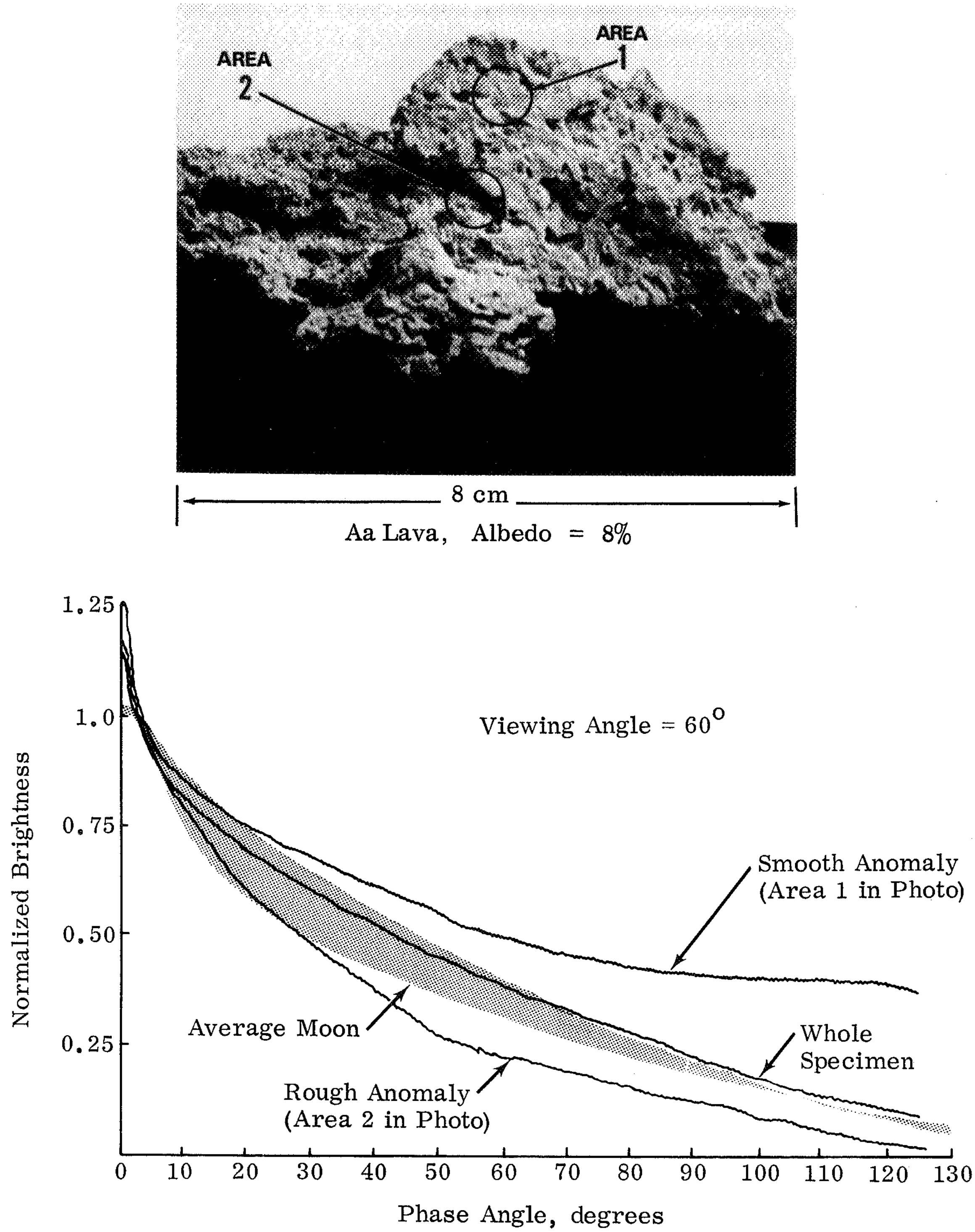


FIGURE 3.—Correlation of total roughness with area under photometric curve.

experiments is shown in figure 3 for the purpose of illustrating the way, in telescopic observation of the Moon, that photometric anomalies could be detected by improving the spatial resolution of the measurements. The specimen selected for this experiment is a dark vesicular lava (8 percent albedo) containing numerous crags and a few isolated smooth anomalies located between the large irregularities. The improvement in spatial resolution is accomplished first by viewing the whole specimen with a large, 1.5° field stop (this corresponds to an area 8 centimeters in diameter on the sample table) and then by reducing the field stop to 0.3° and focusing the photometer successively on one of the smooth and rough anomalies.

In figure 3 the coarse-resolution view gives a good photometric match with the lunar standard (shaded band), but the fine-resolution view of the smooth and rough spots brings out the anomalies. It is clear that the area under the anomaly curves is larger or smaller than the area under the curve representing the whole specimen and that there is a trend of increasing area with decreasing roughness.

The fact that the relative roughness of two or more regions can be predicted in this manner is considered quite favorable to the photometric technique for remote sensing of roughness beyond the imaging resolution of the optical system. Conceivably many photometric anomalies could exist on the Moon that have not been discovered but which could be detected and located by telescopic instrumentation of high resolution and gray-tone accuracy.

The area rule is valid for most rough, textured surfaces encountered in nature, such as rocks, soils, and vegetation, when the specular component of brightness is quite subdued compared with the backscatter component. This case should be the rule rather than the exception for the Moon. If there are exceptions, their discovery will be significant.

Microstructure

Microstructure is defined as the random, small-scale roughness that characterizes the texture or surface porosity of a material. The random orientation of the microelements (that is, random with respect to the gravity vector) makes it possible to distinguish them photometrically from the macroelements which, by our definition, are predominantly oriented by gravity. It is now proposed that the slope of the photometric curve in the region of opposition (between phase angles of 0° to 10°) is an index of microstructure. A surface like the Moon as a whole which exhibits a sharp brightness peak of 0° phase angle, regardless of the direction of viewing, necessarily must be covered with randomly oriented elements interspaced with deep, and possibly interconnected, cavities. It follows that the shadow-casting elements in the opposition region must be small, of the order of centimeters and smaller, in order to maintain their random orientation in a gravity field. As a rule, the steeper the slope of the curve in the opposition region, the rougher is the microstructure.

Macrostructure

Large topographic features such as boulders and craterlets (or mountains and craters, the size depending on the size of the field of view) are categorized as macrostructure by virtue of the orientation of their height (or depth) along the gravity vector. Such features cast shadows that become visible to an observer only when the Sun is on the opposite side of the local vertical, such as early in the morning or late in the afternoon. These shadows largely are responsible for depressing the tail end of the photometric curve. The microstructure has little or no effect on this part of the curve, because the small cavities are saturated with shadows at the large phase angles and a microelement is, by definition, too small to overshadow a photometrically significant number of other microelements. In the absence of large-scale roughness, the photometric curve is most likely to exhibit a "bulge" or a second brightness peak at the specular angle in oblique viewing.

It should not be surprising that lunar areas exhibiting a second brightness peak have not been discovered. In telescopic observation of the Moon, the field of view usually is sufficiently large to include numerous topographic features which cast long shadows at large phase angles and, hence, depress the tail end of the photometric curve. The possibility of discovering optically enhanced (i.e., smooth) areas on the Moon should not be discounted in view of significant improvements that can be made in the quantity and quality of the existing telescopic data.

The following experiment was performed in order to demonstrate the aforementioned proposed relationship between scale of roughness and shape of photometric curve. The photometry of a microrough surface with and without macroroughness was measured at normal and 60° off-normal viewing angles, as shown in figure 4. The microrough surface was simulated by means of a dark, synthetic urethane foam of low albedo (6 percent). This material was selected because of its very high porosity (97 percent) and, consequently, because of its promise of an exaggerated backscatter response in the opposition region as predicted by our hypothesis. Macroroughness was simulated by placing a few centimeter size microporous volcanic cinders on the foam. An area 8 centimeters in diameter was sampled by the photometer. The output of the xy recorder registering the photometric signature was normalized with the lunar standard (shaded band in fig. 4) at a 4° phase angle. The brightness in the opposi-

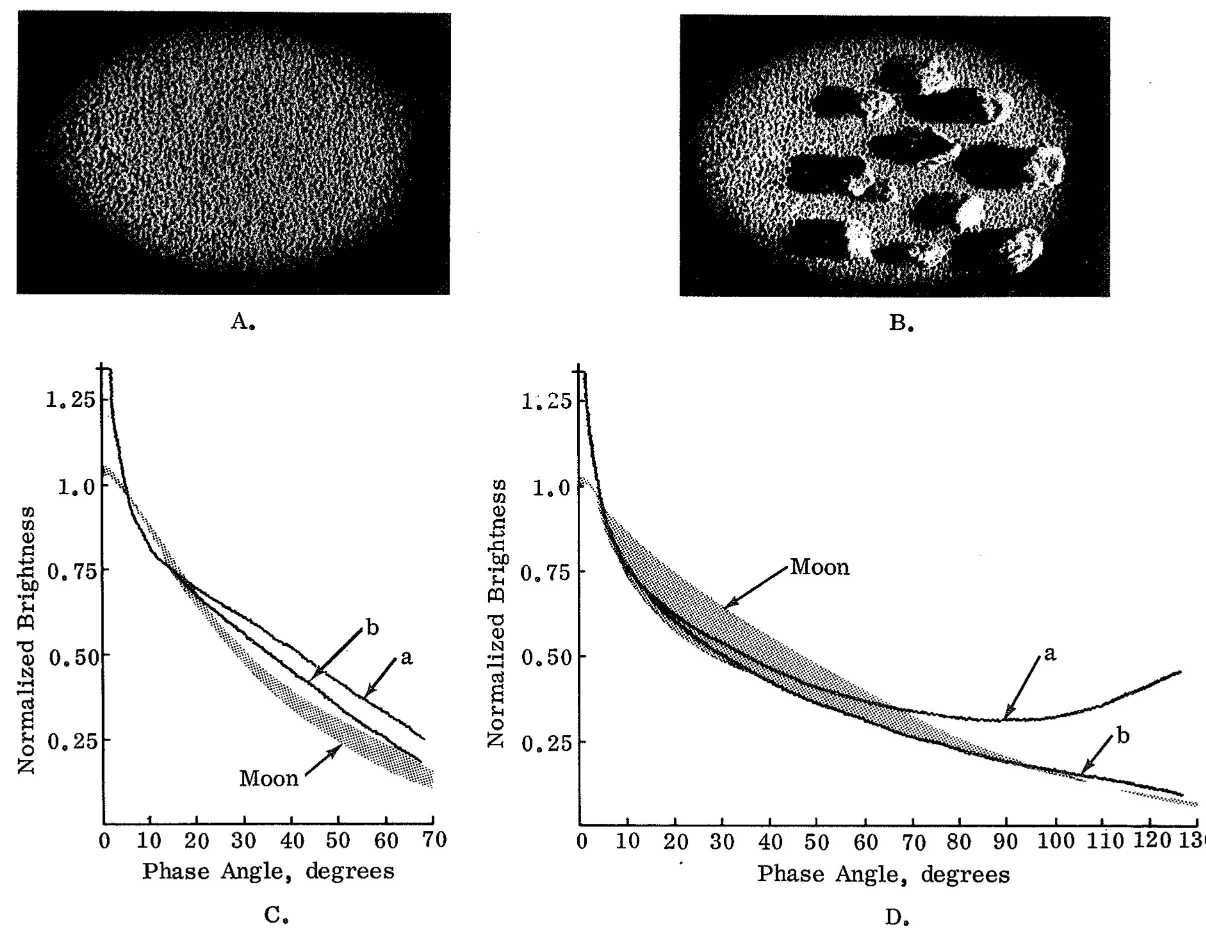


FIGURE 4.—Correlation of microroughness and macroroughness with components of photometric curve.
(*a*) Microrough surface, urethane foam; porosity, 97 percent; albedo, 6 percent; view angle, 90°.
(*b*) Microrough and macrorough surface, foam plus volcanic cinders; albedo, 6 percent; view angle, 90°.
(*c*) View angle, 0°.
(*d*) View angle, 60°.

tion region was measured by means of a beam splitter placed between photometer and sample. The beam splitter was sufficiently long in the plane of the intensity equator to enable brightness measurements between phase angles of −7° to 12° to be made.

As anticipated, the foam, because of its extremely complex microstructure, exhibited a slope in the opposition region that was steeper than anything previously seen. In all cases, the upsurge of brightness was so intense that the output went beyond the field of the recorder, as can be seen in figure 4. Latest lunar data reported by Gehrels et al. (ref. 10) indicate an opposition effect somewhere between the foam curve and the lunar standard in figure 4. From this it may be inferred that the foam is more porous than is the lunar surface.

Notice also in figure 4 that the foam without the volcanic cinders exhibits a second brightness peak toward the specular direction (phase angle 120°), but the addition of the volcanic cinders lowers the brightness to the level of the lunar norm. This experiment also showed that the tail end of the curve is more sensitive to macroroughness at oblique viewing than at normal viewing. Although viewing at oblique angles entails some loss of spatial resolution, we believe that the superior diagnostic value of the photometric curve at oblique viewing more than compensates for this loss.

In conclusion, it seems possible to rate the relative roughness of discrete regions by comparing the time integral of their brightness over an insolation cycle (this is the area under the photometric curve). It also seems possible to infer surface texture and large-scale roughness below the resolution of the viewing system by studying the actual shape of the photometric curve.

Photometry as an Aid in Photographic Interpretation

It is often necessary to study the temporal behavior of photographic features in order to determine whether the apparent diversity of gray tones is caused by differences of composition, of structure, or of both.

The recent controversy concerning the nature of the dark ejecta observed around the Surveyor footprints is a case in point. This problem was discussed in a recent publication and it was shown by means of simulation experiments how accurate data on the albedo and photometry of the gray tones in question could settle the issue (ref. 11). Another example is the case of the lunar rays which, as is well known, are conspicuous at full moon but tend to disappear and blend into the background at large phase angles. It appears that this peculiar photometric behavior indicates that the rays differ from their surroundings in both albedo and structure. This proposition is based on the following reasoning. The brightness of a surface at 0° phase angle depends only on its normal albedo, but at phase angles other than 0° this brightness is attenuated by the extent of shadowing, hence by the roughness or porosity of the surface. Accordingly, two areas of unequal normal albedo when viewed at a large phase angle could conceivably register the same brightness or gray tone on a photograph if the lighter area (in terms of normal albedo) is rougher or more porous than is the darker area. This behavior is indeed exhibited by the lunar rays. Hence, it is sufficient to postulate that the ray areas are inherently lighter and rougher than their surroundings in order to account for this peculiar behavior. The rays cannot be discriminated from their background at large phase angles, because their inherently higher reflectivity is attenuated by a large number of shadows cast by features that are usually too small to be resolved by the viewing system.

An experiment was performed in which the above-postulated properties were simulated in the following manner: A layer of dark, backscattering volcanic powder (particle size 38 to 88 micron and normal albedo 14 percent) was deposited on a flat board and firmly tamped; then a lighter powder (normal albedo 16 percent, same particle size) was loosely sifted over this layer through a template incorporating a ray pattern. Figure 5(*a*) shows a photograph of the simulated rays taken under ambient, noncollimated lighting. Figures 5(*b*) and 5(*c*) show

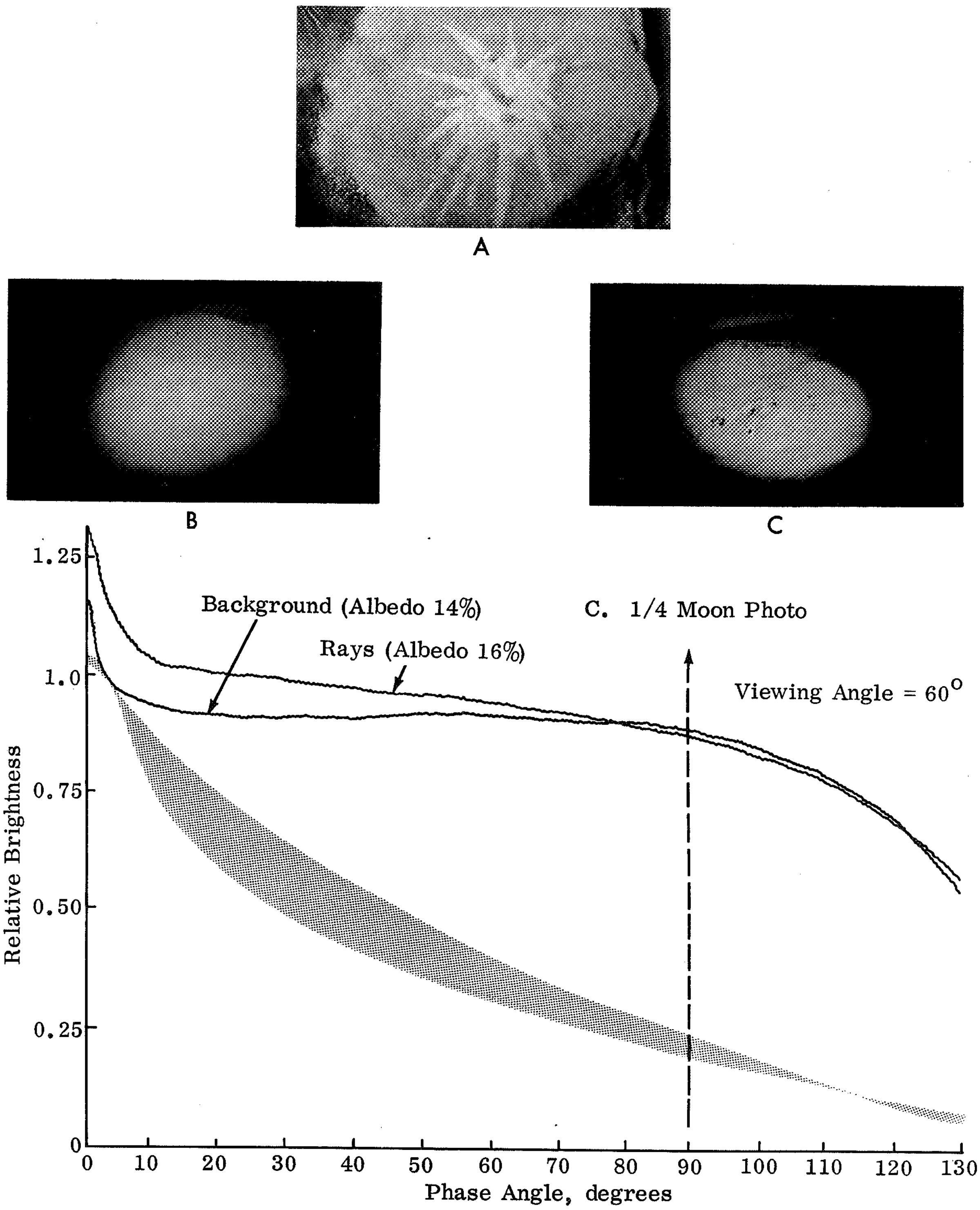


FIGURE 5.—Photometric behavior of simulated lunar rays.
(*a*) Photograph of simulated rays under ambient, noncollimated lighting.
(*b*) Photograph of scene in figure 5(*a*) under collimated lighting at 0° phase angle.
(*c*) Photograph of scene in figure 5(*a*) under collimated lighting at 90° phase angle.
(*d*) Photometric curves of the rays.

the same scene under collimated lighting at 0° (full moon) and 90° (quarter moon) phase angles, respectively. At the full-moon condition the simulated rays are noticeable, whereas at the quarter moon they are not. The photographic observations are confirmed by the relative photometric curves of the rays and of their background, as shown in figure 5(*d*). For the particular albedo-roughness combinations used in the experiment, the two curves nearly coincide beyond 80° phase angle. Other combinations are possible. For instance, it is conceivable that the rays may actually appear darker than their surroundings at large phase angles, if the difference in roughness outweighs, photometrically speaking, the difference in albedo. Such a condition may occur if the rays, unlike their surroundings, are rough both on a microscale and a macroscale. We have not simulated this condition in our experiment nor do we know whether it exists on the Moon.

The present proposition, based on purely photometric considerations, that the lunar rays are on the average "rougher" than their surroundings, is in accord with the commonly accepted view on the structure of the rays. The actual scale of this roughness may range from a fine, intricate microstructure, to macrofeatures such as craterlets and boulders. Although the latter features may be resolved in Orbiter photographs, knowledge of the temporal behavior of gray tones on these photographs is necessary in order to assess the microstructure and, by inference, the porosity and bulk density of the surface layer.

POLARIZATION ANOMALIES AND THEIR MEANING

The polarimetric signature of the lunar surface has distinctive characteristics which have been described earlier in this paper. It is to be expected that selected areas of the Moon will present a polarimetric signature differing substantially from the norm. On the Earth, where features such as vegetation and water break the monotony of the surface, polarimetric anomalies much stronger than those on the Moon may be expected. If the anomalous signature can be shown to be characteristic of certain features, such as vegetation, or more specifically, certain types of vegetation (e.g., evergreen foliage), an important reconnaissance interpretation key may be evolved. On extensive lunar and planetary areas where no vegetation or areas of culture are known to exist, it may be that rather subtle differences in polarimetric response may be interpreted in terms of changes in surface texture or related physical qualities having practical importance.

Early attention to temporal data of lunar origin has led to speculation concerning the occurrence and meaning of lunar polarimetric anomalies and subsequently to application of some of this thinking to the potential value of the terrestrial anomalies. In either case, in order to interpret anomalous data one must understand the physics of the polarization phenomenon and the important factors that shape the polarimetric signature.

The polarization-inducing optical phenomena are those which are associated with boundary conditions between media of different refractive indices. These are reflection, refraction, and diffraction. The interplay of these phenomena in a surface of great complexity is not conducive to ready quantitative analysis. The shadow formation which seems largely responsible for sharp backscattering photometry further complicates lunar polarimetry.

One approach to analysis is polarimetric measurements performed on surfaces of various orders of complexity and attempts to discover generalizations which can be incorporated into a useful hypothesis. Another approach is to apply known physical laws to generalized models and to try to approach the known polarimetric signatures mathematically. We have used both methods of approach but will describe here physical measurements on one reasonably good laboratory analog of the lunar polarimetric signature and on two highly abstracted contrived surfaces.

Figure 6 shows a typical lunar polarimetric signature in terms of percent polarization as a function of phase angle. A curve is also shown representing this same kind of function as determined on the Grumman polarimetric analyzer from a sample of powdered volcanic cinder.

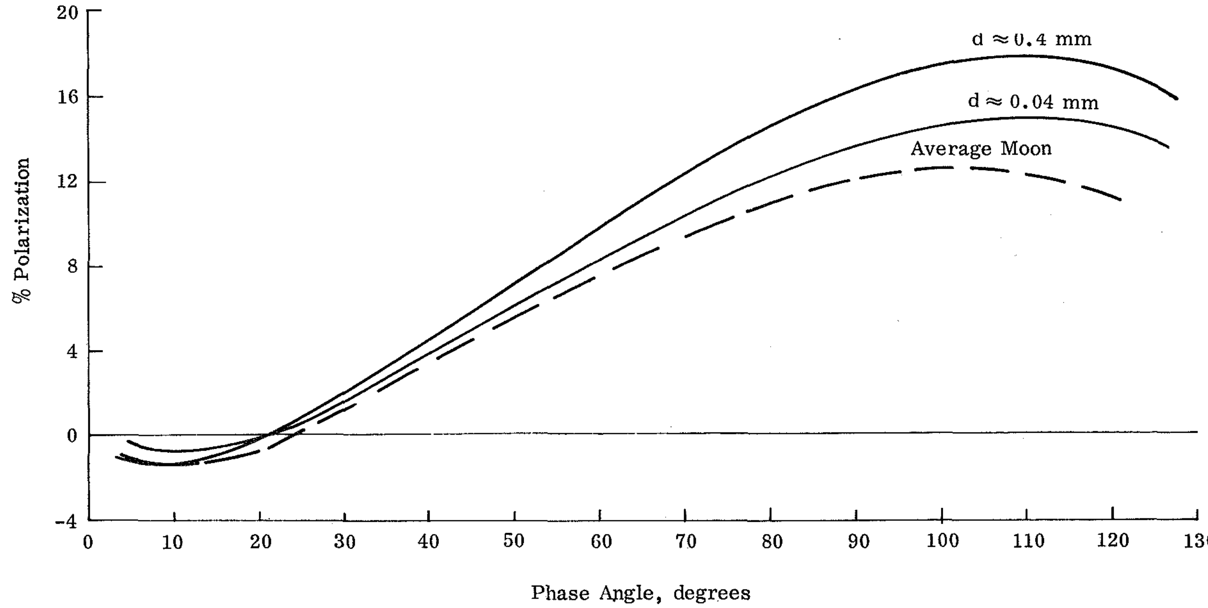


FIGURE 6.—Polarimetric signature of Hawaiian volcanic ash and Moon; *d*, particle size.

The features of negative yielding to positive polarization at a characteristic inversion point are present in the model, but the positive polarization at large angles is too high in the model's function.

One of the simpler approaches to analysis is to make the assumption that the complex surface can be represented by an aggregate of random reflecting plane facets inclined at various angles to the plane of vision. For practically any material the singly reflected light from a facet oriented normal to the plane of vision is positively polarized as referred to the plane of vision. If the facet is not normal to the plane of vision but is rotated about an axis in that plane, the polarization may be quite negative. An experiment is shown in figure 7(*a*) to clarify the point. The masonite board has a pronounced positive signature when presented as a plane surface to the polarimetric analyzer. When two reflecting facets of the masonite are formed into a V-shape and the facets are oriented normal to the plane of vision, the polarimetric signature is pronouncedly positive. When the V-shape is oriented with the vertex in the plane of vision but the facets are inclined to the normal as shown, the polarimetric signature is quite negative at small phase angles and becomes positive only at large phase angles. This trend was anticipated when the experiment was planned because positive polarization becomes negative polarization if the coordinate frame of reference can be rotated 90°. In the signature of this model there evidently is a strong competition between the factors favoring a preponderance of light with the vector arbitrarily defined as negative and the factors favoring the vector defined as positive. The point at which this competition is equal is the inversion phase angle.

An even more striking artificial example of the positive-negative competition is afforded by the polarimetric signature of aluminum structural honeycomb shown in figure 7(*b*). Structural honeycomb is extremely porous and the pore lining is specular in reflecting properties. A signature secured on the polarimetric analyzer with the pores inclined very slightly to the plane of vision shows an exaggerated version of the trend mentioned above. Covering the pores with strips of cardboard results in successive steps of reduction of inversion phase angle and reduction of negative polarization, while the positive component is enhanced. The

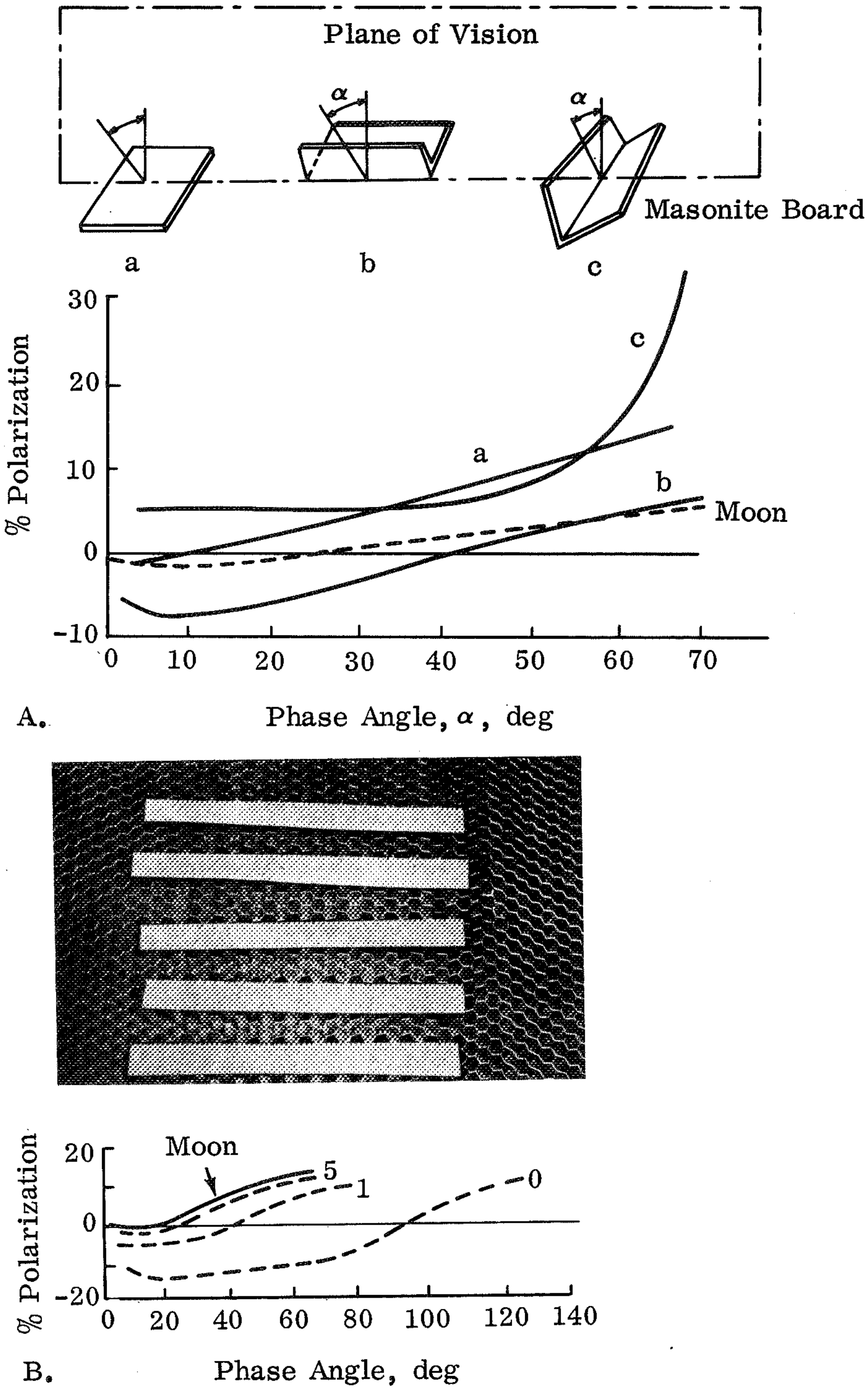


FIGURE 7.—Contrived models showing effect of structure on percent polarization. (*a*) Polarization by orientation of plane facets. (*b*) Polarization of honeycomb covered with varying number of cardboard strips. (Note change of signature with change of surface porosity.) Numbers at each curve are number of cardboard strips.

cardboard is one of the normal opaque reflecting surfaces which have a predominantly positively polarized signature.

Structural effects arising from the orientation of the facets with reference to the plane of vision are not the only mechanism inducing negative polarization. Other experiments with transparent dielectrics, such as water, have demonstrated strong contributions to negative polarization arising from refraction and subsurface reflection (ref. 12). There appears to be a connection here to the polarization signature of vegetation and the degree of turgidity, or state of hydration, of the vegetation. One example is shown in figure 8 for fresh and dehydrated vegetation.

The experiments with two contrived models described in figures 7(*a*) and 7(*b*) demonstrate that the polarimetric signature may be related to structure even on a fairly gross scale. Neither high nor low limits on the scale of the structural grains are set, as long as attention is confined to the opaque reflecting surface facets. When semitransparent grains are considered, the grain size may be an important parameter because of increasing opacity with size. The magnitude of the refractive boundary effects which may tend to enhance negative polarization is related to grain size. This can be verified by examination of the degree of conformance of the signature of our sample of volcanic ash with that of the Moon (fig. 6).

One of the most difficult features of the lunar surface polarimetric signature to duplicate is the relatively low positive polarization at large phase angles. There are many factors related to surface structure which could be postulated to account for this feature, and it is possible to perform experiments which demonstrate trends in this direction. Multiple scattering and high

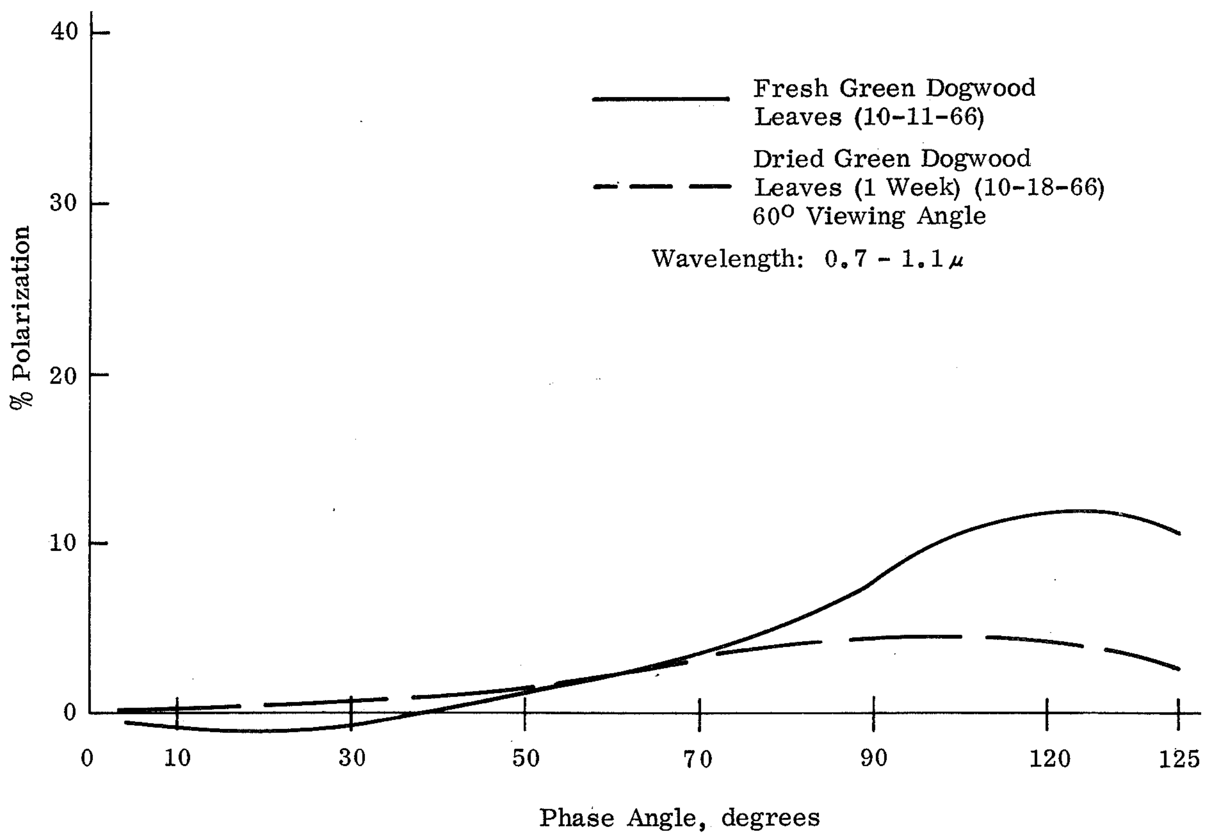


FIGURE 8.—Polarization of fresh and dried vegetation at near infrared wavelength.

albedo, in general, favor depolarization. Multiple scattering combined with factors favoring the negative vector are logical assumptions in the effort to understand and duplicate the lunar signature at large phase angles. Presumably other planetary surfaces may possess the same general characteristics, thereby justifying further attention to rationalization of the lunar polarimetric behavior.

Obviously many factors operate to modify the polarimetric signature. Only in the case of rather simple surfaces is interpretation easy. As in the case of photometry, the utility for remote sensing seems to be largely to draw structural rather than compositional inferences. Also it seems clear that polarization is one of many optical phenomena that could be most meaningful when correlated with other temporal data, such as photometry, and with measurements of albedo and color. In specific instances, such as the example of vegetation mentioned, a polarimetric anomaly should lend itself quite readily to interpretation, but it is felt on the average that considerable analysis of a cross-correlation nature must be done prior to reaching a conclusion.

Inasmuch as polarization is a measurable characteristic and seems to be related to structure, and to some degree to composition, it should be a potential source of additional information. However, it is a very complex phenomenon and much remains to be learned. Certainly field polarimetry concurrent with photometry and radiometry can be justified.

USES OF TEMPORAL DATA IN INTERPRETING INFRARED THERMAL ANOMALIES

Temporal data at optical wavelengths provide, at best, information on surface properties, such as texture and roughness, but are inherently not capable of revealing bulk properties of the surface layer, such as thermal conductivity and bearing strength, unless they are supplemented by data at infrared and longer wavelengths.

Currently available temporal data on the thermal infrared emission of the lunar surface are far from adequate for a meaningful diagnosis. They are, however, surprisingly more extensive than their counterpart at optical wavelengths despite the difficulties inherent in measurements at the longer wavelengths.

Observations to date (refs. 6, 7, and 8), whether made during an eclipse or lunation, have been rewarding insofar as they have revealed a number of anomalies which are generally, but not always, characterized by cooling phase temperatures that are higher than their surroundings. Various hypotheses have been offered to account for the "hotspots." The most plausible among these associate the phenomena with a rough mixed dirt-rock surface (refs. 13 and 14); a more conductive, hence, harder subsurface material (ref. 15); and internal heat sources. Consequently, the problem of exploiting thermal emission in remote sensing as a clue to the nature of the lunar or any remote surface resolves to disentangling these and other relevant factors. In the case of the Moon the factors to consider are the geometrical, mechanical, thermal, and optical properties of the uppermost layer. These unknowns and the assumptions they impose on the analysis have been the main obstacles in past attempts to match lunar data with analytical solutions.

One approach that promises to reduce some of the ambiguities of the data is utilization of the fact that the thermal behavior of the lunar surface can be observed during a day, night, and eclipse cycle. Although such observations of the Moon have been made, there have been no attempts to monitor and correlate the thermal behavior of a given area during all three temporal regimes. Also, the possibility that each regime could contribute an inpendent equation to the solution of the various unknowns has not been adequately explored theoretically. Similar remarks can also be made in favor of lunar investigations at microwave frequencies. However, this topic will not be discussed.

The new approach could begin with analysis and end with observations. In the analytical phase, standard curves can be derived in order to describe the lunation, eclipse, and directional behavior of a homogeneous, semi-infinite, blackbody material with Lambertian elements. Call this the "zero-order model." Next, one

324-954 O—69——4

could upgrade this model and determine the way in which known inputs perturb its lunation, eclipse, and directional signatures. Albedo, emissivity, thermal conductivity, bulk density, particle size, vertical inhomogeneity, surface roughness, and an internal heat source are examples of such inputs. There now is sufficient knowledge to propose that the solution of the higher order models could help narrow the number of possible interpretations that have been given to the lunar thermal anomalies. Some of this knowledge is discussed briefly in quantitative terms whenever possible and qualitatively where no analyses have yet been made.

Consolidation Effects

Bearing strength is a factor for consideration in the interpretation of lunar hotspots because of the relationships that will now be described. The temperature of a cooling surface is a sensitive function of the thermal conductivity of the cooling material; both thermal conductivity and bearing strength are functions of the same physical properties, such as porosity, particle or pore size, the degree of consolidation between the solid elements, and the nature of the solid material. In a recent study by Halajian et al. (ref. 15) these properties were used as a link in order to correlate the midnight temperature of the lunar surface with the bearing strength of postulated lunar surface materials ranging from loose, fluffy powders to solid rock. The analysis was made in terms of nighttime rather than eclipse temperatures, because roughness effects (discussed below) contribute to thermal enhancement during a short cooling transient and consequently complicate the correlation of thermal and mechanical properties. The results of this study based on lunation temperatures are summarized graphically in figure 9. Notice that midnight temperatures are far more sensitive to changes in bearing strength than are noon temperatures. Very low temperatures at night (i.e., coldspots) correlate with soft powders; elevated night temperatures (i.e., hotspots) correlate with porous rocks. The fact that noon and night temperatures show opposite trends with respect to bearing strength should be of diagnostic value and will be discussed later. Figure 9 also shows the bearing strength and day and night temperatures of the Surveyor I landing site. The concurrence of these data with the theoretical curves is quite good.

Roughness Effects

Surface roughness, neglected in the above analysis, is another important factor to consider when one is interpreting thermal emission. Day, night, and eclipse temperatures could be influenced by roughness to an extent and for reasons that differ in each case. These effects are extremely complex and interact with others that are no less complicated. An oversimplified view of the problem is taken here with the hope of identifying areas that deserve close scrutiny.

To begin with the insolation phase, roughness can affect daytime temperatures in two different ways. One is by shadowing which tends to lower the effective temperature and the other is the directionality (of the randomly oriented planes) which tends to raise it. Both effects are pronounced at oblique viewing (i.e., toward the limbs when the Moon is observed from the earth), but fortunately they do not occur simultaneously. Obviously, shadowing effects are most pronounced at large phase angles (during the first and last quarters) but directional effects take place mostly at small phase angles (at or near full moon) because the viewing angle gives more weight to those slopes whose normals are oriented toward the same direction is the incident solar radiation.

Figures 10(*a*) and 10(*b*) illustrate the way in which directional and shadowing effects could respectively enhance or attenuate thermal emission, the variation depending on the phase angle. In our opinion, these effects produce the anomalous temperature variation of the Surveyor landing site shown in figure 10(*c*) (ref. 16). Expressed in graphical terms, roughness tends to skew the overall lunation curve toward the viewer, when the viewing is at oblique angles. This skewing effect should not be surprising since its existence at optical wavelengths is widely recognized. It is tempting to think that its persistence at infrared wavelengths could be exploited as a clue to surface roughness at a scale larger than the

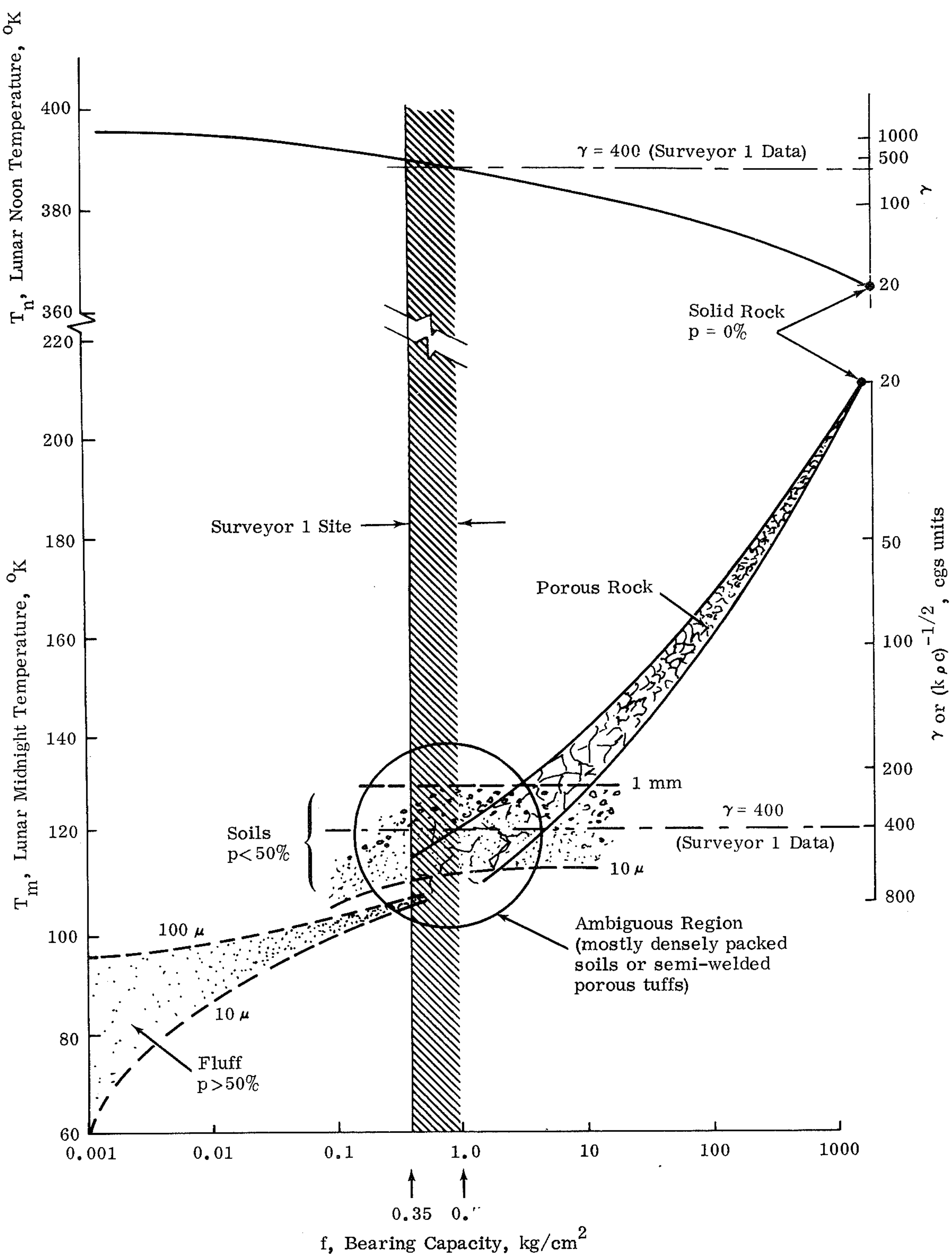


FIGURE 9.—Correlation of lunar temperatures and bearing strength; *p*, porosity, percent; γ, thermal inertia constant.

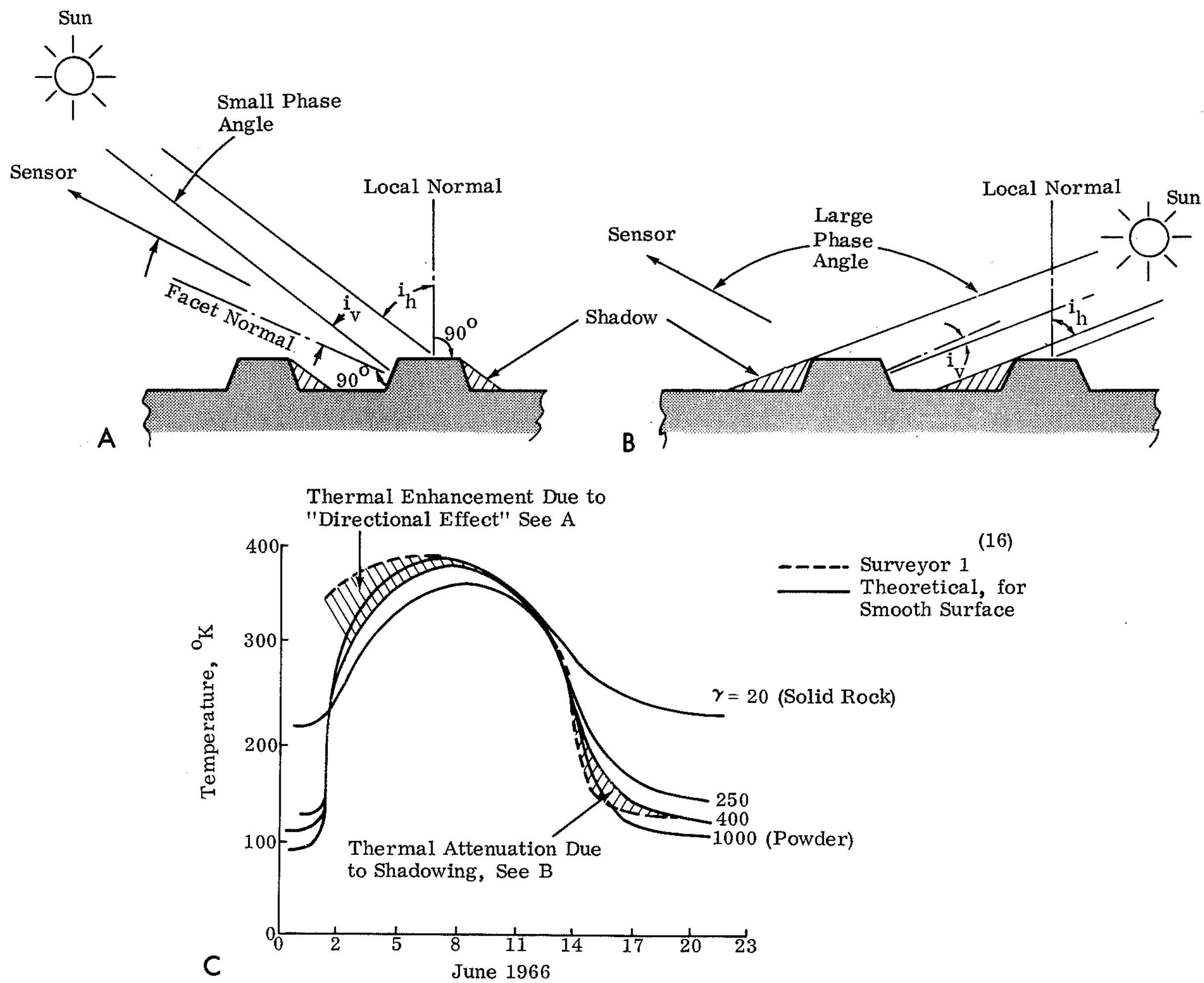


FIGURE 10.—Mechanisms of daytime thermal enhancement and attenuation caused by roughness; diagnosis of Surveyor I data.
(*a*) Directional effect at small phase angles. Observed average temperature is more than temperature predicted for smooth surface because thermally enhanced facets (where $i_v < i_h$) are seen by sensors but shadows are not.
(*b*) Shadowing effect at large phase angles. Observed average temperature is less than temperature predicted for smooth surface because thermally enhanced facets (where $i_v < i_h$) are not seen by sensor but shadows are.
(*c*) Family of theoretical lunation curves and curve for Surveyor I landing site.

microstructure. Thus, a rough area will appear cooler at large phase angles and warmer at small phase angles than will a smooth area, other parameters being equal. The most important of these parameters are albedo, emissivity, and the thermal inertia constant commonly designated as γ. The latter parameter is closely related to hardness or degree of consolidation. Albedo and emissivity could be estimated by using multispectral measurements, but γ must be assumed.

A family of theoretical lunation curves as a function of γ is shown in figure 10(*c*). It previously has been noted that γ does not affect the temperatures at the small phase angles (where directional effects take place) as much as it affects the nighttime temperatures. Notice also that at the large-phase-angle portion of the daytime curve (where shadowing effects are most pronounced) the temperatures are nearly insensitive to wide variations of γ. It appears therefore that thermal emission at large phase angles also is a clue to roughness; this could verify or supplement the roughness inferred from photographic, photometric, radar, and other sources.

Considerations of the scale of roughness that is thermally relevant lead to similar conclusions. The "microshadows" which are formed mostly at the small phase angles are not likely to be thermally as significant as they are at optical wavelengths. During the long lunar day, the small shadows in the recesses of the microstructure progress at a rate slower than that at which heat is transferred into these areas through lateral conduction and radiation. Therefore, the microshadows will be in near thermal equilibrium with their sunlit surroundings. Accordingly, the lunar surface which is known to be rough at optical wavelengths should be relatively smoother at far-infrared wavelengths. In figures 2(*a*) and 2(*d*), a comparison of the sharp backscatter peak of the photometric curve with the convex curvature of the thermal infrared curve supports this view.

If roughness is to have a measurable effect on daytime thermal emissions, it should be at a scale sufficiently large to produce long shadows that remain cooler than their surroundings. In lieu of an actual analysis, one can only speculate that topographic features, including those that are below the resolution of the viewing systems, could cast shadows of this magnitude at large phase angles and reduce the average thermal emission below that predicted for a smooth surface. Thus measurement of lunar temperatures during the early morning and late afternoon periods may have a diagnostic value in terms of roughness that has not been exploited, probably because this possibility is not apparent in the well-known γ-dependent lunation temperature curves in figure 10(*c*). The fact that thermal behavior during these periods is nearly independent of γ should make the interpretation of the data in terms of roughness less ambiguous than it usually is.

Next, consider roughness effects on dark-side temperatures. Roughness will enhance thermal emission during night or eclipse cooling to an extent that is inversely proportional to the duration of the cooling transient. Again, everything else being equal, a rough surface will appear warmer than its smoother surroundings, essentially because its component facets radiate to a value of less than 2π steradians and hence require a longer cooling period than a smooth surface which radiates its heat to a full hemisphere. Unfortunately, the fact that consolidation effects and internal heating also could contribute to thermal enhancement during a cooling phase complicates but does not necessarily obscure the interpretation of lunar hotspots. We suggest the following technique for disentangling the contribution of roughness and internal heating to thermal enhancement observed during the night or an eclipse.

In the first place, one can take advantage of the fact that thermal enhancement caused by roughness, unlike that caused by the other two factors, is of temporary duration. A long cooling transient effectively acts as a time filter during which roughness-induced hotspots fade away and leave those that are caused by internal heating and/or a thermally more conductive, hence, harder, material. Thus, with a sufficiently long cooling period, such as that during the lunar night, a rough and a smooth area of similar thermal and mechanical properties should reach about the same predawn temperature. Interpretation of thermal enhancement during an eclipse would be more ambiguous than would be that of thermal enhancement during the night because it could be caused by any one, or a combination, of the three factors mentioned above. Roughness could be suspected as a primary or unique cause of thermal enhancement during an eclipse only when this enhancement does not persist at night. The converse situation, where an area is thermally enhanced at night but not during an eclipse, is possible in the case of weak anomalies which can be detected only at very low temperatures. In such a case roughness (up to a certain scale than can be estimated) could be eliminated and the interpretation can be narrowed to the other two factors. A similar interpretation may be given to the strong anomalies that are prominent during both the night and eclipse.

A recent quantitative analysis of roughness effects on lunation and eclipse cooling by Staley (ref. 17) and Roelof (ref. 14) support some of these views. Staley estimates that most thermal enhancement in craters observed during eclipse by Shorthill and Saari (ref. 8) can be accounted for in terms of radiative interchange between the crater walls. Roelof reports that during eclipse rocks smaller than a meter in diameter can produce small but detectable variations in Earth-based measurements, but during the night the size of the rocks should be larger than a meter in order that there be a similar effect. He estimates a thermal enhancement of about 3° K during midnight for a typical lunar surface, 1 percent of which is occupied by 3-meter rocks. He points out that this is far more negligible than the value previously estimated by Hopfield (ref. 13). However, he remarks that such rocks could produce strong thermal enhancement in local measurements, such as those made by Surveyor, particularly at sunrise or sunset when the Sun and sensor are on the same side of the local normal. It seems reasonable therefore to neglect roughness as a factor in remotely observed thermal enhancement during the lunar night unless Orbiter photographs and photometric data (if available) indicate otherwise.

As to the other hypothesis (that daytime thermal emission at large phase angles could provide clues to unresolved topographic roughness), it remains to be substantiated by analyses and observations.

Internal Heat Sources

Certainly, the discovery of internal heat sources on the Moon would be of major scientific and engineering significance. The question arises, therefore, whether these sources can be detected by remote means and, if so, whether they can be positively identified as such.

The problem of identification, in the case of the Moon, narrows to being able to discriminate between "geothermal" and "structural" effects since, as we have seen, both effects could contribute to thermal enhancement during the night or eclipse. We focus attention on nighttime temperatures, because they are less subject to roughness effects than are eclipse temperatures and are more likely to reveal weak anomalies that may not be otherwise detected. However, nighttime measurements are not sufficient for a unique identification of the hotspots unless they are supplemented by daytime data. This proposition once more affords an opportunity to stress the importance of temporal data.

We assume for the purpose of this discussion that an internal heat source is detectable, that is, that it is sufficiently strong to have a measurable effect on a remote sensor over and above the thermal emission of the surface because of normal insolation. If this is the case, then it is possible to discriminate between the solar and nonsolar components of the observed emission by balancing the heat budget of the anomaly for a complete day and night cycle. Notice in figures 9 and 10(*c*) that the "hardness" parameter γ perturbs the midnight temperature T_m and the high-noon temperature T_n in opposite directions (T_m increases and T_n decreases with decreasing γ), but an internal heat source would push both day and night temperatures in the same direction (up). Thus, if T_m and T_n are known and the latter is found to exceed the theoretical value predicted by solar input, albedo, emissivity, and T_m, then a nonsolar heat source must be postulated in order to balance the heat budget.

The above concept may be expressed graphically in terms of the area under the curve that represents the thermal-infrared emission during a complete diurnal cycle. This area is independent of the hardness and roughness parameters. In the absence of nonsolar heat and negligible lateral heat losses, it is solely a function of the hemispheric albedo of the surface and the incident solar energy. If it is assumed that the radiated energy is uniform over a hemisphere and albedo differences are accounted for, then processing the data in terms of the area under the lunation curve may be a convenient way of identifying the anomaly. If the index area of the anomaly is more than that of the surrounding region or of the value predicted by solar input, then an internal heat source may be suspected.

The basaltic composition of the maria, as analyzed by Surveyors 5 and 6, suggests that differentiation, probably caused by internal sources of heat, has occurred on the Moon. To date, none of the known thermal anomalies of the Moon have been positively identified as internally hot; this is primarily because of the lack of accurate data on the diurnal behavior of these anomalies, it is believed.

A summary of our thoughts on the nature and meaning of lunar thermal anomalies is presented in table 1. The summary is necessarily oversimplified and is meant to stress major trends in temporal signatures and the supplementary nature of the thermal data during a day, night, and eclipse cycle.

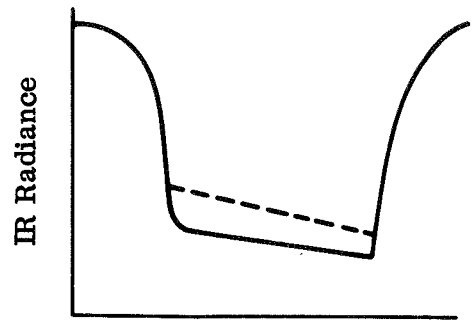
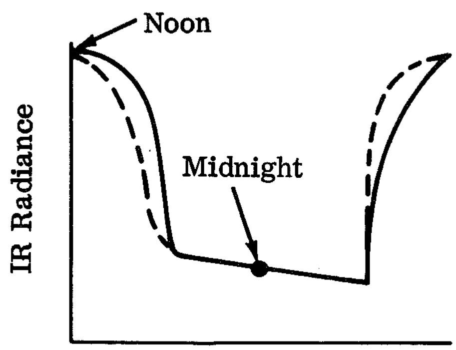
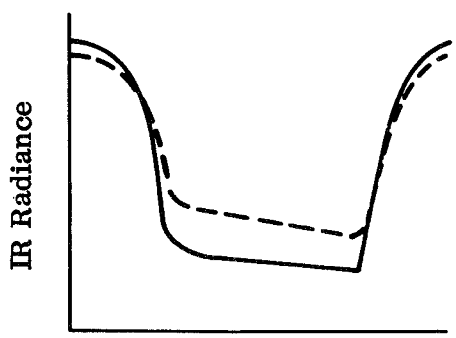
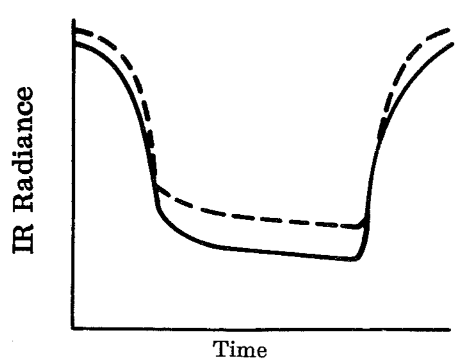
CROSS-CORRELATION OF LUNAR TEMPORAL DATA AT OPTICAL AND INFRARED WAVELENGTHS

The selection of suitable lunar landing sites (suitable from a smoothness and hardness point of view) is discussed here as a case in point to illustrate how temporal data at optical and infrared wavelengths could supplement purely pictorial information including those data recently obtained with the highly successful Lunar Orbiters. We recall how the criteria of smoothness and hardness in the case of the Moon could be correlated, as a first approximation, with the area under the normalized photometric curve and the midnight temperature, respectively. We submit now that accurate measurements of the optical reflections and thermal-infrared emission of the lunar surface during a full lunation, and the computer processing of these data in terms of the above indices, make it possible to rate in a quantitative and objective manner the relative smoothness and hardness of any number of potential landing sites approaching in size the resolution of the viewing system. In Earth-based lunar observations, this resolution can be approximately as fine as a kilometer at optical wavelengths and about 5 to 10 times coarser at infrared wavelengths.

This concept is illustrated in figure 11. The ordinate of the chart, designated as the "optical index," represents the area under the normalized photometric curve and is a direct measure of smoothness as shown in figures 3 and 4. The abscissa, designated as the "thermal-infrared index," represents the midnight temperature and is a direct measure of hardness or bearing strength as shown in figure 9. The data points in the chart represent potential landing sites of known selenographic coordinates selected either at random or from Orbiter photographs. For purposes of discussion, the diagram is arbitrarily divided into four quadrants numbered from 1 to 4 and labeled as soft-rough, soft-smooth, hard-smooth, and hard-rough, respectively. Soft-rough regions are not likely to exist on the Moon as they would be most closely approximated, in our opinion, by forest treetops. A surface of this nature is likely to be optically and thermally subdued at the diagnostic phase angles. In other words, it will appear dark during the day when viewed in the specular direction (i.e., against the Sun) and cold at night. Most lunar areas, including the Surveyor landing sites, are likely to crowd around the center of the diagram, and the anomalies would fall toward the outer edges. Photometric anomalies will occupy the extreme ends of the ordinate, the good (i.e., smooth) anomalies falling in quadrants 2 and 3. Thermal anomalies will occupy the extreme ends of the abscissa, the good (i.e., hard) anomalies falling in quadrants 3 and 4. Consequently, quadrant 3 will be the locus of the best anomalies from the point of view of landing-site selection. These are the areas that are optically enhanced during the day and thermally enhanced during the night.

The classification and pairing of optical and thermal anomalies need not be limited to a few areas of interest, such as those selected from Orbiter photographs. In general, diagnostic indices (such as the coordinates of fig. 11) make it possible to use the computer in processing a vast number of data points, where each point could represent an element of resolution. It should be cautioned that these indices are rarely unambiguous. However, their use in computer processing can be justified as a means of discovering rather than identifying the anomalies. Numerous potential landing sites or prime targets of exploration that may not be otherwise discovered could be located in this

TABLE 1.—*Summary of the Nature and Meaning of Lunar Thermal Anomalies*

Cycle	Temporal signature [a]	Possible clue to—	Comparison index [b]
Eclipse		Roughness Hardness Internal heat (Ambiguous)	Anomaly—warmer during eclipse
Lunation		Roughness	1. Anomaly at oblique viewing is skewed toward small phase angles 2. $A_a = A_b$
		Hardness	1. Anomaly—warmer at night and colder at noon 2. $A_a = A_b$
		Internal heat	1. Anomaly—always warmer 2. $A_a > A_b$

[a] Dotted curve is the anomaly; solid curve is region surrounding anomaly.
[b] A, area under curve; subscripts a and b, anomaly and its surroundings, respectively.

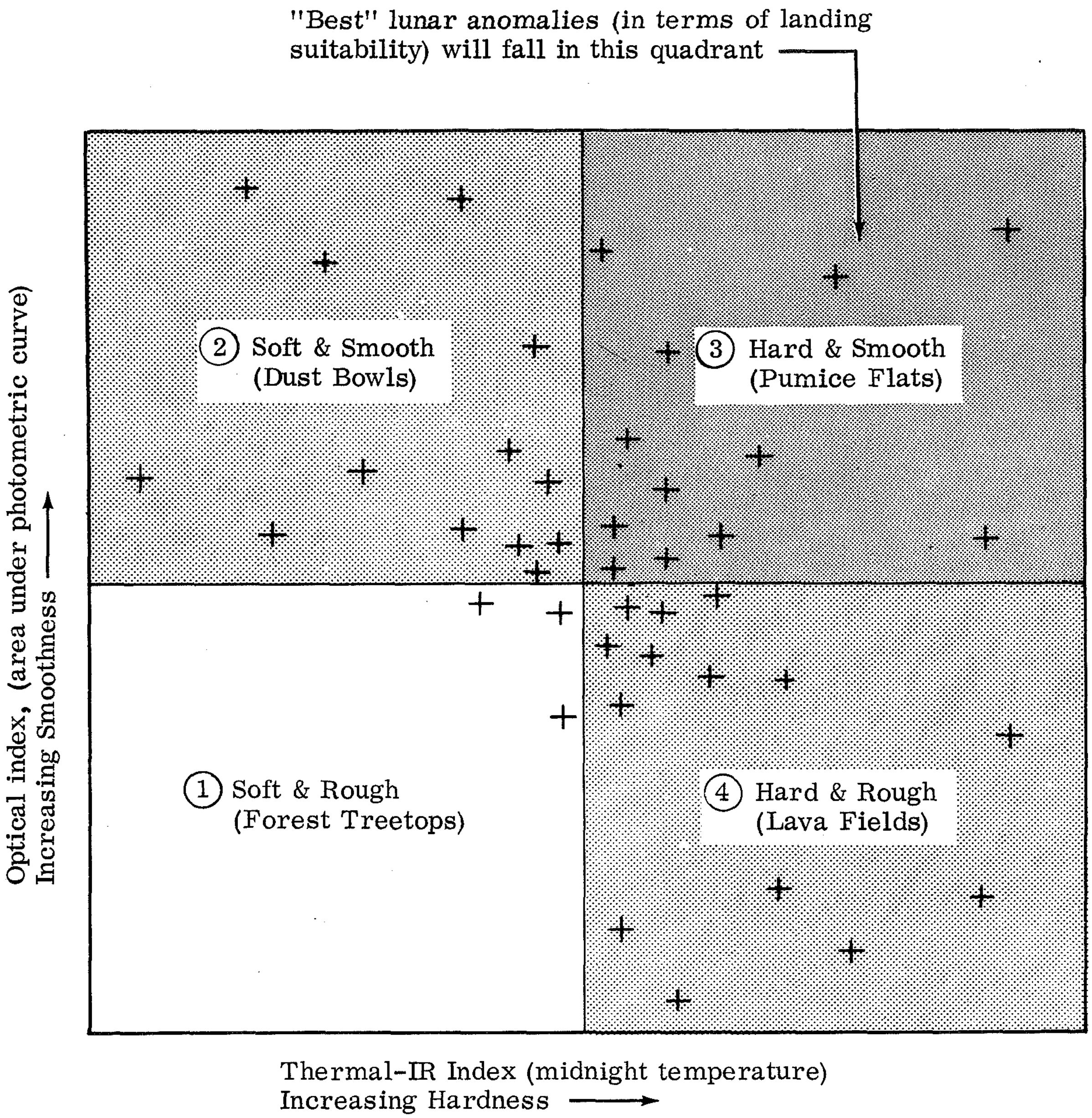


FIGURE 11.—Sorting of lunar photometric and thermal anomalies in terms of correlated terrain smoothness and hardness. Crosses represent investigated areas defined by their selenological coordinates.

manner. Identification could then follow, the process beginning with an examination of the most pronounced anomalies. This process will involve a detailed analysis of the shape and local peculiarities of individual temporal curves. As previously discussed, this analysis could disentangle the contributions of microroughness and macroroughness to the photometric function and the contribution of geometrical, structural, and geothermal factors to the radiometric function. This step could also be automated but only up to a certain point beyond which the interpreter should exercise his judgment.

A CASE FOR EARTH-BASED OBSERVATION OF THE MOON

There is currently a justified optimism on the lunar landing phase of the Apollo mission because of the remarkable success of the Surveyor and Orbiter missions. However, these successes should not obscure the fact that Earth-based observations of the Moon can fill certain specific gaps in our knowledge that were not meant to be explored by these probes. Properties of the lunar surface that can be correlated with temporal observations are examples of such gaps. While temporal data on the Moon can be extracted from thermal measurements and sequential photographs taken by Surveyor craft, such data are limited to the landing sites and can, at best, be used as calibration points for remote, synoptic observations. Orbiter photographs are synoptic in coverage but are presently limited in their spectral and temporal ranges. Earth-based observations of the apparent lunar disk can extend these ranges, although at some loss in spatial resolution. However, the potential of extracting information on surface porosity, subresolution topographic roughness, bearing strength, internal heat sources, and material composition will more than compensate, in our opinion, the loss in resolution.

Ironically, the advent of lunar exploration by manned and unmanned probes is one reason such extensive observations of the Moon have not been made. An equally important reason is that the quantity and quality of the data needed to justify new observations impose severe problems in instrumentation and data processing. For instance, photometric observations are fraught with difficulties of light calibration and film processing when the photographic method is used. More accurate data can be secured by using photocells but at a sacrifice in the quantity and resolution of the data. However, recent advances in image tube technology and digital data processing make it possible to chart the photometry, polarimetry, and spectral reflectance of the apparent lunar disk at a resolution approaching that of conventional lunar photographs and with a gray tone and color fidelity superior to that of these photographs. As to the thermal-infrared emission of the lunar surface, its measurement during the lunar night has been hampered by the limitation of existing sensors to detect temperatures lower than about 100° K. However, progress in this area has been reported by Low (ref. 7), who developed a helium-cooled germanium bolometer capable of measuring these temperatures.

These advances in sensor technology and the availability of ground truth information secured by the Surveyor and Orbiter probes offer the opportunity to verify and refine laboratory-inspired techniques of interpreting lunar pictorial, spectral, and temporal data. Progress in remote sensing, as in other fields of science, will come through continuous feedback between observation and theory. There are cogent reasons why the study of the Moon should be a first step in this particular exercise. The Moon is a more convenient target for temporal observations than is any other object in the sky by virtue of its proximity to and phase relationship with the Earth. Furthermore, the analysis of its optical reflection and thermal-infrared emission is not complicated by convective air currents, ground moisture, and a vegetation or cloud cover, as is usually the case for the Earth and possibly for most other planets. As a proving ground for the subsequent exploration of the planets by remote means, the Moon offers many advantages for developing techniques of data collection and interpretation. Certainly there is no valid reason for doing any observation in space that can be accomplished adequately on the ground.

CONCLUSIONS

We have defined "temporal data" as the repetitive, sequential measurement of electromagnetic radiation from a planetary surface during a periodic cycle and found that these data can be correlated with terrain properties that cannot be readily inferred from pictorial or spectral data.

Information on unresolved structure is the most important payoff resulting from temporal data at optical wavelengths. It can now be reported that both microstructures and macrostructures beyond the resolution of the viewing system are important contributions to the standard lunar photometric function and that they can be discriminated by photometric means. Experiments clearly show that the two scales of roughness perturb the leading edge (i.e., opposition region) and the tail end of the photometric curve independently of each other. They also suggest that improvement in spatial resolution could lead to the discovery of lunar photometric anomalies and to a thematic mapping of the lunar surface in terms of its microstructure and topographic roughness.

The percent polarization-versus-time curve at visible wavelengths appears also to be a function of structure, whether the surface is vegetative or mineral, but it is much less understood.

Temporal data on thermal infrared emission during a heating and cooling cycle appear to be very rewarding but more difficult to measure and interpret. In the case of the Moon, it is well recognized that a number of factors, such as surface roughness, degree of consolidation (i.e., bearing strength), and internal heat sources, could contribute to and hence obscure the meaning of these data. However, our analysis shows that nighttime thermal emissions are less ambiguous (although more difficult to measure) than those during an eclipse. When nighttime temperatures are supplemented by daytime data, it appears theoretically possible to disentangle the contribution of the relevant factors. These possibilities suggest that accurate measurements and proper analysis of the thermal infrared emission of the lunar surface during a complete day-and-night cycle could lead to the discovery of suitable landing sites and geothermal heat sources.

One last point should be explained regarding the logistics of acquiring temporal data, particularly from an Orbiter. Temporal observations in the field need not consist, as we have tacitly implied throughout this report, of repetitive measurements made at relatively close intervals of time, such as those made in the laboratory. Model-matching studies indicate that a considerable saving in the quantity of data could be accomplished, without appreciable loss of information, by limiting the field observations to a few specific Sun and viewing angles. For instance, the critical diagnostic moments during photometric observations occur at oblique viewing (say, at 60° off the local vertical) when the Sun is (1) in opposition, (2) a few degrees past opposition in the direction of the local vertical, and (3) in the specular direction. A fourth intermediate point at high noon is desirable but is not necessary. The ratio of the brightness at points (1) and (2) is a measure of textural complexity or surface porosity. (Large features as such have no effect on this ratio unless, of course, their microstructure differs from that of their surroundings.) The ratio of points (1) and (3) is a sensitive clue to macrostructure or topographic roughness. Similarly, at far-infrared wavelengths, the critical measurements are those made at high noon and midnight. While midnight temperatures are sufficient to reveal thermal anomalies, data on albedo, emissivity, and noon temperatures are necessary to identify the anomaly in terms of geophysical and geothermal factors. These considerations suggest a polar, Sun-synchronous orbit around the Moon as the most suitable for infrared observations. The complete lunation curve serves only to refine these estimates and provide additional clues to surface structure when the viewing is at oblique angles.

The usefulness of temporal data coupled with recent advances in sensor and computer technologies justify, in our opinion, renewed telescopic observations of the Moon as a source of information for lunar mission planning and possibly as a prelude to similar measurements from space.

REFERENCES

1. ADAMS, J. B.: Lunar Surface Composition and Particle Size: Implications of Laboratory and Lunar Spectral Reflectance Data. J. Geophys. Res., vol. 72, 1967, pp. 5715–5720.
2. HOVIS, N. A., JR.; AND TOBIN, M.: Spectral Measurements from 1.6 μ to 5.4 μ of Natural Surfaces and Clouds. Appl. Opt., vol. 6, 1967, pp. 1399–1402.
3. LYON, R. J. P.: Evaluation of Infrared Spectrophotometry for Compositional Analysis of Lunar and Planetary Soils. NASA CR 100, 1964.
4. ORLOVA, N. S.: Selected Articles on Light Scatter-

ing and Photometric Relief of the Lunar Surface. NASA TT F-74, 1962.

5. LYOT, B.: Research on the Polarization of Light From Planets and From Some Terrestrial Substances. NASA TT F-187, 1964.
6. PETTIT, E.; AND NICHOLSON, S. B.: Lunar Radiation and Temperatures. Astrophys. J., vol. 71, 1930, p. 102.
7. LOW, F.: Lunar Nighttime Temperature Measured at 20 Microns. Astrophys. J., vol. 142, 1965, p. 806.
8. SHORTHILL, R. W.; AND SAARI, T. M.: Non-Uniform Cooling of the Eclipsed Moon. A Listing of Thirty Anomalies. Science, vol. 150, 1965, pp. 211–212.
9. HALAJIAN, J. D.: Photometric Investigation of Simulated Lunar Surfaces. J. Astronaut. Sci., vol. XIV, no. 1, 1967, pp. 1–12.
10. GEHRELS, T.; COFFEEN, T.; AND OWINGS, D.: Wavelength Dependence of Polarization of the Lunar Surface. Astron. J., vol. 69, no. 10, 1964.
11. HALAJIAN, J. D.: Albedo and Photometry of Surveyor Footprints. Grumman Rept. No. AS 424-5, Grumman Aircraft Eng. Corp., 1968.
12. HALLOCK, H. B.; AND GRUSAUSKAS, J.: Polarimetric Signature of Natural Water Surfaces. J. Opt. Soc. Am., vol. 57, no. 4, Paper FE12, 1967.
13. HOPFIELD, J. J.: Lunar Temperatures. T.G. No. 26, Tycho Group, Univ. of Minnesota, 1966.
14. ROELOF, E. C.: Thermal Behavior of Rocks on the Lunar Surface. Boeing Sci. Res. Lab. Rept. 01-82-0641, Boeing Co., 1967.
15. HALAJIAN, J. D.; REICHMAN, J.; AND KARAFIATH, L. L.: Correlation of Mechanical and Thermal Properties of Extraterrestrial Materials. Grumman Res. Dept. Rept. No. RE-280, Grumman Aircraft Eng. Corp., 1967.
16. LUCAS, J. W.; CONEL, J. E.; AND HAGEMEYER, W. A.: Lunar Surface Thermal Characteristics from Surveyor 1. J. Geophys. Res., vol. 72, no. 2, 1967, pp. 779–789.
17. STALEY, D. O.: Radiative Enhancement of Lunar Hot Spots During Eclipse. J. Geophys. Res., vol. 73, no. 6, 1968, pp. 2049–2055.

NORMAN N. GREENMAN and W. BRYAN MILTON
Douglas Aircraft Co.
Santa Monica, Calif.

Silicate Luminescence and Remote Compositional Mapping

Exploration for resources on the Moon will require, as it does on Earth, geologic maps of large areas of the surface. These can best be provided by remote sensing techniques from lunar orbiters. Almost two decades ago, when Link proposed that luminescence exists on the Moon, the possibility arose that this property could be the basis for such a technique, both for mapping the country rocks and for localizing the more rare mineralized zones. To evaluate this possibility, luminescence intensities of the common igneous rock-forming minerals (to represent likely lunar country rock constituents) were measured with proton, electron, and X-ray excitation. The feldspars showed the highest intensities, and quartz, the next highest; intensities of the ferromagnesian minerals (mica, amphibole, pyroxene, and olivine) were very low, for the most part. This order of intensity was the same with all three excitation types. These results indicate that lunar acidic, basic, and ultrabasic rocks could be distinguished from one another on the basis of luminescence intensity. To represent possible lunar resource materials, volcanic, hydrothermal, and pneumatolytic minerals that may exist on the Moon, many of which contain water or OH groups in the lattice, will be measured in continuation studies now in progress. These studies will also include the measurement of luminescence spectra, grain size, temperature, and radiation damage effects and the use of ultraviolet radiation as an excitation source.

INTRODUCTION

The exploitation of lunar resources is one of the prime practical objectives of the Nation's space program. Water will head the list of resources to be located because of its importance for life support and for supplying hydrogen and oxygen for rocket fuel, but iron and metals generally, sulfur, and other useful materials will also have high priority. If experience on Earth is any guide, an exploitable deposit of a given resource will probably be associated with specific rock types and/or specific geologic environments such as volcanic terrains, areas of intrusives, and faulted and fractured zones. Exploration will therefore be best pursued as on Earth by first mapping the lithologic composition and other geologic features over large areas of the Moon and then by exploring intensively the areas shown by the mapping to have most promise. The compositional information derived in the early manned landing missions from limited areal reconnaissance by the astronauts and from the returned samples will not fulfill these needs because it will represent only a few sampled points from a surface as large as one-fourth the land area of the Earth. Remote sensing techniques from lunar orbiters will therefore play an indispensable role in the search for lunar resources, both in mapping the surface composition over large areas and in selecting promising localities for on-the-ground exploration.

The possibility of using luminescence measurement and analysis as a suitable technique for remote compositional mapping arose when Link (ref. 1) first proposed the existence of luminescence on the lunar surface to explain the excess of light he observed in the penumbra during many lunar eclipses. Its existence was later confirmed by Kozyrev (ref. 2), Dubois (ref. 3), Grainger (ref. 4), and Spinrad (ref. 5) by means of the sensitive line-depth technique, in which the depths of corresponding Fraunhofer lines in the solar and lunar spectra are compared. We are making laboratory measurements of terrestrial rocks and minerals likely to occur on the Moon to test whether they display distinctive luminescence characteristics upon which a remote sensing system can be based and, if they do, to gather the information needed to interpret the remote sensing data. Two groups of samples are required in these measurements—one to represent the common rock types that may be present over most of the lunar surface, and the other to represent the more rare mineralized zones where the resources are likely to be concentrated. In this paper we report some results of our studies with the first group to answer, in particular, the question of whether the common lunar rock types can be distinguished on the basis of their luminescence intensity.

EXPERIMENTAL ARRANGEMENT

Luminescence was excited with protons, X-rays, and electrons. (Ultraviolet excitation, the most important source in the natural radiation environment of the Moon, was not used in these first measurements because more complex instrumentation would have been required to eliminate the interfering background of visible light present in ultraviolet lamps; it is being used in our later studies.) Total luminescence intensity was measured with all three types; measurements of luminescence spectra with proton excitation were also made.

Figure 1 shows the experimental arrangement for the measurements with proton excitation. A Texas nuclear neutron generator was used to provide a 2.5-centimeter-diameter beam of 20 keV protons with a flux of 10^{12} protons cm^{-2} sec^{-1} for the total intensity measurements. The light was detected by an RCA 931A photomultiplier (3000- to 7000-ampere response, 4000-ampere peak) placed at the sample chamber window directly above the sample. For the spectral measurements, the entrance slit of a Gaertner quartz-prism monochromator was placed at the sample chamber window, as shown in the figure, and the detector at the exit

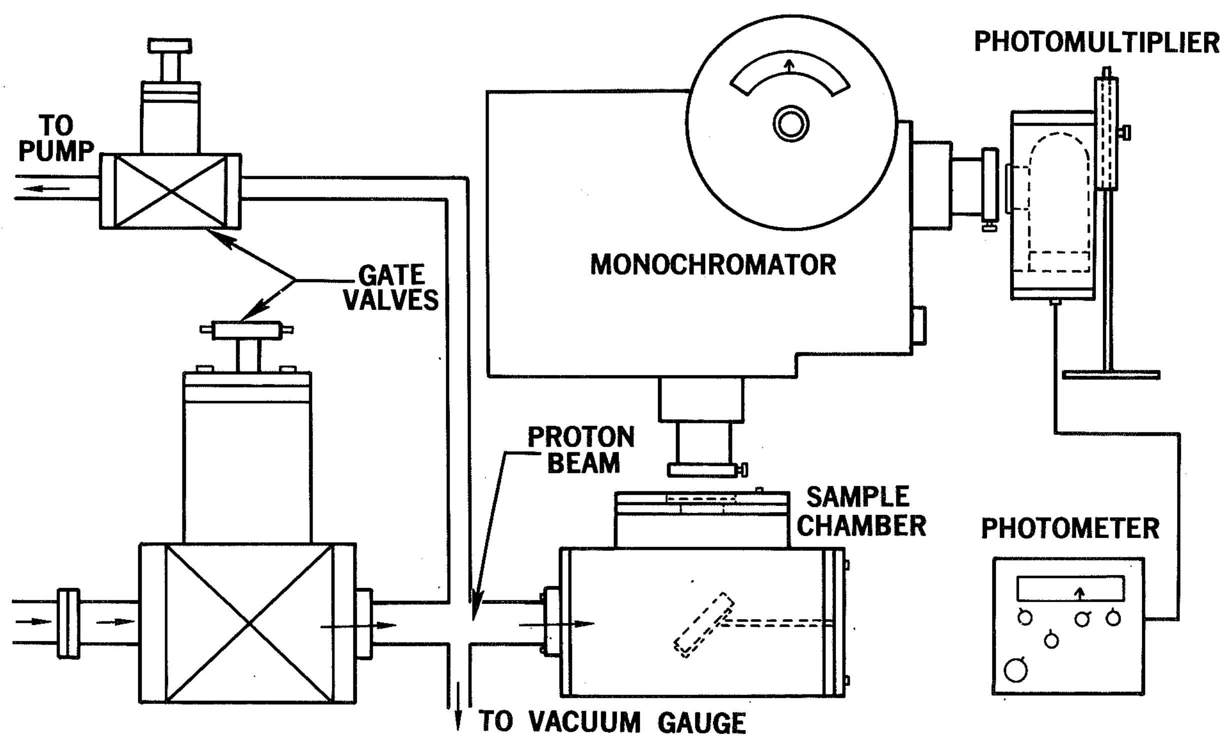


Figure 1.—Luminescence measurement apparatus for proton excitation.

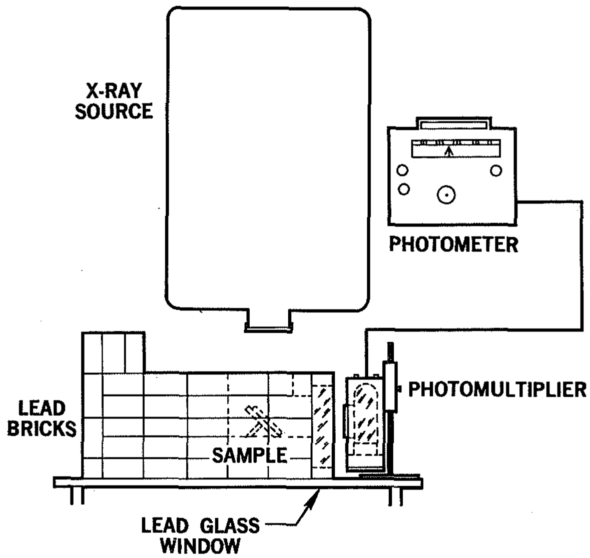


FIGURE 2.—Luminescence measurement apparatus for X-ray excitation.

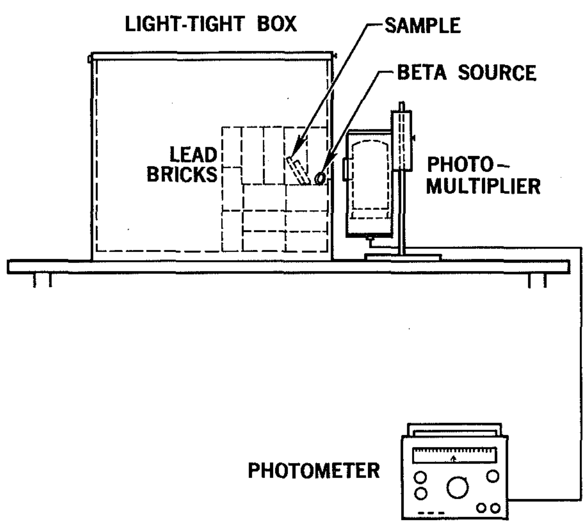


FIGURE 3.—Luminescence measurement apparatus for electron excitation.

slit was an RCA 1P28 photomultiplier (2000- to 7000-ampere response, 3500-ampere peak) designed to give better sensitivity at the short-wavelength end of the range. For these measurements the proton energy was increased to 150 keV and the flux to 8×10^{12} protons cm^{-2} sec^{-1}.

The experimental arrangement for the measurements with X-ray excitation is shown in figure 2. The X-rays were from a tungsten target, and the tube was operated at 200 kilovolts and 4.5 milliamperes. A lead-glass window was used to shield the RCA 931A photomultiplier from scattered X-rays. Transmission measurements of the lead glass showed that it cut out some of the blue end of the spectrum, but this introduced no serious error in the relative luminescence intensities because the mineral spectral peaks, except in the case of the low-intensity mineral hornblende, are in the region of high transmission of the glass.

Figure 3 shows the experimental arrangement for the measurements with electron excitation. The electrons were obtained from the beta decay of ^{90}Sr which provided electrons of up to 2.3 MeV energy with a flux, in this configuration, of about 10^8 electrons cm^{-2} sec^{-1}. The RCA 931A photomultiplier was the light detector here, also.

SAMPLES

Even before the Surveyor landings, the evidence of the meteorites and other considerations suggested that the lunar rocks were probably silicates and probably most closely resembled terrestrial igneous rocks. The results of the Surveyor alpha-scattering experiments are in remarkable agreement with this; they give chemical compositions very close to those of terrestrial basalt and gabbro (refs. 6 and 7). Therefore, the common igneous rock-forming minerals were chosen to represent the rock types likely to be most abundant on the lunar surface for this first study. Minerals were chosen because they are more restricted in composition and structure than are rocks and, as a result, can be expected to give a more nearly uniform response. Rocks, by definition, are aggregates of minerals, and their luminescence characteristics can be deduced from the characteristics of their constituent minerals. Single crystals or coarsely crystalline aggregates were measured.

With mineral data, luminescence intensity calculations can be made for any rock in the differentiation series. The extent to which differentiation may have occurred on the Moon is unknown. The one published Surveyor VII chemical analysis from a lunar continental area is not greatly different from the maria analyses of Surveyors V and VI (ref. 8), which suggests that differentiation, if it occurred at all, may be much less advanced than it is on Earth. However, the data are too few to be conclusive, so that in this study the entire range from granitic to ultrabasic was considered.

No meteorite samples were measured, but since the average meteorite composition is approximated very closely by one part iron, which is not luminescent, to three parts peridotite, the luminescence characteristics of meteorites can be deduced from the mineral data. The Surveyor V, VI, and VII magnet experiments indicated that little or no material of chondritic or iron meteorite composition was present at the landing sites (refs. 9 to 11), but, again, these few data do not eliminate the possibility that such material exists elsewhere on the Moon. In fact, any local accumulations of iron or iron-rich meteorites would constitute important resources; therefore, meteorites were considered in this study.

RESULTS

The relative luminescence intensities of the measured samples are shown in table 1, with the value for smoky quartz, set at 100, taken as the standard. With a few exceptions the results for the three types of excitation are in generally good agreement. The highest intensities are shown by the potassium feldspars and the sodic members of the plagioclase feldspars (albite and oligoclase). Next in intensity are quartz and the calcic plagioclases (labradorite and bytownite). The ferromagnesian minerals (mica and all those listed below it in the table) show very low intensities. Nash, in his experiments with proton excitation, also found quartz and the feldspars to exceed the ferromagnesians in luminescence intensity, although he found the quartz intensity to be higher than that of feldspar (ref. 12).

Quartz and feldspar make up the bulk of most of the common igneous rocks, so that, on the basis of both abundance and intensity, these minerals clearly dominate the luminescence response of the igneous rocks. The higher intensity members—quartz, potassium feldspar, and sodic plagioclase—occur typically in the acid, or granitic, rocks; the basic, or gabbroic, rocks typically contain the lower intensity calcic plagioclase and little or no quartz. These two rock types, therefore, can be expected to differ significantly in luninescence intensity. Figure 4 summarizes these relations.

The luminescence intensities of the igneous rocks can be estimated in greater detail by applying the data in table 1 to the known or calculated mineral compositions of the various rocks in the differentiation series. Listed in table 2 are average chemical compositions of these rocks. Granite and basalt are the acidic and basic members, respectively. Diorite and the average igneous represent intermediate members, and peridotite the ultrabasic. The stony component that makes up about three-fourths of the average meteorite is very close in composition to peridotite. With these data and the known chemical compositions of the minerals, the mineral composition was calculated for each rock. The results are shown in table 3; they clearly indicate the decrease in quartz and potassium feldspar and the increase in plagioclase (except in the ultrabasic rocks) and ferromagnesians in going from granite to peridotite. Though not shown in the table, the increase in plagioclase also involves a progressive change from dominantly sodic composition at the granite end of the range to dominantly calcic composition at the basalt and peridotite end. Finally, for each rock the mineral proportions were multiplied by the relative luminescence intensity of the corresponding minerals from table 1 and the results were added to give the numbers shown in table 4; these are the estimated relative luminescence intensities of the various igneous rocks, including meteorites, that would be measured with proton, X-ray, and electron excitation.

For all three excitation types, the data of table 4 show a maximum intensity for granite and a progressive decrease to a minimum intensity at the ultrabasic end of the differentiation series. Moreover, over the granite-peridotite range there is no overlap between rocks of the intensity values for the three excitation types, except in the case of diorite and basalt which, in any event, are close together in the differentiation series. Applied to

TABLE 1.—*Relative Luminescence Intensity of the Common Igneous Rock-Forming Minerals With Various Types of Excitation*

[Value for smoky quartz, 100, taken as standard]

Mineral	Intensity with excitation by—		
	Proton	X-ray	Electron
Quartz:			
Milky	57	54	250
Rose	49	43	120
Smoky	100	100	100
K-feldspar:			
Orthoclase	380	270	260
Microcline	720	680	410
Plagioclase feldspar:			
Albite	450	200	400
Oligoclase	320	590	730
Labradorite	58	19	21
Bytownite	74	260	92
Mica:			
Muscovite	1. 8	0	2. 8
Biotite	. 4	0	. 8
Amphibole: Hornblende	. 1	0	1. 6
Pyroxene:			
Enstatite	3. 2	0	13
Diopside	. 5	57	47
Hypersthene	1. 4	0	1. 5
Hedenbergite	. 1	15	3. 6
Augite	2. 8	1. 4	6. 3
Olivine:			
Olivine I (Arizona)	5. 5	0	15
Olivine II (North Carolina)	. 6	0	12

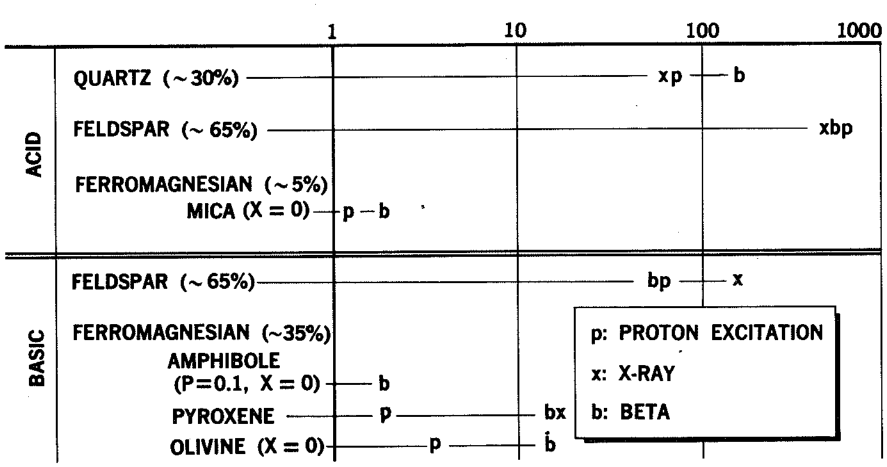


FIGURE 4.—Relative luminescence intensity of acid and basic igneous rock minerals.

TABLE 2.—*Chemical Composition of Possible Lunar Rocks*

Oxide	Amount, percent, in—					
	Granite [a]	Average igneous rocks [b]	Diorite [c]	Basalt [d]	Peridotite [e]	Meteorite [f]
SiO_2	71.6	59.4	55.5	49.1	42.0	35.3
Al_2O_3	14.5	15.4	17.0	15.7	4.7	2.9
Fe_2O_3	1.5	6.4	2.7	5.4	8.1	.1
FeO	1.1		4.8	6.4	5.6	13.0
MgO	.9	3.5	4.4	6.2	25.5	19.7
CaO	2.0	5.1	7.3	9.0	6.4	2.6
Na_2O	3.0	3.8	3.6	3.1	.8	.8
K_2O	4.1	3.1	2.4	1.5	.2	.2
Others	1.3	3.3	2.3	3.6	6.8	2.3
Total	100.0	100.0	100.0	100.0	100.1	76.9
Iron meteorite						23.0
Total						99.9

[a] From work of Tschirwinsky, cited in ref. 13.
[b] From work of Goldschmidt, cited in ref. 13.
[c] From work of Rosenbusch-Osann, cited in ref. 13.
[d] From work of Daly, cited in ref. 13.
[e] From work of Pirsson and Knopf, ref. 13.
[f] From work of Daly, cited in ref. 14; Watson, cited in ref. 15; and Mason, ref. 15.

TABLE 3.—*Mineral Composition of Possible Lunar Rocks*

	Amount, percent, in—					
	Granite	Average igneous	Diorite	Basalt	Peridotite	Meteorite
Quartz	32	13	6			
K-feldspar	23	19	15	10	1	1
Plagioclase	38	42	47	54	17	11
Mica	4					
Amphibole		21	20			
Pyroxene:						
Enstatite		3	6	7	22	17
Other		2	6	13	12	10
Olivine				13	42	38
Accessories	3	1	1	4	6	
Total	100	101	101	101	100	77
Iron meteorite						23
Total						100

TABLE 4.—*Estimated Relative Luminescence Intensity of Possible Lunar Rocks*

Rock	Intensity with excitation by—		
	Proton	X-ray	Electron
Granite	300	280	350
Average igneous	210	210	220
Diorite	120	140	89
Basalt	91	130	69
Peridotite	19	31	24
Meteorite	15	22	19

remote sensing, these results indicate that lunar counterparts of the rocks listed in the table should be distinguishable on the basis of luminescence response. At the very least, it should be possible to map lithologic differences over large areas. The particular rock types could then be identified by the use of spectral data in addition to intensity data and by calibration of the detected signal with the samples returned by the Apollo manned landing missions.

The meteorite and peridotite values in table 4 also represent a case of overlap, but this, it should be recalled, applies to the average meteorite composition, which contains about one part in four of iron. In any particular instance, an area of the Moon covered by iron meteorites only, a most favorable resource locality, would show almost zero luminescence. Chondritic stony meteorites, on the other hand, would be expected to have a luminescence intensity indistinguishable from that of peridotite, whereas the basaltic achondrites could probably not be distinguished from basalt on the basis of intensity.

Some of the luminescence spectra of the minerals measured with proton excitation are shown in figures 5 and 6. The bandwidth of the quartz prism monochromator with the slit widths required was rather wide in the visible wavelengths; therefore, the spectra have been corrected to give values over more narrow intervals. The most outstanding feature is the tendency for the quartz and the feldspar spectral peaks to occur at wavelengths longer than 500 mμ and for the ferromagnesian spectral peaks to occur at wavelengths shorter than 500 mμ. Other spectral differences are apparent, but their significance cannot be evaluated without additional study, especially of numerous samples of each mineral representing various localities, geologic ages, and forms of crystallization, and of the flash and aging effects described by Nash (ref. 12). These additional studies are now in progress.

The measurements of the common igneous rock-forming minerals just described will assist in mapping the country rocks of the Moon and, to the extent that resource deposits are associated with one or another rock type, will assist in selecting areas that should be explored more intensively. We would like also to use remote sensing techniques based on luminescence to detect resource deposits directly. For this purpose we are studying some of the more important pneumatolytic and hydrothermal minerals that may be stable or metastable under lunar-surface conditions. Hydrothermal and pneumatolytic deposits may occur on the Moon if internal processes, such as local volcanism and defluidization, have been active, as seems to be the case according to evidence from lunar orbiter photographs and from studies of lunar transient events. The deposits could occur as surface blankets or as fillings and linings of fissures opened by either impact or internal forces. They will be a prime target for lunar resource exploration both because of the water and other resources contained in the minerals and because the fissure itself, in the case of fissure occurrences, may have been an avenue for rising fluids and may contain bodies of water (or ice) trapped below the surface. The hydrothermal and pneumatolytic minerals included in our studies are the silicates, epidote, serpentine, chlorite, and the zeolites, which contain water or OH groups; sulfur and the sulfates; barite and alunite, which are sources of sulfur; and the carbonates calcite and magnesite, of which calcite, at least in some of its forms, is known to be a strongly luminescent mineral.

Some resource materials are known to be strongly luminescent and could be detected against the relatively much more weak lumi-

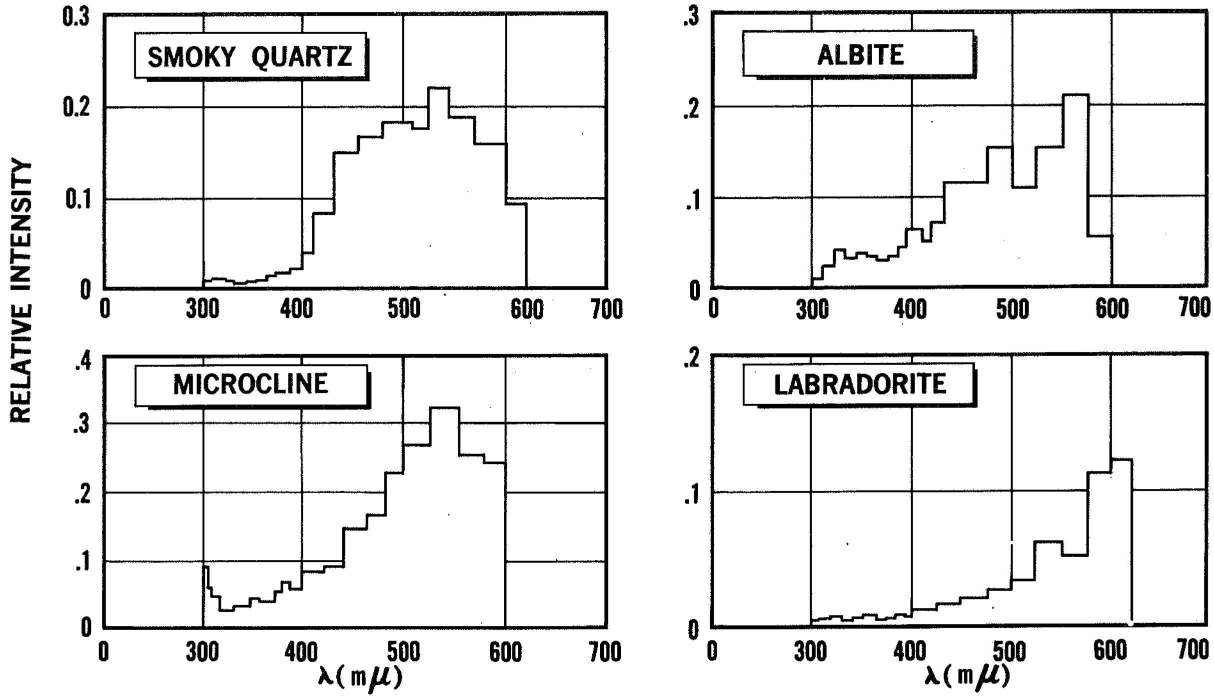


Figure 5.—Luminescence spectra of quartz and feldspars with proton excitation.

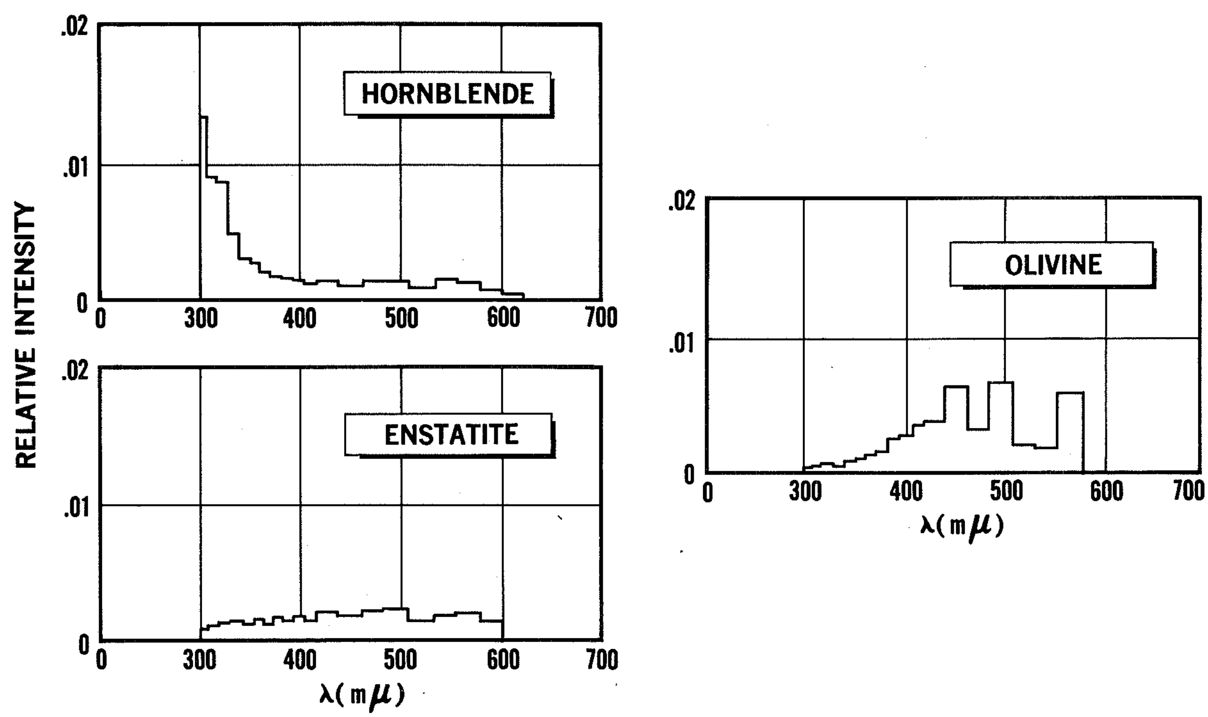


Figure 6.—Luminescence spectra of ferromagnesian minerals with proton excitation.

nescence of the common igneous rocks. These include fluorite (CaF_2), scheelite ($CaWO_4$), and kunzite, a type of spodumene ($LiAlSi_2O_6$).

In the studies now in progress, we are also evaluating ultraviolet radiation as an excitation source and studying the effects of grain-size variation, temperature variation, and radiation damage on the luminescence characteristics. The results of these studies are expected to provide a foundation upon which a luminescence remote sensing technique can be built both for general geologic mapping and for the discovery of resource deposits.

REFERENCES

1. Link, F.: Sur la Luminescence Lunaire. Compt. Rend. Acad. Sci., vol. 223, 1946, p. 976.
2. Kozyrev, N. A.: The Luminescence of the Lunar Surface and the Intensity of Solar Corpuscular Radiation. Izv. Krymsk. Astronfiz. Observ., vol. 16, 1956, pp. 148–158.
3. Dubois, J.: Contribution à l'Étude de la Luminescence Lunaire. Rozpravy Cesk. Akad. Věd, vol. 69, 1959, pp. 1–42.
4. Grainger, J. F.: Lunar Luminescence Investigations. Astron. Contributions Univ. of Manchester, ser. III, no. 104, June 1963.
5. Spinrad, H.: Lunar Luminescence in the Near Ultraviolet. Icarus, vol. 3, Dec. 1964, pp. 500–501.
6. Turkevich, A. L.; Franzgrote, E. J.; and Patterson, J. H.: Chemical Analysis of the Moon at Surveyor V Landing Site: Preliminary Results. Surveyor V—A Preliminary Report. NASA SP-163, 1967, pp. 107–132.
7. Turkevich, A. L.; Franzgrote, E. J.; and Patterson, J. H.: Chemical Analysis of the Moon at Surveyor VI Landing Site: Preliminary Results. Surveyor VI—A Preliminary Report. NASA SP-166, 1968, pp. 109–132.
8. Turkevich, A.: Lunar Surface Chemical Composition. American Geophysical Paper P118, 49th Annual Meeting, Am. Geophys. Union (Washington, D.C.), Apr. 8–11, 1968.
9. De Wys, J. N.: Lunar Surface Electromagnetic Properties. Surveyor V—A Preliminary Report. NASA SP-163, 1967, pp. 133–154.
10. De Wys, J. N.: Electromagnetic Properties: Magnet Test. Surveyor VI—A Preliminary Report. NASA SP-166, 1968, pp. 133–143.
11. De Wys, J. N.: Results and Implications of Magnet Experiments on Surveyor 5, 6, and 7 Spacecrafts. Paper P118a, 49th Annual Meeting, Am. Geophys. Union (Washington, D.C.), Apr. 8–11, 1968.
12. Nash, D. B.: Proton-Excited Luminescence of Silicates: Experimental Results and Lunar Implications. J. Geophys. Res., vol. 71, May 1966, pp. 2517–2534.
13. Pirsson, L. V.; and Knopf, A.: Rocks and Rock Minerals. John Wiley & Sons, Inc., 1946.
14. Krinov, E. L.: Principles of Meteoritics. Pergamon Press (New York), 1960.
15. Mason, B.: Principles of Geochemistry. John Wiley & Sons, Inc., 1952.

Page intentionally left blank

THOMAS C. ATCHISON and CLIFFORD W. SCHULTZ
Bureau of Mines
Twin Cities Mining Research Center
Minneapolis, Minn.

Bureau of Mines Research on Lunar Resource Utilization

The Bureau of Mines is cooperating with NASA to provide through a program of multidisciplinary research the basic scientific and engineering knowledge that will be needed to utilize extraterrestrial mineral resources for support of future space missions. The concept, scope, and present status of the Bureau's program are described in this paper.

INTRODUCTION

A scientific challenge unparalleled in history faces man in his exploration of space. In an amazingly short time he has demonstrated his ability to probe the far reaches of the solar system by sending unmanned space vehicles to the Moon, Mars, and Venus, and into orbit around the Sun. In the next few years he expects to land on the Moon. This achievement will mark the beginning of the exploration of the Moon and the planets by man himself.

The problems posed by manned lunar exploration have been receiving serious study for several years. In some cases, such as the problem of transporting man on the Moon, full-scale vehicles have already been constructed. Much thought has also gone into the design of lunar bases which will be essential for any sustained exploration effort. Because supplying these bases will be a major logistical problem, success in using the Moon's raw materials to reduce the dependence of lunar bases on supplies shipped from Earth may be a critical element in advancing lunar and planetary exploration (refs. 1 to 8).

Although the actual use of raw materials that may be available on the Moon for the support of manned bases is probably at least a decade away, the problems of lunar mining and processing have been under active consideration for some time (refs. 9 to 19). When requirements for a new technology are foreseen, it is important to allow adequate leadtime for obtaining the basic knowledge needed for the efficient solution of engineering and hardware development problems. The need for a farsighted approach is especially acute in the area of extraterrestrial resource utilization, where learning by experience is not tolerable and crash programs to develop urgently needed information are very costly. This is exactly what NASA's Office of Advanced Research and Technology had in mind when, in mid-1965, it began providing funds to the Bureau of Mines for research on the basic scientific and engineering knowledge needed for developing an extraterrestrial mining and processing technology.

The purpose of the present paper is to describe the nature and extent of the Bureau's research and to outline briefly the progress thus far achieved. References 20 to 22 report in some detail on specific parts of the research program.

METHOD OF ATTACK

Although the use of mineral resources on any body in space falls within the scope of the Bureau's program, emphasis has been placed on mining and processing problems on the Moon as a matter of first priority. The idea of mining and processing mineral resources is intended to apply here in its broadest sense.

Thus we are concerned with problems involved in using lunar-surface materials in virgin form for such purposes as shielding or insulation, in modifying surface materials for use in construction or other applications, and in extracting from lunar-surface or near-surface materials such products as water, oxygen, or other useful constituents.

Our method of attack on these problems is based on the premise that mining and processing of mineral resources involve the application of energy to a material to accomplish the removal or separation of all or part of the material under the conditions imposed by the environment in which the material exists or is placed. Mining and processing technology will evolve from research in an orderly and progressive manner as knowledge of the following is developed:

(1) Properties of the material

(2) Effect of environmental factors on these properties

(3) Parameters of the various energy mechanisms that can accomplish removal of the material

(4) Laws or relationships that govern the interaction of a specific energy mechanism and material under the existing or an imposed environment

Because the Bureau is using the same approach to develop new and improved methods for mining and processing on Earth, we are meeting the needs of the NASA program largely by extending the scope of research already in progress at the Twin Cities Mining Research Center and a number of other Bureau centers. The resulting expanded research benefits the Bureau by providing new information and fresh perspectives that may apply to its own program. At the same time it meets the needs of NASA in an efficient manner, since it makes use of a broad base of capability in Bureau manpower and facilities and limits NASA funding to that required to extend the current research to the extraterrestrial situation.

Actually the basic knowledge needed to develop a technology for mining and processing on the Moon is the same as that needed for advancing mining and processing technology on Earth, except for the modifying effects of two important factors: (1) space logistics and economics, and (2) the lunar environment. Operations under conditions where air and water are precious materials, where initial plant investment is of minor concern, and where ordinary manual labor is difficult or impossible are bound to be different from operations that we are familiar with on Earth. A gravity force one-sixth that of Earth, surface temperatures ranging from $-250°$ to $250°$ F, the absence of an atmosphere (resulting in a pressure 10^{-13} that of Earth), and no protection from radiation or micrometeorites will certainly affect the properties of materials and the nature of physical processes in ways not always easily predicted from our earthbound experience.

The first factor—space logistics and economics—imposes limits on the size, weight, and power requirements for mining and processing equipment and emphasizes the need for simplicity, reliability, and automation for mining and processing systems. These restrictions must be considered when one is contemplating the scientific knowledge needed for developing a lunar technology because they will be critical at the later stage of actual engineering development. The second factor—the lunar environment—is critical to all aspects of mining and processing on the Moon. It undoubtedly has had a major influence on the present character of the lunar surface. The effects of the lunar environment, particularly the hard vacuum, on the properties of the materials being mined and processed and on the physical mechanisms involved in the mining and processing pose some of the most difficult problems in obtaining the basic knowledge needed. The lunar environment will continue to be a determining factor when the time comes to design specific equipment and methods for use on the Moon.

THE RESEARCH PROGRAM

The present program consists of 16 closely related research tasks at 7 Bureau centers, with planning and coordinating activities carried out by a small interdisciplinary core group at the Twin Cities Mining Research Center. The individual tasks were initiated at different times between September 1965 and January

1967 after an initial period of background study and task definition by the core group. Most of the tasks are planned for a 3-year duration, although a few are 1- or 2-year survey or feasibility studies.

Figure 1 shows the locations of the centers involved in the program. The number of tasks at each center is indicated. Each task involves a multidisciplinary team of from two to eight researchers working under the investigator in charge. Each task is a part of regular Bureau research at the particular center concerned, and most members of a research team work only part time on the NASA task. The total effort involved in the program represents about 15 man-years per year.

The research tasks are concerned with the major problem areas of mining and processing which we categorize as follows: resource identification, rock fragmentation, materials handling, ground control and support, mineral beneficiation, thermal decomposition, electrolytic reduction, chemical reduction, and secondary processing.

Two of the seven tasks at the Twin Cities Mining Research Center are providing general support for lunar resource utilization studies. The first of these, under the direction of David Fogelson, comprises the selection and collection of materials that simulate those likely to be found on the Moon. The second, which involves all of the research laboratories at the Center, incorporates these simulated lunar materials into the basic fragmentation research currently in progress in order to determine a broad range of physical properties of the materials in Earth environment. Mr. Fogelson will describe the progress of these two tasks in another paper in this volume (ref. 20).

One of the other tasks at the Twin Cities Mining Research Center is providing additional insight into the possibilities of finding mineral resources on the Moon. Dr. Rolland Blake has completed a study of volcanism and

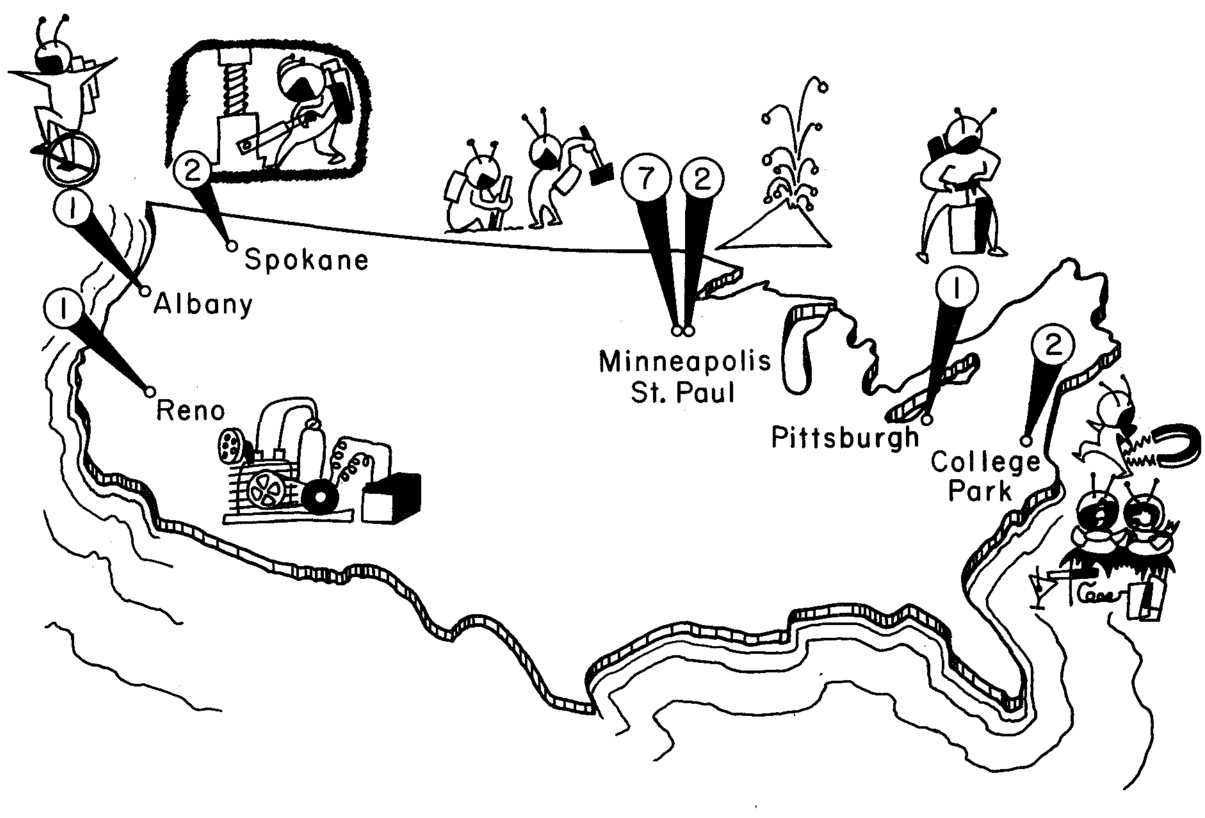


FIGURE 1.—Task location for Bureau of Mines program of multidisciplinary research leading to utilization of extraterrestrial resources. The number of tasks at each center is indicated.

ore genesis as related to lunar mining and will report the results in another paper in this volume (ref. 21).

Rock Fragmentation and Basic Property Studies

The other tasks at the Twin Cities Mining Research Center are aimed primarily at rock fragmentation, but some of them are providing basic information pertinent to other problem areas of mining and to some areas of processing, too. They are all concerned with the effects of lunar environment on the properties and behavoir of rock.

One of them is a study of chemical reactivity and cold welding of freshly formed surfaces. This task is under the direction of Clifford Schultz and its objective is to measure equilibrium constants for the adsorption of gases on the surfaces of silicate minerals and to relate them to the fractional coverage necessary to inhibit cold welding of vacuum-formed surfaces. Measurement equipment has been devised, constructed, and calibrated, and experimental work is in progress. These studies will complement the excellent work by Ryan on adhesion of mineral surfaces in ultrahigh vacuum (ref. 23).

In a closely related task, also under the direction of Schultz, the effect of lunar vacuum on surface properties of rock is being determined. Here the objective is to develop information on the fundamental frictional behavior of mineral surfaces as related to their environment; to measure friction, surface energy, and hardness in ultrahigh vacuum; and to establish relations among these surface properties and between surface and bulk properties. An ultrahigh vacuum system capable of simulating lunar vacuum has been placed in operation together with auxiliary equipment capable of accurately determining conditions in the system while experiments are underway. A device for use in the vacuum system to measure friction between different mineral and mineral-metal combinations was designed and constructed.

Outgassing studies were conducted with the simulated lunar rocks that are being used in this and other research tasks. Results of these studies were reported in October 1967 (ref. 24). Table 1 shows representative data. Reliable information on the state of the test specimen, not available in many vacuum tests conducted previously, is essential for planning or interpreting results of property measurements or behavioral studies in ultrahigh vacuum.

TABLE 1.—*Outgassing of Simulated Lunar Rocks in Ultrahigh Vacuum (Low Bakeout Temperature)*

Sample	Ultimate pressure, 10^{-10} torr	Outgassing rate at ultimate, 10^{-12} torr liter/sec
Empty chamber	1.5	
Dacite	2.0	Nil
Pumice	2.5	2.0
Tuff	4.5	8.0
Serpentinite	7.0	8.0
Basalt	25	100
Granodiorite	30	250

The fifth research task at the Twin Cities Mining Research Center is under the direction of Egons Podnieks. Its objective is to determine the effect of lunar vacuum on the strength and elastic properties of rock and on rock-failure processes. The task is an extension of fundamental rock physics studies in progress at the Center to develop an understanding of rock bonding and failure mechanisms and the factors which affect these mechanisms. In essence, the experimental method used in these studies consists of analysis of the microstructure of rock specimens before and after loading with an elaborately controlled and instrumented compression machine. Auxiliary equipment used with the uniaxial loading machine includes a pressure cell for controlling the environment and confining pressure around the test specimen and an ultrasonic pulsing system for measuring pulse velocity and attenuation in the specimen during loading.

An ultrahigh vacuum system for use with the loading machine has been purchased. Its performance characteristics are identical with those of the system being used in the surface property studies, but the chamber configuration is designed to fit the loading ram. A bellows system and specially designed platens were constructed and are being installed in the chamber. Specimen preparation and preconditioning methods and experimental techniques for use in the chamber were worked out making use of the experience and data developed in the surface properties studies. While the ultrahigh vacuum system was being readied for use, preliminary studies of environmental effects on two simulated lunar rocks were carried out using the pressure cell. Variation of specimen environment from water-vapor-saturated, atmospheric pressure to ultradry, moderate vacuum (10^{-3} torr) produced significant changes in strength and elastic properties. Of particular interest to the study of failure mechanisms were indications in the moderate vacuum tests of degassing bursts, which occurred simultaneously with microseismic noise indications picked up by the pulsing system, as the load-versus-deformation curve became nonlinear just prior to failure of the specimen. Quantitative measurement of the extent and nature of such outgassing will be possible in the ultrahigh vacuum chamber.

The sixth research task at the Twin Cities Mining Research Center is a 2-year study, scheduled to be completed in 1968, of the feasibility of extending to lunar vacuum environment current thermal fragmentation studies and property measurements at elevated temperatures. The task, which is under the direction of Robert Marovelli, also includes measurements at atmospheric pressure of thermophysical, strength, and elastic properties of rock over the lunar-temperature range. In this latter phase of the task, measurements of thermal expansion, tensile strength, and bending strength have been completed on 10 simulated lunar rocks. For most of the rocks the expansion coefficient increases with increasing temperature in a uniform manner through the lunar-temperature range. Rock strengths are significantly greater at the low end and significantly smaller at the high end of the lunar range than are room-temperature values. The strength of basalt was found to increase 50 percent in going from room to liquid nitrogen temperature (ref. 25). Measurements of thermal conductivity are in progress and attempts to reduce the size of specimens needed for these measurements so they may eventually be conducted in the Center's vacuum chambers have been successful.

High-energy electrothermal techniques of rock fragmentation are of major interest for lunar application. Direct use of electrical energy on the Moon has advantages over mechanical or explosive energy, and high voltages and high frequencies may be more manageable in the lunar environment than they are on Earth. In order to help determine the feasibility of studying thermal fragmentation in simulated lunar vacuum, modest vacuum capability (10^{-5} torr at 2000° C) was added to a recently purchased thermal shock research furnace. Thermal fragmentation studies over the pressure and temperature range of this equipment are in progress.

Use of a high-temperature furnace similar to the thermal shock furnace is not practical in a small ultrahigh vacuum system because the heating elements sublime. Other heat sources in use at the Center, such as the oxygen lance and plasma torch, are even less practical. A more promising heat source is the high-frequency dielectric heating apparatus. However, fragmentation techniques involve multielectrode arrays and meaningful results require test specimens a cubic foot or larger in size. Probably the most realistic approach for initial studies of thermal fragmentation in lunar vacuum is a combination of a small vacuum chamber and an external heat source, such as a laser, or the focused energy from one of the more conventional light sources. Final recommendations will be made after the studies in the thermal shock furnace are completed.

The seventh research task at the Twin Cities Mining Research Center is a study of the basic problems involved in drilling on the Moon. The effects of lunar vacuum and temperatures on cuttings removal and on cooling and lubricating bits are being investigated under the direction of James Paone, who will report the progress of this work as part of a paper on lunar drilling in this volume (ref. 22).

The last of the current research tasks in the problem area of rock fragmentation is located at the Bureau's Pittsburgh Explosives Research Center where information relevant to the use of explosives on the Moon is being developed under the direction of Frank Gibson. Problems of safety and contamination weigh against the use of explosives, but their efficiency and versatility make them very attractive as a primary tool for lunar excavating. The work at Pittsburgh is aimed at minimizing possible hazards associated with the storage, handling, and use of explosives in an environment characterized by high vacuum, extreme temperatures, and a flux of small hypervelocity particles.

Short-term effects of low pressure (10^{-4} torr) and lunar temperature extremes on explosive sensitivity and detonation velocity were investigated using several explosives with stability characteristics that make them candidates for lunar application. The only significant effect detected was a decrease in sensitivity at low temperatures. X-ray crystallography and thin-film chromatography are being investigated as methods for detection of possible long-term effects.

The sensitivity of explosives to initiation by impact of small particles, such as might occur from micrometeoroid bombardment, is being determined by adapting techniques developed for other types of hypervelocity studies at the Pittsburgh Center. Preliminary experiments using ½- to ⅛-inch-diameter spherical projectiles launched from a 50-caliber antitank gun showed that explosive detonation occurred at velocities of the order of 1 km/sec for projectile mass of the order of 1 gram. The relation between projectile mass and velocity for detonation determined from these experiments was extrapolated to smaller masses and higher velocities to assist in the design of hypervelocity impact experiments now in progress.

A third phase of this task consists of the study of explosive blast-wave propagation in low-pressure environment. Particularly critical for lunar use of explosives is the problem of acceleration of solid explosion products or pieces of encapsulating material by the explosive gases when no atmosphere opposes the expanding gases. A 12-foot spherical firing chamber is being equipped to study detonation of 100- to 1000-gram charges at pressures of the order of 10^{-4} torr.

Material-Handling and Ground-Support Studies

Two research tasks are being carried out at the Bureau's Spokane Mining Research Laboratory, one concerned with material-handling problems and one with ground-support problems. The first is a study under the direction of David Nicholson of the effect of lunar environment on the behavior of fine particles. Bureau studies of the behavior of fine-particle slurries used in mine backfill applications have been extended to include dry fine particles and lunar vacuum, temperature, and gravity influences.

Static and dynamic frictional properties important in handling, transporting, and stowing fine particles are being measured, first in controlled Earth atmosphere and then in lunar vacuum. Property measurement techniques are designed so that vacuum tests can be performed in the Bureau's ultrahigh vacuum chambers at the Twin Cities Center. Parameters included in the property studies, in addition to environment, are composition, density of packing, size distribution, and shape. Property measurements in Earth atmosphere are being made on both basalt prepared in an impact mill and basalt prepared in a ball mill. Basalt prepared in the impact mill, and having a particle-size distribution close to that determined for the lunar surface from the Surveyor III pictures, demonstrated a substantial degree of cohesion after moderate compression. Trenching of the perfectly dry material in normal Earth atmosphere produced results qualitatively identical with those of the Surveyor III trenching experiment.

In the second task at the Spokane Laboratory, protection and support problems for underground lunar shelters are being studied under Robert Bates. Research is being conducted on the properties of synthetic materials, such as foamed plastics, and natural materials, such as sulfur. The load-behavior relations for underground linings in the lunar environment are being studied.

The most important factors controlling lunar shelter design have been delineated. They include radiation, meteorite, and thermal protection, sealing for internal pressurization, and stability and support of ground. At depths less than 25 feet, the primary concern is adequate radiation and meteorite protection. Below 150 feet, support for overburden loads becomes important. Between 25 and 150 feet, the only significant problem is sealing to retain internal pressure. Because the most pressing problems are those involved in constructing near-surface shelters using indigenous materials, emphasis is being placed on using possible lunar-surface materials for protection and sealing purposes.

Mineral-Processing Studies

The five remaining research tasks in the Bureau's program are concerned with the different problem areas of processing technology. Four of these are devoted to fundamental problems of extracting water or oxygen from lunar rocks. The importance of studying these problems was pointed out at the first meeting of the Working Group on Extraterrestrial Resources in 1962 (refs. 26 to 28), and the recommendations of the Working Group (ref. 2), stimulated research on some of the problems. The Bureau's tasks are intended to supplement the excellent work that has been done by others over the past several years.

One of the tasks falls in the problem area of mineral beneficiation. Foster Fraas at the College Park Metallurgy Research Center is investigating adsorption and contact electrification in a vacuum to determine their effects on the separability of nonconducting minerals. The possibility of working with mineral concentrates rather than rocks to extract water or oxygen is an appealing one because of the lower energy requirements and higher productivity. If intrusive igneous rocks are found on the Moon, concentration of minerals which are easily reduced or contain significant amounts of water may be a good possibility, for the grain size of intrusive rocks is normally larger than that of extrusive rocks.

Equipment which has been designed and constructed for the College Park task includes a stainless-steel vacuum chamber with a turbomolecular pump and bakeout system capable of 10^{-9} torr, a vibrating electrifier with bellows feedthrough, a feed hopper, and a particle recirculating system. Initial tests using a mixture of quartz and microcline particles about one-half millimeter in size are in progress.

The research task at the Albany Metallurgy Research Center is related to the problems of thermal decomposition. Hal Kelly is directing a 2-year study of the stability of hydrous silicates and oxides in high-temperature and high-vacuum environment. The presence on the Moon of hydrothermally altered rocks, because of their high water content and the relative ease with which water can be extracted, would be of major importance for lunar resource utilization. This class of rocks has been the subject of intensive investigation (refs. 29 to 35). The work at Albany is providing data previously lacking on the probable stability of various minerals on the lunar surface and the energy required to remove water or oxygen from these minerals by thermal decomposition in a high-vacuum environment.

Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) equipment at Albany were modified to provide testing capability in air and in vacuum down to 10^{-6} torr at temperatures up to 1200° C. Specially designed tantalum calorimeter parts permit DTA measurements up to 1500° C in vacuum. Data have been obtained on one or more minerals in the olivine, mica, zeolite, epidote, bauxite, and amphibole groups. Other minerals are presently being tested.

Information needed to determine the feasibility of electrowinning oxygen from silicate rocks is being obtained in the research task under Donald Kesterke at the Bureau's Reno Metallurgy Research Center. The most readily available raw material on the Moon is likely to be extrusive igneous rocks. Oxygen is present in these rocks in the form of silicates and oxides. Production of oxygen by electrolysis of molten rock is theoretically possible, through modification of techniques developed for preparing various reactive metals by fused-fluoride electrolysis of their oxides. Previous investigations of this method of oxygen production (refs. 33 and 36) have shown a need for more information to determine whether it may be practical. The work at Reno is aimed at determining the fundamental physical and electrical properties of various silicate melts and finding suitable nonreactive electrode and crucible materials for use with the melts.

Various silicate rocks were tested to determine their melting characteristics, relative viscosities, and relative electrical conductivities. Fluxing agents in amounts of 10 weight-percent were required to promote fluidity and conductivity in the 1200° to 1300° C temperature range. Fluoride, oxide, borate, and phosphate agents were evaluated. Silicate melts containing lithium fluoride were the most conductive. Increasing the temperatures of the melts to the 1400° to 1500° C range improved conductivities by factors of two or three compared with conductivities at 1300° C. Currents of more than 100 amperes at 40 volts can be attained at 1500° C.

Consumable graphite electrodes are being used in the experimental work. Investigation of possible nonreactive electrode materials, which would be desirable for successful lunar application, has been disappointing. Experiments with platinum and iridium exposed to 1200° to 1500° C melts resulted in complete dissolution or severe corrosion of the metals within a short time after immersion. Attempts to saturate hot-pressed boron nitride with a silicate-flux mixture for possible use as an electrode material were unsuccessful. Search for suitable materials will continue.

The fourth task related to the extraction of water or oxygen from rock is in the problem area of chemical reduction. Dr. Sanaa Khalafalla at the Twin Cities Metallurgy Research Center is supervising a study of the basic mechanism and reaction kinetics involved in the reduction of silicates with carbon. The reduction of silicates with carbon is neither new nor exotic. It is the basis for a substantial ferrosilicon industry in this country and Canada. Rosenberg and others, studying the manufacture of oxygen from lunar materials, demonstrated that a closed-cycle silicate reduction by methane can be carried out with virtually no loss of methane (ref. 37). However, very little fundamental kinetic data are available on direct reduction by carbon.

Dr. Khalafalla's group is obtaining such data for reactions between carbon and various oxides and silicates in a vacuum furnace. A simple mineral system (silica) is being studied first. More complex mineral systems (silicates) will be investigated later.

The degree of reduction of silica-graphite mixtures in both loose powder and briquet form was studied at pressures below 10^{-2} torr and temperatures up to 1450° C. Graphite particle size was varied from 0.04 to 25 millimeters and silica size from 0.06 to 1.4 millimeters. Maximum reaction occurred with a reactant particle size of about 0.10 millimeter. With this size, the bed porosity was sufficient to permit the escape of carbon monoxide while securing maximum interparticle contacts. Molar ratios of silica to graphite were varied from 0.05 to 6.5, with maximum reaction at a ratio of about 2. The reaction appeared to be a solid-solid one not involving gaseous intermediates, as a better correlation of the extent of reaction was found with number of interparticle contacts than with surface area of the reactants. In a 5-hour period at 1400° C, over half of the oxygen present was extracted from an equimolar mixture of 0.15 millimeter silica and graphite powder.

Dr. Khalafalla's group also completed a 1-year study of the feasibility of reducing silicates with activated hydrogen in a plasma torch. They concluded that the process was not feasible, although the phenomena involved in mineral dissociation in the high-temperature plasma arc might be worth further investigation.

REFERENCES

1. Thompson, G. V. E.: The Lunar Base. J. Brit. Interplanet. Soc., vol. 10, no. 2, Mar. 1951, pp. 49–70.
2. Johnson, G. W. S., ed.: Recommendations for Utilization of Lunar Resources by the Working Group on Extraterrestrial Resources. Jet Propulsion Lab. (Pasadena, Calif.), Mar. 1963.
3. Steinhoff, E. A.: The Use of Extraterrestrial Resources to Advance Interplanetary Flight. Proc. Intern. Symp. on Bioastronaut. and the Exploration of Space (San Antonio, Tex.), Bedwell and Strughold, eds., Apr. 1965, pp. 77–115.

4. PENN, S. H.: The Exploitation of Lunar Natural Resources. RM–305J, Grumman Aircraft Eng. Corp., Dec. 1965.
5. RŮZIG, N. P.: The Case for Going to the Moon. G. P. Putnam's Sons (New York), 1965.
6. GREEN, J.: Lunar Exploration and Survival. Paper 4038, Douglas Advanced Research Lab., June 1966.
7. LOWMAN, P. D.: Lunar Resources: Their Value in Lunar and Planetary Exploration. Astronautica Acta, vol. 12, nos. 5–6, Dec. 1966, pp. 384–393.
8. SALMANSON, J. A.: Implications of Use of Lunar Propellants in Space Transportation Systems. Proc. Fifth Annual Meeting, Working Group on Extraterrestrial Resources, Marshall Space Flight Center (Huntsville, Ala.), Mar. 1967, pp. 107–116.
9. AWDRY, G. E. V.: Development of a Lunar Base. J. Brit. Interplanet. Soc., vol. 13, no. 3, May 1954, pp. 166–169.
10. ROZELAAR, A. J. W.: Extra-Terrestrial Mining. J. Brit. Interplanet. Soc., vol. 15, no. 6, Dec. 1956, pp. 308–314.
11. O'KOBRICK, J. J.: Lunar Excavation Techniques in Rock. Thesis, GSF/Mech 64–38, Air Force Inst. of Technology, Wright-Patterson Air Force Base, Aug. 1964.
12. VASILIK, M. V.: Exploitation of Lunar Water Resources. Thesis, GSF/Mech 64–41, Air Force Inst. of Technology, Wright-Patterson Air Force Base, Aug. 1964.
13. MCCUTCHAN, R. T.: Chemical Manufacture on the Moon. Science J., vol. 1, no. 7, July 1965, pp. 47–52.
14. HAYWARD, C. B.: A Preliminary Logistics Burden Model for the Production of Lunar Ores. Proc. Fourth Annual Meeting, Working Group on Extraterrestrial Resources, Air Force Academy (Colorado Springs, Colo.), Dec. 1965, pp. 289–311.
15. DELINOIS, S. L.: Mining on the Moon. Mining Eng., vol. 18, no. 1, Jan. 1966, pp. 63–69.
16. SHOTTS, R. Q.; COX, R. M.; GRUBBS, D. M.; AND AHRENHOLZ, H. W.: A Study of Lunar Resources: A Preliminary Report on Surface and Some Other Mining Systems. Bur. Eng. Res., Univ. of Alabama, Apr. 1966.
17. SCHULTZ, C. W.: Mining on the Moon. New Scientist, July 7, 1966.
18. FIELDS, S. A.; WEATHERS, H. M.; COX, R. M.; AND SHOTTS, R. G.: Problems and Techniques of Lunar Surface Mining. NASA TM X–53560, 1967.
19. LEONARD, G. W.; AND FULMER, R.: Fuel and Propellants From Lunar Geothermal Fluids. Proc. Fifth Annual Meeting, Working Group on Extraterrestrial Resources, Marshall Space Flight Center (Huntsville, Ala.), Mar. 1967, pp. 121–134.
20. FOGELSON, D. E.: Simulated Lunar Rocks. NASA SP–177, 1968.
21. BLAKE, R. L.: Ore Deposits in Volcanic Rocks With Lunar Extrapolation. NASA SP–177, 1968.
22. PAONE, J.; AND SCHMIDT, R. L.: Lunar Drilling. NASA SP–177, 1968.
23. RYAN, J. A.: Ultrahigh Vacuum Adhesion Related to the Lunar Surface. Summary Rept., Contract NAS7–307, McDonnell Douglas Aircraft Co., Sept. 1967.
24. ROEPKE, W. W.; AND SCHULTZ, C. W.: Mass Spectrometer Studies of Outgassing from Simulated Lunar Materials in Ultrahigh Vacuum. 14th Nat. Symp. of the American Vacuum Soc. (Kansas City, Mo.), Oct. 1967.
25. HEINS, R. W.; AND FRIZ, T. O.: The Effect of Low Temperature on Some Physical Properties of Rock. AIME Preprint SPE 1714, Third Conference on Drilling and Rock Mechanics (Univ. of Texas, Austin, Tex.), AIME, Jan. 1967.
26. FOWLE, A. A.: Processing of Water on the Moon. Utilization of Extraterrestrial Resources Seminar Proc., Jet Propulsion Laboratory, Sept. 1962, pp. 16–18.
27. POOLE, H. G.: Lunar Rocks as a Source of Oxygen. Utilization of Extraterrestrial Resources Seminar Proc., Jet Propulsion Laboratory (Pasadena, Calif.), Sept. 1962, pp. 21–25.
28. SPEED, R. C.: Water in Lunar Materials. Utilization of Extraterrestrial Resources Seminar Proc., Jet Propulsion Lab. (Pasadena, Calif.), Sept. 1962, pp. 26–32.
29. WECHSLER, A. E.; GLASER, P. E.; AND SALISBURY, J. W.: Water Extraction in the Lunar Environment. Proc. Second Annual Meeting, Working Group on Extraterrestrial Resources, Holloman Air Force Base (Alamogordo, N. Mex.), Oct. 1963, pp. 57–68.
30. BRINDLEY, G. W.; AND ROY, N. R.: Thermodynamics and Kinetics of the Dehydroxylation of Hydrous Minerals. Rept. 64–817, Cambridge Res. Lab., U.S. Air Force, Aug. 1964.
31. WEBER, J. N.; ROY, R.; AND GREER, R. T.: Serpentine as a Source of Water on the Moon: Thermodynamics and Kinetics of Dehydration and the Effects of Particle Size and Chemical Composition. Proc. Third Annual Meeting, Working Group on Extraterrestrial Resources, Kennedy Space Center (Cocoa Beach, Fla.), Nov. 1964, pp. 83–109.
32. ROY, R.; AND WEBER, J. N.: Stability-Metastability Relationships of Hydrous Minerals and Their Importance in Designing Facilities for the Extraction of Water from Lunar Rocks and Minerals. Proc. Third Annual Meeting, Working Group on Extraterrestrial Resources, Kennedy Space Center (Cocoa Beach, Fla.), Nov. 1964, pp. 117–130.
33. CARR, B. B.: Study on Extraction of Water,

Hydrogen, and Oxygen From Lunar Materials. Final Rept., Contract NAS 9-1645, Callery Chemical Co., Mar. 1965.

34. GREEN, J.: A Study of the Feasibility of Using Nuclear Versus Solar Power in Water Extraction From Rocks. Rept. 65-596, Cambridge Res. Lab., U.S. Air Force, Sept. 1965.

35. WEBER, J. N.; BRINDLEY, G. W.; ROY, R.; AND SHARP, J. H.: Lunar Water Resources. Proc. Fourth Annual Meeting, Working Group on Extraterrestrial Resources, Air Force Academy (Colorado Springs, Colo.), Dec. 1965, pp. 194-233.

36. HEROLD, P. G.; AND BOVING, H. J.: Removal of Oxygen From Oxides by Fused Salt Electrolysis in a Vacuum. Proc. Third Annual Meeting, Working Group on Extraterrestrial Resources, Kennedy Space Center (Cocoa Beach, Fla.), Nov. 1964, pp. 111-116.

37. ROSENBERG, S. D.; BEEGLE, R. L., JR.; GUTER, G. A.; MILLER, F. E.; AND ROTHENBERG, M.: The Manufacture of Propellants for the Support of Advanced Lunar Bases. SAE Preprint 650835, Nat. Aeron. and Space Eng. and Manuf. Meeting (Los Angeles, Calif.), October 1965.

DAVID E. FOGELSON
Bureau of Mines
Twin Cities Mining Research Center
Minneapolis, Minn.

Simulated Lunar Rocks

The present paper describes the selection of rock materials for use by the Bureau of Mines in its extraterrestrial resource utilization studies which are designed to simulate the range of materials likely to be found on the Moon. It includes preliminary results of the measurement of the engineering properties of these materials.

INTRODUCTION

One of the first problems facing the Bureau of Mines in 1965 in its NASA-sponsored program of providing the basic scientific and engineering knowledge for extraterrestrial mining and processing was the selection of representative materials (refs. 1 and 2). Because we expect the first manned bases will be on the Moon, our immediate concern was with the nature of the lunar surface. Up until the successful chemical analysis of the lunar surface by Surveyor V, we knew nothing of its chemical composition. We supposed that the same elements might be available for rock-forming processes as are present on Earth because the relative abundance of the different elements is much the same throughout the universe. We also believed that if the Moon's composition was the result of differentiation like the Earth's, then certain elements like O, Si, Al, Na, Ca, Fe, Mg, and K would be concentrated in the crust. That the Moon's rocks were also likely to be silicates followed from what is known about the composition of the Earth and from what meteorites implied about other bodies in the solar system.

We still know very little about how the various dynamic processes such as mountain building, weathering, volcanism, and meteorite impact change the crustal rocks on other planets. These processes may affect the rocks in ways unfamiliar to us; they may operate to a different degree or not at all. A good example on the Moon would be the lack of weathering as we know it on the Earth. The absence of any atmosphere on the Moon suggests that the rounded boulders in the Surveyor pictures may be mostly a result of micrometeoroid erosion or thermal spalling.

Another example is that on the Moon we do not see any of the great linear mountain ranges which have originated on Earth through crustal activity and folding. If crustal activity in the form of mountain-building forces is limited and erosion of the rocks is minimal, it is unlikely that the deeper intrusive rocks, like granite, are widely exposed.

Most of the controversy about the Moon has focused on the problem of the origin of the craters and maria (ref. 3). Some experts say that impact by meteors and other bodies has been the principal surface-forming process. On the other hand, there are those who maintain endogenous volcanism was largely responsible. Although excellent arguments and examples can be offered supporting either concept of crater formation, it is not the purpose of this paper to discuss these theories. We are mainly interested in recognizing their implications in the selection of a range of materials suitable for use in developing a lunar mining technology.

Let us accept the fact that both impact and volcanism have been important factors in creating the Moon's surface. If this assumption is true, then the main types of material we are concerned with in the maria are the rubble

324-954 O—69——6

produced by impact and rocks or fragmental material of volcanic origin. The rubble will probably consist of reworked volcanic and meteoritic material. In any case, volcanic rocks must receive considerable attention, not only because they appear to be quite widespread on the Moon, but also because a volcanic terrain is likely to provide more usable resources than does an impact terrain. Green, in reference 3, says:

Volcanic terrain offers more shelter, more useful minerals and rocks, more subsurface heat, and more water than an impacted one. Therefore, to whatever degree the lunar surface is volcanic, we must seek out volcanic areas on the Moon because that is where the survival advantages lie.

We wish to thank the following individuals and organizations for their assistance in making the collection of this suite of simulated lunar materials possible: E. Groh, N. Peterson, L. Ramp, and H. Dole of the Oregon State Department of Geology and Mineral Industries; G. Oakeshott of the California State Division of Mines and Geology; R. Hogberg of the Minnesota State Geological Survey; J. Green of McDonnell Douglas Aircraft Co.; W. Kennedy, Superintendent, National Park Service, Lava Beds National Monument; W. Miller of the Central Oregon Pumice Co.; the U.S. Forest Service; the Oregon State Highway Department; the Hanna Nickel Mining Co.; and the Chamber of Commerce, Bend, Oreg.

Rock properties were measured by personnel of the Rock Physics, Thermal Fragmentation, Chemical Fragmentation, Hydraulic Fragmentation, and Mechanical Fragmentation Laboratories at the Bureau of Mines Twin Cities Mining Research Center. Petrographic and chemical analyses of the six rocks selected by Green were made by personnel of North American Aviation Co. The other rocks were analyzed by personnel of the Petrographic and Chemical Laboratories at the Bureau of Mines Twin Cities Metallurgy Research Center.

SELECTION OF SIMULATED LUNAR ROCKS

It is apparent that the volcanic rocks formed on Earth may be used to simulate such rocks on the Moon. Consequently, we have chosen these rocks for our research to assure that we cover the range of physical and chemical properties that are likely to be found on the lunar surface. As we learn more about the Moon, we can concentrate on those rocks which are more representative or are of particular interest. The recent chemical analyses of the lunar surface performed by Surveyor V and Surveyor VI, which indicated a composition similar to terrestrial basalts, provide additional confidence in using volcanic rocks in our studies.

In choosing a source for volcanic material, we turned to the large areas of volcanism in Oregon and northern California. Green had already selected six rocks from this region for lunar research, and his work has been of considerable value to our program (ref. 4). His criteria for selecting the specific rocks were: (1) they should be representative of possible lunar rocks; (2) they should have the specific characteristics needed for the particular research to be performed; (3) they should come from an outcrop uniform in composition and texture; and (4) samples should be convenient to collect in sufficient quantity for the research to be performed.

Using these criteria as a guide, Green selected these rocks: a tholeiitic basalt, to simulate rock from large basalt flows such as might be found in the maria (tholeiitic basalt was chosen because low-pressure environments might favor their evolution on the Moon); a semiwelded tuff, in case the maria are filled with ash flows; an obsidian, to simulate rock from a flow of quickly chilled rhyolitic lava; an altered rhyolite, to represent a hydrothermally altered material containing a high water concentration; and, finally, two intrusive igneous rocks, a serpentine (serpentinite) for its high water content and to allow for an ultramafic Moon or a Moon with considerable iron and magnesium in its composition, and a granodiorite, to represent a deep-seated rock exposed on the lunar surface. No meteoritic material was included because of the difficulty of obtaining bulk quantities.

In choosing our suite of simulated lunar materials, we decided to include all of the rocks selected by Green. Our research program, however, required a broader range of rocks to assure that our fundamental work on material properties and behavior will be adequate. For this reason we have added the following volcanic rocks: a rhyolite, as a fine-grained extrusive silicic rock; a dacite, to simulate an extrusive rock of composition intermediate between rhyolite and basalt; a pumice; and three vesicular basalts with different size vesicles, to allow for the very likely possibility of vesicular rocks on the Moon.

We have also included a gabbro, to simulate a coarse-grained basic intrusive, and a dunite, in the event that the Moon has a composition similar to chondritic meteorites or to the Earth's mantle. Like Green, we made no attempt to collect meteoritic material because of the need for large quantities. The 14 figures in appendix A are photographs of hand specimens and photomicrographs of all the rocks mentioned. Petrographic descriptions and chemical analyses are given in appendixes A and B, respectively. For completeness, Green's petrographic descriptions and chemical analyses have also been included (ref. 4).

Other rocks may later be added to our suite of simulated lunar materials. We intend to look at the problem of shock metamorphism in natural materials, such as that associated with impact craters (ref. 5). We also intend to look at the problem of obtaining larger and more uniform vesicles by artificially frothing basalts or obsidians (ref. 6). The Moon's lower gravity and lack of atmosphere suggests that nucleation of the gas bubbles within lunar lavas occurs at greater depths than on Earth. As the bubbles rise toward the surface, they expand at a rapidly increasing rate to form correspondingly larger vesicles as the lava cools. The effect of vesicle size on the engineering properties of the lunar rocks will be an important consideration.

PROPERTIES OF SIMULATED LUNAR ROCKS

The simulated lunar rocks are being used in their unfragmented form to represent a bedrock lunar surface, and in a fragmented and pulverized form, to represent rubble surface. Each of these situations raises particular problems with respect to extraction and processing of the rocks. In the former case, problems of rock fragmentation are paramount. In the latter, material-handling problems are more important. In both cases we are concerned with physical and chemical composition, surface properties, elastic properties, strength properties, thermal properties, electrical and magnetic properties, and explosive shock properties. In order to show the range of property values represented by the materials we have selected, average values for some of the properties that have been measured on core and block specimens of the rocks are given in table 1. These data are preliminary and may be modified by additional work which will take into account the anisotropy that is characteristic of most of the rocks as well as refinements in measurement and analysis. Final results and descriptions of experimental techniques will be reported by the individual researchers of the Bureau of Mines Twin Cities Mining Research Center.

All of the properties shown in the table other than the coefficient of rock strength were measured by common laboratory methods. This strength measurement is a simple test of the energy involved in breaking a unit volume of rock to a given size. It is performed by placing a specimen in a tube, dropping a standard weight from a standard height, and measuring the volume of material that is produced below a standard size. The table illustrates the broad range of property values covered by the simulated lunar materials. At the low-density, low-strength, and low-hardness end of the scale, this range extends beyond that usually encountered in mining problems on Earth.

The group of rocks we are using is primarily composed of volcanic rocks, although we have included some rocks which may be expected to form at depth. We have included intrusive, aside from allowing for the possibility of their being exposed on the Moon's surface, in order to provide a broader range of materials for the use of other research groups. Although in past years we have worked with many intrusive igneous rocks and also metamorphic and sedimentary rocks associated with mining and

TABLE 1.—*Properties of Simulated Lunar Rocks in Earth Environment*

Rock type	Bulk density, g/cc	Apparent porosity, percent	Permeability, darcys	Hardness, shore units	Pulse velocity, m/sec	Young's modulus, psi	Compressive strength, psi	Tensile strength, psi	Strength coefficient, ratio	Thermal expansion	Magnetic susceptibility, cgs units	Dielectric constant ratio	Dissipation factor ratio
Dunite	3.19	1	$<<1$	73	7500	18.7×10^{6}	27 000	2000	1.32	6.2×10^{-6}	400×10^{-6}	5.0	0.008
Gabbro	3.11	<1	<1	84	7100	16.6	30 000	2000	.96	3.9	6000	15.4	.081
Tholeiitic basalt	2.84	2	$<<1$	84	6000	10.3	53 000	3400	1.91	4.5	2000	11.1	.099
Granodiorite	2.58	1	<1	87	3000	6.1	21 000	950	.51	5.6	Negligible	5.5	.004
Serpentinite	2.56	3	$<<1$	68	6000	5.7	18 000	800	1.37	5.3	6000	([a])	([a])
Obsidian	2.39	1	$<<1$	103	5600	9.2	65 000	2200	.53	4.1	100	6.3	.010
Altered rhyolite	2.36	8	<1	59	3300	2.6	16 000	1100	.74	([a])	Negligible	4.8	.017
Rhyolite	2.35	8	$<<1$	79	4200	2.4	22 000	1200	.89	4.5	400	5.1	.003
Vesicular basalt 1	2.25	20	Varies	81	3800	2.8	10 000	1100	1.01	3.2	400	6.0	.012
Vesicular basalt 2	2.22	24	Varies	67	4500	2.5	5 500	590	.75	([a])	500	6.7	.036
Dacite	1.98	17	4	35	4500	2.0	6 000	620	.42	3.1	600	5.0	.008
Vesicular basalt 3	1.52	46	Varies	80	4800	2.7	5 600	810	.77	([a])	200	4.2	.005
Semiwelded tuff	1.15	50	58	10	2500	.3	850	100	.10	3.3	400	2.9	.015
Pumice	.76	62	840	5	2500	.5	1 500	240	.08	4.5	Negligible	2.3	.008

[a] Not yet measured.

quarrying operations, we have done little research on volcanic rocks prior to the present program for NASA.

The present selection of rocks represents a range of lithologies and textures that we hope will appeal to other organizations requiring simulated lunar materials. We believe that it is very desirable for all groups doing research related to lunar resource utilization to use the same rocks in order to facilitate comparison of their results. A number of organizations are already using some of these rocks. The Bureau of Mines is providing samples of the rocks, on request, to any group doing research related to our program. We can provide quantities up to several pounds of any of the materials we have on hand, and we can usually provide the material in a form that will satisfy particular requirements.

REFERENCES

1. ATCHISON, T. C.; ET AL.: Annual Status Report for Fiscal Year 1966, Multidisciplinary Research Leading to Utilization of Extraterrestrial Resources. NASA contract R-09-040-001, Bur. Mines, July 1966.
2. ATCHISON, T. C.; ET AL.: Annual Status Report for Fiscal Year 1967, Multidisciplinary Research Leading to Utilization of Extraterrestrial Resources. NASA contract R-09-040-001, Bur. Mines, July 1967.
3. GREEN, JACK: Lunar Exploration and Survival. Douglas Paper 4038, Advanced Res. Lab., Douglas Aircraft Co., Inc., June 1966.
4. GREEN, JACK: Selection of Rock Standards for Lunar Research. Ann. N.Y. Acad. Sci., vol. 123, art. 2, July 15, 1965, pp. 1123–1147.
5. SHORT, N. M.: Shock Processes in Geology. J. Geol. Education, vol. 14, no. 4, Oct. 1966, pp. 149–166.
6. DOBAR, W. I.; GNOEDINGER, J. P.; AND TIFFANY, O. L.: Simulated Extrusive Magma Solidification in Vacuum. Icarus, vol. 3, no. 4, Nov. 1964, pp. 323–331.

APPENDIX A—PETROGRAPHY OF SIMULATED LUNAR ROCKS

The petrography of the simulated lunar rocks is given in the following outline. Analyses of rocks I to VI were made by J. Kennedy. (See ref. 4.) Analyses of rocks VII to XIV were made by M. Boucher.

I. Basalt, Tholeiitic

A. Macroscopic:
1. *Color.*—Black.
2. *Texture.*—Aphanitic.
3. *Structure.*—Massive columnar.
4. *Field name.*—Basalt.

B. Microscopic:
1. *Texture.*—Merocrystalline probably describes the texture best because both glass and crystals are present. However, the interstitial glass is charged with microlites of magnetite and plagioclase which impart a hyalopilitic texture to the matrix material. Only two large phenocrysts of plagioclase were found within the sections analyzed, but there are definitely two generations of plagioclase present. Most of the crystals are subhedral in form with the exception of the older generation plagioclase which have reentrants and rounded corners which indicate partial resorption.
2. *Structure.*—The spectrum of grain size is not wide except for that of the microlites found in the matrix glass. The older generation plagioclase are the largest crystals and average 0.15 millimeter in length and 0.03 millimeter in width. This does not include the phenocrysts mentioned above. The next largest crystals are the second-generation plagioclase which average 0.10 millimeter in length and 0.025 millimeter in width. The augite and olivine grains are approximately the same size with the former averaging 0.05 millimeter in diameter and the latter, 0.04 millimeter in diameter; the smaller microlites are less than 0.008 millimeter in diameter. The chlorite grains are variable with some being marginal alterations of the pyroxenes and some occurring as discrete entities.

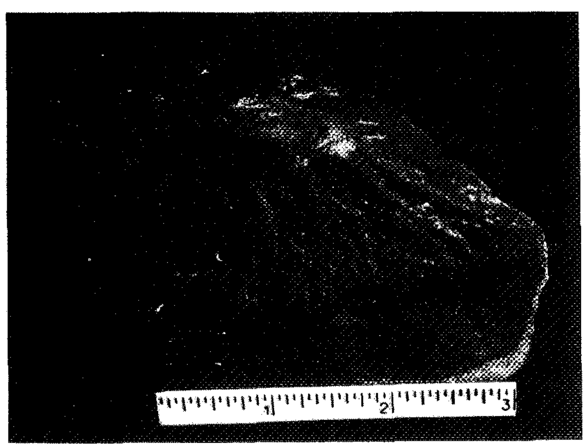
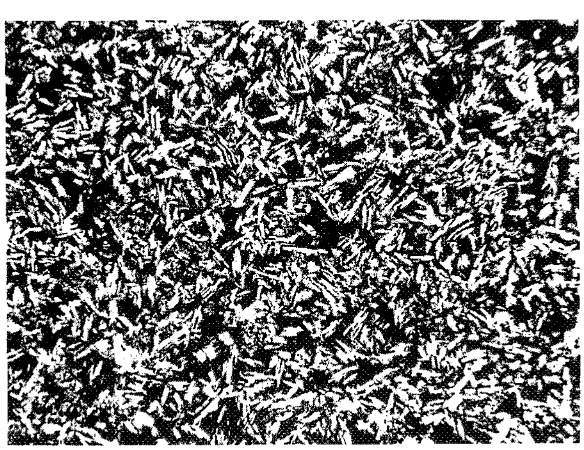


Figure 1.—Tholeiitic basalt; occurs northeast of Madras, Oreg. Above, hand specimen; below, photomicrograph, × 13.



C. Essential minerals:	*Content, percent*
1. Plagioclase An_{67} and An_{54}	39
2. Olivine	13. 5
3. Augite	10. 5

D. Accessory minerals and glass:	*Content, percent*
1. Plagioclase microlites	12
2. Magnetite (titaniferous) and ilmenite	8
3. Glass	12
4. Chlorite	4
5. Quartz (very small inclusions in plagioclase)	1
6. Apatite	<1
7. Epidote	<1

E. Description of most commonly occurring minerals:
1. *Plagioclase.*—$NaAlSi_3O_8$; $CaAl_2Si_2O_8$.
(*a*) *General.*—Two generations of well-developed crystals of plagioclase are present along with needlelike plagioclase microlites, which occur in the groundmass glass. The older generation crystals appear to be brecciated phenocrysts. Large phenocrysts must have existed in the magma prior to flow. During the flow process these were broken and shattered and now appear only as fragments of former large crystals. A very few survived as discrete phenocrysts. These early crystals have retained only shadows of their former twinned planes, and zoning is pronounced. Zoning ranges from An_{60-82}, with most of the crystal being approximately An_{67}. Reverse zoning is prominently displayed, with the greatest Na molecule density occurring in the interior adjacent to the twin planes and

becoming more basic toward the margins of the crystal.

The later, or youngest, crystals show the reverse effect. Twin planes are sharp and distinct with a small amount of normal zoning present. The composition ranges from An_{51-54} with the exterior margins being the more alkaline. Crystallization was much later in the magmatic history than in the earlier former plagioclase and orthobrecciation is not an important feature as it is with the older generation plagioclase.

(*b*) *Crystal development.*—Crystal faces of the older generation plagioclase are well developed but show rounding and corroded boundaries adjacent to matrix material. When other crystals such as olivine, pyroxene, and magnetite are found in contact with the older plagioclase, a well-developed sharp boundary is formed between the two minerals. Fractures, splintering, and separation along twin lamellae are common. Crystal boundaries of the younger generation plagioclase are well developed adjacent to all other crystals. The boundaries are sharp and well defined. Separation along twin lamellae and rounding of crystal corners is extremely rare.

(*c*) *Alteration.*—Small granules occur along twin lamellae separations in the older generation plagioclase. These have been tentatively identified as epidote and are probably an alteration product of the older plagioclase. The younger generation plagioclase does not show this feature or any other feature indicating alteration.

(*d*) *Inclusions.*—Several small inclusions are found within the plagioclase. These have tentatively been identified as epidote, quartz, or apatite. The inclusions occur as small round or slightly elongate globules, the largest being about 0.012 millimeter long and 0.007 millimeter wide. The inclusions are a primary feature of the plagioclase and are not an alteration product.

2. *Olivine.*—Fe_2SiO_4; Mg_2SiO_4.

(*a*) *General.*—Olivine occurs as small euhedral to subhedral crystals occupying the interstices between plagioclase laths along with augite, glass, and magnetite (ilmenite). In general, the crystals are smaller than those of augite but larger than the largest magnetite grains. Some crystals show broad twin lines, but these are relatively rare.

(*b*) *Crystal development.*—The crystals are partly euhedral and show typical olivine outline. Good face development against plagioclase, augite, and magnetite is common. In the section where it is found in subhedral form it is probably caused by separation along irregular fractures rather than poor development. It is colorless in this section but stands out prominently because of its high relief and strong birefringence.

(*c*) *Alteration.*—In general, the olivine is unaltered, but in rare cases small patches of chlorite develop along some margins. A single instance was found of a euhedral crystal of olivine that was completely altered to chlorite.

(*d*) *Inclusions.*—Inclusions are practically absent in the olivine. However, occasionally it appears to contain small magnetic grains.

3. *Augite.*—(Ca, Mg, Fe^{2+}, Fe^{3+}, Ti, Al)$_2$ (Si, Al)$_2O_6$.

(*a*) *General.*—Augite is distinguished from olivine by its lower birefringence and its cleavage. These features were used to identify or separate augite from olivine during the point-count procedure.

(*b*) *Crystal development.*—Crystal faces are, in general, poorly developed, but euhedral crystals are present. In the case where glass is the surrounding medium, crystals are best developed. If augite is developed adjacent to olivine, the olivine deforms the augite to follow the shape of the olivine crystal. The same is true for some of the larger crystals of magnetite (ilmenite).

(*c*) *Alteration.*—In rare cases augite is seen to be slightly altered to serpentine(?). This is especially true when augite has come in close proximity to fragments of chlorite which contain plagioclase.

(*d*) *Inclusions.*—Small euhedral crystals of apatite are sometimes found in the larger augite crystals. This seems to be especially true when the augite occurs as a euhedral crystal of larger than average size. A few large augite crystals were observed. These were corroded to such a degree that only vestigial outlines were present.

4. *Magnetite* (*ilmenite or ore minerals*).—$Fe^{2+}Fe_2^{3+}O_4$; $FeTiO_3$.

(*a*) *Crystal development.*—Magnetite occurs in three forms: (1) fill for irregular voids, (2) euhedral crystals, and (3) microlites. The irregular masses occur most generally where there is the greatest concentration of other crystals. All crystals seem to deform magnetite, and its irregular nature indicates it emerged in the later cooling phase. However, some of the larger magnetite crystals form anhedral faces against augite. In general, the euhedral crystals and well-developed microlites occur in the glassy matrix material and do not contact other minerals. Because of the large microlites and the greenish tinge surrounding the grains of magnetite, the grains may be ilmenite in many cases; probably there is a mixture of both ilmenite and magnetite.

(*b*) *Alteration.*—None present. Hematite surrounding the ore minerals is conspicuous because of its absence. Lack of magnetite alteration indicates the rock is fresh.

(*c*) *Inclusions.*—None apparent.

5. *Chlorite.*—$Mg_3Si_2O_5(OH)_4$.

(*a*) *General.*—Most of the chlorite found in the sections of basalt occur as fragments rather than grains. These fragments consist of only chlorite and plagioclase.

(*b*) *Crystal development.*—The fragments are anhedral and the included chlorite portion is also anhedral. However, the included plagioclase is euhedral and has extremely well-developed faces, which stand out in sharp contrast to plagioclase belonging to the original magma.

(*c*) *Alteration.*—The chlorite itself is probably an alteration product.

(*d*) *Inclusions.*—Large plagioclase crystals described above.

6. *Glass:*

(*a*) *General.*—The glass occurs as a brown matrix material charged with microlites of magnetite and plagioclase. Also, euhedral crystals of magnetite are common throughout the matrix. Fracturing in the glass is uncommon and the microlites within the matrix have a random orientation. This gives the interstitial glass an extremely irregular appearance.

(*b*) *Alteration.*—The glass does not appear to be devitrified; however, its dark brown color may mask some devitrification. Microlites intimately mixed with the glass may cause some error in index determination. The index has been measured as approximately $n=1.525$.

II. SEMIWELDED TUFF

A. Macroscopic:

1. *Color.*—Light brown mottled with reddish-brown, brown, and black lapilli.
2. *Texture.*—Fragmental lapilli breccia consisting of pumice, dacite vitrophyre, and welded-tuff fragments in a volcanic dust and glass matrix.
3. *Structure.*—Generally massive with elongated fragments having a preferred orientation. These are subparallel but do not form definite bedding planes.
4. *Field name.*—Lapilli tuff.
5. *General observations.*—Fragments greater than 4 millimeters in diameter but less than 32 millimeters in diameter make up more than 25 percent of the total rock mass. Therefore, the prefix "lapilli" was assigned to the rock type. However, the rock is more consolidated than the usual tuff and has a semiwelded fabric.

B. Microscopic:

1. *Texture.*—The microscopic texture is divided into parts which depend on the portions of the thin section being examined. The divisions are: matrix, pumice lapilli, dacite vitrophyre lapilli, welded-tuff lapilli, and crystal fragments.

(*a*) *Matrix texture.*—The matrix consists of arcuate glass shards, rounded ash particles, occasional droplets of clear brown glass, and occasional perlites, all cemented together with an almost impalpable, slightly vesicular glass dust. "Vitroclastic," as used by Dr. H. Williams, is the term that most nearly describes the matrix texture.

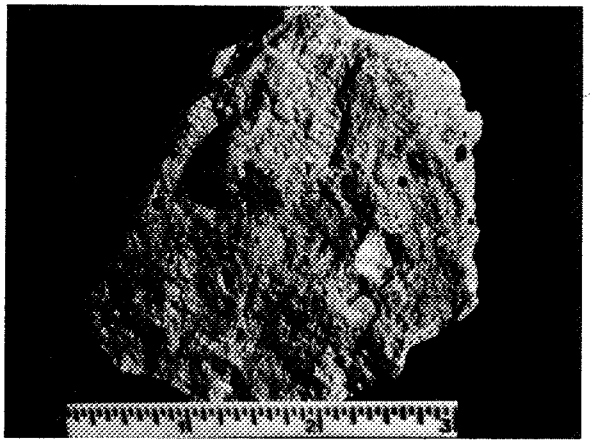
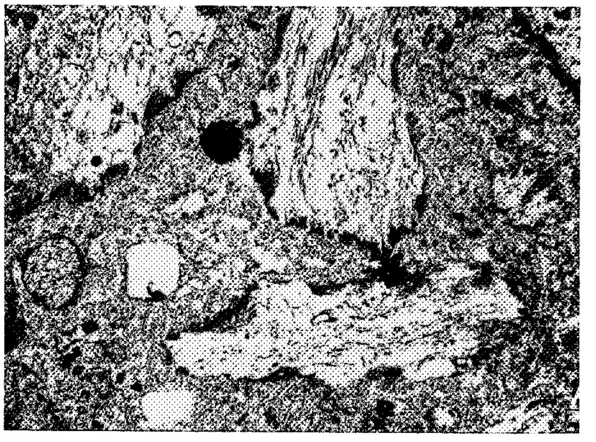


FIGURE 2.—Semiwelded tuff; Bend, Oreg. Above, hand specimen; below, photomicrograph, × 13.



(*b*) *Pumice lapilli texture.*—The pumice fragments consist of a highly vesicular brown dust glass. The vesicles are variable in size and density both within a particular fragment and from fragment to fragment. In general, the vesicles are round or spherical; this is, typical of pumiceous texture, but irregular and ellipsoidal forms are not rare.

(*c*) *Dacite vitrophyre lapilli texture.*—The dacite vitrophyre fragments consist of lathlike microlites of andesine-labradorite plagioclase and interstitial pyroxene crystallites in a matrix of dark gray-green glass charged with ore mineral microlites. Occasional phenocrysts of plagioclase (An_{45-50}) are found and small vesicles are common.

(*d*) *Welded-tuff lapilli texture.*—The welded-tuff lapilli has good lineation formed by thin discontinuous threads of brown dusty glass. Microscopic vesicles are numerous and are in general of two types: (1) long thin extended vesicles which occur within the threads and (2) almond-shaped vesicles which occur between threads. Flattening of ash particles is very evident in cases where they occur as discrete units. In general, ash particles have been completely fused and particle boundaries are not evident.

(e) *Included crystals.*—The included crystals occur as individual fragments making up part of the matrix material, with the exception of the plagioclase phenocrysts which occur in the dacite vitrophyre. The crystal boundaries are clear and sharp and crystal faces are common. However, some rounding has taken place, especially where faces intersect to form corners. The edges have been eroded away, presumably by abrasive action of ash particles. This is suggested, rather than magmatic resorption, because each crystal fragment is surrounded by a clear glass rind which indicate very rapid cooling. The best overall textural term must also refer to the rock type, that is, a lapilli or lithic tuff.

2. *Structure.*—On a macroscopic scale the lapilli show fair lineation, which is more preferred orientation rather than lineation because actual continuous bedding does not exist. On a microscopic scale this preferred orientation is not apparent.

(a) *Matrix structure.*—No apparent structure exists in the matrix. All particles have a random orientation, and flattening of ash grains is not evident. The vesicles, which are ellipsoidal and somewhat flattened, do not possess a preferred orientation. The most impressive feature of the matrix material is the way the vitreous dust completely fills the interstices between glass shards, ash particles, and lapilli. No void spaces are present in the matrix, with the exception of vesicles. In a few widely scattered areas, some welding has taken place and microscopic sinuous lamellae are present and are very similar to those of a welded tuff.

(b) *Pumice lapilli structure.*—Each ash particle is slightly flattened against each adjacent grain. However, the grains maintain an almost spherical shape and the flattening effect does not have a preferred orientation. Lineation within the lapilli is not apparent.

(c) *Dacite vitrophyre structure.*—Small crystallites of plagioclase have a subparallel alinement that is deflected by included larger crystals such as hypersthene or plagioclase phenocrysts. A few reentrants around the margins and some included vesicles indicate the parent rock was of a vesicular nature.

(d) *Welded-tuff lapilli structure.*—Good lineation is apparent in the welded-tuff lapilli even on a microscopic scale. Thin discontinuous threads of brown dusty glass, which are slightly blocky on the ends, lie parallel to one another. These threads are deflected around vesicles and almond-shaped ash particles. This gives a gentle wavy appearance to the lineation. The structure as a whole is somewhat eutaxitic in nature.

(e) *Included crystals.*—The included crystals occur in all forms from euhedral to anhedral, but in general they have a euhedral outline with slightly rounded corners. These crystals have a completely random orientation and even the plagioclase laths, which would be expected to take on an orientation with their long dimension paralleling the surface, exhibit a random pattern.

C. General statement:

1. Many other fragments or lapilli of other rock types exist in the lapilli tuff, but in general these are variations of those listed above or are minor constituents. Two fragments of rhyolite (porphyritic), a few small fragments of obsidian, and one fragment of porphyritic basalt were observed, but because they are minor constituents they are not described in detail.

III. Obsidian

A. Macroscopic:

1. *Color.*—Dark gray with a slight brown tint.
2. *Texture.*—Glassy, macroscopically holohyaline.
3. *Structure.*—Massive with an oriented splintery fracture system. Fractures perpendicular to the splintery system are conchoidal.
4. *Minerals.*—None identifiable.
5. *Field name.*—Obsidian.

B. Microscopic:

1. *Texture.*—Glass matrix charged with glass shards, microlites, and crystallites. The microlites are of the longulite and belonite varieties. The glass shards have rounded resorption boundaries, and some are cloudy under crossed nicols indicating devitrification. A few widely scattered plagioclase grains also are present.
2. *Structure.*—The glass shards and microlites show a general preferred orientation with their long dimension parallel to the splinter-fracture pattern. Microlite density is variable; it occurs in streaks nearly parallel to the splinter-fracture system. Relic plagioclase laths occur as scattered unoriented grains.

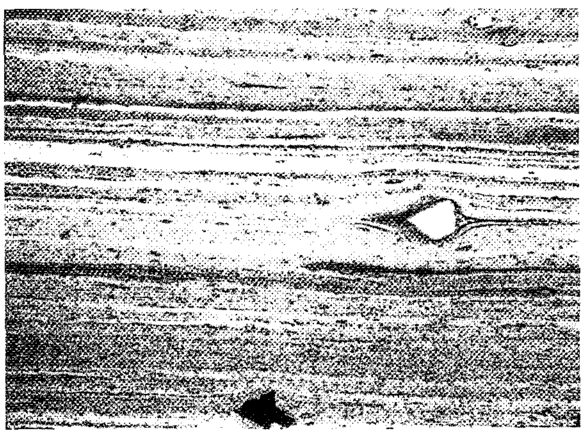
C. Essential and accessory constituents or minerals:

	Content, percent
1. Glass	60
2. Microlites	30
3. Plagioclase	5
4. Augite	3
5. Ore minerals	2

D. Secondary minerals:

	Content, percent
1. Chlorite	1

FIGURE 3.—Obsidian; Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.



E. Essential constituents:
1. *Glass*.—Content, 65 percent (index of refraction $n=1.495$). There is no crystalline form to the glass, but there are two varieties occurring in this obsidian: matrix glass and darker glass shards. The glass shards make up approximately 40 percent of the total glass content. The shards have conchoidal boundaries and rounded reentrants of matrix glass. Apparently, during cooling orthobrecciation was occurring along with resorption.
2. *Ore minerals*.—The ore minerals occur as very small spherical globules. In some cases, vestiges of face development can be seen.
(a) *Inclusions*.—None.
(b) *Alteration*.—None.

IV. ALTERED RHYOLITE

A. Macroscopic:
1. *Color*.—Cream colored with streaks of brown limonite in fractured regions.
2. *Texture*.—Dense aphanitic, with scattered small vesicles. Some small (1 millimeter or less) crystals, probably sanidine.
3. *Structure*.—Numerous fractures with random orientation and small (1 millimeter in diameter) widely scattered vesicles.
4. *Field name*.—Altered rhyolite.

B. Microscopic:
1. *Texture*.—Minute lath-shaped crystals, principally feldspar with some interstitial glass in a matrix of felty crystallites and small microlites. Scattered random-oriented crystals 0.1 to 0.4 millimeter in diameter.
2. *Structure*.—The plagioclase laths occur in subparallel clusters, thereby imparting some lineation to the overall structure. Deflection of these crystals around knots of felted crystallites and vesicles gives a semiwavy pattern. The vesicles are not spherical but are irregular in shape and somewhat flattened and lined with small crystallites, which probably are quartz.

C. Essential minerals (percentages are visually estimated and should be considered only as approximations):

	Content, percent
1. Plagioclase (An_{24})	25
2. Sanidine	10
3. Quartz	2
4. Felty groundmass and glass	60

D. Accessory minerals:

	Content, percent
1. Pyroxene(?) microlites	1

E. Secondary minerals:

	Content, percent
1. Hematite and clay	2

(a) *Inclusions*.—Glass is the matrix material. Therefore, all minerals are essentially included in the glass. However, the glass shards do not contain microlites or other crystalline material.
(b) *Alteration*.—Patches and widely scattered small spherical areas appear cloudy under crossed nicols (devitrification). These areas are generally around relic plagioclase or adjacent to a long fracture.
2. *Microlites*.—The microlites are oblong rectangles, in general, with some showing slightly bulbous ends. The outlines are clear and sharp, and they are mostly of the longulite class. Some of the larger microlites show extinction under crossed nicols. The extinction angle averages about 37°. If the orientation is considered as being normal to the (010) the microlites would be approximately An_{65}.
(a) *Inclusions*.—None apparent.
(b) *Alteration*.—None apparent.
3. *Plagioclase*.—Most of the plagioclase grains are highly fractured and very few crystal boundaries are well defined. The highly fractured nature and the angularity of the corners suggest orthobrecciation and partial resorption. Clouding of the glass adjacent to the plagioclase grains is common. No sharp twin planes are evident and

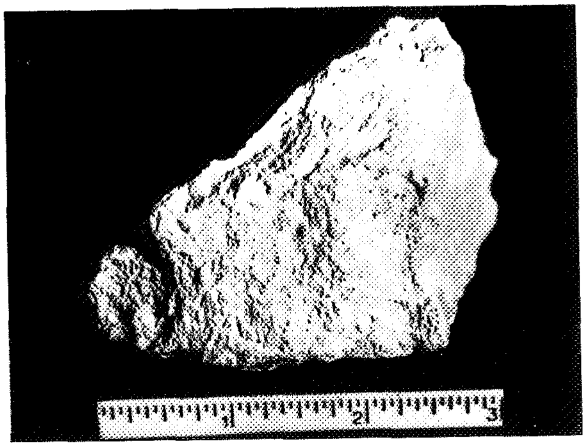
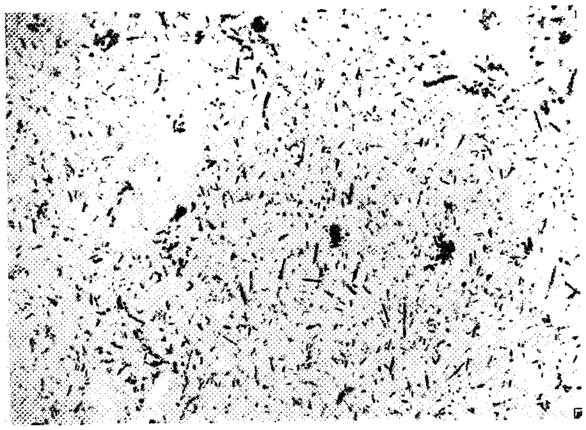


FIGURE 4.—Altered rhyolite; occurs east of Bend, Oreg Above, hand specimen; below, photomicrograph, × 13.



the fragments are highly zoned. A few oriented grains show zoned extinction from An_{27} to An_{61}.
(*a*) *Inclusions.*—None apparent.
(*b*) *Alteration.*—The cloudy area surrounding the plagioclase fragments indicates that resorption was taking place and enriching the surrounding glass. The alteration product has not been identified.

4. *Augite.*—Augite occurs as small semiglobular patches with serrate projections into the glass and microlite areas. No crystal faces are present and only in very widely scattered large grains is the cleavage visible. In general, the augite occurs as grains larger than those of the plagioclase. However, it is much more rare.
(*a*) *Inclusions.*—None apparent.
(*b*) *Alteration.*—In a few instances chlorite or a light green coloration surrounds the augite and projects a short distance into the glassy groundmass. In cases where microlites are adjacent to the augite the coloration surrounds the microlite.

F. Common minerals:
1. *Plagioclase* (An_{24}).—The plagioclase laths occur as discrete laths in the felty groundmass and are generally not twinned. However, occasional albite twins are present. In general, the crystals are poorly formed and are subhedral in outline.
2. *Sanidine.*—The sanidine crystals are anhedral with very poor crystal development. However, excellent interference figures are available and the 2V is approximately 4° and very nearly uniaxial in character. Some small glass shard inclusions are present. The irregular crystals are approximately 0.10 millimeter in diameter.
3. *Quartz.*—Quartz occurs in two phases: One mode very similar to that of the sanidine and the other as very small crystallites partially lining small vesicles.

V. SERPENTINE (SERPENTINITE)

A. Macroscopic:
1. *Color.*—Dark green mottled with apple green.
2. *Texture.*—Lineated with chrysotile phenocrysts and numerous randomly oriented hairline fractures filled with chlorite and ore minerals.
3. *Structure.*—Massive, with good subparallel lineation and some mammillary inclusions which interrupt lineation.
4. *Field name.*—Serpentine.

B. Miscroscopic:
1. *Texture.*—The texture is typical of serpentine. It consists of the typical mesh texture of antigorite with flakes of wavy fibrous chrysotile scattered at random. The apple-green lineations seen in the hand specimen are aggregates of crystals consisting of olivine, pyroxene, and amphibole.
2. *Structure.*—Grains as discrete entities are not evident except in the crystalline veinlets, where amphibole dominates with some crystals as large as 0.4 millimeter in diameter. Chainlike lineation of the ore minerals (magnetite and chromite) and also elongated masses are common. In some sections of the slide, especially in the massive antigorite regions, a poorly developed bastite structure is recognized.

C. *Essential minerals.*—Point-count procedures to determine the quantitative percentages of mineral composition of the serpentine are in progress; the following percentages are estimates based on visual thin-section examination.

	Content, percent
1. Antigorite	50
2. Chrysotile	20
3. Ore minerals	7

D. Accessory minerals:	*Content, percent*
1. Enstatite	5

FIGURE 5.—Serpentinite; Rogue River, occurs northwest of Grants Pass, Oreg. Above, hand specimen; below, photomicrograph, × 13.

	Content, percent
2. Augite	5
3. Olivine	8

E. Secondary minerals:	Content, percent
1. Chlorite	2
2. Talc	1
3. Tremolite	1
4. Dolomite or magnesite	1

F. Description of commonly occurring minerals:

1. *Antigorite* ($Mg_6(OH)_8Si_4O_{10}$).—Antigorite is the dominant mineral and it surrounds all minerals, veinlets, and other features. The structure is a combination beam-and-mesh type with the beam structure being predominate. Antigorite is also found as a minor secondary mineral within the apple-green veinlets of amphibole and pyroxene. Small groups of irregular carbonate minerals (dolomite or magnesite) are found between antigorite plates in some cases. However, tremolite crystals are rather common and show good crystalline form.
2. *Chrysotile* ($Mg_3(OH)_4Si_2O_5$).—Chrysotile crystals have an apparent random orientation with little or no relation to veinlets or fracture patterns. The crystals are irregular in shape and very finely fibrous. In some cases small crystals of tremolite are found within the chrysotile phenocrysts.
3. *Ore minerals.*—The ore minerals (magnetite or chromite) occur both as lineated stringers and irregular masses. However, the irregular masses also show some lineation. Almost all the chrysotile crystals have some ore minerals surrounding the crystal as a partial, discontinuous rim. Inclusion of ore minerals within the chrysotile is rare.

VI. GRANODIORITE

A. Macroscopic:

1. *Color.*—Light gray to white mottled with black minerals.
2. *Texture.*—Crystalline.
3. *Structure.*—Massive unfractured.
4. *Field name.*—Granite.

B. Microscopic:

1. *Texture.*—A number of randomly oriented grains are completely enclosed in optically continuous crystals of different composition (poikilitic texture). Some fingerlike intergrowths of quartz are found penetrating plagioclase crystals (myrmekitic intergrowths). However, this condition is a rare rather than a general characteristic.
2. *Structure.*—There is a wide spectrum of grain size, but in general the rock is medium grained with hypidiomorphic structure. Small grain or crystal inclusions in the larger grains consist of zircon, sphene, apatite, and opaque ore minerals.

C. Essential minerals:	Content, percent
1. Plagioclase (zoned An_{22-50})	40
2. Quartz	39
3. Orthoclase (untwinned)	8
4. Microcline (twinned)	2

D. Accessory minerals:	Content, percent
1. Biotite	7
2. Muscovite	1
3. Zircon	1
4. Apatite	1
5. Ore mineral	1
6. Sphene	1

E. Secondary minerals:	Content, percent
1. Chlorite	1
2. Epidote	1
Rock type, biotite granodiorite	

F. Description of most commonly occurring minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).—Crystal faces are well developed against orthoclase and

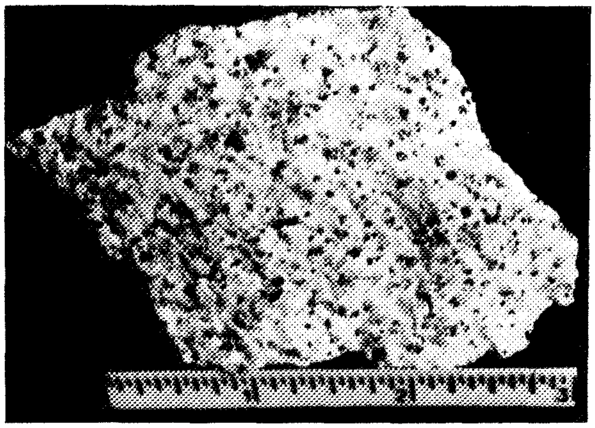


FIGURE 6.—Granodiorite; Bates Station, occurs east of Madera, Calif. Above, hand specimen; below, photomicrograph, × 13.

microline crystals, except where myrmekitic texture exists. Crystal faces are generally but, not always well developed against quartz crystals. The crystals are zoned from An_{50} to An_{22}. However, the rims extinguish at the same time as the core does and, in general, are of about the same composition. Three types of twinning are apparent: (1) albite, (2) carlsbad, and (3) pericline.

(*a*) *Alteration.*—White mica is found as small crystals along cleavage planes or as larger crystals in the core. The boundary between plagioclase and biotite contains both white mica and epidote.

(*b*) *Inclusions.*—Euhedral zircon, euhedral and subhedral biotite, anhedral ore minerals, and euhedral apatite.

2. *Quartz* (SiO_2).—Crystal faces are, in general, well developed against orthoclase, microcline, and quartz but are anhedral against other major minerals.

   (*a*) *Alteration.*—None apparent.

   (*b*) *Inclusions.*—Subhedral and euhedral biotite and plagioclase, euhedral zircon and apatite, subhedral muscovite, and anhedral opaque ore minerals.

3. *Orthoclase* ($KAlSi_3O_8$).—Very few crystal faces are developed, but some are found adjacent to quartz grains and other K feldspar.

   (*a*) *Alteration.*—Myrmekite is fairly common and either may be a replacement phenomenon or may represent the final stages of crystallization.

   (*b*) *Inclusions.*—Euhedral plagioclase both twinned and zoned and anhedral plagioclase with myrmekitic patches. Zircon and apatite occur as poikilitic anhedral crystals with inclusions of plagioclase, quartz, and biotite.

4. *Microcline* ($KAlSi_3O_8$; $NaAlSi_3O_8$).—Microcline crystals show a typical quadrille structure and are easily identified thereby. The crystals are, in general, anhedral with crystal faces being rare. The grains are poikilitic with numerous inclusions of euhedral plagioclase, quartz, and biotite.

   (*a*) *Alteration.*—Myrmekite is found in some crystals, but it does not occur as often as in the case of orthoclase.

   (*b*) *Inclusions.*—Euhedral plagioclase both twinned and zoned. Quartz, biotite, zircon, and apatite are common.

5. *Biotite* ($K_2(Mg, Fe)_{4-6}$ $(Fe, Al, Ti)_{0-2}Si_{5-6}Al_{2-3}O_{20}$ O_{0-2} $(OH, F)_{2-4}$).—Crystals occur as large grains with no apparent original face boundary, but this is difficult to detect because of the excellent cleavage parallel to (001). Numerous elongate grains occur oriented with the (001) in the plane of the thin section. These show serrated edges that are slightly bent. This characteristic also is true of the elongate crystals near the ends where cleavage separation is more apparent.

   (*a*) *Inclusions.*—Euhedral zircon, apatite, and ore minerals are common. There are some anhedral ore minerals and rare anhedral quartz crystals.

   (*b*) *Alteration.*—Some grains are wholly altered to chlorite and most show chlorite alterations around the edges. Sphene and epidote also occur as alterations where biltite is in contact with plagioclase crystals.

6. *Muscovite* ($K_2Al_4(Si_6Al_2)O_{20}$ $(OH, F)_4$).—The (001) faces are well developed, but other faces are not. Ore-mineral inclusions are common and occur most often between the (001) cleavages.

   (*a*) *Inclusions.*—Mostly free of inclusions except for the above-mentioned ore minerals.

   (*b*) *Alteration.*—None apparent.

VII. PORPHYRITIC RHYOLITE VITROPHYRE

A. Macroscopic:

1. *Color.*—Gray.
2. *Texture.*—Aphanitic with feldspar microphenocrysts.

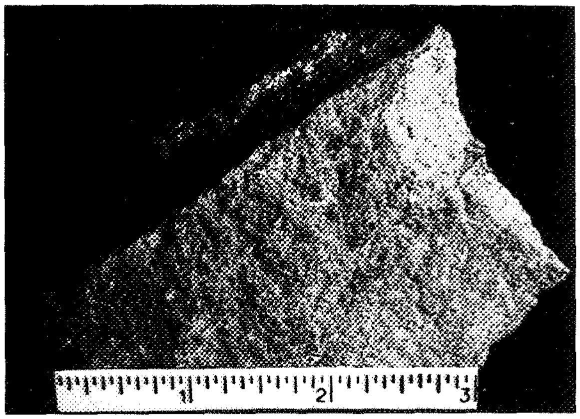
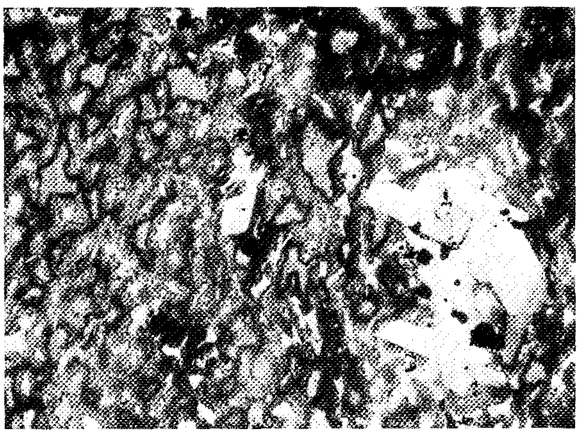


FIGURE 7.—Rhyolite; Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.



3. *Structure.*—Massive.
4. *Field name.*—Porphyritic felsite.

B. Microscopic:
1. *Texture.*—This rock is hyaline and microporphyritic. The glassy matrix is filled with acicular crystallites which cannot be identified. Use of the term rhyolite is based mainly on the strength of the high SiO_2 percentage of rock. Tiny vesicles occur within the rock, and iron-stained alteration halos surround them.
2. *Structure.*—The plagioclase microphenocrysts range in size from 0.1 to 1.5 millimeters in length. The pyroxene grains range from 0.2 to 1 millimeter in length, and the magnetite grains range from 0.001 to 0.2 millimeter on an edge.

C. Composition:

(Visual estimates only)	*Content, percent*
1. Glass and crystallites	95
2. Plagioclase microphenocrysts (albite or oligoclase)	4
3. Pyroxene (augite)	<1
4. Magnetite	<1
5. Hematite	<<1

D. Mineral description:
1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).
(*a*) *General.*—The plagioclase occurs as zoned crystals with carlsbad and albite twinning. The composition of the plagioclase indicated by its optical properties is in the high-temperature albite or oligoclase range.
(*b*) *Crystal development.*—Most crystals are euhedral with sharp boundaries, but some are broken and show rounding.
(*c*) *Alteration.*—None observed.
(*d*) *Inclusions.*—Glass and crystallites are included in the plagioclase grains.
2. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).
(*a*) *General.*—The pyroxene is light green in color and augite in composition.
(*b*) *Crystal development.*—The pyroxene occurs in euhedral prisms, with some grains broken and rounded.
(*c*) *Alteration.*—A fibrous brown reaction rim (?) was noted on one pyroxene.
(*d*) *Inclusions.*—Magnetite occurs in the pyroxenes with some glass and crystallites.

VIII. DACITE

A. Macroscopic:
1. *Color.*—Dark gray.
2. *Texture.*—Glassy, with feldspar microphenocrysts.
3. *Structure.*—Massive.
4. *Field name.*—Dacite(?).

B. Microscopic:
1. *Texture.*—This rock is hypocrystalline, with a microporphyritic, hyalopilitic texture. Some plagioclase microphenocrysts tend to be clustered together in small groups. The name dacite is based on the high percentage of silica and the composition of the plagioclase.
2. *Structure.*—The plagioclase microphenocrysts range in size from 0.2 to 2 millimeters in length. The matrix plagioclase averages 0.05 millimeter in length. The pyroxene ranges from 0.2 to 0.8 millimeter in length and the few oxyhornblende crosssections seen are 0.2 millimeter in the longer direction. The magnetite occurs in cubes with edges as large as 0.2 millimeter.

C. Essential minerals and glass:(Visual estimates only)

	Content, percent
1. Plagioclase (microlites) (labradorite)	40
2. Glass	36
3. Plagioclase (microphenocrysts) (labradorite)	15

D. Accessory minerals:

	Content, percent
1. Pyroxene (pseudomorph of hornblende after augite?)	5
2. Magnetite	3
3. Oxyhornblende	<1

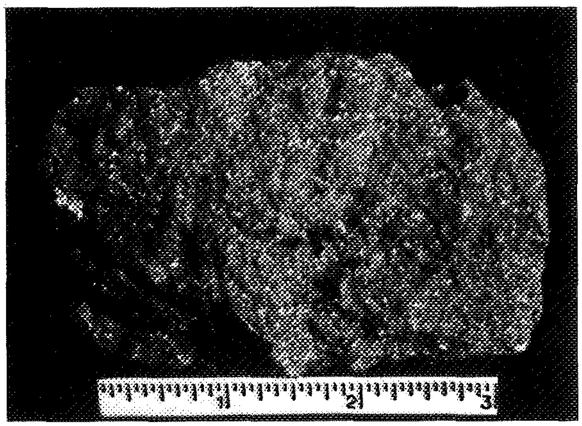
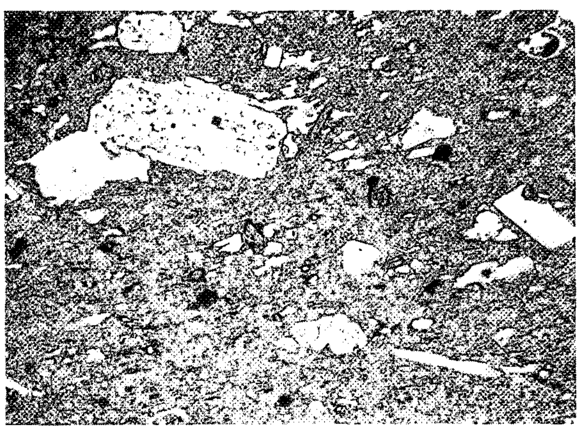


FIGURE 8.—Dacite; west of Bend, Oreg. Above, hand specimen; below, photomicrograph, × 13.



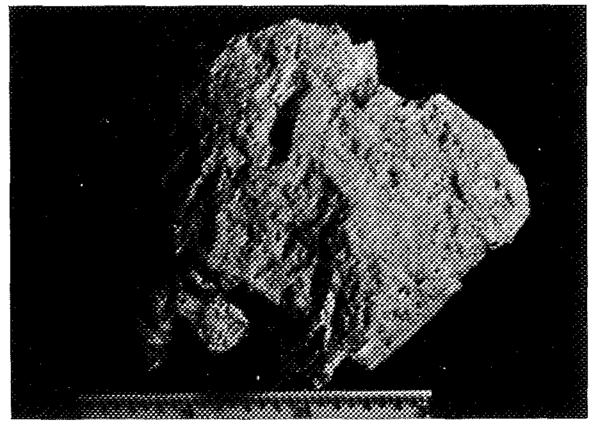
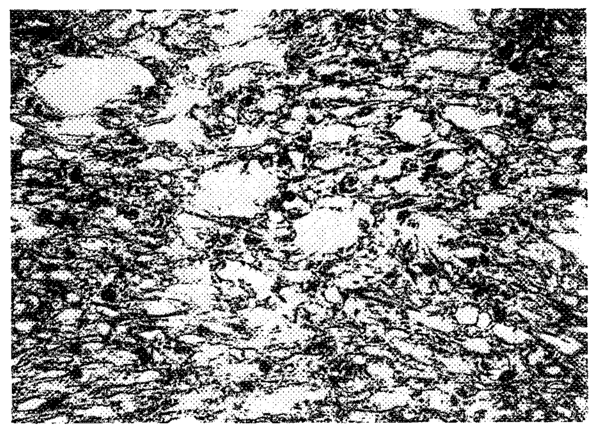


FIGURE 9.—Pumice; Newberry Caldera, Oreg. Above, hand specimen; below, photomicrograph, × 13.



E. Description of essential minerals:

1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).

(*a*) *General.*—The microphenocrysts are high-temperature, zoned crystals with both albite and carlsbad twinning. The microlites are unzoned with some carlsbad twinning in the larger grains. The composition of the plagioclase is labradorite.

(*b*) *Crystal development.*—The microphenocrysts range from good euhedral crystals to broken, skeletal, spongy, corroded remnants. The matrix grains are somewhat euhedral and range in shape from laths to blocky grains.

(*c*) *Alteration.*—None, other than corrosion of microphenocrysts.

(*d*) *Inclusions.*—Glass and euhedral magnetite occur as inclusions in the microphenocrysts.

IX. Pumice

A. Macroscopic:

1. *Color.*—Light tan.
2. *Texture.*—Porous, glassy.
3. *Structure.*—Massive.
4. *Field name.*—Pumice.

B. Microscopic:

1. *Texture and structure.*—This rock is vitreous and is macrovesicular to microvesicular. Microscopic spherulites are present, and there is a definite lineation to the rock imparted by the ellipsoidal shape of the spherulites and vesicles and the flow lines. Some devitrification of the glass has taken place, and a few feldspar crystallites can be seen in the less glassy areas. The average vesicle size is about 0.2 millimeter at its longest ellipse axis. The glass is clear to cloudy (devitrifying) with an index of refraction of about 1.49. The spherulites make up an estimated 20 percent of the rock and the vesicles, about 40 percent. No alteration other than devitrification was observed.

X. Vesicular Basalt 1

A. Macroscopic:

1. *Color.*—Gray.

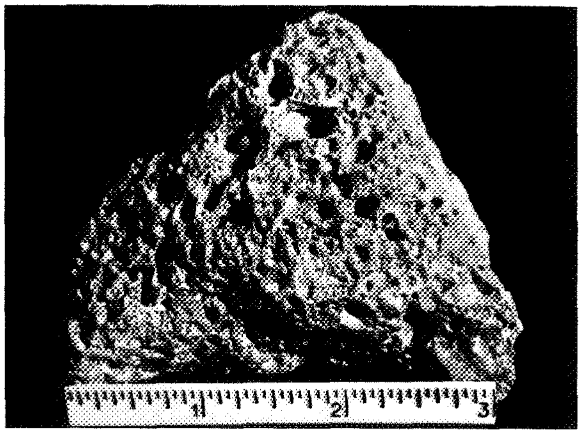
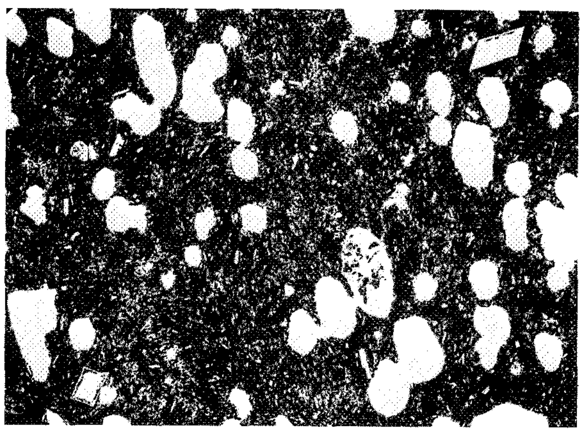


FIGURE 10.—Vesicular basalt 1; occurs south of Bend, Oreg. Above, hand specimen; below, photomicrograph, × 4.6.



2. *Texture.*—Vesicular, with microphenocrysts and aphanitic matrix.
3. *Structure.*—Massive.
4. *Field name.*—Vesicular basalt.

B. Microscopic:

1. *Texture.*—The texture of this rock may be described as hypocrystalline, vesicular, microporphyritic, and hyalopilitic. The plagioclase has a fairly continuous size range from microphenocrysts to matrix; this imparts a seriate texture for that mineral. This case exists similarly for the pyroxene and olivine.
2. *Structure.*—The vesicles are somewhat elongate in one direction, range in size from 0.1 to 0.5 millimeter long, and represent almost 35 percent of the total area of the section. The plagioclase laths vary from 0.01 to 0.5 millimeter in length. The pyroxene and olivine occur mainly as matrix minerals and occasionally as microphenocrysts. They range in size from 0.01 to 0.7 millimeter in diameter. Magnetite occurs as subhedral to euhedral grains about 0.01 millimeter in diameter.

C. Essential minerals and glass:

(Visual estimates only)	*Content, percent*
1. Plagioclase (matrix) (labradorite)	50
2. Pyroxene (augite)	20
3. Glass	15
4. Plagioclase (microphenocrysts) (labradorite or bytownite)	10

D. Accessory minerals:

	Content, percent
1. Olivine (forsterite, Fo_{88}–Fo_{100})	<3
2. Magnetite	2
3. Hematite	<1

E. Description of essential minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).

(*a*) *General.*—The euhedral plagioclase microphenocrysts are zoned both continuously and discontinuously. Many crystals are "stuffed" zonally with dust, glass, and small nonpolarizing crystallites. Albite twinning is common for both the matrix and phenocrystic sizes. The smaller matrix laths are subhedral to euhedral, are unzoned, and have no particular orientation within the matrix. The composition of the plagioclase is at least labradorite or more calcic.

(*b*) *Crystal development.*—The crystal development becomes poorer as the plagioclase size decreases; therefore the microphenocrysts have the better crystal development and the matrix plagioclase microlites the least.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Dusty glass and crystallites of olivine(?) and pyroxene(?) occur zonally within the larger plagioclase crystals.

2. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).

(*a*) *General.*—The pyroxene occurs as subhedral to euhedral grains of both matrix and microphenocryst size. No zoning or twinning is apparent, and the composition is probably augite.

(*b*) *Crystal development.*—Most grains have good crystal development, with the matrix–size grains being the more euhedral.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Some very small crystallites are included within the pyroxene grains.

XI. VESICULAR OLIVINE BASALT 2

A. Macroscopic:

1. *Color.*—Dark gray to black.
2. *Texture.*—Vesicular, aphanitic.
3. *Structure.*—Massive.
4. *Field name.*—Vesicular basalt.

B. Microscopic:

1. *Texture.*—This rock may be described as hypo-

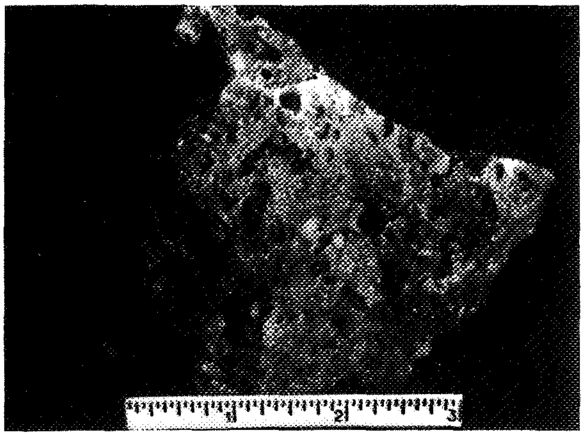
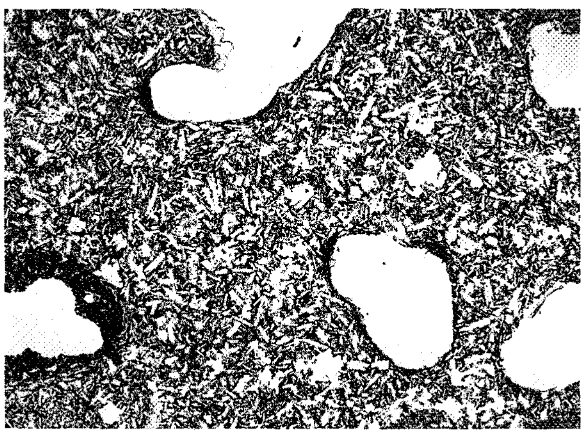


FIGURE 11.—Vesicular basalt 2; occurs south of Bend, Oreg. Above, hand specimen; below, photomicrograph, × 4.6.



crystalline and as having a vesicular, hyalopilitic texture. The plagioclase and pyroxene have no specific orientation.

2. *Structure.*—The plagioclase laths range in size from 0.1 to 1.5 millimeters long and average about 0.7 millimeter. The olivine grains are rounded and range from about 0.05 to 0.5 millimeter in diameter. The pyroxene grains are elongated prisms averaging about 0.3 to 0.5 millimeter in length, and they are the main constituents of the vesicle walls. The vesicles represent about 40 percent of the area of the section. They are somewhat elongate and range from 2 to 15 millimeters in the longest dimension. The magnetite occurs in anhedral to euhedral grains ranging from 0.01 to 0.30 millimeter in diameter. Some alteration of magnetite to hematite has occurred.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Plagioclase (labradorite, An_{68})	50
2. Olivine (Fo_{50}–Fo_{88})	25
3. Pyroxene (augite)	15

D. Accessory minerals and glass:

	Content, percent
1. Magnetite	5
2. Glass	5
3. Hematite	<1

E. Description of essential minerals:

1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).
   (*a*) *General.*—The plagioclase occurs as laths with polysynthetic twinning, with compositional zoning apparent in some more equant (older?) grains. The composition indicated by the Michel-Levy method for the twinned laths is about An_{68} in the labradorite range.
   (*b*) *Crystal development.*—The laths are subhedral with splintered, broken ends. Twin planes and intergranular boundaries are sharp.
   (*c*) *Alteration.*—None observed.
   (*d*) *Inclusions.*—A few inclusions occur in the plagioclase and are probably olivine (?).
2. *Olivine* ($(Mg, Fe_2)_2SiO_4$).
   (*a*) *General.*—The olivine grains are indicated to be in the Fo_{50}–Fo_{88} range.
   (*b*) *Crystal development.*—The grains are rounded to euhedral, with the small grains being the most euhedral. Some resorption may have occurred, thereby causing the rounding of the (older?) larger grains.
   (*c*) *Alteration.*—None observed.
   (*d*) *Inclusions.*—A few inclusions of undetermined composition occur in the olivine grains.
3. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).
   (*a*) *General.*—The pyroxene is brown in color and probably augite.
   (*b*) *Crystal development.*—The grains forming the vesicle walls are elongate, somewhat radiating, and poorly developed. Pyroxene also occurs in the matrix as interstitial and more euhedral grains.
   (*c*) *Alteration.*—None observed.
   (*d*) *Inclusions.*—Most magnetite occurs as inclusions within the augite.

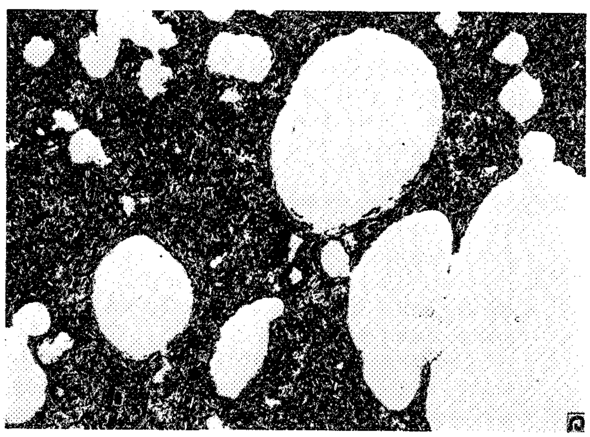
XII. VESICULAR OLIVINE BASALT 3

A. Macroscopic:
1. *Color.*—Dark gray.
2. *Texture.*—Vesicular, aphanitic.
3. *Structure.*—Massive.
4. *Field name.*—Vesicular basalt.

B. Microscopic:
1. *Texture.*—The rock is hypocrystalline with a vesicular, microporphyritic, hyalopilitic texture. The plagioclase laths have no specific orientation in either section (perpendicular or parallel).
2. *Structure.*—The plagioclase microphenocrysts range in size from 0.2 to 1.5 millimeters long. The plagioclase microlites range from 0.01 to 0.3 millimeter long. The olivine grains are from 0.01 to 0.4 millimeter in diameter. The mag-

324-954 O—69——7

FIGURE 12.—Vesicular basalt 3; Lava Beds National Monument, Calif. Above, hand specimen: below, photomicrograph, × 4.6.



netite grains are very small and average 0.002 millimeter in diameter. The vesicles represent about 35 percent of the area of the section, are ovoid in shape, and range from 2 to 10 millimeters in diameter. Some of the vesicle walls have colloform opal linings. The glass, although cloudy, is not particularly altered.

C. Essential minerals and glass:

(Visual estimates only)	Content, percent
1. Plagioclase (matrix) (labradorite, An_{53})	45
2. Olivine forsterite (Fo_{88}–Fo_{100})	20
3. Plagioclase (microphenocrysts) (bytownite)	10
4. Glass	20

D. Accessory minerals:

	Content, percent
1. Magnetite	5

E. Description of essential minerals:

1. *Plagioclase* ($CaAl_2Si_2O_8$; $NaAlSi_3O_8$).

(*a*) *General.*—The microphenocrysts are zoned and have a compositional range averaging about sodic bytownite. Carlsbad twinning is common, with some albite twinning. The matrix plagioclase displays albite twinning and is in the labradorite (An_{53}) range; this is determined by using the Michel-Levy technique.

(*b*) *Crystal development.*—The microphenocrysts are corroded remnants of euhedral, twinned crystals, but they still retain much of their original outline. The matrix crystals are subhedral laths with splintery ends, and are not well crystallized.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Dust and glass are zonally included in the plagioclase microphenocrysts in the center or middle zones.

2. *Olivine* ($(Mg, Fe_2)_2SiO_4$).

(*a*) *General.*—The olivine is mostly matrix size with a few larger grains. The composition is indicated to be in the forsterite range (Fo_{88}–Fo_{100}).

(*b*) *Crystal development.*—The matrix grains are very crystalline and euhedral. Some larger (older ?) grains tend to be somewhat rounded.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—A few unidentified inclusions are scattered through the grains.

XIII. GABBRO

A. Macroscopic:

1. *Color.*—Dark brown, mottled.
2. *Texture.*—Medium-grained feldspar has some orientation.
3. *Structure.*—Dense, massive.
4. *Field name.*—Gabbro.

B. Microscopic:

1. *Texture.*—The rock has a phaneritic, hollocrystalline, anhedral-interstitial texture. The plagioclase laths do not appear well oriented in thin section. The subhedral plagioclase laths are surrounded by anhedral grains of pyroxene, olivine, and magnetite which impart the anhedral—interstitial texture.
2. *Structure.*—The grain size is fairly uniform for all species except plagioclase, which has laths that average 10 to 15 millimeters long and 1 millimeter wide but range from 0.3 millimeter long. The pyroxene grains range from 1 to 2 millimeters and the olivines from 0.5 to 1.5 millimeters in diameter. Most olivines show some incipient alteration to fibrous serpentine along fractures and grain boundaries. The magnetite grains vary in size from 0.1 to 1.5 millimeters in diameter, although most grains are at the larger end of the range.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Plagioclase (labradorite, An_{52})	50
2. Pyroxene (pigeonite)	35

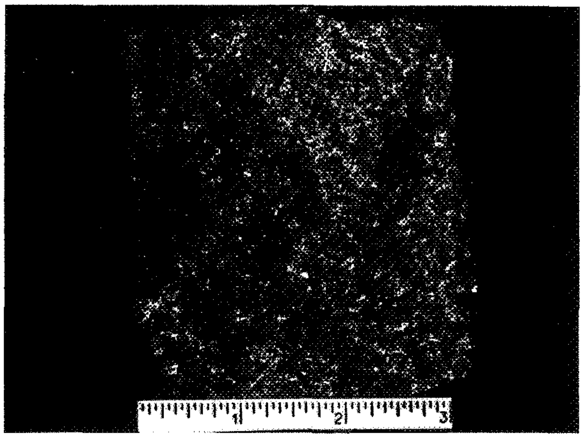


FIGURE 13.—Gabbro; occurs north of Duluth, Minn. Above, hand specimen; below, photomicrograph, × 13.

D. Accessory minerals:

	Content, percent
1. Magnetite	10
2. Olivine (forsterite (Fo_{50}–Fo_{88}))	5
3. Serpentine	<1
4. Pyrite	<<1

E. Description of essential minerals:

1. *Plagioclase* ($NaAlSi_3O_8$; $CaAl_2Si_2O_8$).

(*a*) *General.*—The laths are unzoned, with both albite and carlsbad twinning present. The composition is indicated as about An_{52} (labradorite) by using the Michel-Levy technique.

(*b*) *Crystal development.*—Outlines are irregular with no good faces developed, but the twin and intergranular boundaries are sharp.

(*c*) *Alteration.*—Some apparent sericitic (?) alteration was observed on several grains.

(*d*) *Inclusions.*—Tiny, nonpolarizing crystallites occur scattered evenly throughout the plagioclase grains, and these probably are primary inclusions.

2. *Pyroxene* ($Ca(Mg, Fe_2, Al)(Si, Al)_2O_6$).

(*a*) *General.*—The pyroxene grains are anhedral, unzoned pigeonite.

(*b*) *Crystal development.*—There are no crystal outlines, but grain boundaries are sharp.

(*c*) *Alteration.*—None observed.

(*d*) *Inclusions.*—Some (exsolved ?) crystallites were noted along two or more crystal directions and these may be another pyroxene phase.

XIV. DUNITE (HARSBURGITE)

A. Macroscopic:

1. *Color.*—Green-black.
2. *Texture.*—Fine-grained, some surface alteration.
3. *Structure.*—Dense, highly fractured.
4. *Field name.*—Dunite.

B. Microscopic:

1. *Texture.*—This rock is phaneritic and holocrystalline with a mosaic texture. The grains are anhedral and equant to elongate.
2. *Structure.*—The larger, more elongate grains of olivine and pyroxene give a layered appearance to the rock. Many olivines have undulatory extinction, and many pyroxenes are sheared along cleavage directions. The rock is highly fractured but healed by serpentine. The fractures are long, are closely spaced, and occur in several directions. The olivine grains range in size from 0.2 millimeter in diameter to 6 millimeters long and 2 millimeters wide. The pyroxenes range from 0.2 to 4 millimeters long. The spinel is yellow-brown, varies in size from 0.02 millimeter to 1 millimeter in diameter, and occurs as irregular interstitial grains.

C. Essential minerals:

(Visual estimates only)	Content, percent
1. Olivine (forsterite)	60
2. Orthopyroxene (enstatite)	35

D. Accessory minerals:

	Content, percent
1. Spinel (chromite)	3
2. Serpentine	1
3. Magnetite	<<1

E. Mineral descriptions:

1. *Olivine* ($(Mg, Fe_2)_2SiO_4$).

(*a*) *General.*—The olivine grains are unzoned, but they are strained and show wavy extinction. The composition is in the forsterite range.

(*b*) *Crystal development.*—None, but grain boundaries are well defined.

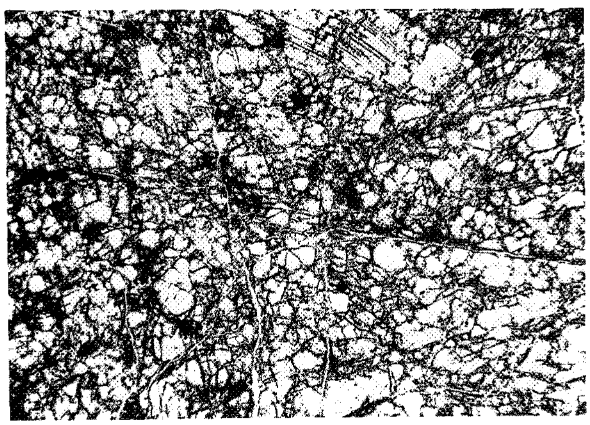
(*c*) *Alteration.*—Some alteration of olivine to fibrous serpentine has occurred along fractures.

(*d*) *Inclusions.*—Some very small crystallites are present in the olivine grains.

2. *Orthopyroxene* ($(Mg, Fe_2)SiO_3$).

(*a*) *General.*—The larger grains show a zoning parallel to the cleavage which may be due to an exsolved pyroxene phase, twinning, or a shearing effect. The lamellar zones are continuous and very closely spaced. The pyroxene is enstatite

FIGURE 14.—Dunite; Riddle, Oreg. Above, hand specimen; below, photomicrograph, × 13.



and occurs in local concentrations rather than in even distributions throughout the rock.

(*b*) *Crystal development.*—None, but boundaries are sharp.

(*c*) *Alteration.*—Some serpentine and sericite occur along fractures in the pyroxene.

(*d*) *Inclusions.*—Very tiny crystallites occur scattered throughout the grains.

APPENDIX B—CHEMICAL ANALYSES OF SIMULATED LUNAR ROCKS

Chemical analyses of the simulated lunar rocks are given in table B1. Analyses of rocks I to VI were made by T. Cook. (See ref. 4.) Analyses of rocks VII to XIV were made by R. Jefferson.

TABLE B1.—*Chemical Analyses of Simulated Lunar Rocks*

Constituent	Content, percent, in—					
	I Tholeiitic basalt	II Semiwelded tuff	III Obsidian	IV Altered rhyolite	V Serpentine	VI Granodiorite
SiO_2	51.0	71.2	72.8	72.5	40.0	70.0
TiO_2	2.7	.23	.23	.33	.04	.34
Al_2O_3	14.0	14.0	14.4	15.7	1.8	16.0
Fe_2O_3	3.4	1.4	.54	.76	6.4	.07
FeO	8.8	.89	1.5	.0	1.8	2.1
MnO	.25	.08	.07	.02	.11	.04
MgO	4.4	.34	.04	.26	37.2	.64
CaO	8.0	.95	.84	.68	.9	3.2
Na_2O	3.4	5.0	4.9	3.7	.08	4.4
K_2O	1.7	3.0	4.0	5.0	.04	2.2
P_2O_5	1.4	.08	.03	.03	.02	.1
H_2O+	.76	2.3	.2	1.4	12.5	.47
H_2O-	.1	.15	.1	.2	.3	.2
Total H_2O	.86	2.45	.3	1.6	12.8	.67
CO_2	.03	.16	.0	.0	.04	.05
S	.004	Nil	Nil	.045	.022	Nil
Total	100.0	99.7	99.7	100.6	101.2	99.8

Constituent	Content, percent, in—							
	VII Rhyolite	VIII Dacite	IX Pumice	X Vesicular basalt 1	XI Vesicular basalt 2	XII Vesicular basalt 3	XIII Gabbro	XIV Dunite
SiO_2	70.1	71.5	71.8	54.4	47.6	53.0	43.3	42.2
TiO_2	.26	.33	.23	1.13	1.42	.77	5.97	Nil
Al_2O_3	14.9	14.5	13.6	16.8	17.0	16.2	13.1	1.60
Fe_2O_3	2.77	.61	1.10	3.17	3.56	3.26	6.46	1.67
FeO	.44	1.92	1.03	5.39	6.33	5.19	9.97	6.51
MnO	.18	.12	.13	.23	.18	.17	.22	.22
MgO	.20	.55	.29	4.94	8.09	6.73	7.33	45.71
CaO	1.33	2.05	1.30	7.67	10.99	8.56	11.50	.63
Na_2O	5.74	4.35	4.54	2.43	2.29	3.01	1.76	.01
K_2O	2.60	2.81	3.98	.92	.29	1.00	.12	Nil
P_2O_5	.050	.11	.05	.28	.23	.13	.02	.005
H_2O+	.13	.09	.08	.68	.36	.51	.12	.25
H_2O-	.48	.40	1.07	.15	.23	.09	.10	2.28
Total H_2O	.61	.49	1.15	.83	.59	.60	.22	2.53
CO_2	$<.10$	$<.10$	$<.10$	.26	$<.10$	.40	.26	$<.10$
S	.011	.005	Nil	.005	.005	.009	.054	.004
Total	99.3	99.4	99.3	98.5	98.7	99.0	100.3	101.1

Page intentionally left blank

ROLLAND L. BLAKE
Bureau of Mines
Twin Cities Metallurgy Research Center
Minneapolis, Minn.

Ore Deposits in Volcanic Rocks on Earth With Lunar Extrapolation

A literature search was made on the origin of ore deposits in volcanic rocks on Earth. The close association between mineralization of the rocks in a region and the later stages of volcanism is well established. Also recognized is the prominent role of magmatic solutions composed mostly of juvenile water, but frequently supplemented with ground water, in the formation of mineral deposits by such processes as hydrothermal deposition and sublimation. Ten ore-forming processes were recognized, and eight of these form ore deposits in Earth volcanic rocks.

Effects of the inferred lunar environment on processes forming ore deposits were also studied. Mineral deposits thought to exist in volcanic rocks on the Moon, in order of decreasing amount and likelihood, are those formed by the following six processes: Hydrothermal deposition, sublimation, combined eruption and exhalation, volcanic eruption, and, rarely, contact metasomatism and evaporation. The Moon is viewed by the writer as a still-dynamic body with some volcanism likely.

Areas needing further work are summarized in the following suggested work plan: (1) Develop sensors for both remote and near-source detection of water in sublimates, rocks, and volcanic exhalations; (2) study volcanic sublimates, their properties and probable stability, in the lunar-surface environment; (3) investigate gases other than steam as a resource for life support; (4) assemble a space-geology nomenclature for efficient communication; (5) improve geophysical-geological techniques and equipment so that mineral deposits other than water can be located in volcanic rocks; and (6) compile information and stimulate research for answers to problems related to volcanism, meteorite impact, and formation of mineral deposits.

INTRODUCTION

Astronomical, geophysical, geochemical, and geological evidence and reasoning from lunar studies indicate that natural materials and processes similar to those on Earth should be expected on the Moon as changed by the modifying effects of the surface and near-surface environment. The role of volcanic activity in forming and modifying the lunar surface and crust is becoming apparent from study and interpretation of space-probe photographs by U.S. Geological Survey geologists and NASA scientists and by individuals such as Green (refs. 1 and 2) and Fielder (ref. 3). On Earth the close association of volcanic activity with mineralization of the adjacent country rock has been recognized for many years.

This study involves a literature search to: (1) study formation of Earth ore deposits in volcanic rocks; (2) study effects of the lunar environment on formation and occurrence of lunar mineral deposits; (3) summarize expected lunar mineral resources in volcanic rocks; and (4) recommend further Earth studies that will aid in the location and use of mineral resources in volcanic rocks on the Moon and perhaps on other extraterrestrial bodies.

Dr. Jack Green of the Douglas Advanced Research Laboratories prepared a survey report entitled "Calderas as Related to Lunar Exploration" (ref. 4). Green's report has greatly aided the preparation of the present report and together they constitute a summary of the funded work.

EARTH MODEL

Earth's Crust

The outer 16 kilometers (10 miles) of the Earth's crust is estimated to consist of 95 percent igneous and metaigneous rocks and 5 percent sedimentary and metasedimentary rocks (ref. 5). (The prefix "meta," or metamorphosed, means altered by pressure and/or heat.) No estimate of the amount of igneous rocks that are volcanic (extrusive) was found, but volcanic rocks are prominent. As an example, Waters estimates that basalts in the Eocene epoch in the Pacific Northwest (estimated as a 20-million-year time interval) covered an area of 155 000 km^2 (60 000 mi^2) and attained a volume of 170 000 km^3 (40 000 mi^3) (ref. 6). Thus, the Earth's crust contains a substantial proportion of volcanic rocks which may be host to mineralization that forms ore bodies both on the surface and within the crust.

The 12 most abundant elements constitute over 99 percent of the Earth's crust; of these, only 3 (Fe, Ti, Mn) form extensive metallic ore deposits. The remaining elements of the crust are present in small to trace amounts. The ore-forming processes must concentrate Pb about 1200 times, Zn 150 times, and Cu 70 times to form currently economic deposits.

The continental areas of the Earth's crust are fairly stable, but the oceanic-continental border areas are less stable and undergo large-scale, gradual deformation (tectonism) such as folding, faulting, and fracturing accompanied by igneous rock intrusions at various depths. Superimposed on these large-scale events are smaller scale volcanic eruptions caused by some of the intrusive magmas (molten rocks) reaching the surface. Also, on this smaller scale, and either during the late volcanic stage or afterward, the rocks in the region are usually mineralized. This mineralization is often aided by uplift or doming that produces fracturing of near-surface rocks on a large scale (refs. 7 and 8).

Cooling intrusive rocks give off fluids containing metals derived mostly from the intrusives and partly from the intruded rocks. The fluids are composed of water and compounds of B, F, Cl, P, S, C, As, and other rarer elements (ref. 9). Magmas are the original source of all mineral-deposit ingredients as is emphasized by Bateman (ref. 10).

Ore Deposits in Volcanic Rocks

Ore deposits are formed by the following processes:

(1) Magmatic concentration
(2) Contact metasomatism
(3) Hydrothermal deposition
(4) Sublimation
(5) Evaporation
(6) Sedimentation
(7) Residual and mechanical concentration
(8) Submarine volcanic exhalation
(9) Volcanic eruption
(10) Eruption-exhalation

This list is from the work of Lindgren (ref. 9) and Bateman (ref. 10). These authors have summarized much literature information and personal experience to present examples of ore deposits and concepts on their origin that are essentially valid today. Each process is briefly described below, and the extent to which it forms ore deposits in volcanic rocks is mentioned.

The process of magmatic concentration involves the differentiation (or separation and concentration) of certain elements and minerals within the cooling magma at considerable depths below the surface. The resulting deposits do not form in volcanic rocks. Contact metasomatic deposits are formed in intruded rocks by high-temperature gaseous emanations escaping from intruding igneous magmas. The rocks replaced by such ores are usually limestone and calcareous shales, and occasionally quartzites and older intrusive rocks. It is possible that such deposits could form in older volcanic rocks, but no such reference was found.

Hydrothermal solutions of deep origin are mixtures of high-temperature gases and liquids given off by a cooling intrusive mass. As they progress away from the magma source, they are, or become, liquids and gradually lose heat.

Deposition occurs by replacement or by filling, or a combination of these processes. Replacement, or metasomatic replacement, is defined as "a process of essentially simultaneous capillary solution and deposition by which a new mineral is substituted for one or more earlier formed minerals" essentially on a volume-for-volume basis (ref. 10, p. 137).

Lindgren (ref. 9) recognized three groups of hydrothermal deposits based on distance outward from the intrusive, hypothermal, mesothermal, and epithermal, and to these has been added hot-spring deposits. The essential characteristics of each group are summarized in table 1. Hypothermal solutions are thought to be composed of water almost entirely of magmatic origin. Mesothermal solutions are diluted by ground water in degrees ranging from slight to great, and epithermal and hot-spring solutions are thought to be composed mostly of heated ground water.

A rather small number of hypothermal deposits occur in older volcanic rocks which were deeply buried at the time of mineralization. Mesothermal deposits in volcanic rocks are more numerous than hypothermal ones. Epithermal deposits are one of the most valuable classes of ores, having furnished much silver, gold, and mercury with lesser amounts of copper, lead, and zinc. These deposits are located in regions of comparatively recent volcanic activity. Hot-spring waters and their deposits are also nearly always found in areas of recent volcanic activity but are not so numerous in volcanic rocks as are epithermal deposits.

Small but important mineral concentrations are formed near and at the Earth's surface by the process of sublimation from vapors issuing quietly to violently at vents or fissures under atmospheric conditions. Rittmann recognizes two major types of gaseous emanations: solfataras and fumaroles (ref. 11, pp. 5–11). Solfataras are steam spouts at temperatures of 90° to 300° C with small amounts of CO_2 and H_2S that occur in all volcanic regions of the world. Free sulfur is deposited in crystals around the vents, sometimes in volumes large enough to be mined. A special type of solfatara-like steam spout occurs in Lardarello, Tuscany, Italy, where geothermal gases are exploited for generating electric power and for producing chemicals. Average composition of the vapor is as follows: H_2O, 95 percent; CO_2, 4.3 percent; H_2S, 0.9 percent; boric acid, 0.3 percent; NH_3, 0.3 percent; CH_4, 0.15 percent; and H_2, 0.04 percent. Each year 26 million tons of steam generate about 2 billion kilowatts of electricity (ref. 11). According to Bullard (ref. 12), the chemicals produced include Dry Ice (CO_2),

TABLE 1.—*Characteristics of Formation of the 4 Groups of Hydrothermal Deposits*

Deposits	Parameter					
	Temp, °C	Depth, km	Pressure, atm		Ores	
			Lithostatic	Hydrostatic	Common	Less common
Hypothermal	300 to 600	1.6 to 4.8	450 to 1350	150 to 450	Au, Cu, Fe, Pb, Sn, Zn	Mo, W
Mesothermal	175 to 300	1.6 to 3.2	450 to 900	150 to 300	Ag, As, Au, Cu, Pb, Sb, Te, Zn	Bi, Co, Mn, Ni, Pt
Epithermal	50 to 200	Surface to 0.8 or 1.6	1 to 112 or 225	1 to 37 or 75	Ag, Au, Hg, Pb, Zn	Cu, Pt, Sb
Hot spring	40 to 100	Surface		1	Ag, As, Au, Cu, Hg, Pb, Sn	

liquid NH_3, $(NH_4)_2CO_3$ and NH_4Cl, sodium perborate, manganese borate, and boron carbide. Around 1940, 8000 tons of boric acid and 4500 tons of borax were produced each year.

Rittmann's fumarole types are as follows: (1) "cool" emanations (called moffete) producing water vapor and some CO_2, but not H_2S, at temperatures seldom exceeding 101° C; and (2) very hot fumaroles with temperatures up to 900° C found in craters or at fissures in active volcanoes. They always carry HCl, volatile chlorides and, especially, NaCl and $FeCl_3$ in addition to the constituents of solfataras.

The importance of calderas as sites of sublimate ore deposits has been stressed by Green (ref. 4), who has covered the recent Japanese literature contributions.

Extensive deposits of salts are formed by evaporation of water from lakes in closed basins in arid lands. Much smaller deposits are formed by evaporation at the surface of salt-containing waters ascending by capillary action, and just below the surface in caves and in smaller openings such as vesicles in lava flows and in loose volcanic aggregates. The amount of evaporite deposits in volcanic rocks is apparently very small.

Sedimentation in bodies of water by mechanical, chemical, or biochemical deposition has formed large ore deposits in sedimentary rocks, but only a few are interbedded with volcanic rocks and none are expected to form in such rocks.

Residual concentration may form an ore deposit by physical or chemical weathering involving air, water, acids (as H_2CO_3), and gravity; these agents remove the gangue material and leave behind the valuable ore mineral. Mechanical concentration takes place in moving water or air so that heavier minerals derived from various rock types and deposits are sorted to form placers. No ore deposits in volcanic rocks with origin recognized as residual or mechanical concentration have come to the author's attention.

Submarine volcanic exhalation is a process of simultaneous gaseous, hydrothermal, and solid/molten magma emanations, all ejected under a sea-water medium. The gases entrapped in the volcanic rocks may deposit native sulfur and iron sulfides with minor quantities of lead, zinc, and copper. Certain massive sulfide and sulfur ores in volcanic pillow lavas are thought to have such an origin (refs. 13 and 14). Hydrothermal deposition may account for other such deposits.

Volcanic eruptions normally do not produce mineral deposits. Several very interesting exceptions to this normal behavior are described in the literature, however, and they involve an actual extrusion or flow of the ore mineral itself. Watanabe describes molten sulfur flows (ref. 15), Dawson describes sodium carbonate flows (ref. 6), and Park describes a magnetite-hematite flow in Chile (ref. 17).

It is likely that a process similar to submarine volcanic exhalation could take place on land without the presence and pressure of a confining hydrosphere. The term "eruption-exhalation" in the list refers to this possible process in which much of the gases would be lost to the atmosphere, but some could be trapped within the cooling lava and pyroclastic deposits near the main vents. This type of deposit may be similar to one that Green briefly described (ref. 4, p. 40) and associated with Jenks (ref. 18).

The Earth model discussed previously emerges as a dynamic body undergoing gradual crustal changes which are mostly confined to certain areas. Ore deposits are formed in some older volcanic rocks buried within the crust and in more recent ones at the surface. Volcanic activity is closely related to some mineralization, but nonvolcanic agents may also produce ore deposits in volcanic rocks.

LUNAR MODEL

Environmental Effects

The writer believes that the Moon was formed at the same time as was the Earth and is of similar materials. That the proportion of these materials and their possible distribution are not identical to those of the Earth is suggested by the density difference.

Green (ref. 4) suggests that the lunar body tides that might be induced by Earth's mass and proximity may have the following effects: (1) they may create major fracture systems in the lunar crust; (2) they may generate heat by crustal flexing; and (3) they may provide periodic pressure release under crustal blocks to cause (or favor) the start of magma formation.

The Moon's crust is believed to be made up of almost 100 percent igneous and meta-igneous rocks with small amounts of meteoritic and shocked rock debris. The ratio of intrusive to volcanic rock would be difficult to surmise. No significant amounts of sedimentary rocks or their metamorphosed products would be present. On Earth, crustal and subcrustal forces can form mountains and ocean basins. Water and sediments collect in the basins and may reinforce or attenuate these forces. The same kind of forces acting in the absence of a hydrosphere and an atmosphere might be expected on a planetary body the size of our Moon. The resulting tectonism could provide openings and release fluids toward the surface, bury surface rocks at depths, and expose intrusive rocks at the surface. Burial and exposure would be considerably less than on Earth because of the lack of erosion and sedimentation effects of a hydrosphere and atmosphere. The extent of lunar tectonism and defluidization cannot be reasonably speculated upon at this time.

The generation at depth of different magma compositions by any of the several types of differentiation processes may occur on the Moon. On Earth the record shows that more mineralization is associated with magmas of acidic than with those of basic or intermediate composition (ref. 9). Estimates of the amount of lunar differentiation range from none at all, because the Moon always has been cold and lacked enough radiogenic heat to melt rock and form magma, to the other extreme of a small body giving off its contained heat so rapidly and early in its history that its later history is devoid of melting and possible differentiation and defluidization. The theory favored here is that of a cooling history rather like that of Earth, with gradual differentiation and volcanic activity throughout the Moon's history; this theory suggests a still-dynamic body rather than a now-dead Moon.

In lunar magma chambers the reduced gravity is believed to cause nucleation and coalescence of gas bubbles at greater depths than in the Earth analog (ref. 4, p. 22). This early removal of disseminated volatiles could provide a more viscous magma and a greater volume of fluids expelled during eruptions or available for mineralization. During mineralization the reduced gravity, and therefore lower lithostatic pressure, would favor earlier release of the more volatile substances which would be expelled ahead of the less volatile ones. This behavior might tend to deposit minerals at greater depths from the less volatile fluids and at shallower depths from the more volatile fluids. The results could be formation of deeper hypothermal deposits than on Earth, stretching out of mesothermal deposits in a greater vertical interval, and formation of smaller epithermal deposits. It would be difficult to predict on a temperature basis whether lunar hydrothermal deposits would have formed shallower or deeper than on Earth.

Close to the surface, the reduced gravity effect, especially where coupled with the lunar vacuum effect, is expected to cause greater vesiculation of outpouring lava, involve several times as much volume of explosive ejectamenta (ref. 1), and probably cause greater loss of volatiles in a volcanic area on the Moon than occurs on Earth.

Lunar surface temperatures vary from night to day in the approximate range of $-150°$ to over 100° C. The highest vacuum measured by remote means of the lunavac (a word that can be defined as the lunar atmosphere which is a high vacuum with traces of gases and particulate matter) is about 10^{-13} atmosphere. The warmest temperatures in direct sunlight would have the effect of boiling off water as vapor from fumarole or solfatara vents and perhaps from any concentration in the upper part of the "soil." At lower temperatures, in the shadows or during the lunar night, water being expelled in magmatic fluids might freeze in the outer layers of soil or in rock cavities such as lava vesicles or lava caves. The lunavac would contain little or no oxygen, so that there would be negligible oxidation of compounds or gases. As Green points out (ref. 19), the sublimates expected would be those not requiring oxygen from the lunar atmosphere; if they exist in sunlight, they must not photodecompose.

We can be reasonably certain that both volcanism and impact have occurred on the lunar surface. Proponents of both processes have by now presented enough evidence to confirm this statement. Future efforts should be directed toward recognizing rock products of each process and determining product ratios in the lunar crust. The suggestion by Beals (ref. 20) to establish criteria for each type of rock product seems necessary; and excellent starts on this, slanted toward impact, are French's search for criteria of shock metamorphism (ref. 21) and the papers presented in the 1966 Conference on Shock Metamorphism of Natural Materials (ref. 22). More work of this nature should be done on suspected volcanic explosion structures.

Weathering of lunar-surface materials is expected to be mostly physical, such as: temperature-extreme spalling; alteration and disintegration by solar ultraviolet and X-rays, protons, alpha particles, and cosmic rays; and meteorite damage ranging from slight to extreme. Fracturing of solid rock from moonquakes could trigger landslides, and, because of the reduced gravity and friction, some workers have proposed extreme gliding that would tend to level the loose soil. However, the lack of an air cushion between very fine particles should partially compensate for the gravity effect.

Lunar Mineral Deposits in Volcanic Rocks

Volcanic rocks and related mineral resources on the Moon's surface would be accessible to early lunar explorers. The nature and utilization of such resources have been reviewed by several authors including Lowman (ref. 23) and Penn (ref. 24). While surface deposits are most accessible, subsurface deposits may be important in the future. Minerals and elements expected in lunar deposits are in general those found in corresponding Earth deposits, although sublimate minerals on the Moon's surface may differ somewhat in amount, stability, and composition.

Table 2 lists the 10 processes described earlier that form ore deposits on Earth. The known occurrences of such ore deposits in Earth volcanic rocks are indicated, and their likelihood in volcanic rocks on the Moon are suggested.

TABLE 2.—*Ore Deposits in Volcanic Rocks Known on Earth and Likely on the Moon*

Process of formation	Occurrence of deposits	
	Earth (known)	Lunar (likelihood)
Magmatic concentration	None	None
Contact metasomatism	Rare	Rare
Hydrothermal deposition:		
Hypothermal	Few	Few
Mesothermal	Some	Some
Epithermal	Many	Some
Hot springs	Some	Few
Sublimation	Some	Some
Evaporation	Small	Rare
Sedimentation	Few	None
Residual and mechanical concentration.	None	None
Submarine volcanic exhalation	Many	None
Volcanic eruption	Few	Few
Eruption-exhalation	Some	Some

Contact metasomatic deposits conceivably could form in deeply buried lunar volcanic rocks. Hydrothermal deposits formed by ascending magmatic fluids are very likely present. A few of the deep-seated hypothermal deposits are expected. However, they may occur at much greater depths than on Earth if lunar environmental effects suggested previously are correct. Less erosion is expected on the Moon; thus fewer deep-seated deposits would be exposed than on Earth. Mesothermal deposits are expected, but they may extend a longer vertical interval, be at deeper levels, and be less extensive than on Earth where some of them are believed to form from a mixture of magmatic and ground waters. Epithermal and hot-spring deposits are expected to be fewer and smaller on the Moon because of the expected scarcity of ground water.

Sublimates and their associated gaseous emanations are believed to be the most easily accessible deposits. Processes forming submarine volcanic exhalative deposits on Earth operate beneath a hydrosphere which is not expected on the Moon. It is possible that a combined gaseous/molten-magma/solidified-magma complex on the Moon could have some deposits of massive sulfide ores formed within it during and shortly after an eruption. Evaporation might conceivably operate near or at the lunar surface to extract water from depressions near volcanic activity where magmatic waters approached the surface, dissolved substances, and carried them into these depressions. No sedimentation or residual and mechanical concentration processes are envisioned to operate on the Moon that could form ore deposits in volcanic rocks because such concentrations are effected on Earth by air and/or water agents of weathering. Volcanic eruptions that on Earth furnish only a few flows of mineral concentrates such as sulfur, magnetite, or sodium carbonate represent an unusual concentration not expected to be any more widespread on the Moon than on Earth.

The sublimate deposits would be found near and at the surface in volcanic areas and probably predominantly in calderas. In early stages of lunar basing, the sublimates offer two advantages over other sources: (1) they offer a surface deposit not requiring much mining equipment; and (2) they are usually a highly concentrated mineral supply not requiring complicated processing treatment. Volcanic areas, especially those with sublimates, would be likely targets for future exploration at depths for hydrothermal deposits.

Water is a most valuable mineral resource of any extraterrestrial body, and its location and extraction from the body's natural minerals is important to future space exploration. Therefore its occurrence in Earth volcanic rocks has been summarized by Green (ref. 25) and its extraction studied by Wechsler et al. (ref. 26) and, extensively, by Green (ref. 25). The most likely sources of lunar-surface water, in order of decreasing concentration and ease of extraction, seem to be: (1) solfataras and fumaroles in volcanic areas, and especially in calderas; (2) mineral sublimates, especially in calderas; and (3) volcanic rocks exposed at the surface, such as tuffs and lavas, and hydrothermally altered rocks. Somewhat less likely because of special conditions necessary, but still very possible, are the following sources: (1) steam-spout areas; (2) water or ice in caves or other openings; and (3) water or ice (as permafrost) in the lower part of soils, especially near exhalation vents.

Expected lunar rocks as a resource have not been elaborated on in this report except as a source of water. Other uses for such rocks have been considered by Bensko and Shotts (ref. 27) for extraction of propellant substances such as water, hydrocarbons, carbon (graphite), oxygen, fluorine, and chlorine, and metals such as beryllium, boron, magnesium, aluminum, iron, and calcium. Green has considered the use of cast basalt for pipes and structural components based on the Czechoslovakian industry (ref. 4). Rosenberg et al. investigated extraction of oxygen from magnesium silicate (ref. 28).

Gases other than steam are often reported from volcanic exhalations; these include N_2 or NH_3, O_2, CO_2, CH_4, H_2S, SO_2, H_2, Ar, HCl, and HF. Most of these are of considerable interest as possible sources of life-support gases. Helium would also be of interest if present. Astronauts are to be provided atmospheres either entirely of oxygen (which strongly supports combustion) or of some artificial air mixture. Large volumes of air are required for permanent lunar stations or shelters. Man is searching for a source of oxygen on the Moon to save efforts required to transport it from Earth to Moon for an air mixture, and he should also be interested in finding a lunar source for the inert gases required to complete the air mixture. A possible source of these gases is volcanic exhalation, but more research is needed in detecting and measuring gases which occur in small amounts. Probably the required amounts could be collected from large volumes of such exhalations by an efficient collector.

SUMMARY AND RECOMMENDATIONS

A literature search was made on the origin of ore deposits in volcanic rocks on Earth. Ten ore-forming processes were recognized and eight of these form ore deposits in Earth volcanic rocks. After considering the lunar environmental effects on ore formation, it was suggested that six of the eight processes could form ore deposits in volcanic rocks on the Moon. These are, in order of decreasing amount and likelihood: hydrothermal deposition, sublimation, combined eruption-exhalation, volcanic eruption, and, rarely, contact metasomatism and evaporation. The possibility of finding fumaroles, solfataras, and steam spouts suggests a plentiful source of water, gases, sublimate minerals, and energy in the form of heat and dynamic fluids.

Areas recommended for further work as a result of this study are given in the following work plan.

Location and Use of Lunar Mineral Resources in Volcanic Rocks

The objective is to develop a body of knowledge on mineral resources in Earth volcanic rocks that will be needed to locate and utilize similar resources likely to occur on the Moon and other extraterrestrial bodies. The information gathered (from the literature, field studies, and laboratory research) and its interpretation would have a twofold benefit:

(1) It would provide a single source of information which is now either scattered in the literature or nonexistent.

(2) It would reveal gaps in our knowledge of these mineral resources and thereby guide future research in the fields of geophysics, geology, mining, and metallurgy to provide this information.

Work Plan

The following work plan is recommended:

A. Locate possible sources of water on the Moon:
   1. Locate lunar landing areas:
      Examine lunar orbiter photographs to find desirable landing areas near locations showing evidence of recent volcanism so that early lunar exploration can emphasize search for water sources.
   2. Develop water sensors:
      a. Determine the feasibility of developing water sensor(s) for remote- and near-source detection and, if possible, measurement of water content of rocks and of mineral concentrations.
      b. If feasibility study is positive, start development of sensor(s), and plan to test them on Earth, both remote-source (Eros satellite), near-source (hovering vehicle, roving vehicle, and on-foot exploration), and in the laboratory under simulated lunar, near-source conditions.
      c. Guide lunar testing of the sensor(s) by insuring its inclusion in mission planning and follow its lunar application.
      d. Use A2*a* and A2*b* information to develop sensor(s) to locate and measure water-bearing (steam) fumaroles, solfataras, and steam spouts. A heat sensor might be coupled with another type of sensor.
   3. Collect, separate, and analyze volcanic exhalations:
      Develop mechanical apparatus for lunar application to confine and collect very hot, high-velocity, vapor exhalations together with the auxiliary apparatus to separate and analyze the water and the vapor-transported compounds. Start with existing technology from geothermal installations. Develop apparatus to utilize heat and velocity of exhalations to supply heat and power to lunar basing needs.
   4. Study volcanic sublimates:
      a. Study sublimate deposition on Earth to determine if the hydrated minerals reported have derived their water from the exhalative steam or from rain and ground water.
      b. Compile reliable physical and chemical data on sublimates and their vapors to assemble enough information so that, together with existing understanding of the theory of vapor-collection, vapor-transport, and vapor-deposition, a reasonable prediction can be made of what minerals will be precipitated, and in what order, at the lunar surface. Encourage and support laboratory research to furnish reliable information that is missing in the compilation.

      This information should be useful in studies of A2*d*, A3, B2, B3, and B4.

5. Study calderas:
   Carry out systematic caldera studies to determine fully their lunar basing potentialities and to aid the plans of A1 through A4.

B. Investigate gases (other than steam) on the Moon:
   1. Determine potential need for life-support "artificial air" gas components.
   2. If a lunar source is desired, study literature and collect and analyze Earth volcanic gases to determine how much atmospheric contamination is present. Establish whether the gases sought might be found in lunar exhalations of only magmatic origin.
   3. Start development of sensors to detect and possibly measure these gases in volcanic gas streams and chambers.
   4. Develop apparatus to collect and purify the gases for use; couple work with A3 and A4.

C. Assemble nomenclature for space geology communication:
   Work out a short, but useful, geological nomenclature for space exploration communication as proposed by Green (ref. 4). This nomenclature could be an example for the other sciences, such as geophysics and mining, to follow.

D. Locate lunar mineral deposits other than water in volcanic rocks:
   Improve geophysical techniques and equipment to detect and locate materials (both surface and subsurface) selected on a needs priority for lunar basing operations. Consider both remote- and near-source sensing. Both geology and geophysics would be needed to improve upon and test techniques and equipment.

E. Compile information on volcanism and ore deposits:
   Stimulate research by industry, universities, and Government agencies on some of the problems outlined previously by providing the information and the gaps in it as the body of knowledge in the objective is developed. Some interesting geological areas of study would be:
   1. Can volcanic explosions form shatter cones in rocks? Shatter cones are structures that some investigators regard as positive criteria for meteorite impact.
   2. Examine rocks for evidence of volcanic explosion effects. Compare these effects with those caused by meteorite impacts. Try to determine criteria unique to volcanic explosions and to meteorite impacts.
   3. Can impact trigger volcanism?
   4. Can impact trigger formation of ore deposits?
   5. Are rare-earth materials or other valuable mineral resources ever associated with the volcanic carbonatites? What is the likelihood of their lunar existence? Can carbonatite activity be triggered by meteorite impact? (On Earth, carbonatites are formed mostly by intrusive activity, although a small number are formed by extrusive volcanic activity.)

REFERENCES

1. Green, Jack: Tidal and Gravity Effects Intensifying Lunar Defluidization and Volcanism. Proc. N.Y. Acad. Sci., vol. 123, no. 2, 1965a, pp. 403–469.
2. Green, Jack: The Moon's Surface. Int. Sci. Tech., Sept. 1966, pp. 59–67, 82, 84.
3. Fielder, Gilbert: Lunar Geology. DuFour Editions (Chester Springs, Pa.), 1965.
4. Green, Jack: Calderas as Related to Lunar Exploration. Rept. DAC 61305, U.S. Bur. Mines, Apr. 1967.
5. Clarke, F. W.; and Washington, H. S.: The Composition of the Earth's Crust. Prof. Paper 127, U.S. Geol. Surv., 1924.
6. Dawson, J. B.: Sodium Carbonate Lavas From Oldoinyo Lengai, Tanganyika. Nature, vol. 195, 1962, pp. 1075–1076.
7. Wisser, E.: Relation of Ore Deposition to Doming in the North American Cordillera. Memoir 77, Bull. Geol. Soc. Amer., 1960, p. 117.
8. Goodwin, A. M.: Mineralized Volcanic Complexes in the Porcupine-Kirkland Lake-Noranda Region, Canada. Econ. Geol., vol. 60, no. 5, 1965, pp. 955–971.
9. Lindgren, Waldemar: Mineral Deposits. McGraw-Hill Book Co., Inc., 1933.
10. Bateman, Alan M.: Economic Mineral Deposits. John Wiley & Sons, Inc., 1950.
11. Rittmann, A.: Volcanoes and Their Activity. Transl. from the 1960 2d German ed. by E. A. Vincent. Interscience Publishers, 1962.

12. Bullard, F. M.: Volcanoes in History, in Theory, in Eruption. Univ. Texas Press, 1962.
13. Ridge, J. D.: Suggested Volcanic Syngenetic Origin for Certain European Massive Sulphide Deposits. Trans. Soc. Min. Eng., AIME, vol. 226, pp. 28–41.
14. Kinkel, A. R., Jr.: Massive Pyritic Deposits Related to Volcanism, and Possible Methods of Emplacement. Econ. Geol., vol. 61, no. 4, 1966, pp. 673–694.
15. Watanabe, T.: Eruptions of Molten Sulphur From Siretoko-Iôsan Volcano, Japan. Jap. J. Geol. Geog., vol. 17, 1940, pp. 289–310.
16. Waters, A. C.: Volcanic Rocks and the Tectonic Cycle. Spec. Paper 62, Geol. Soc. Amer., 1955, pp. 703–722.
17. Park, C. F.: A Magnetite "Flow" in Northern Chile. Econ. Geol., vol. 56, 1961, pp. 431–436.
18. Jenks, W. F.: Some Relations Between Cenozoic Volcanism and Ore Deposits in Northern Japan. Trans. N.Y. Acad. Sci., vol. 28, 1966, pp. 463–747.
19. Green, Jack: The Geosciences Applied to Lunar Exploration. The Moon, Z. Kopal and Z. Mikhailov, eds., Academic Press Inc. (New York), 1962, pp. 169–257. Proc. 14th Symp. Int. Astron. Union (Leningrad, Dec. 1960).
20. Beals, C. S.: The Identification of Ancient Craters. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 904–914.
21. French, Bevan M.: Sudbury Structure, Ontario: Some Petrographic Evidence for an Origin by Meteorite Impact. NASA TM X–55789, 1967.
22. Proc. 1966 Conf. of Shock Metamorphism of Natural Materials, Goddard Space Flight Center (Greenbelt, Md., Apr. 14–19, 1966).
23. Lowman, P. D., Jr.: Lunar Resources: Their Value in Lunar and Planetary Exploration. Astronaut. Acta 2, vol. 12, nos. 5–6, 1966, pp. 384–393.
24. Penn, S. H.: A Preliminary Look at Lunar Natural Resources. Trans. Soc. Min. Eng., vol. 235, Mar. 1966, pp. 66–70.
25. Green, Jack: A Study of the Feasibility of Using Nuclear Versus Solar Power in Water Extraction From Rocks. Final Rept., Contract no. AF 19(628)–3292, Proj. No. 000, Task No. 000011, North American Aviation, Inc. (Downey, Calif.), Sept. 30, 1965.
26. Wechsler, A. E.; Glaser, P. E.; and Germeles, A. E.: Investigation of Water Extraction Processes for Use on the Moon. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 1148–1159.
27. Bensko, John; and Shotts, Reynold Q.: Lunar Resources. Advances in Space Science and Technology, vol. 7, ch. 2, Academic Press Inc. (New York), 1965, pp. 147–214.
28. Rosenberg, S. D.; Guter, G. A.; and Miller, F. E.: Manufacture of Oxygen From Lunar Materials. Ann. N.Y. Acad. Sci., vol. 123, art. 2, 1965, pp. 1106–1122.

JAMES PAONE and R. L. SCHMIDT
Bureau of Mines
Twin Cities Mining Research Center
Minneapolis, Minn.

Lunar Drilling

The association of the Bureau of Mines with lunar-drill programs since 1964 includes: (1) advising and consulting with NASA and with contractors making prototype drills, and (2) conducting laboratory investigations of problems related to drilling in ultrahigh vacuum, at lunar temperature extremes, and in reduced gravity. This paper reviews problems related to lunar drilling, data from Bureau drilling tests for lunar applications, and possible methods for predicting drillability of lunar materials from their engineering properties.

INTRODUCTION AND BACKGROUND

In his quest for knowledge of the Moon, man will need to examine lunar-subsurface phenomena. In order to obtain data on these phenomena, he will require adequate drilling systems. NASA has been conducting two lunar-drill programs to complement the manned spaceflight program. The Apollo Lunar Surface Drill (ALSD) Program is developing a lightweight, hand-held, rotary-percussive drill capable of boring a 1-inch-diameter hole to a depth of 10 feet in the Moon's surface. The other program is developing a moderate-depth drill for post-Apollo applications and includes two different models, each designed to bore a 2-inch-diameter hole to a depth of 100 feet.

Developing a lunar drill is a necessary first step in the exploration of the Moon because it provides the key to the subsurface geology. All drills being developed for this purpose are core drills; that is, they cut a solid cylindrical core which can be transported back to Earth for subsequent analysis. The extraction of this core sample, however, is not the sole objective of the lunar drills, for after the core is taken the hole will be available for the emplacement of geophysical instruments such as heat probes, radiation detectors, and seismic devices.

Drilling a hole on the Moon does not, at first glance, appear extraordinarily difficult. We have, after all, mechanically drilled rock on Earth for more than a century, although the greatest advances did not occur until the last 20 years (tungsten-carbide insert bits for percussive drilling and the wire-line system for diamond drilling). When all factors of lunar drilling are considered, however, they combine into an intricate and complex problem involving the environmental effects of high vacuum, reduced gravity, and temperature extremes not encountered on Earth (ref. 1).

To drill a hole on Earth to a predetermined depth within a rigid time schedule, while collecting good samples, requires a certain amount of skill. The Earth driller uses a machine which has been thoroughly tested, and, in addition, he probably has access to an unlimited supply of replacement parts. Although the components of the lunar drills will have been rigorously tested, it is extremely difficult to test-run the complete drilling system in the temperature-vacuum-gravity environment to be encountered on the Moon.

The lunar environment, the most hostile yet encountered by man, will have a significant effect on the design and operation of a drill. Systems for drilling deep holes on Earth depend on water or air as the flushing medium to remove cuttings and cool the bit. Normally the flushing medium flows down through the hollow drill rods, across the face of the bit, and then out of the hole in the annular space between the drill rod and hole wall. A liquid flushing medium probably accounts for some lubricating

324-954 O—69——8

action at the bit-rock interface; soap or glycerine additives are sometimes used to enhance this action (ref. 2).

Lack of water and the ultrahigh vacuum necessitate that drilling on the Moon must be accomplished dry; that is, without any flushing medium. Although liquids could be used in lunar drilling, spacecraft weight limitations prohibit transport of the required quantity from Earth. The possibility that Earth-produced media used on the Moon may contaminate lunar samples also bars their use. Consequently, all lunar-drill systems under development use an augering action to remove cuttings from the bottom of the hole mechanically.

Cooling the drill bit without a flushing medium is a significant problem, especially in rotary systems which convert a high percent of the available energy into heat at the bit. One approach to the problem is an internally cooled diamond bit that uses a closed-loop cooling system and a highly conductive matrix material that will conduct bit heat through the drill string rapidly. Removal of heat through the cuttings which serve as a heat sink is another possibility.

Another possible difficulty in lunar drilling is that lunar vacuum may cause rock cuttings to adhere to each other or to the drill steel (ref. 3). Drilling tests have been conducted in vacuum chambers in the range of 10^{-6} to 10^{-7} torr and, at these pressures, there do not appear to be any adhesion problems with the proposed cutting-removal systems. No drilling under simulated lunar vacuum conditions has been performed. Bottom-hole pressures caused by outgassing of rock as it is being drilled may also inhibit particle adhesion or welding in these tests. Whether outgassing will occur in lunar rocks is not known, although information on the outgassing characteristics of simulated lunar rocks being developed by the Bureau of Mines may help to answer this question (ref. 4).

The other difficulties that lunar temperature and gravity impose on drilling systems and techniques can probably be overcome by our present technology. Suitable design criteria should be adequate to cope with the temperature range of $-250°$ to $+250°$ F to be encountered on the Moon. Thrust, an important parameter in drilling, will be affected by lunar gravity, which is approximately one-sixth that of Earth. For example, the ALSD, which will be hand-held by the astronaut, must operate under an axial thrust of somewhat less than 20 pounds. This thrust will be adequate for unconsolidated material or soft rock, but will be insufficient for drilling harder rocks. The moderate-depth lunar drill attached to the lunar module (LM) should provide adequate thrust for drilling hard rock.

Other constraints that are placed on lunar-drill systems are total weight and available power. Since the volume of rock removed is directly proportional to power input, the energy source powering the drill becomes a critical factor in its performance. The Bureau of Mines is studying the ability of both drilling systems to operate effectively within existing power and weight limitations.

DESCRIPTION OF SYSTEMS

Apollo Lunar-Surface Drill (ALSD)

Figure 1 shows the development model of the ALSD. This drill is being developed by the Martin Co. under a contract awarded by NASA's Manned Spacecraft Center, Houston, Tex., in November 1966.

The complete drill system will weigh about 25 Earth-pounds and will be operated by one astronaut. The drill is battery powered, with the power pack located above the drill motor. This electric rotary-percussive system is designed to drill a 1-inch-diameter hole 10 feet deep and to take a core sample approximately three-fourths inch in diameter. Helical auger flights (flutes) on the drill steel remove the cuttings.

Figure 2 shows three test bits of different configurations for the ALSD; the bits illustrated have, respectively, three, four, and five tungsten-carbide inserts as cutting elements. Comparative laboratory tests of the bits in several simulated lunar rocks at the Twin Cities Mining Research Center have determined the optimum bit configuration to be the one with five inserts. Scientists at the NASA Marshall

FIGURE 1.—Development model of Apollo lunar surface drill.

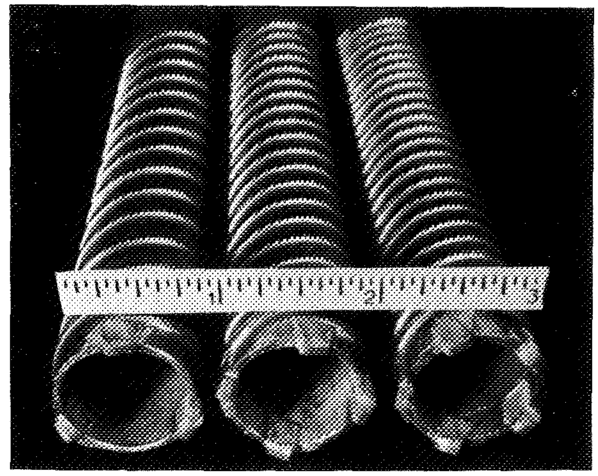


FIGURE 2.—Apollo lunar surface drill test bits.

Space Flight Center have recently completed tests in which the ALSD drilled two holes in vesicular basalt in a vacuum chamber at a pressure of 10^{-6} to 10^{-7} torr. These test results are presently being analyzed.

Moderate-Depth Lunar Drill

Two parallel contracts were awarded in mid-1965 by the NASA Marshall Space Flight Center for developing a drill capable of drilling a 2-inch-diameter hole to a depth of 100 feet while taking a solid core sample. Specifications for the drills included a system weight of 200 Earth-pounds (exclusive of power supply), a power draw of 5 kilowatts from the spacecraft, and the capability of removing cuttings mechanically.

Under one contract, a gas-operated, down-hole percussive drill (figs. 3 and 4) was developed by Northrop Space Laboratories. In this system, nitrogen gas is compressed in the surface unit located inside the revolving drum. A flexible concentric steel hose wrapped on the drum advances and retracts the down-hole drill and conveys the operating and exhaust gases to the down-hole hammer. The down-hole portion consists of a core-type tungsten-carbide button bit; a reciprocating piston to provide the necessary blow intensity; a hollow, teflon-coated core barrel; and a cuttings container or chip basket.

Spiral flutes on the outside of the down-hole section auger the cuttings from the bit face, up past the core barrel, and into the top of the chip basket. After each 3½-foot drill advance, the drill is retracted from the hole by the flexible drill string. The core barrel and chip basket are then emptied, and the cycle is repeated.

The other moderate-depth lunar-drill system was developed by the Westinghouse Defense and Space Center. This system (figs. 5 and 6) is like conventional wire-line diamond drills except for the cuttings-removal mechanism. The down-hole portion consists of a surface-set diamond coring bit, a core barrel, and a chip basket. As with the percussive moderate-depth drill, spiral flutes on the outside of the down-hole portion transport the rock cuttings to the chip basket. The rotary mechanism is housed

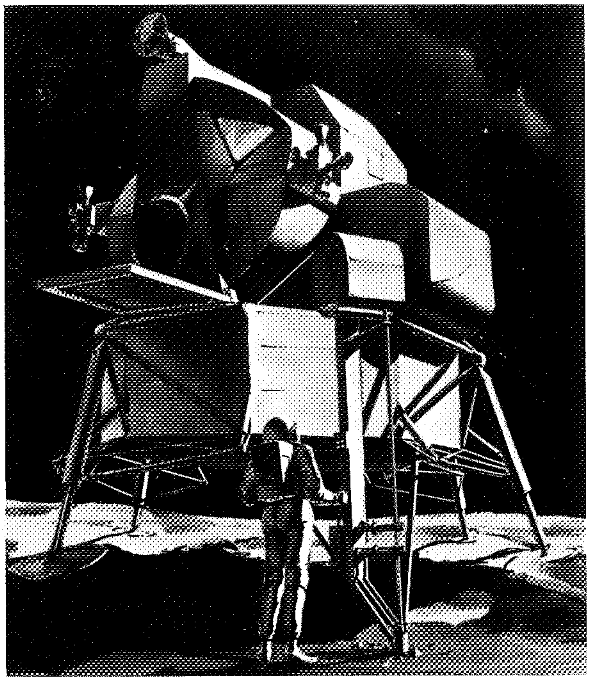


FIGURE 3.—Moderate-depth lunar drill, percussive type.

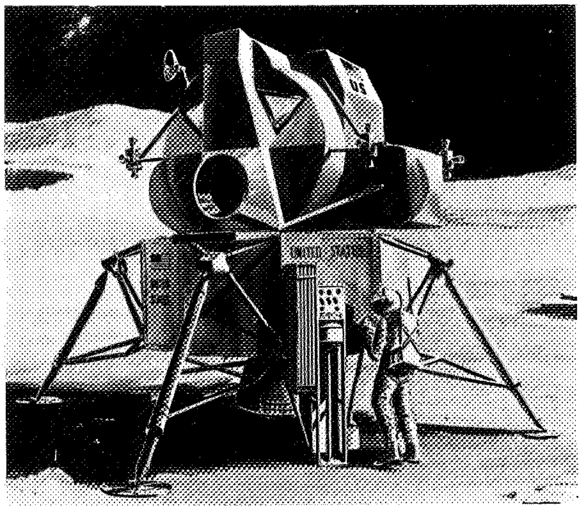


FIGURE 5.—Moderate-depth lunar drill, diamond rotary type.

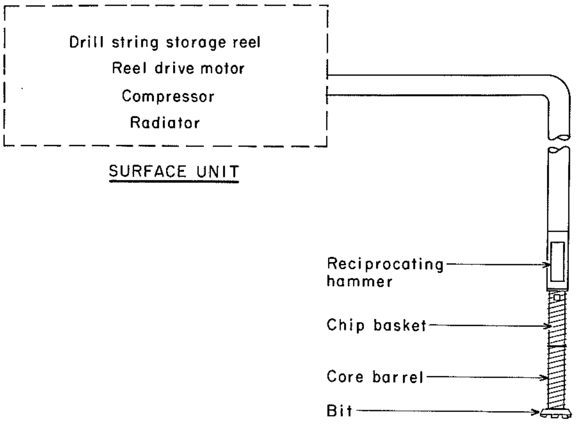


FIGURE 4.—Schematic of percussive drill.

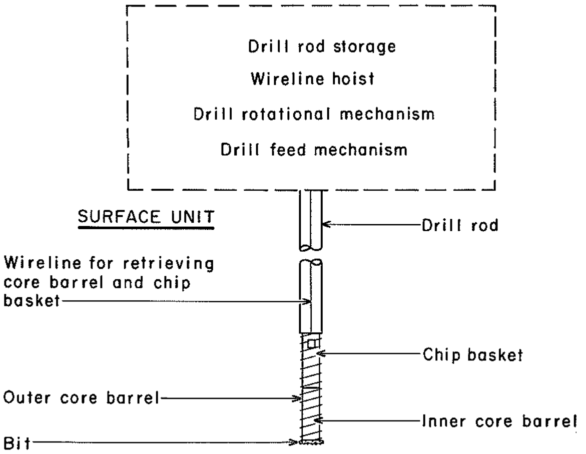


FIGURE 6.—Schematic of diamond rotary drill.

in the surface unit attached to the lunar module.

The down-hole portion contains a rotating outer barrel, to which the bit is attached, and a stationary inner tube containing the core barrel and the chip basket. After drilling has progressed 5 feet, an "overshot" assembly is lowered on the end of a line inside the drill pipe and attached to the inner tube assembly; the core barrel and chip basket are then pulled to the surface, while the bit and drill string remain in the hole. After the inner tube assembly has been replaced, another 5-foot section of drill pipe is added and the cycle is repeated. If the bit life is adequate, the entire 100 feet can thus be drilled without removing the drill string from the hole. The diamond bit is one of the most critical components of this system.

BUREAU OF MINES PARTICIPATION

Testing Lunar-Drill Hardware

The Bureau of Mines has provided both consulting services and laboratory support ever since the moderate-depth lunar-drill development program was initiated in 1964. Laboratory drilling tests with the down-hole assembly of the percussive-type drill have been started at the Bureau's Twin Cities Mining Research Center laboratories. The apparatus being tested includes a core barrel and bit from the Northrop system attached to a percussive drill that provides the same blow intensity as does the engineering model (fig. 7). A range of simulated lunar materials has been drilled to study penetration rates and cuttings-removal characteristics.

Bureau support for the diamond rotary lunar drill has included dry drilling tests of bits to study cuttings removal, bit life, and bit heat generation (fig. 8). The studies show that, if the cuttings are not removed rapidly enough, drilling efficiency falls off because the energy lost in attrition of the cuttings creates sufficient heat to damage both the drill bit and the core sample.

In a series of tests with the diamond-drill bit, we were able to drill more than 10 feet into Dresser basalt without a flushing medium (fig. 9). A similar bit has been tested by Westinghouse in a vacuum chamber at pressures of 10^{-6} to 10^{-7} torr. When the drilling was done in vacuum, the cuttings appeared to be ejected from the hole at a much greater velocity than that which occurred when the drilling was done in atmosphere; this is probably a result of outgassing of the rock at the bit-rock interface. This, the first of the vacuum drilling tests, indicated that a vacuum of this magnitude had no adverse effect on drill performance (ref. 5).

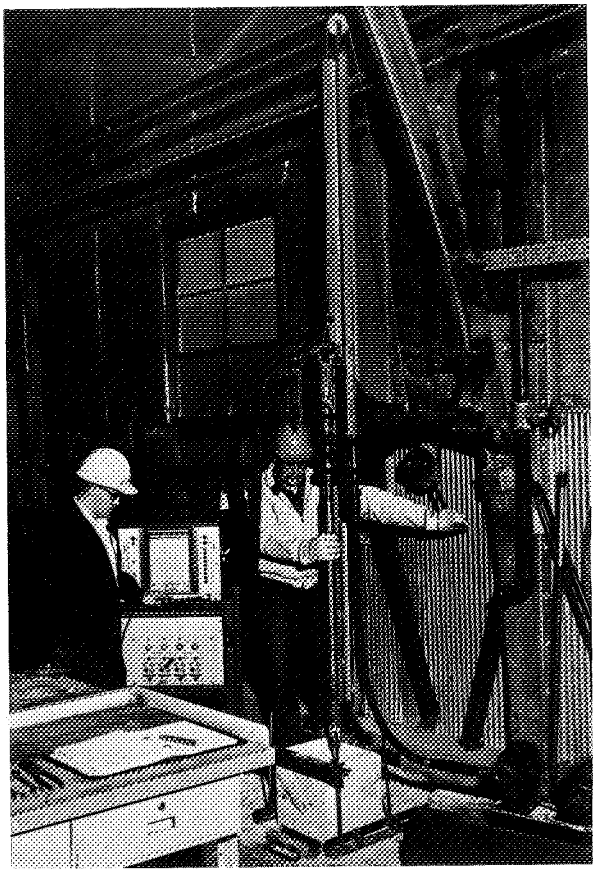


FIGURE 7.—Laboratory simulation of moderate-depth percussive drill.

Other Laboratory Experiments

In addition to testing lunar-drill hardware, the Bureau has been studying the fundamental problems associated with drilling in a lunar environment. Since drilling without a flushing medium represents a critical problem, a series of experiments has been conducted to investigate the effects of flushing media on drilling efficiency and penetration rate. In these experiments a laboratory diamond drill and a rotary-percussive drill were tested on several simulated lunar rocks selected to represent a wide range of physical properties. The rocks included flow (tholeiitic) basalt, fresh rhyolite, vesicular basalt, and dacite. Dresser basalt, a hard, dense, intrusive basalt, was also included.

The bench-mounted diamond drill was instrumented to record penetration rate, power consumption, bit rotational speed, and bit temperature while drilling in a block of rock. These tests were run: (*a*) with water flush, (*b*) with air flush, and (*c*) with no flushing medium. When there was no flushing medium, the drill hole was alined on the edge of a square block with a segment of the hole exposed to allow cuttings to spin out.

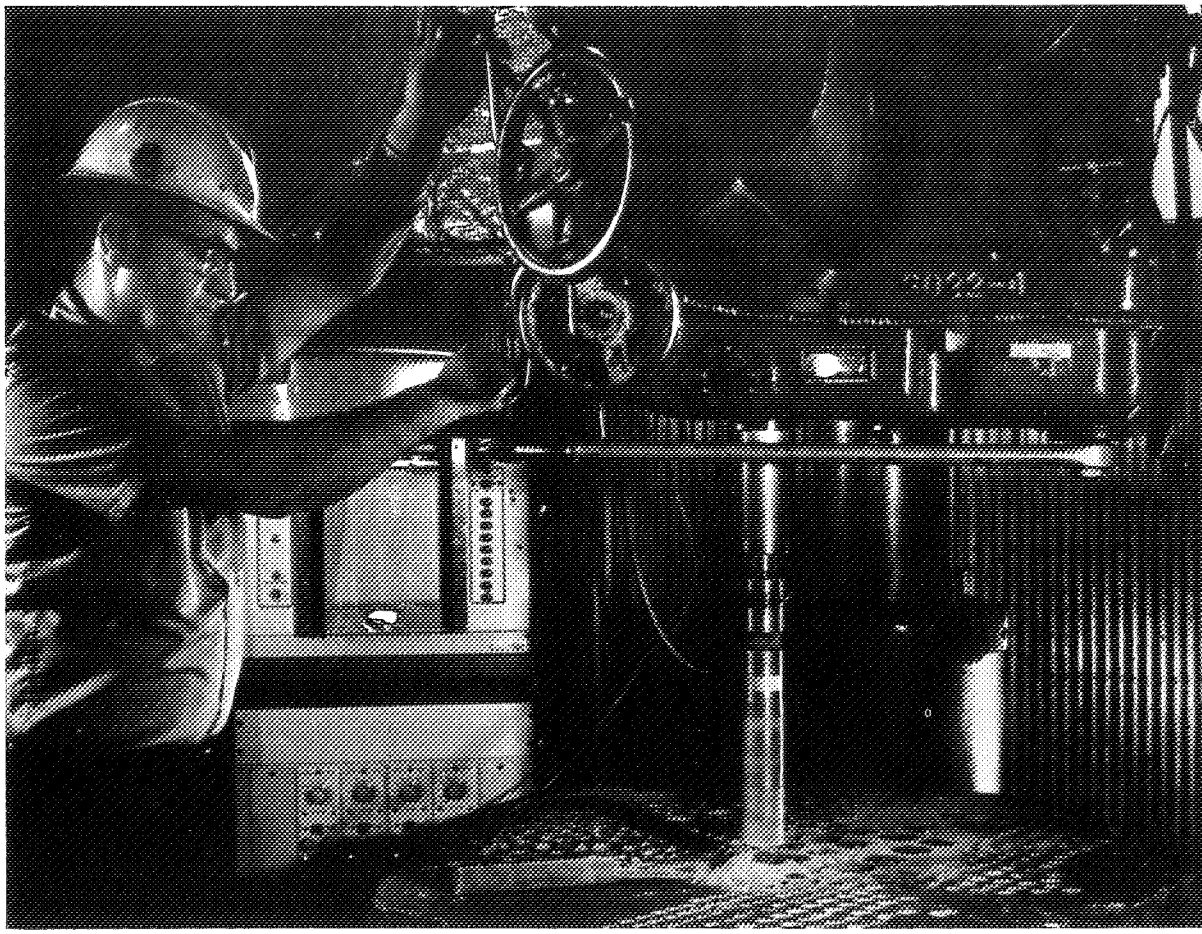


FIGURE 8.—Dry drilling in basalt with lunar test bit.

Figures 10 to 14 show relative penetration rates with diamond bits in five rock types using water flush, air flush, and no flushing medium. In general, highest penetration rates were obtained with water flush, followed by air flush and no flushing medium in that order. However, for vesicular basalt and dacite (figs. 13 and 14), drilling without any flushing medium produced higher rates than did air flush.

In addition to the effects of the flushing medium on diamond drilling, other factors such as bit crown design, diamond count, and diamond size influence bit performance. Figure 15 compares the performance of three ½-inch-diameter diamond bits in a soft and a hard rock with water flush. The highest penetration rate in hard rock (basalt) was obtained with the small diamonds, while the highest rate in soft rock (rhyolite) was with the largest diamonds.

Experiments were then conducted on the same rock samples with a bench-mounted electric rotary-percussive drill with the same parameters recorded. Figure 16 compares penetration rates for the laboratory rotary-percussive drill in the five rocks drilled. Since the penetration rate-thrust curve "tops out" at a different thrust level for each rock drilled, each rock has its own point of optimum thrust with a specific drill.

Since optimum thrust is important in lunar drilling, where thrust is severely limited by the low lunar gravity, a separate study was made of this phenomenon. Figure 17 shows a direct relationship between optimum thrust and coefficient of rock strength. This strength

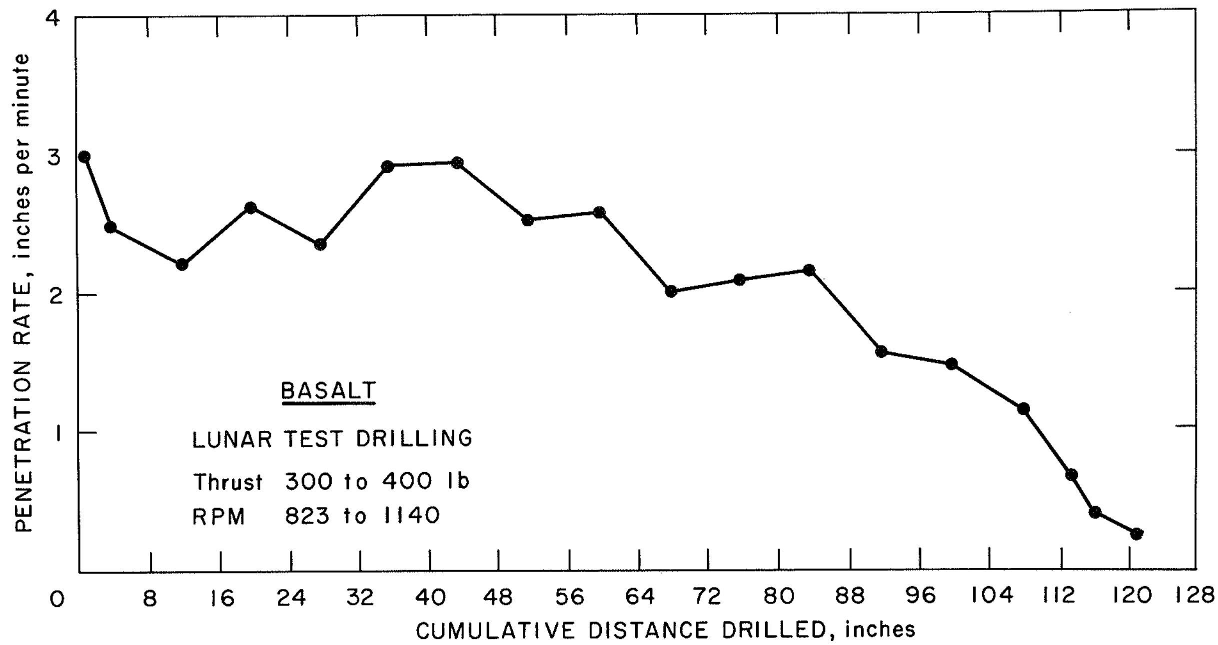


FIGURE 9.—Penetration rate against distance drilled with a prototype lunar diamond bit. Material drilled, basalt; thrust, 300 to 400 pounds; speed, 823 to 1140 rpm.

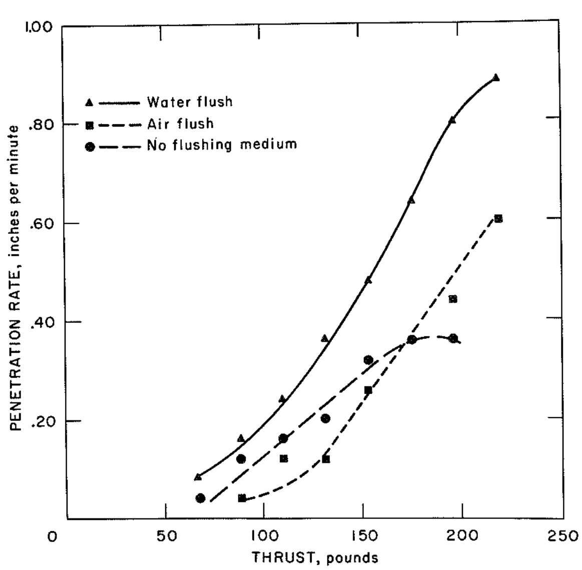


FIGURE 10.—Effects of flushing methods on penetration rate in Dresser basalt with ½-inch diamond rotary bit.

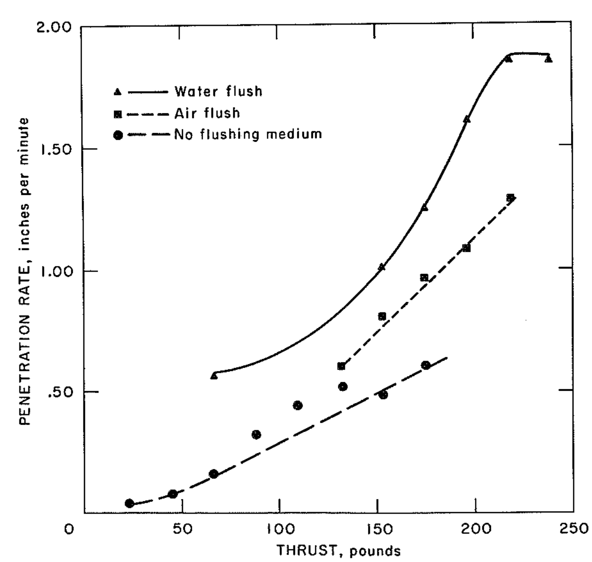


FIGURE 11.—Effects of flushing methods on penetration rate in flow basalt with ½-inch diamond rotary bit.

measurement is a simple test of the energy involved in breaking a unit volume of rock to a given size. It is performed by placing a rock sample in a tube, dropping a standard weight from a standard height, and measuring the volume of minus 35-mesh material produced.

Another important drilling problem that was investigated in the Bureau laboratories

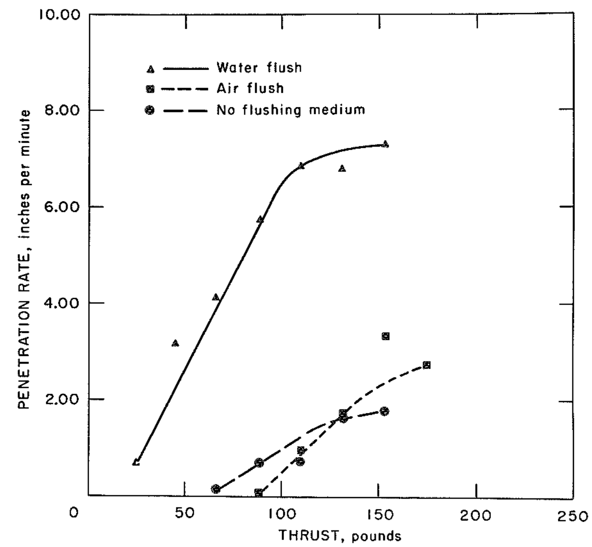


FIGURE 12.—Effects of flushing methods on penetration rate in rhyolite with ½-inch diamond rotary bit.

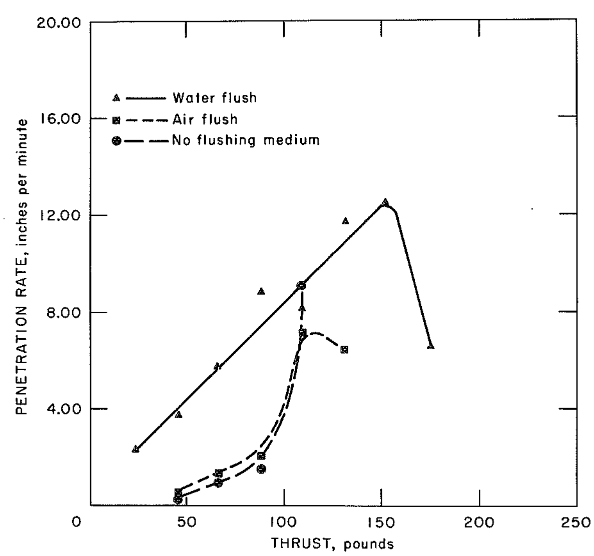


FIGURE 13.—Effects of flushing methods on penetration rate in vesicular basalt with ½-inch diamond rotary bit.

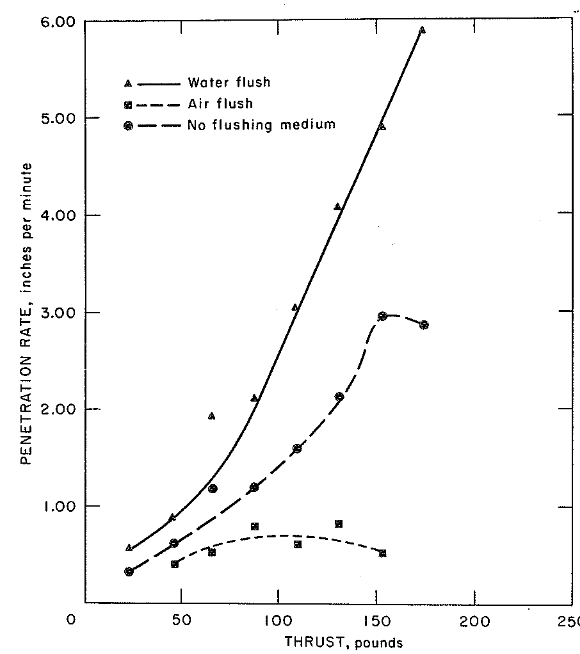


FIGURE 14.—Effects of flushing methods on penetration rate in dacite with ½-inch diamond rotary bit.

was bit heat generated by a drill with no flushing medium. Figures 18 and 19 show the effects of thrust and drilling time on the bit temperature of a laboratory rotary-percussive drill. Increased thrust and increased drilling time do not increase bit temperature significantly as long as cuttings are removed promptly.

In an effort to find a substitute for liquid and gaseous flushing media for the lunar diamond drill, the Bureau experimented with solid lubricants introduced to the bit-rock interface. Preliminary experiments show that these lubricants improved the efficiency of a bench-mounted diamond rotary drill. It appears that a solid lubricant, if properly used, can reduce side-hole and matrix friction without impairing the cutting capability of the diamonds. Further drilling tests with dry lubricants are underway at the Twin Cities Mining Research Center, along with efforts to design a reliable system to introduce these lubricants to the bit-rock interface.

Studies of cuttings removal by mechanical means are also underway; the down-hole assembly of the percussive-type lunar drill and a transparent tube to simulate the drill hole are being used in these studies.

Discussion of Laboratory Results

Analysis of the data in figures 10 to 14 shows that water flush yields a higher penetration rate in diamond drilling than does either air

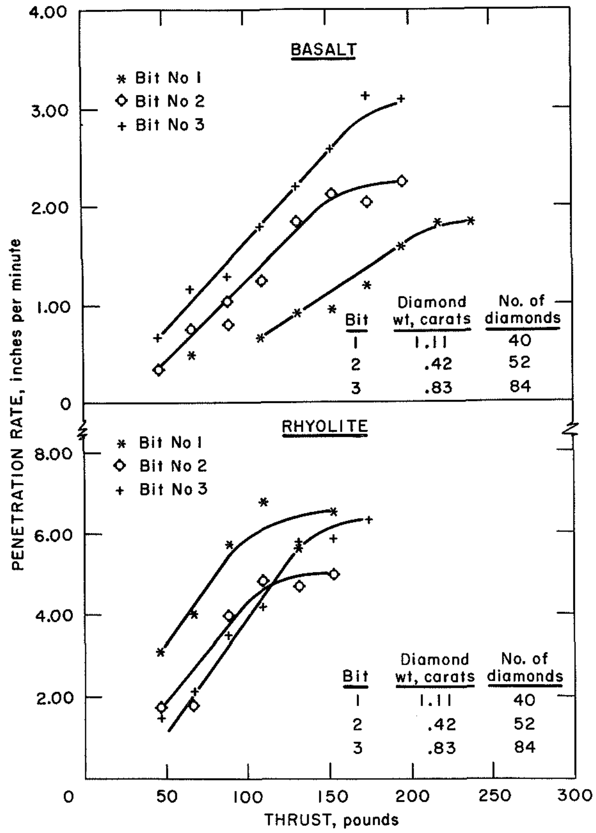


FIGURE 15.—Comparison of three different ½-inch rotary diamond bits in basalt and rhyolite with water flush.

	Bit no. 1	Bit no. 2	Bit no. 3
Kerf area, sq. in	0. 178	0. 187	0. 151
Matrix hardness, RC	30–40	35–40	30–35
Diamond weight, kt	1. 11	0. 48	0. 83
Diamond count	40	52	84
Diamond grade	AAA	A	AAA

flush or no flushing. Therefore, in diamond drilling on the Moon when mechanical means are used for removing cuttings, lower penetration rates would be expected than those obtainable on the same rocks when a liquid flush is used.

Comparative studies of different bits show that matching diamond bit crown design to rock type is an important consideration in lunar drilling. A hard rock, such as basalt,

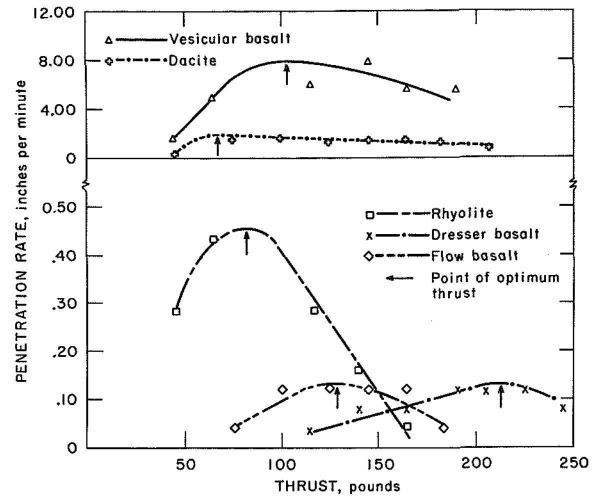


FIGURE 16.—Penetration rate against thrust in simulated lunar rocks for laboratory rotary-percussive drill with 1-inch core bit.

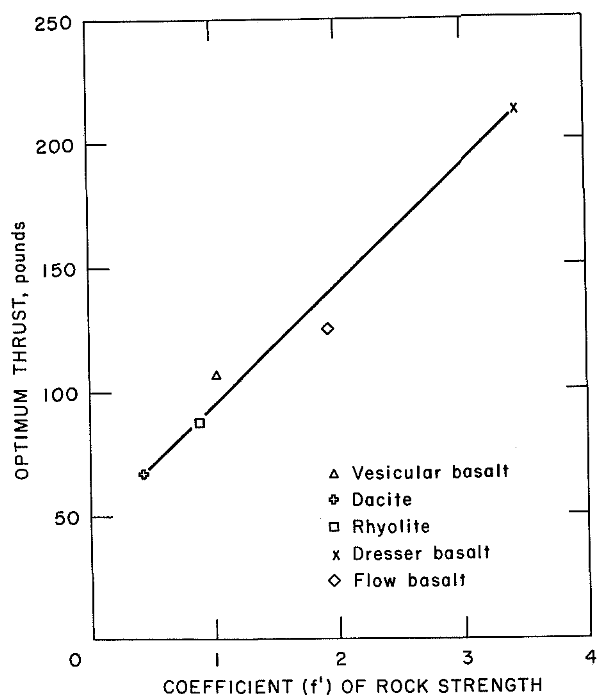


FIGURE 17.—Optimum thrust for each rock type against coefficient of rock strength for laboratory rotary-percussive drill with 1-inch core bit.

is best drilled with a bit consisting of a large number of small, close-set stones, and a soft rock is more vulnerable to a bit with fewer,

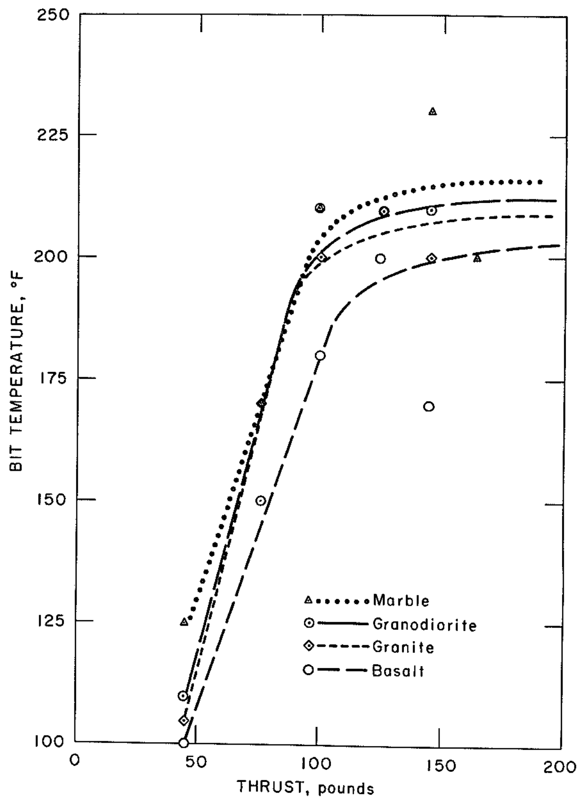


FIGURE 18.—Bit temperature against thrust in four rock types using laboratory rotary-percussive drill with 2-inch core bit.

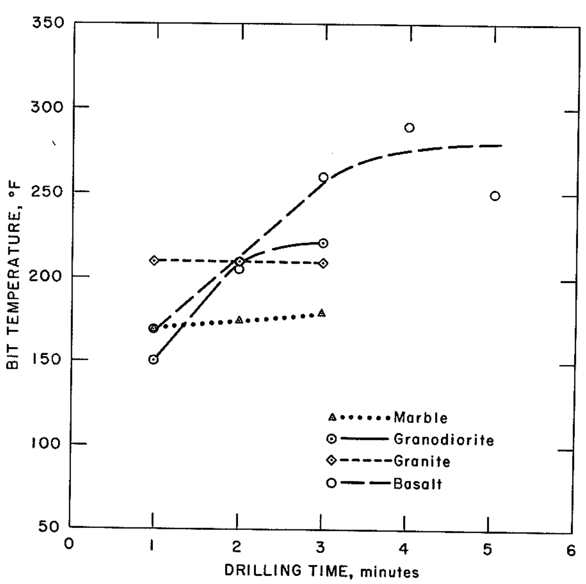


FIGURE 19.—Bit temperature against drilling time in four rock types using laboratory rotary-percussive drill with 2-inch core bit.

larger stones. Carat weight alone does not appear to be an important criterion, except possibly to increase the reliability of the bit. As more information is obtained about the stratigraphy of the Moon, we will be better able to specify bit-design criteria for lunar drills.

The optimum thrust for a rotary-percussive drill shows a linear relationship with the coefficient of rock strength. The results of similar studies in a range of simulated lunar rocks should predict optimum thrust values for any percussive or rotary-percussive drill in any specific rock expected to be encountered on the Moon. This comparison shows the value of physical properties of materials as an engineering tool used to predict drillability.

Bit-temperature studies of an uncooled rotary-percussive drill bit show that temperatures tend to stabilize after a sharp rise with increased thrust or drilling time as long as cuttings are removed promptly. Further tests of longer drilling times and in deeper holes will be necessary. As mentioned earlier, vacuum drilling tests conducted to date have been in the pressure range of 10^{-6} to 10^{-7} torr. Further drill tests in higher vacuum should be conducted.

SUMMARY

Drilling on the Moon, according to studies performed to date, will be affected by lack of atmosphere which necessitates drilling dry, by reduced gravity which means drills will have to be carefully designed to take advantage of available thrust, and, possibly, by temperature extremes when bit cooling may be a problem.

Experimental work conducted by the Bureau of Mines, by NASA, and by contractors has demonstrated that rock can be drilled dry, that is, without the use of flushing media, with adequate mechanical cuttings-removal systems. With further work, it should be possible, within the framework of our present technology, to raise the efficiency of dry drilling to a point where it approaches that of drilling with a flushing medium.

Thrust, or force required to hold the bit on the bottom of the hole, is usually obtained through use of the weight of the drill system.

Optimum drilling rates in specific rocks require an optimum thrust with a particular drill system; therefore, appropriate design features should be incorporated in a lunar-drill system to offset the effects of the reduced lunar gravity.

Initial studies and experiments were made to predict drilling rates with a specific drill in some simulated lunar rocks on the basis of their physical properties. Further work on drillability of a range of materials with prototype lunar drills would eliminate uncertainty about the performance of the drills.

A full understanding of the effects of vacuum on bit temperature and material adhesion in a lunar environment will require further tests in ultrahigh vacuum with particular attention given to drill instrumentation and sample preparation. The solutions to these problems will contribute to terrestrial drilling problems, just as our present drill technology has provided a foundation for the lunar drill.

REFERENCES

1. Baier, W. H.; and Campbell, J. A.: Lunar Drilling Study. Proc. 5th Symp. on Rock Mechanics, Univ. of Minn., May 1962, pp. 205–228.
2. Joris, A. C. T.; and McLaren, G.: Additives to Coolants Used in Diamond Drilling and Sawing in Australia. Min. Miner. Eng., vol. 3, no. 5, May 1967, p. 190.
3. Penn, S. H.: Wildcatting on the Moon. AIME preprint, Proc. 7th Symp. on Rock Mechanics, Pa. State Univ., June 1965, pp. 491–517.
4. Roepke, W. W.; and Schultz, C. W.: Mass Spectrometer Studies of Outgassing From Simulated Lunar Materials in Ultrahigh Vacuum. 14th Nat. Symp. Am. Vacuum Soc., Kansas City, Mo., Oct. 1967.
5. Woo, W. George: A Lunar Drill. Res./Develop., vol. 18, no. 12, Dec. 1967, pp. 44–45.

Page intentionally left blank

GARRY C. HENDERSON
Applied Research Laboratory
General Dynamics Corp.
Fort Worth, Tex.

Lunar Exploration for Water Deposits by Electrical Methods

Several electrical techniques employed in terrestrial exploration geophysics appear to show considerable promise for lunar-surface applications, particularly in the search for water in the upper 100 meters of the surface. All of these methods rely primarily on the degree and extent of contrasts in the electrical properties of materials which lend themselves quantitatively to the interpretation process. The choice of scientific methods depends largely on the properties suspected to exist; the choice of operational methods influences the choice of scientific methods by limitations imposed by mission constraints. The selection of frequency (or frequency spectrum) in orbital or surface electromagnetic methods requires considerably different analyses than do the LF-DC (low frequency-direct current) resistivity techniques.

Since there may be subsurface water as well as ice in some cases, the various kinds of ice, impurities (such as minerals, debris, and chemical contaminants), and multiphase systems and the effects on the conductivities of these water deposits are investigated primarily from the familiar resistivity viewpoint.

INTRODUCTION

Numerous geophysical techniques have been suggested in the exploration for lunar water deposits, be they liquid, ice, or in the form of hydrated rocks. Seismic and electrical techniques have logically received the most serious attention, although magnetic and even gravity methods have been proposed. (See, e.g., the work of Speed (ref. 1) and Westhusing and Crowe (ref. 2).) Obviously, the parameters on which the interpretation of gravimetric, magnetic, and, to an extent, seismic data depend do not readily lend themselves to such purposes on early missions.

Variations in the magnitude and extent of density contrasts are the basis for gravimetric exploration; besides the stringent survey requirements for meaningful exploration by gravimetry (ref. 3), the number of models relating density contrasts to water deposits is infinite. Even if a very sizable body of ice were present, the inherent ambiguity of gravity data necessitates reliance on other types of information in the process of interpretation. Essentially the same can be said for magnetic prospecting, except for the possibility of locating likely zones of volcanics (which may stand out even in the weak magnetic field of the Moon), thereby allowing one to suspect a greater likelihood of water association in that particular locale. Seismic methods, one of the most powerful tools in exploration geophysics, may be a rewarding means to determine the presence of bulk ice (or water) in early missions (ref. 4), but again the nature of velocity discontinuities, related parameters, and environmental conditions may limit the early utility of these methods for this purpose. A good knowledge of the lunar subsurface is necessary to the choice of: method(s) (refraction and/or reflection); the technique(s) (profiling, fan shooting, etc.); instrumentation (seismic energy source, filters, amplifiers, telemetry, etc.); and, of course, interpretation (ref. 5).

The principal method of geophysical prospecting for water on Earth, the electrical method, appears to be as potentially useful, if not more so, on the Moon, providing the pertinent parametric factors relating to such experiments are ascertained. Mathematical treatments and case histories of electrical methods are amply described in the literature and so are not presented here. A brief bibliography is included with this paper to give the reader a fair sampling of available literature on the subject.

LUNAR WATER SOURCES

It is probably incorrect to assume that much, if any, water beneath the Moon's surface is in the liquid state. Such a case would require an impervious interface to prevent migration of liquid or vapor to the surface and, of course, a temperature sufficiently high to prevent solidification. However, in heated zones, electrolytic action might feasibly result from "ground water" in the presence of certain minerals (sulfides, for example); this might create a self-potential field in the vicinity of contact. It appears, for early missions, that the possibility of useful water resources is probably limited to subsurface ice in the maria.

If the original source of the ice is accepted to be of volcanic origin, that is, condensates of vent or fumarole vapor trapped in ground fissures, veins, or porous material, it can also be assumed that the ice is contaminated to a degree and is more conductive than if it were pure. At standard atmospheric pressure, conductivities range from about 2.3×10^{-8} (ohm-cm)$^{-1}$ for pure water at 10° C to 5×10^{-10} (ohm-cm)$^{-1}$ for certain pure ices at low temperatures (−70° C or so). A method of determining the direct-current values is described by Bradley (ref. 6). For near-surface (about 1 meter) temperatures of −23° to −53° C (ref. 7), the vapor pressure of ice ranges from about 7.5×10^{-1} torr to approximately 4×10^{-2} torr (ref. 8); therefore, the base of the surface layer must be impervious if it contains the ice or water for any appreciable period of time.

Bernett and others (ref. 9) noted that pulverized olivine basalt, material apparently analogous to the lunar-surface covering, has a thermal conductivity about 2 orders of magnitude less in a vacuum of 5×10^{-6} torr than at 1 atmosphere. Moreover, they observed that the variation of the particle sizes tested had more effect on the thermal conductivity in a vacuum than in air and that compaction markedly increased these values.

The various forms of ice (see Dorsey, ref. 8) may affect the interpretation of electrical exploration data because of the crystalline structure system associated with the circumstances under which it formed and the nature of the present environment. For example, the intercrystalline material existing between the surfaces of crystals becomes more concentrated by repeated fractional freezing, with the result that the ice itself becomes more pure and is composed of larger grains, perhaps in a different crystallographic system. For bulk ice (essentially homogeneous as a body compared with that filling pore spaces in rock), effective interstitial material may eventually migrate to the outer periphery of the mass, thereby emphasizing the conductivity contrast. The more rapidly the transition from vapor (if any) to water to ice occurs, the more likely it is that conducting and/or resistive materials are entrapped in the body of ice.

Dorsey (ref. 8) proposes that no type other than ice-I exists at pressures less than 2000 atmospheres unless the temperature is very low; he also states that both ice-II and ice-III types proceed very slowly to ice-I. All known varieties of ice, except ice-I, are denser than water under identical conditions of temperature and pressure; however, to the writer's knowledge, this has not been verified for a vacuum and low-temperature environment such as that found on the Moon.

Under the action of an induced electric field, a space charge will be acquired by the ice unless it is extremely pure. A sort of polarization will result from a direct-current field, and an alternating-current field will cause a varying concentration of the field, the end result being a reasonable probability of misinterpretation unless proof of the existence of the ice is established by other means (visible exposure or coring). The relationship of field frequency to the measured variation of the dielectric constant of ice is given in figure 1(*a*); the thermal variations of the dielectric constant of ice are shown in figure 1(*b*). A compilation of observed laboratory data on the apparent resistivity of ice at various frequencies is shown in figure 2. The primary point to be made here is that some preknowledge of the temperatures of the ice and the overlying material greatly reduces the probability of misinterpreting the data from electrical methods.

Various factors are related to the wide range of resistivities encountered in Earth materials. Some of these may be more pronounced for

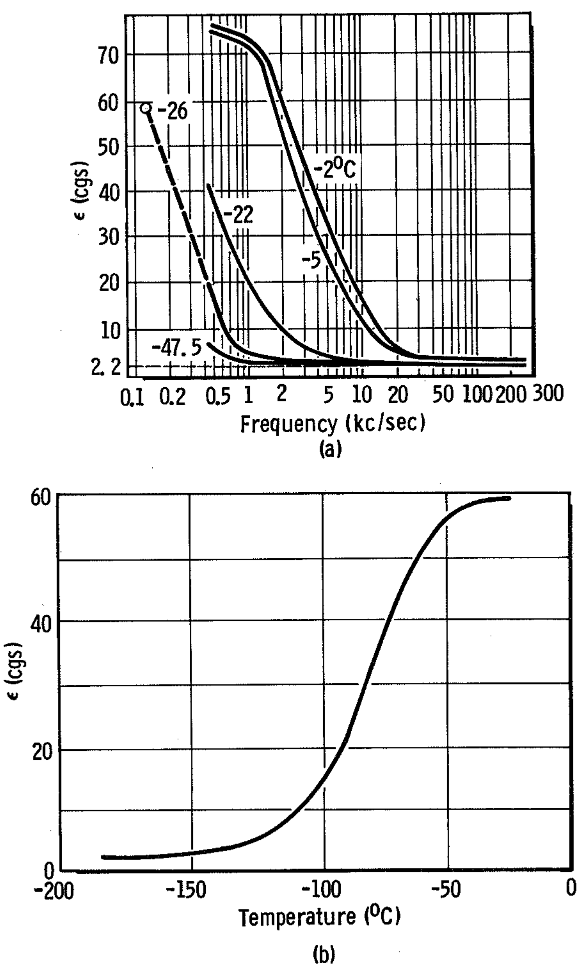


FIGURE 1.—Dielectric constant of ice against frequency and temperature. Data taken from reference 8, pp. 502 and 503. (*a*) Field frequency versus the dielectric constant of ice. (*b*) Temperature versus the dielectric constant of ice at 120 charges and discharges per second.

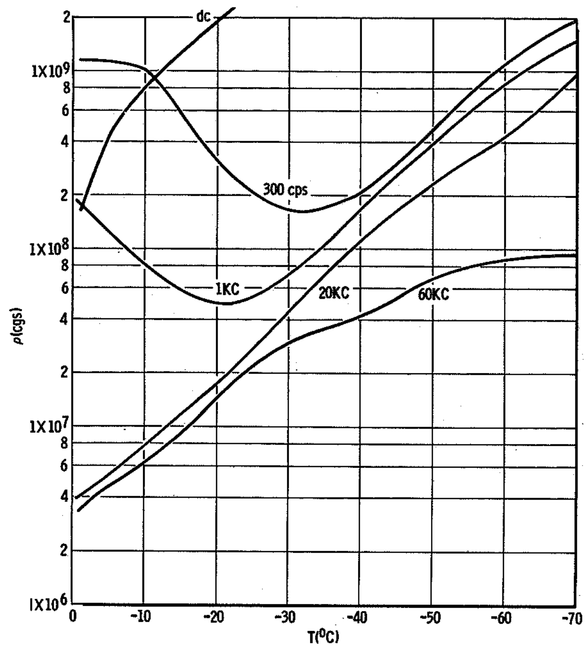


FIGURE 2.—A compilation of observed apparent conductivities of ice versus temperature at various frequencies (frequency data from ref. 8, p. 506; direct current data from ref. 6).

water exploration on the Moon. Not necessarily in order of importance, these are—

(1) Temperature of the ice and thermal gradients of the surrounding materials

(2) Inhomogeneity of the ice and the surrounding materials

(3) Degree and type of hydration of the surrounding materials

(4) Particle size and degree of compaction of unconsolidated materials surrounding a body of ice

(5) Choice of electrical method, configuration, and frequency

(6) Degree of polarization in connection with associated fluids or ionized gases (if any)

(7) Magnitude of lithostatic pressure

(8) Lunar-surface state and topography

It would appear that a real requirement exists, regardless of the intended method of geophysical exploration, that one acquire some borehole data before one attempts a surface reconnaissance for bulk water deposits. Although the probability of drilling into ice or water-bearing strata by chance cannot be determined at this time, it seems that it would be very low. A useful accumulation of subsurface data would act as a guide for planning surface exploration.

GENERAL ELECTRICAL METHODS

Electrical methods in exploration geophysics may be broadly categorized as self-potential (SP), induced potential (IP), magnetotelluric (and telluric), electromagnetic (EM), resistivity, and borehole logging, which may involve any one or a combination of these methods. Interpretation processes of the SP and IP methods are dependent on polarization phenomena associated with electrochemical reactions between the different subsurface constituents. Although such phenomena may occur on the Moon, the likelihood seems sufficiently small to the author to exclude these methods from this discussion. Magnetoselenics is not discussed here because the probability of locating recoverable deposits of ice by this method in early missions seems unlikely.

One of the most attractive aspects of electromagnetic exploration is that of being amenable to remote (orbital altitude) or surface (roving vehicle or contact) operations. In the preceding discussion of lunar water, it was noted that the effects of material temperature and sensing frequency lead to possibilities of misinterpretation. Ward and others (ref. 10) report a study on electromagnetic reflections in the 10^{-4}- to 10^{9}-hertz range in which they describe a method of the "possibility of uniquely determining the presence of water, in solid or pore liquid form, from electromagnetic soundings made on or above the lunar surface." They detail the distribution and sequential variations of electrical parameters of several models to determine responses for each range and combination they selected.

Because of the promise of remote sensing, considerable emphasis has been placed on electromagnetic methods. This is particularly true in terrestrial applications, as evidenced by the numerous applications and investigations on the subject. Since the primary purpose here is to discuss electrical resistivity techniques of water exploration, let it suffice to refer the reader to publications listed in the bibliography at the end of this paper.

SURFACE RESISTIVITY METHODS

The classical resistivity methods of measuring irregularities in the conductivity of subsurface materials depend on the determination of the magnitude and extent of the potential gradient on the surface caused by the asymmetric flow of current introduced into the subsurface. The measurements made on the surface result in quantitative values of the apparent resistivity caused by conductivity contrasts in the subsurface.

Various electrode configurations exist for resistivity surveying along the surface; these are used to determine the approximate depth, shape, and anomalous resistivity of discrete bodies or features. A simple illustration of the concept, using the common Wenner configuration, is shown in figure 3. Since potential lines are by definition perpendicular to current flow lines, any distortion of the current lines by material of anomalous conductivity is expressed on the surface by a distortion of the potential field. In practice, two general field techniques are employed: (1) maintaining fixed electrode separation and moving the array along a profile line, then plotting resistivity values at the midpoint of the array, that is, resistivity profiling at a given electrode separation a approximately equivalent to the maximum depth of effective penetration; or (2) systematically varying a for successively greater depths of effective penetration and repeating this process at points along a line, that is, resistivity sounding. Often both techniques are used in the same area and parallel profiles must be employed to ascertain the lateral extent of an anomalous body.

Theoretical studies of the mathematical modeling of various resistivity systems have been pursued for many decades and are for the most part very straightforward; however, the quantitative interpretation of these data seems to be as much an art as a science because of several complicating factors. For example, Earth ground water and moisture in the weathered zone cause some difficulties, pri-

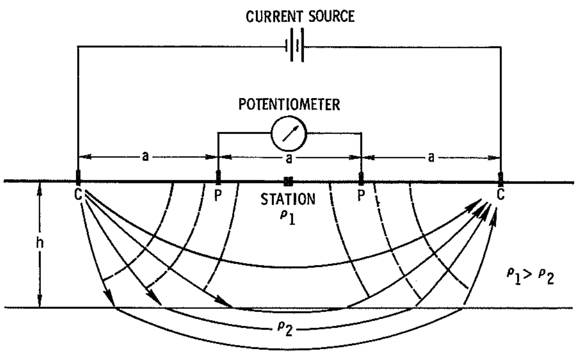


FIGURE 3.—The Wenner electrode configuration.

marily because of a wide range of mineral content affecting conductivity, as well as gross irregularities in their extent. In some areal surveys, fences, railroad tracks, underground cables, etc., cause distortions in the potential field. Coupling of the electrodes to the surface layer is often inconsistent as a result of several factors (variability of surface materials, variability of the degree and type of surface moisture, improper implacement and/or care of the electrodes, etc.). The Moon may be 2 or 3 orders of magnitude more amenable to such surveys than are terrestrial sites because of the obvious lack of some of these troublesome features. A few of the more subtle implications presently suspected may enhance the attractiveness of resistivity techniques. For instance, if discrete layering of near-surface materials is prevalent in the maria, we approach the ideal case and thereby may rely more on scientific than on "analogy-type" interpretations.

Several model studies of geophysical methods for lunar water exploration have been reported by Westhusing and Crowe (see, in particular, pp. 278–279 and 348–351 of ref. 2). In most cases reported by them, apparent resistivity measurements yield significant responses for the resistivity contrasts they considered (assuming, of course, that high resistivities may be measured with the lunar system). Their conclusions are summarized in reference 2 in tables, all of which are worthy of the reader's review. (Methods in orbital mode, pp. 337–339; instrumentation in orbital mode, p. 340; methods in surface mode, pp. 343–346; and instrumentation in surface mode, pp. 355–357.)

Preliminary tests with resistivity models in a vacuum chamber have been initiated using olivine basalt. Temperature ranges of 150° to 100° C have been employed in a vacuum of 4 to 8×10^9 torr with two parallel Wenner electrode configurations. A thermally and electrically isolated ceramic container is used to house the model. (See fig. 4.) Preliminary studies were performed with a mechanical-diffusion pump system, the results of which were inconclusive; the suspected cause was oil contamination of the sample material. Sorbent roughing pumps and ion pumps have been installed on the chamber, and models are currently being prepared to conduct a more complete series of measurements. Materials with electrical properties similar to those of ice are placed in various subsurface positions in the model. To date, samples of granite, rock salt, limestone, Bakelite 140, and marble (for high resistivity) have been studied as model substitutes for ice. The two electrode arrangements are alternately activated at given model temperatures for a certain electrode separation a. Then the process is repeated for different values of a. Results obtained with the new system are not presently available; however, it is reasonable to say at this time that the method appears promising.

Probably the greatest operational disadvan-

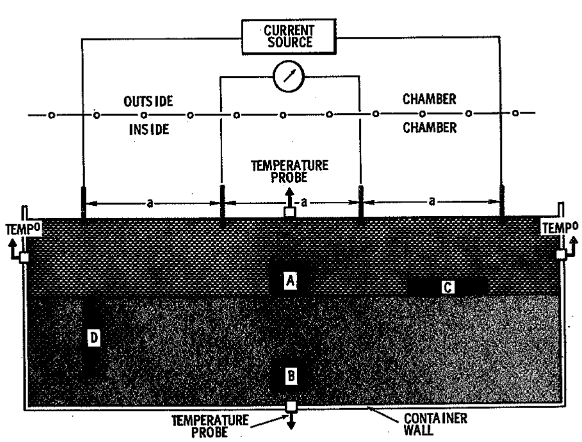


FIGURE 4.—Schematic of the model arrangement of the resistivity tests in the vacuum chamber. A, B, C, and D are test materials.

tages to resistivity methods are (1) the time-consuming, cumbersome handling of the electric cables; and (2) the power required for high-resistivity measurements and widespread electrodes. On Earth, vegetation, creeks, large rocks, hills, etc., aggravate the problem, but in the lunar maria, and considering the early, limited profiles, the resistivity method may be comparatively quite rapid. Of course the restrictions on the astronauts' dexterity and mobility caused by their space suits will be a handicap and must be considered in planning experiments of this type.

SUBSURFACE ELECTRICAL METHODS

Early lunar missions preclude any *in situ* subsurface techniques other than borehole logging, unless tunnels or accessible fissures are found and explored. The more advanced missions may employ tunnel and shaft applications of electrical methods.

Borehole logging by electrical methods consists essentially of recording the resistivities and potentials of subsurface formations by down-hole instruments applied throughout the depth of the borehole. Discussion of potential measurements is excluded in this section because of the assumed lack of fluids in the lunar subsurface.

Common electric logging techniques are designated as standard, or conventional (lateral, normal, induction, micro, etc.). However, these are usually employed in the fluid medium of the water or oil well; therefore, there are necessary modifications to terrestrial practices in electric logging for lunar applications. (See, e.g., the work of Tixier, ref. 11.; Stratton and Ford, ref. 12; Dieter and Paterson, ref. 13; and Guyod, ref. 14.)

Several resistivity-measuring systems exist for logging purposes, but the most adaptable for lunar logging appear to be the multielectrode normal techniques. Logging electrode configurations are basically those used in surface methods. With contact electrodes rather than insertion electrodes, continuous recording is possible by pulling the sonde from the bottom to the top of the hole.

Induction logging measures formation resistivity by electromagnetic means. Where conductivity contrasts exist, induction logging yields a sharper delineation of interfaces than do conventional means and may be more feasible in lunar logging than are conventional resisitivity logs, since no contact with the hole wall is necessary. Definition of thin beds is better with induction logs. One reason for this difference is that eddy currents induced in the formation tend to circulate through the less resistive formations, and thereby sharpen the record response.

Lateral logging forces current to flow radially through beds as a "sheet" of predetermined thickness by placing electrode contacts in such a way as to allow continuous adjustment of potential differences between them. However, fluid is required for this otherwise desirable method.

Combination logging tools are in use and are worthy of consideration in early lunar missions in prospecting for water. They have advantages in terms of simplicity, ease of adaptation for lunar missions, and low power/size/weight specifications; however, logging tools are characteristically cumbersome and, in the case of lunar work, may require severe operational modifications to alleviate excessive astronaut participation.

Where lunar boreholes are not widely separated, resistivity measurements between holes may be performed in addition to standard logging. Equipotential points may be mapped locally when identical logging tools are used simultaneously. It is sufficient to say that the subject should have much more study.

REFERENCES

1. Speed, R. C.: Water in Lunar Materials. Seminar Proc. Util. of Extraterrest. Res., NASA Jet Propulsion Lab. (Pasadena, Calif.), Apr. 1962, pp. 26–32.
2. Westhusing, J. K.; and Crowe, C.: Techniques for Lunar Water Exploration. Final Rept. AFCRL–64–814, Texas Instruments, Inc., Sept. 1964.
3. Henderson, G. C.; and Strange, W. E.: Requirements for Gravity Measurements on the Moon: A Review. Rept. ERR–FW–707, Fort Worth Div., Gen. Dynamics Corp., Feb. 1968.
4. Watkins, J. S.; and Kovach, R. L.: A Lunar Seismic Refraction Experiment. Paper pre-

sented at 36th Annual Meeting, Soc. Explor. Geophys. (Houston, Tex.), Nov. 1966.

5. BAKER, A.; HEAD, V., AND RICHARDS, G.: Conceptual Design for an Active Seismic Experiment for the Lunar Surface. Paper presented at the Am. Astron. Soc. Conf. on the Use of Space Systems for Plan. Geol. and Geophys. (Boston, Mass.), May 1967.
6. BRADLEY, R. S.: The Electrical Conductivity of Ice. Trans. Faraday Soc., vol. 53, 1957, pp. 687–691.
7. SHOTTS, R. Q.; COX, R. M.; GRUBBS, D. M.; AND AHRENHOLZ, H. W.: A Study of Lunar Resources: A Preliminary Report of Surface and Some Other Mining Systems. Univ. Ala. Summary Rept., Contract NAS8-20134, Apr. 1966.
8. DORSEY, N. E.: Properties of Ordinary Water-Substance. Am. Chem. Soc. Mon. Series, Reinhold Publ. Corp., 1940.
9. BERNETT, E. C.; WOOD, H. L.; JAFFE, L. D.; AND MARTENS, H. E.: Thermal Properties of a Simulated Lunar Material in Air and in Vacuum. Am. Inst. Aero. and Astron. J., vol. 1, 1963, pp. 1402–1407.
10. WARD, S. H.; JIRACEK, G. R.; AND LINLOR, W. I.: Electromagnetic Reflection From a Plane Layered Lunar Model. J. Geophys. Res., vol. 73, Feb. 15, 1968.
11. TIXIER, M. P.: Electric Logging. Subsurface Geology in Petroleum Exploration, J. D. Haun and J. W. LeRoy, eds., Colo. School of Mines (Boulder, Colo.), 1958, pp. 267–328.
12. STRATTON, E. F.; AND FORD, R. D.: Electric Logging. Subsurface Geological Methods, L. W. LeRoy, ed., Colo. School of Mines (Boulder, Colo.), 1951, pp. 364–392.
13. DIETER, K. H., AND PATERSON, N. R.: A New Quantitative Approach to I. P. and Resistivity Interpretation. Paper presented at the 36th Annual Meeting, Soc. Explor. Geophys. (Houston, Tex.), Nov. 1966.
14. GUYOD, H.: Interpretation of Electric and Gamma Ray Logs in Water Wells. Reprinted from: Well Log Analysts (Jan.–Mar. 1966), Gearhart-Own Ind. (Fort Worth, Tex.), 1966.

BIBLIOGRAPHY

ALFANO, L.: Introduction to the Interpretation of Resistivity Measurements for Complicated Structural Conditions. Geophys. Prospecting, vol. 7, 1959, pp. 311–366.

BHATTACHARYYA, B. K.: Electromagnetic Fields of a Small Loop Antenna on the Surface of a Polarizable Medium. Geophysics, vol. 29, 1964, pp. 814–831.

BREUSSE, J. J.: Modern Geophysical Methods for Subsurface Water Exploration Geophysics, vol. 28, 1963, pp. 633–657.

COSTER, H. P.: Electrical Conductivity of Rocks at High Temperature. Monog. Nat. Roy. Astron. Soc., Geophys. Suppl., vol. 5, 1948, pp. 193–199.

DOBRIN, M. B.: Introduction to Geophysical Prospecting. Ch. 17, McGraw-Hill Book Co., Inc., 1960.

FRASER, D. C.; AND WARD, S. H.: Analytic and Model Studies of a Rotatable Field Electromagnetic Prospecting System. Geophysics, vol. 32, 1967, pp. 899–917.

HATHERTON, T.: Electrical Resistivity of Frozen Earth. J. Geophys. Res., vol. 65, 1960, pp. 3023–3024.

JONES, P. H.; AND H. E. SKIBITZKE: Subsurface Geophysical Methods in Ground-Water Hydrology. Advances in Geophysics, vol. III, Academic Press (New York), 1957, pp. 241–300.

KELLER, G. V.; AND FRISCHKNECHT, F. C.: Electrical Methods in Geophysical Prospecting. Pergamon Press (London), 1966.

LOWRIE, W.; AND WEST, G. F.: The Effect of a Conducting Overburden on Electromagnetic Prospecting Measurements. Geophysics, vol. 30, 1965, pp. 624–632.

MAEDA, K.: Apparent Resistivity for Dipping Beds. Geophysics, vol. 20, 1955, pp. 123–147. (Discussion by K. Cook and R. Van Nostrand.)

MARKOV, A. V., ED.: The Moon. MCL–882/142, Tech. Doc. Liaison Office, 1960, pp. 219–240. (Available from CFSTI as AD 261784.)

MEIDAV, T.: An Electrical Resistivity Survey for Ground Water. Geophysics, vol. 25, 1960, pp. 1035–1053.

MIDDLEHURST, B. M.: An Analysis of Lunar Events. Rev. of Geophys., vol. 5, 1967, pp. 173–189.

NESS, N. F.: Resistivity Interpretation in Geophysical Prospecting. Ph. D. Thesis, Dept. Geol. and Geophys., Mass. Inst. of Technology, 1959.

ORSINGER, A.; AND VAN NOSTRAND, R.: A Field Evaluation of the Electromagnetic Reflection Method. Geophysics, vol. 19, 1954, pp. 478–489.

ROY, A.: Downward Continuation and Its Application to Electromagnetic Data Interpretation. Geophysics, vol. 31, 1966, pp. 167–184.

SARMA, V. V.; AND RAO, V. B.: Variation of Electrical Resistivity of River Sands, Calcite, and Quartz Powders with Water Content. Geophysics, vol. 27, 1962, pp. 470–479.

WARD, S. H.: Unique Determination of Conductivity, Susceptibility, Size and Depth in Multifrequency Electromagnetic Exploration. Geophysics, vol. 24, 1959, pp. 531–546.

WARD, S. H.: Electromagnetic Theory for Geophysical Applications. Mining Geophys., vol. II, pt. A, Soc. Explor. Geophys., 1967, pp. 10–196.

WIEDOWILT, W. G.: Interpretation Techniques for a Single Frequency Airborne Electromagnetic Device. Geophysics, vol. 27, 1962, pp. 493–506.

YUNGUL, S. H.: Telluric Sounding—A Magnetotelluric Method Without Magnetic Measurements. Geophysics, vol. 31, 1966, pp. 185–191.

Page intentionally left blank

RAYMOND T. GREER, VLADIMIR VAND, JON N. WEBER, and EUGENE W. WHITE
Materials Research Laboratory and Department of Geochemistry and Mineralogy
The Pennsylvania State University

Developments in Quantitative Luminescence Techniques

In conjunction with the use of luminescence for the identification of lunar materials, a basic laboratory study has demonstrated the feasibility of obtaining useful correlations of mineral luminescent phenomena. Two monochromator-photomultiplier attachments to an electron microprobe have been developed which permit the study of cathodoluminescence phenomena on a micron scale. The attachments extend the analytical capabilities of the instrument and facilitate: (1) recording of luminescence spectra, (2) obtaining the distribution of luminescent phases in microspecimens and bulk specimens, (3) evaluating and recording the relationships between fluorescence patterns and conventional X-ray representation of an area scan, (4) studying radiation influence on fluorescence decay, and (5) relating luminescence intensity to composition within a phase. This information provides a basis more reasonable than that formerly used for interpreting recent observations of lunar luminescence.

INTRODUCTION

The use of luminescence to characterize lunar-surface materials was prompted by observations of lunar luminescence reported by Kopal (ref. 1), Rackham (ref. 2), and Cameron and Gilheany (ref. 3). An investigation of terrestrial minerals likely to occur on the Moon has demonstrated the feasibility of obtaining quantitative measurements of mineral luminescence. It has also indicated striking variations of spectral energy distributions and excitation efficiencies within the individual specimen grains and thus emphasized the importance of a precise localized investigation of a multiphase assemblage to provide an understanding of the bulk luminescent response of the material.

In order to achieve the level of precision and discrimination necessary for evaluating the interrelations of wavelength and intensity with various elements, compositions, structures, and degree of recrystallization, two equipment modifications were developed for use with an electron-microprobe X-ray analyzer. The work reported here describes the development and application of two basic cathodoluminescence detector units: (1) an electron-microprobe, interference filter attachment; and (2) an electron-microprobe, light-wire grating monochromator assembly. Although other equipment units are available for observing luminescence phenomena (refs. 4 to 9), the microprobe and cathodoluminescence detector units offer a comprehensive analytical system for detailed investigations.

Some of the electron-excited luminescence information obtained in this study may be used to predict the physical, and to some extent the chemical, properties of minerals which may be present on the lunar surface and which have been exposed to various forms of radiation. This may then lead to the determination of the spatial distribution or availability of specific indigenous lunar or planetary surface resources.

Research reported in this paper was sponsored by the National Aeronautics and Space Administration. The authors wish to thank Dr. Brian Mason, Curator of Meteorites, Smithsonian Institution, for his help in securing subsamples of meteorite specimens.

EXPERIMENTAL

Luminescence Display System

The two cathodoluminescence units are used for the identification and distinction of phase assemblages, for the determination of the distribution of reaction products, and for the quantitative evaluation of the luminescent properties for specimens of microscopic size. The two units facilitate the study of cathodoluminescence phenomena on a micron scale of the specimen without disturbing the normal function of the microprobe. Either detector unit replaces the ocular tube on the microscope of an Applied Research Laboratories model EMX microprobe. Most nonmetallic materials luminesce in the visible region when bombarded by relatively high energy electrons (5 to 50 keV). Since the intensity and spectral distribution of the luminescence can vary even with small changes in impurity content, the luminescence characteristics give important information concerning the trace composition and growth characteristics of a given phase. With these detection units, quantitative measurements of the luminescence spectra are obtained without impeding the inherent use of the microprobe as an analytical tool.

The monochromator (interference filter) attachment consists of a housing, a monochromator, an ocular tube, a selection of interchangeable slits, and interchangeable photomultiplier detectors. A diagram of this attachment is shown in figure 1. The attachment replaces the ocular tube of the optical microscope on the microprobe. The interchangeable components are readily permuted so that the operator can perform a variety of experiments or use the microscope in the normal manner without having to remove the attachment. For visual microscopic examination, the ocular is inserted in the attachment. Then the specimen can be viewed through the monochromator, in which case the specimen is seen in a given colored light, or, alternatively, the monochromator can be bypassed for normal microscopic observation. Defining slits for the monochromator are inserted in place of the ocular, and then photomultiplier tubes in light-tight housings are slipped onto the attachment for electronic detection of light intensities.

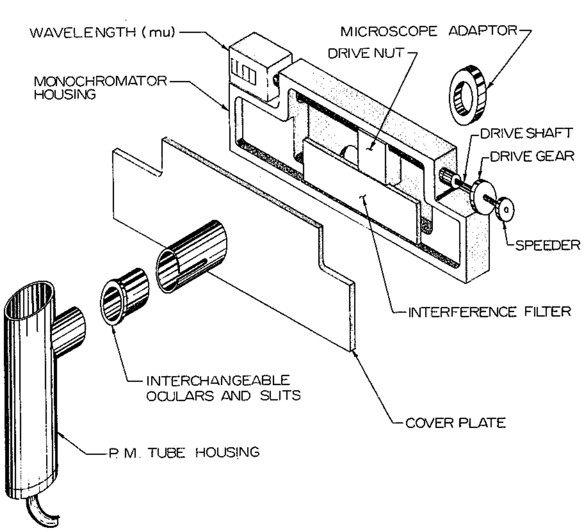


FIGURE 1.—Cathodoluminescence interference filter attachment.

The monochromator within the attachment is a Bausch & Lomb wedge interference filter of narrow bandwidth (10 nanometers (nm)) and 35 percent transmission. The linear dispersion is 5.5 nm/mm with a useful wavelength range of 400 to 700 nanometers. An odometer is used to read wavelength directly to the nearest 1.0. The visible spectrum is scanned by use of a synchronous motor drive on the monochromator with strip-chart recording of the signal. In this manner the complete visible emission spectrum of a luminescent area on the surface of the sample can be obtained. The amplified photomultiplier signal can also be displayed on the oscilloscope in a way analogous to the conventional electron-backscatter image or X-ray images as described earlier by Heinrich (refs. 10 and 11). Recently, infrared microprobe display capabilities have been developed (refs. 12 to 15); however, with this attachment, light intensity displays at a particular wavelength in the visible spectrum can be photographically recorded.

A second cathodoluminescence detection unit is a light-wire grating monochromator assembly. The light generated by the action of the electron beam (typically, 30 keV and 0.03 microampere) on the specimen is collected by replacing the ocular of the electron-microprobe optical microscope with a flexible, ⅛-inch Bausch & Lomb noncoherent light wire. Typical incident light-gathering efficiency of the fiber optic rod is 60 percent at the receiving end, with a light-transmitting efficiency of 5 percent absorbance loss per foot and a transmittance capability in the visible and near-infrared zones. A variety of signal readouts, such as Teletype printout, strip-chart recording, and oscillographic display, are available.

A Bausch & Lomb 500-millimeter-focal-length monochromator with two interchangeable diffraction gratings, one blazed at 7500 Å with 600 grooves/mm and one blazed at 3000 Å with 1200 grooves/mm, permits narrowband spectra to be obtained when necessary.

Experimental Procedure

As one part of a systematic study of luminescence of natural materials likely to occur on lunar and planetary surfaces, a variety of meteorite specimens were examined under electron bombardment. Detailed examination of what at first appeared to be homogeneous material, free from obvious inclusions of extraneous phases (i.e., metals, sulfides, and silicates other than enstatite), revealed striking variation in fluorescence and chemical composition between meteorites. In order to characterize the extent of such variation, an electron microprobe was utilized to examine enstatite ($MgSiO_3$) grains derived from the following meteorite specimens: (1) enstatite chondrites: Abee, Adhi Kot, Atlanta, Blithfield, Khairpur, Jajh deh Kot Lalu, and Hvittis; and (2) enstatite achondrites: Bishopville, Cumberland Falls, Khor Temiki, Pesyanoe, and Shallowater. Individual grains, 10 to 200 microns in diameter, were selected for analysis, and these samples were embedded in ¼-inch-diameter plastic rods. Polishing was done by the sequential use of 6-, 3-, and 1-micron diamond paste and ¼-micron Gamol polishing suspension. The samples were carbon coated to a thickness of about 200 to 400 Å to provide a conducting path for absorbed electrons and were placed in a brass holder in the microprobe chamber for analysis.

Intensity of luminescence was recorded on a dual-pen strip recorder. The wavelength range from 400 to 700 nanometers was investigated in two ways: At monochromator settings to monitor and compare the blue and the red portion of the spectrum (for enstatite, the host crystal luminescence emission is in the blue, and the activator-induced luminescence emission is in the red, portion of the spectrum), and at a variety of settings to obtain oscillographic displays of the luminescence for comparison with conventional electron-backscatter and X-ray images.

All the X-ray measurements were made on an Applied Research Laboratories model EMX microprobe equipped with three dispersive channels. X-ray intensities were read from Hamner 6-decade scalers or printed by a Teletype machine. The probe was operated with a 1-micron spot size. The majority of the intensities were measured on a 4-inch LiF spectrometer using a sealed 0.001-inch beryllium-window argon detector (argon Exatron); silicon intensities were measured using a 4-inch ADP (ammonium dihydrogen phosphate) spectrometer with a 0.004-mm-thick, carbon-coated, nonsupported, Mylar window and a flow proportional counter with P–10 gas at atmospheric pressure.

The procedure for making X-ray intensity measurements was to select a grain using reflected light optics and simultaneously record the luminescence signal from the instant the electron beam impinged on the specimen and the X-ray signals. For individual grains derived from the larger samples, iron (Fe), manganese (Mn), chromium (Cr), calcium (Ca), and silicon (Si) were determined. The intensity of the SiK_α X-ray emission line signal was utilized to monitor the phase (in this case, enstatite, $MgSiO_3$). The Fe, Ca, and Cr were monitored so as to determine their influence on the optical fluorescence response of the enstatite host crystal. The Mn was monitored to determine its contribution to the activator-induced red luminescence band for an enstatite host. Although group IVB oxides can increase the host luminescence (in the blue), they were not monitored since their presence in these meteorite grains is well below the 1 weight-percent necessary to enhance the enstatite blue emission band. The LiF spectrometer was used to scan for the K_α X-ray emission lines of the elements Ca, Fe, Mn, and Cr; the ADP spectrometer was used to identify the K_α X-ray emission lines for Si.

Operational technique was as follows: (1) obtain the luminescence intensity measurements; (2) record five replications at each element odometer setting and at the background odometer setting for that element for a series of points within a grain or grains (ref. 16); and (3) photograph luminescence oscillographic displays and the conventional cathode-ray-tube electron-backscatter image and X-ray images.

Procedure for Analysis of Experimental Data

Multivariate statistical analytical techniques (refs. 17 and 18) were utilized to process the data. From this information it was possible to determine to what extent fluorescence spectra of the meteorites vary from sample to sample and to correlate the intensity and wavelength of fluorescence with chemical composition. Since some zero values for the elements were present (corresponding to the probe analysis detection limit for the element), the data transformation log $(X+1)$ was appropriate for the statistical analysis.

RESULTS AND DISCUSSION

When the samples were observed microscopically during electron bombardment, large differences in both the intensity and wavelength of the resulting luminescence were evident. Different portions of a single mineral sample emitted at wavelengths ranging to both limits of the visible spectrum. Within an individual specimen the variation in intensity and/or wavelength of fluorescence appears to be accounted for by corresponding variation in chemical composition. Higher concentrations of Fe, Ca, and Cr tend to suppress fluorescence. In many cases, exsolution phenomena (refs. 19 and 20) representing areas of high Ca and low Ca pyroxene are sharply contrasted by monitoring the optical fluorescent emission intensity with the monochromator set in the red portion of the visible spectrum. Both the high and low Ca pyroxene luminesce in the blue; however, the high Ca quenches strong luminescence in the red, and consequently the oscillographic displays clearly show the location of each.

Fluorescence is most intense in the red portion of the spectrum. Almost all of the strong luminescent samples contain very little Fe or Ca, and the achondrite enstatite specimens luminesce stronger than do the chondrites throughout the visible spectrum.

The clinoenstatite specimens luminesce with relatively low efficiency and primarily in the blue, and the orthorhombic enstatite specimens luminesce with relatively higher efficiency both in the blue and in the red part of the visible spectrum. Fe readily substitutes for Mg in enstatite and diopside and is in larger concentrations in the clinoenstatite specimens. The presence of Fe quenches luminescence and also can effectively reduce the Mn luminescent emission contribution to red emission. (Manganese in $MgSiO_3$ produces new emission bands at the expense of the original bands of the host crystal; the Mn activator would normally be responsible for the long-wavelength emission band in this case.) In numerous measurements the Mn and Fe indicated a significant positive correlation, and this association usually decreased the red contribution to the luminescent response for the specimens. In addition, the observed decrease in luminescent efficiency in going from an orthorhombic enstatite to a monoclinic enstatite specimen is consistent with the crystal-field-theory explanation concerning the environment of the atoms when the lattice spacing is altered and also when there is a reduction in site symmetry.

An examination of selected mineral grains by the electron microprobe revealed that the dispersion of concentrations of Fe, Mn, Cr, and Ca in these samples is also large. This variability indicates why a variety of intensity and wavelength responses may be possible within a specimen. These chemical peculiarities effectively define the two groups (enstatite chondrites and enstatite achondrites) (refs. 21 to 27), as well as tend to delineate the enstatite polymorph present. The enstatite chondrites are characterized by a high degree of reduction. The principal mineral is pure or nearly pure $MgSiO_3$ as rhombic enstatite, or clinoenstatite in part. Some chondrites show well-developed chondritic structure; others are primarily granular aggregates of enstatite. The luminescence efficiency tends to follow the textural relationships in terms of the sample purity represented by coarse grains and, consequently, the slow crystallization of the granular aggregates (poor chondrules) compared with the lower intensity registered for the good chondrule types. Also, the degree of recrystallization results in minor chemical and mineralogical changes which can influence unique luminescent response. For example, the Blithfield specimen lacks chondritic structure, and the recrystallization is clearly indicated by red luminescent rings corresponding to areas depleted in impurities by the recrystallization process. The enstatite achondrites represent an even higher degree of reduction than the chondrites, and the achondrite pyroxene is essentially Fe free. This purity is mirrored by the greater luminescence intensity shown by the enstatite achondrites for both the range of 400 to 500 and 600 to 700 nanometers.

Constant exposure of the enstatite specimen point to the electron beam causes a fatigue of the phosphor which is described by power-law decay relating intensity and time:

$$I=t^{-n}$$

where I is the intensity at a time, n is a constant evaluated for the particular curve, and t is the time in seconds. Young (ref. 28), Massey and Burhop (ref. 29), Leverenz (refs. 30 and 31), and others (refs. 32 to 34) provide appropriate discussions of electronic and ionic impact, penetration, and reaction phenomena.

CONCLUDING REMARKS

Quantitative optical fluorescence spectra and color pattern displays have application in the characterization of inorganic solids as demonstrated by newly developed, nondestructive, analytical techniques. By conveniently utilizing the analytical capabilities of an electron-microprobe X-ray analyzer and specialized monochromator-photomultiplier cathodoluminescence detection units, spectral data of micron-size particles and of preselected micron-size areas of larger mineral grains can be collected, and the variations in the optical fluorescence response of the specimens can be correlated with chemical composition and structure. The scheme of successive operations permits the investigation of natural phosphors singly or in mixtures, with the luminescence emphasized as a complementary diagnostic tool.

By demonstrating the influence and interrelations of such system parameters as crystal host, activator, purity, and chemical composition, luminescence may eventually be used as a satisfactory remote sensing technique similar to the statistical air-survey evaluations of various sand deposits accomplished by Romanova (ref. 35) and the variety of natural resources by Colwell (ref. 36).

REFERENCES

1. Kopal, Zdenek: Photographic Atlas of the Moon. Academic Press Inc. (New York), 1965, pp. 54–61.
2. Rackham, T. W.: Color on the Moon. Icarus, vol. 7, 1967, pp. 297–300.
3. Cameron, Winifred Sawtell; and Gilheany, John J.: Operation Moon Blink and Report of Observations of Lunar Transient Phenomena. Icarus, vol. 7, 1967, pp. 29–41.
4. Weiblen, Paul: Investigations of Cathodoluminescence With the Petrographic Microscope. Developments in Applied Spectroscopy, vol. 4, E. N. Davis, ed., Plenum Press (New York), 1965, pp. 245–251.
5. Korda, E. J.; Pruden, I. H.; and Williams, J. P.: Scanning Electron Microscopy of a P–16 Phosphor-Cathodoluminescent and Secondary Electron Emission Modes. Appl. Phys. Let., vol. 10, 1967, pp. 205–206.
6. Hardy, Austin E.: A Combination Phosphorometer and Spectroradiometer for Luminescent Materials. Trans. Electrochem. Soc., vol. 91, 1947, pp. 221–240.
7. Gallup, John: The Vacuum Cell Luminescence Microscope and Its Use in the Study of Luminescent Materials. J. Opt. Soc. Am., vol. 26, 1936, pp. 213–215.
8. Sippel, Robert F.; and Glover, Everett D.: Structures in Carbonate Rocks Made Visible by Luminescence Petrography. Science, vol. 150, 1965, pp. 1283–1287.
9. Greer, R. T.; Staley, W. G., Jr.; and Vand, V.: Cathodoluminescence Device for Rapid Identification of Phase Assemblages. Am. Ceram. Soc. Bull., vol. 46, 1967, pp. 829–832.
10. Heinrich, K. F. J.: Oscilloscope Readout of

Electron Microprobe Data. Advances in X-ray Analysis, vol. 3, Plenum Press (New York), 1962, pp. 291–300.

11. Heinrich, K. F. J.: Concentration Mapping Device for the Scanning Electron Probe Microanalyzer. Rev. Sci. Instr., vol. 33, 1962, p. 884.
12. Wittry, David B.; and Kyser, David F.: Use of Electron Probes in the Study of Recombination Radiation. J. Appl. Phys., vol. 35, 1964, pp. 2439–2442.
13. Wittry, David B.; and Kyser, David F.: Cathodoluminescence at *p-n* Junctions in GaAs. J. Appl. Phys., vol. 36, 1965, pp. 1387–1389.
14. Wittry, David B.: Cathodoluminescence and Impurity Variations in TeDoped GaAs. Appl. Phys. Lett., vol. 8, 1966, pp. 142–144.
15. Kyser, David F.; and Wittry, David B.: Cathodoluminescence in Gallium Arsenide. The Electron Microprobe, T. D. McKinley, K. F. J. Heinrich, and D. B. Wittry, eds., John Wiley & Sons, Inc., 1966, pp. 691–714.
16. Spidel, David H.: Evaluation of Quantitative Microprobe Analyses of Multiphase Microcrystalline Refractory Materials. Advances in X-Ray Anal., vol. 9, 1966, pp. 259–294.
17. Dixon, W. J.; and Massey, F. J., Jr.: Introduction to Statistical Analysis. McGraw-Hill Book Co., Inc., 1957.
18. Snedecor, G. W.; and Cochran, W. G.: Statistical Methods Applied to Experiments in Agriculture and Biology. The Iowa State Univ. Press (Ames, Iowa), 1962, pp. 169–193 and 428–433.
19. Boyd, F. R.; and Schairer, J. F.: The System $MgSiO_3$-$CaMgSi_2O_6$. J. Petrol., vol. 5, pt. 2, 1964, pp. 275–309.
20. Atlas, L.: The Polymorphism of $MgSiO_3$ and Solid-State Equilibria in the System $MgSiO_3$-$CaMgSi_2O_6$. J. Geol., vol. 60, 1952, pp. 125–14.
21. Mason, Brian: Meteorites. John Wiley & Sons, Inc., 1962.
22. Reid, Arch M.; and Cohen, Alvin J.: Some Characteristics of Enstatite From Enstatite Achondrites. Geochim. Cosmochim. Acta, vol. 31, 1967, pp. 661–672.
23. Larimer, John W.: Chemical Fractionation in Meteorites. I. Condensation of the Elements. Geochim. Cosmochim. Acta, vol. 31, 1967, pp. 1215–1238.
24. Larimer, John W.; and Anders, Edward: Chemical Fractionations in Meteorites. II. Abundance Patterns and Their Interpretation. Geochim. Cosmochim. Acta, vol. 31, 1967, pp. 1239–1270.
25. Wiik, H. B.: The Chemical Composition of Some Stony Meteorites. Geochim. Cosmochim. Acta, vol. 9, 1956, pp. 279–289.
26. Van Schmus, W. R.; and Wood, J. A.: A Chemical-Petrologic Classification for the Chondritic Meteorites. Geochim. Cosmochim. Acta, vol. 31, 1967, pp. 747–765.
27. Keil, Klaus: Chemical and Mineralogical Relationships Among Enstatic Chondrites. G.S.A. Meeting (New Orleans, La., Nov. 20–22, 1967).
28. Young, J. R.: Deterioration of Luminescent Phosphors Under Positive Ion Bombardment. J. Appl. Phys., vol. 26, 1953, pp. 1302–1306.
29. Massey, H. S. W.; and Burhop, E. H. S.: Electronic and Ionic Impact Phenomena. Oxford Univ. Press (London), 1952.
30. Leverenz, H. W.: Cathodoluminescence as Applied in Television. RCA Rev., vol. 5, 1940, pp. 131–175.
31. Leverenz, H. W.: Introduction to Luminescence of Solids. John Wiley & Sons, Inc., 1950.
32. Burton, M.: Radiation Chemistry. J. Phys. Colloid Chem., vol. 51, 1947, p. 611.
33. Ehrenberg, W.; and King, D. E. N.: The Penetration of Electrons Into Luminescent Materials. Proc. Phys. Soc., vol. 81, 1963, pp. 751–766.
34. Studies in Penetration of Charged Particles in Matter. NAS-NRC Pub. 1133, 1964.
35. Romanova, Mariya A.: Air Survey of Sand Deposits by Spectral Luminance. Consultants Bur. (New York), 1964.
36. Colwell, Robert N.: Remote Sensing of Natural Resources. Sci. Am., vol. 218, 1968, pp. 54–69.

HUBERTUS STRUGHOLD
Aerospace Medical Division
Brooks Air Force Base, Tex.

Unorthodoxies and Controversies in Planetary and Space Science

I feel very honored to have been invited to speak at the fifth annual meeting of the Working Group on Extraterrestrial Resources. It is not only a great privilege but also a very difficult task to select a suitable topic for this audience of experts in the fields of geology, selenology, and planetology. I have decided to talk about theories which are not in accord with the present generally accepted ones, but which should not be ignored because they might, after all, be correct. I shall discuss some freely selected examples of unorthodoxies and controversies with special reference to the space-life sciences.

I would like to begin with a theory proposed in 1937 by Prof. P. A. M. Dirac of London, a Nobel Prize winner in physics (ref. 1). He suggested that Newton's constant of gravitation is actually not a constant but has decreased slightly during the lifetime of the solar system and continues to decrease in correlation with the expanding universe. This idea was not accepted in physical science, and 2 years ago, when I had the opportunity to talk with Prof. Dirac about his theory, he emphasized that most physicists are hostile to it. But 5 years ago Prof. R. H. Dicke, physicist at Cornell University, came to the same conclusion (ref. 2), and, at about the same time, Pascual Jordan, physicist at the University of Hamburg, published several papers in favor of Dirac's theory (ref. 3).

An acceptance of Dirac's theory leads to interesting conclusions. Generally, it is assumed that the Earth is contracting like a "shrinking apple." This probably was the case during the time when the protoearth cooled off from a much higher temperature. But after it had reached a temperature equilibrium, about 1 billion years ago, the decrease of the gravitational constant might have become the dominant factor in shaping the volume and surface of the Earth by causing the opposite of shrinking; namely, expansion. It has been calculated that the radius of our globe during the past half billion years has increased by 37 meters, and its circumference, by 600 kilometers. This tendency to expand has led, and still leads, to tension cracks in its crust. This explains why the primordial supercontinents, Gondwanaland and Laurasia, were split into a number of secondary continents, which then drifted apart (continental drift). Formerly, the African Continent was connected with the South American Continent, and the North American Continent, Greenland, and Iceland were part of the Eurasian Continent. The islands off the east and west coasts of the United States and Canada have been split off from the continent by tension cracks, and there are numerous faults on the continents; for example, the San Andreas Fault in California.

Recently, explorers working in oceanography have discovered fissures of several thousand kilometers in length at the bottoms of the Atlantic and Pacific Oceans. These, too, have been interpreted as expansion tension cracks. Thus the Earth can no longer be compared with a shrinking apple; rather, it seems to be an expanding planetary body. Its tendency to expand may be a factor in making earthquakes produced by volcanic activities more destructive.

The phenomenon of gravitational decrease is not restricted to our planet; it includes the whole universe. However, I would like to confine myself to our local universe, the solar system, and specifically to Mars. (See ref. 4.)

In contrast with the surface of Earth, the surface of Mars is a stony solid with no open waters. The generally accepted theory is that Mars formerly had oceans, but, because of its lower gravity, most of the water molecules have escaped into space. However, around 1910, Baumann of Zurich (ref. 5) suggested that parts of the Martian ancient oceans are now frozen and covered with dust which has become solidified in the course of millions of years. In Urey's book (ref. 6), H. E. Suess, at that time at the University of Chicago, is quoted as stating that "substantial quantities of water may be buried under dust and never become volatile at the low temperature of parts of the planet." As you know, the average temperature on Mars is about 15° C lower than that on Earth. This somewhat forgotten, unorthodox, frozen-ocean theory has been recently revived and developed in more detail in references 7 and 8 by V. D. Davydov, an astronomer at the Sternberg Astronomical Institute in Moscow. He theorizes that there may be a subsurface ice layer 500 meters thick in the equatorial regions now covered by a 100-meter-thick layer of solidified dust. He even expressed the opinion that beneath this frozen conglomerate, or "cryosphere," as he called it, water might be found in the liquid state because of an increase of temperature in the interior of Mars.

If we combine this unorthodox hypothesis of the existence of a hydrocryosphere below the surface of Mars with Dirac's unorthodox theory of the gravitational constant, we get an interesting picture. The gravitational decrease would cause on Mars, too, a volume expansion and tension cracks. Their appearance might be triggered by the impact of meteorites and asteroids which should produce fissures of tremendous length in a crust of nonuniform composition. This threefold environmental combination—planetary volume expansion, subsurface ice layer, and meteoroid impacts—might well be the mechanism producing the dark spots called oases and the dark linear markings, or canali, which generally originate in the dark spots and radiate over tremendous distances.

The existence of a subsurface ice and water table on Mars would increase the humidity in and around the meteoritic impact craters and along the fissures, and make them more suitable ecologically for the growth of vegetation. Actually, it might be the soil's humidity and vegetation that make these surface features visible to Earth-based optical astronomy.

The theory of the existence of a subsurface hydrocryosphere on Mars is unorthodox, but there are some astronomical arguments and indications that speak for it. For instance, according to Barabashov (ref. 9), without such a subsurface ice table all the water molecules might have disappeared into space in the course of millions of years. Furthermore, when cracks caused by Mars quakes occur in this kind of crust, water may reach the surface and produce localized giant clouds and white streaks of fog; such clouds, visible for days, have been described by Lowell (ref. 10) and Slipher (ref. 11). White spots glittering like ice have been observed in the equatorial regions by Saheki of Tokyo (ref. 12).

How does this combination of theories look in the light of the Mariner IV pictures? Their initial interpretation was that the visible Martian surface is extremely old and that neither a dense atmosphere nor oceans have been present on the planet since the cratered surface was formed. But later evaluations of Mariner IV photographs led to the consideration that the surface of Mars was only 300 to 500 million years old and to the statement that: "The crater density on Mars no longer precludes the possibility that liquid water and a denser atmosphere were present on Mars during the first 3.5 billion years of its existence." (See ref. 13.) Thus, the ancient ocean theory might be correct after all. It might be that some 300 million years ago, after Mars had lost most of its water into space, it entered a permanent ice age; the remaining frozen water in the course of millions of years became covered with a deep layer of dust that became solidified and was bombarded by numerous asteroidal meteoroids, starting some 300 million years ago with the disruption of Planet X, the matrix planet of the asteroids. This might indeed be the history of the features on the red planet as we see it today.

Now, I would like to go into a little more detail about some controversies concerning life on Mars. The dark areas, according to most observers, show seasonal color changes from dark to bluish-green, to yellow-gold, to brown, and back to dark, which is interpreted as an indication of green vegetation on Mars. But to some observers these regions always appear to be dark gray. These observations can be accepted only from persons with normal color vision, as confirmed by an ophthalmologist (ref. 14). As you know, 7 percent of human males are color defective.

The bluish-green color is also interpreted as a visual contrast phenomenon against the ocher-reddish surroundings. Visual contrast effects certainly occur, especially if the areas are small, but the bluish-green coloration of large areas, such as Syrtis Major, which is about the size and shape of Texas, is in all probability real. This is also supported by the observation of Tombaugh (ref. 15), according to whom certain areas occasionally look dark when others look green, despite the fact that both are surrounded by reddish areas. The final answer in this color dispute might come from color photographs made by future flyby probes. But, of course, the green color is not decisive of the existence of life on Mars.

Fifty years ago, Arrhenius (ref. 16) advanced the theory that the dark areas are salt beds of dried-out oceans and concluded that "Mars is indubitably a dead world." But on Earth the Dead Sea, in Palestine, which is an extremely salty medium, was for thousands of years considered to be without life, whence its name. Recently, however, numerous species of microorganisms, bacteria, and algae have been detected therein. The Dead Sea, therefore, is not so dead as was believed, and the red planet, Mars, might not be so dead either.

Recent spectroscopic studies indicate that carbon dioxide pressure in the Martian air might amount to 3 millibars; that is, 10 times as high as that on Earth. The opinion has been expressed that this would exclude life; but, actually, it would even be an advantage for the growth of green vegetation, because carbon dioxide in this pressure range increases photosynthesis; although beyond 22 mm Hg it has an inhibiting effect on this process.

It has been argued that the low density of a 10-millibar-pressure atmosphere, as revealed by Mariner IV, might not provide effective protection from harmful solar ultraviolet and X-rays. But, first of all, the intensity of solar irradiation at Mars' distance from the Sun is less than one-half of that at the Earth's solar distance. Furthermore, a certain amount of these rays is certainly absorbed within the atmosphere. It is, of course, well known that ultraviolet rays, particularly in the range from 2500 to 2800 Å, are indeed very destructive to most terrestrial micro-organisms. For this reason they are used for sterilization of food and of lunar and planetary probes to prevent interplanetary contamination. But there are various degrees of resistance to ultraviolet rays and X-rays. Moreover, certain microorganisms are even stimulated in growth when exposed to low-intensity ultraviolet rays and X-rays, as was found in bacteriological experiments around 1930.

The temperature on the Martian surface during the night is always and everywhere below the freezing point of water. This is considered to be particularly prohibitive for life; but experiments in Mars environmental simulators have shown that many organisms survive the freeze-thaw cycle for some time. If there is a Mars biology, during the night it is always a cryobiology; that is, a low-temperature biology.

All in all, the question of life on the Martian surface is still more a matter of probability than possibility. If there is life on the Martian surface, a precondition for it would have been the existence of open waters for its origin and development. Furthermore, if there is a water table below the ice layer, as mentioned earlier, this water table could be a second habitat for life based on chemosynthesis. This, of course, sounds ultraunorthodox; but on Earth the water of the geysers contain micro-organisms, and there are microbes even in oilwells and jet-fuel containers. This has led to the establishment of a new branch of bacteriology called petroleum bacteriology.

Finally, I would like to touch upon some controversial points concerning human physiology in space flight. In all space medical discussions the duration of the flight plays an important role. What might be the time limit in this respect? A flight to the Moon is no problem because this takes only about 3 days, but a flight to Mars, based on a minimum energy trajectory, lasts more than 8 months. This is, of course, the simplest and most economic method for unmanned automated planetary probes, such as Mariner IV.

But is such a long duration also acceptable for a manned planetary mission? To get a realistic judgment in this respect, we must consider the whole complexity of life of the mission crew, a team of perhaps six or more, living in a cramped, closed ecological world with its own economy and autonomy. The activities of this "capsule society," as Sells calls it (ref. 17), include power control, navigation, exploration, telecommunication, control of the life-support system, hygiene, housekeeping, and so forth. Weightlessness complicates some of these activities and facilitates others.

The astronauts, after some 20 hours of flight, should be in a state of "relatively stable adaptation to weightlessness," as has been concluded from the medical observations taken in orbital flight. Anthropometric comfort, appropriate exercise, and a well-regulated sleep-duty regime might enable them to endure space flight lasting for months. Artificial gravity might not be required. Be that as it may, it seems to me advisable, if not even a requirement, to base a flight plan to Mars on a high-energy trajectory so that the duration of the minimum-energy trajectory of about 8 months can be shortened to 20 to 30 percent of this time. This can be achieved by novel methods of propulsion.

In addition to the man-machine-intracabin environment complex, the external space environment also must be taken into account. A shorter time reduces the possibility of meteoritic incidents and the radiation hazards after solar flares.

In brief, a minimum in time and an optimum in comfort is the prescription for achieving a maximum of success of any manned planetary landing mission (ref. 18). Of course, astronauts with week-long experiences in orbital flight and the space medical practitioners who have controlled these flights will have a decisive voice in this respect.

In the case of long-range manned space operations, as, for instance, a flight to Mars, preflight prophylactic surgical measures in addition to preventive dentistry must be considered. Appendectomy and even cholecystectomy would certainly be advisable; the latter may be necessary only if there is some doubt that the astronaut is completely free of positive and negative gall-bladder stones. This much, according to my opinion, makes sense. But the suggestion to transform astronauts into cyborgs, that is, persons with artificial organs, which hit the headlines of the press some 10 years ago and might be revived since the successful transplantation of organs, will probably remain a matter of wild imagination; for it is not the task of space bioengineering to adapt the human body artificially to the extraterrestrial environment. Rather, it is our aim to make the extraterrestrial environment artificially as physiologically suitable as possible. This is the challenging task of the Working Group on Extraterrestrial Resources.

The present main object of your working group is the Moon. I would like to conclude this discussion with a brief remark about the controversial question: How should selenonauts, the Moon explorers, walk on the Moon? At the 1966 meeting of the Lunar International Laboratory Committee in Madrid, Margaria of Milano suggested that the selenonauts should take advantage of the Moon's low gravity by jumping some 5 meters, like grasshoppers (ref. 19). This might be acceptable if the surface is smooth, but if the "moonhoppers" should lose their balance and hit the ground on a rough surface, they might risk a leak in their pressure suits. In contrast, at the same meeting, I suggested that the selenonauts should increase their weight by carrying, in addition to the life-support equipment, some 30 kilopounds of material, maybe moonpebbles, in pockets around their waist or shoulders (ref. 20). This would increase stimulation of the peripheral mechanoreceptors in the skin and muscles of the legs and would help them to keep their balance. It would make the stimulation of these mechanoreceptors more Earth-gravity equivalent, but it will not, of course, affect the otolith apparatus.

In conclusion, there are many more controversies in space medicine, lunar and Martian medicine, and Martian biology that will be a stimulus for further theorization and experimentation. The technological and scientific achievements in man's advance on the space frontier have so far been spectacular and will be even more fantastic in the years to come. Nevertheless, despite the possibility of some of the unorthodox theories I have presented, in the area of space medicine we must be realistic and sensible, particularly in our extrapolations for long-range, manned missions such as a flight to Mars.

REFERENCES

1. Dirac, P. A. M.: The Cosmological Constants. Nature, vol. 139, no. 323, 1937.
2. Dicke, R. H.; and Peebles, P. Y.: Gravitation and Space Science. Space Sci. Rev., vol. 4, 1965, pp. 419–460.
3. Jordan, P.: Die Expansion der Erde. Das Bild Wiss. vol. 2, no. 15, 1965.
4. Michaux, C. M.: Handbook of the Physical Properties of the Planet Mars. NASA SP–3030, 1967.
5. Baumann, A.: Erklarung der Oberflache des Planeten Mars. Zurich, 1910.
6. Urey, H. C.: The Planets, Their Origin and Development. Yale Univ. Press (New Haven, Conn.), 1952.
7. Davydov, V. D.: Behavior of the Hydrosphere Under Martian Conditions and the Phenomena Observed. Voprosky Kosmogonii, Akad. Nauk. SSSR, vol. 7, 1961.
8. Davydov, V. D.: Ist der Mars mit Eis bedeckt? Weltraumfahrt, vol. 12, Jan. 1961, p. 14.
9. Barabashov, N. P.: Physical Conditions on Mars. J. Acad. Sci. USSR, no. 10, 1962.
10. Lowell, P.: Mars and Its Canals. Macmillan Co., 1906.
11. Slipher, E. C.: The Photographic Story of Mars. Sky Publ. Co. (Cambridge, Mass.), 1962.
12. Saheki, T.: Martian Phenomena Suggesting Volcanic Activity. Sky and Telescope, vol. 14, Feb. 1955, pp. 144–146.
13. Anders, E.; and Arnold, J. R.: Age of Craters on Mars. Science, vol. 149, 1965, pp. 1494–1496.
14. Schmidt, I.: Green Areas of Mars and Color Vision. Proc. 10th Int. Astron. Congr., 1959, pp. 171–180. Also, Springer-Verlag (Vienna), 1960.
15. Tombaugh, C. W.: Mars—A World for Exploration. Astronaut., vol. 4, 1959, pp. 30–31 and 86–93.
16. Arrhenius, S.: Worlds in the Making. Macmillan Co., 1908.
17. Sells, S. B.: Capsule Society. New Problems for Man in Space on Long-Duration Missions. Conf. on Bioastronaut., Va. Polytech. Inst. (Blacksburg, Va.), 1967.
18. Strughold, H.: Synopsis of Martian Life Theories. *In* Advances in Space Science and Technology, vol. 9, pp. 105–122. Academic Press (New York), 1967.
19. Margaria, R.; et al.: Human Locomotion at Reduced Gravity. Proc. 2d Lunar Int. Laboratory (LIL) Symp. (XVIIth Int. Astronaut. Cong., Madrid, Spain), Oct. 1966.
20. Strughold, H.: Lunar Medicine. Proc. 2d Lunar Int. Laboratory (LIL) Symp. (XVIIth Int. Astronaut. Cong., Madrid, Spain), Oct. 1966.

Page intentionally left blank

GORDON R. WOODCOCK and JAMES B. BREWER
Advanced Systems Office
Marshall Space Flight Center, NASA
Huntsville, Ala.

Reactor Power for Lunar Exploration

This paper is based primarily on results of a joint study conducted for NASA and the AEC by industry. Prime contractor for the NASA study was Lockheed Missiles & Space Co.; Aerojet-General Corp. supported the study as a subcontractor. Certain information on Brayton cycle hardware and performance was supplied by the AiResearch Manufacturing Division of the Garrett Corp. The AEC contractor was Atomics International Division of North American Aviation, Inc. Results of these studies have been reported in references 1 and 2.

STUDY OBJECTIVES

The study of the application of reactor power systems to manned lunar missions upon which the present paper is based was instituted with the following principal objectives:

(1) To evaluate the capabilities of the hardware and technology under development by the SNAP–8 and associated programs.

(2) To identify and evaluate the major operational interfaces between a manned lunar-surface mission and the reactor power systems and to determine the influence of each upon the other.

(3) To determine desirable modifications to the SNAP–8 and other reactor power systems to enhance their applicability to manned lunar-surface missions.

(4) To develop guidelines and design criteria for ongoing reactor power technology development programs.

In order to attain the study objectives, concepts were developed and evaluated for integration into the manned lunar mission of a SNAP–8 reactor, Rankine cycle system; a SNAP–8 reactor, thermoelectric system; and a SNAP–8 reactor, Brayton cycle system. The major emphasis was on the SNAP–8 reactor, Rankine cycle system. Although less emphasis was placed on the thermoelectric and Brayton systems, many results of the Rankine cycle work are applicable to lunar-surface reactor power systems in general.

BACKGROUND

Over the past several years NASA and other organizations have conducted studies of concepts for extension of manned lunar exploration beyond Apollo (refs. 3 to 7). These concepts have ranged from minor extensions of Apollo systems to concepts for semipermanent lunar bases. Lunar bases that can support about 12 men appear feasible from the logistics standpoint with uprated versions of the present Saturn V and reasonable extensions of Apollo spacecraft technology. Apollo Applications Program (AAP) missions currently under study are quite modest extensions of the existing Apollo systems aimed at attaining staytimes on the lunar surface of up to about 12 days, and these concepts project only a very few years beyond the Apollo missions.

AAP-class missions are expected to employ a combination of solar cells and batteries for power. Power requirements on the lunar surface are on the order of 1 to 2 kilowatts, durations are up to 12 days, and operations on the surface will be restricted to daytime. Studies of small expendable bases (two to six men with durations of up to 2 or 3 months) have indicated that for this level of activity, fuel-cell power is the best choice. Larger semipermanent bases are expected to require nuclear reactor power.

Prior studies of nuclear reactor power systems for lunar-base operations have established the basic feasibility of lunar surface reactor power (ref. 8). The study in reference 8 is a conceptual design of an optimized system not based on technology presently in development, and it assumed a requirement for power levels in excess of the capabilities of current technology such as SNAP–8. However, more recent estimates of the power requirements for lunar-base operations have indicated that the previous power requirement estimates were too high.

NASA and the AEC currently have under technology development several systems which could be utilized for nuclear power production on the lunar surface or in other space environments. These include the SNAP–10A and SNAP–8 family of zirconium-uranium hydride reactors, the SNAP–2 and SNAP–8 mercury Rankine turbo generator systems, the Brayton cycle turbo generator systems, and direct radiator and compact converter thermoelectric systems. A recent study directed by the NASA Langley Research Center carried out an investigation of the use of this technology for providing power to a manned orbital laboratory (ref. 9). The study here reported was undertaken to examine the capability of this technology base as support for possible future lunar missions. Whereas no such missions as those postulated for this study are presently planned, the lead time required for development of nuclear technology is quite long, and the study therefore was timely in providing missions application information to the technology development programs. The NASA and AEC space reactor power system technology programs have utilized development guidelines and criteria established primarily for unmanned applications. The presence of man in a mission application will have a substantial impact on reactor power system design criteria, operation techniques, and development requirements. Reliability, operating modes, radiation levels, repair and maintenance capability, and mission integration considerations of unmanned mission cases will be altered.

ESTABLISHMENT OF MISSION MODEL

Lunar-base concepts are generally associated with the idea of extensive scientific mission activity on the lunar surface. Deep geologic core drilling, special laboratories utilizing the "hard" lunar vacuum, and large radio or optical telescopes are typical postulated scientific activities. The referenced advanced studies have indicated that these classes of missions could be conducted on the lunar surface with a base crew of about 12 men.

The mission model was formulated around concepts of a 6-to-12-man semipermanent lunar base developed by the aforementioned and contemporary advanced mission studies. These studies have assumed use of the Saturn V launch vehicle and appropriate spacecraft hardware for crew and logistics transport. Estimates of required electric power for such base operations range from about 15 kWe to more than 100 kWe, with estimates above 30 kWe generally associated with assumption of some sort of natural resources processing (e.g., propellant production) on the lunar surface. Although resources processing ultimately may be of importance for lunar operations, it is our opinion that this will not be the case for the first lunar activities extensive enough to require nuclear power. Therefore, for the purpose of the subject study, resources processing was not assumed, and the range of power requirement considered was 20 to 35 kWe. However, a brief examination was made of the capability of the SNAP–8 mercury Rankine system to provide higher power levels.

Before outlining power requirements in somewhat more detail, it is pertinent to summarize the motivation for nuclear power for lunar surface operations. A design for a power system for a lunar base must take into consideration the problem of supplying power during the lunar night; therefore, systems employing solar cells as the primary source of power must provide an alternate source for the night period. The alternate source could employ rechargeable batteries or fuel cells with a regeneration plant powered by the solar cells during the day in order to regenerate the fuel expended at night. Clearly, a battery system which will supply several kilowatts of power for 2 weeks would be quite heavy. The fuel regeneration concept sounds better but becomes unattractive upon examination, principally

TABLE 1.—*Gross Systems Characteristics for Delivery of 30 kWe for 1 Year on Lunar Surface*

Power system	Hardware mass, lb	Expendables mass, lb	Total radiator plus solar array area, sq ft
Solar plus recharged batteries	140 000	0	10 000
Solar plus fuel cells	6 500	60 000	6 000
Solar plus fuel cells with regeneration	50 000	0	31 000
Nuclear (SNAP-8)	28 000	0	1 700

because the regeneration process (electrolysis plus liquefaction of reactants) is rather inefficient and the required solar array becomes very large. Also, the regeneration plant itself is very complex and is more complex than some of the nuclear powerplant concepts investigated in this study. As indicated by table 1, other power concepts investigated to date are not competitive in performance with nuclear power for production of electricity for a lunar-base operation.

Housekeeping functions for support of a lunar base require roughly 1 kilowatt of electric power for each man supported (ref. 10). This value is to some extent dependent on the source of electric power. With a nuclear source, it is economical to expend electric energy in order to regenerate life-support expendables (e.g., water and air). With a chemical source of electric power, this is not necessarily true, and somewhat less electric power per man will be required. Experiment programs and surface operations will require additional power. The electric power requirements assumed for this study are summarized in table 2.

Logistics delivery to the lunar surface was postulated as being accomplished by an unmanned flight mode of a hypothetical propulsive spacecraft called lunar landing vehicle (LLV), launched to translunar trajectory by Saturn V. Figure 1 shows a typical LLV concept. (This concept is typical of those under study; NASA has no plans at present for initiating development of an LLV.) The LLV flight mode is entry into a lunar orbit, followed by descent and landing.

For the purposes of this study a gross lunar landed payload capability of 29 475 pounds was assumed for the LLV. Mass required for payload support structure must be subtracted from this figure in order to determine net payload capability. Continued study of LLV concepts has indicated that the above payload figure is quite conservative.

TABLE 2.—*Typical Power Requirements for 12-Man Lunar Base*

Load	Average power, kWe
Housekeeping [a]	12
Deep drilling and trenching	4. 5
External lighting	5
Battery charging for various portable equipment	2
Miscellaneous experiments	2
Subtotal	25. 5
10 percent design margin	2. 6
Total	28. 1

[a] Includes life support, communications, and shelter internal lighting.

The lunar-base crew was assumed to occupy one or two six-man shelters delivered from Earth by Saturn V/LLV. It was assumed that necessary control panel space for control and monitoring of the powerplant would be available within the shelter. It was also assumed that no advantage could be taken of lunar terrain for shielding between the powerplant and the shelters and that the base would be located at a place near the lunar equator, this area being the most severe thermal environment. An excursion area around the powerplant was assumed permissible. The major emphasis for this study was placed on a 12-man base for

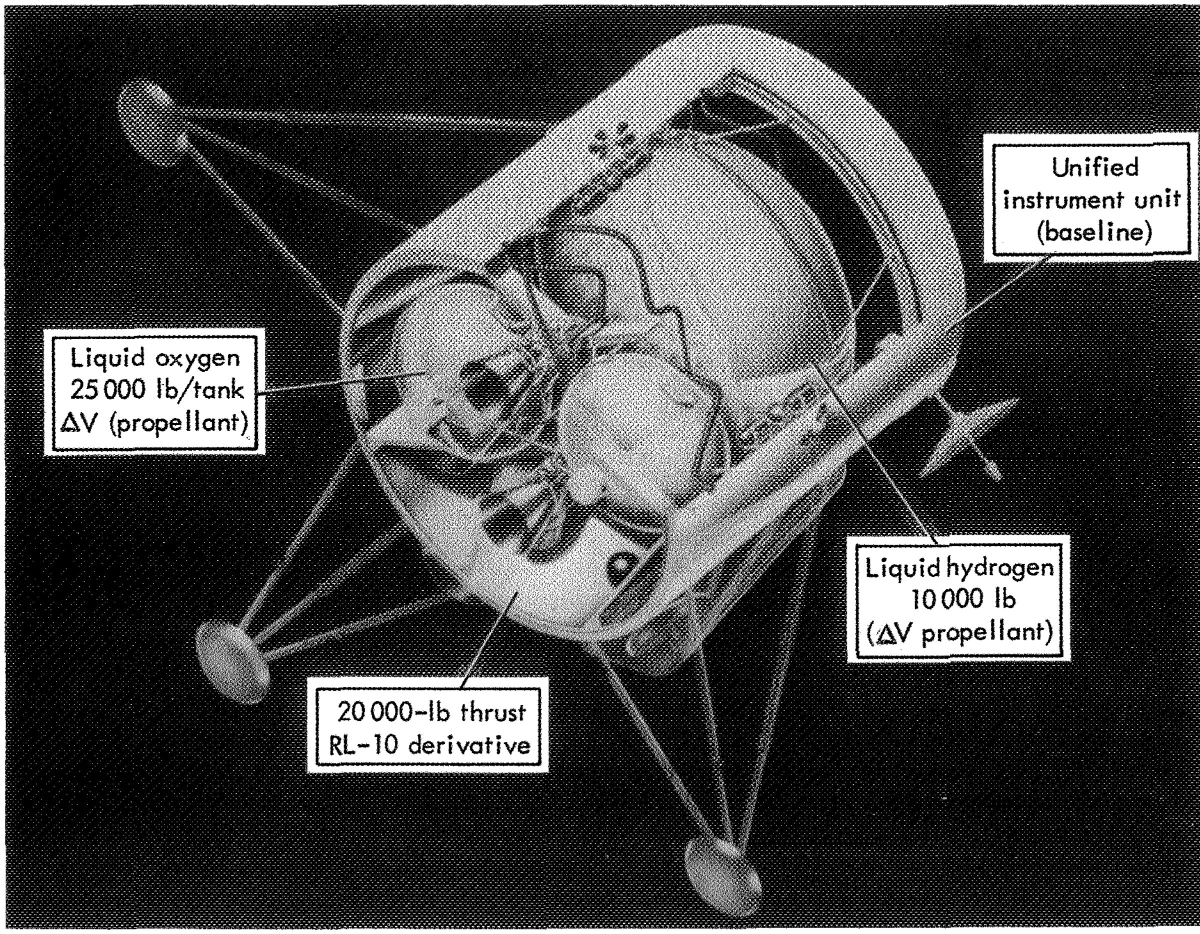


FIGURE 1.—Early cargo stage lunar landing vehicle concept.

10 000 hours or more of continuous operation. The base crew staytime was fixed at a maximum of 1 year for the purpose of analysis of shielding and calculation of crew exposure to radiation from all sources.

The radiation dose allowable to each astronaut on the lunar surface was based upon criteria suggested by the NASA Manned Spacecraft Center. These criteria allow a maximum, fractionated, annual, whole-body dose to the astronaut of 100 rem and a single, acute dose of 50 rem. These criteria are reasonable extrapolations of the Apollo criteria for longer duration missions.

The total dose to the astronaut is the summation of the doses from the reactor sources and from solar flares and other natural sources. The solar-flare dose was selected on the basis of a tradeoff analysis of base separation distance from the powerplant when the total astronaut dose from all sources is maintained at 100 rem. A solar-flare dose of 30 rem was selected, since the separation distance from the power system to the base sharply increases for larger solar-flare dosages. The maximum allowable dose from the reactor sources is 70 rem. This exposure allowance is allocated as: normal operation, 46 rem; maintenance and repair on the powerplant, 24 rem. Additional shielding on the outer airlock of the lunar shelter (about 3000 pounds) may be added in order to reduce the solar flare dose to 30 rem; it is assumed that this outer airlock will be used as a storm shelter in the event of a hazardous solar flare. A problem arises in the probabilities of incurring exposure from various sources. The probability of incurring the dose within the shelter from the operating reactor is essentially 100 percent. The probability of incurring a radiation dose during maintenance and repair will be smaller, while the probability associated with the 30-rem solar flare dose is in the 1-percent range. Therefore, the expected dose will be well below the 100-rem limit. It could be reasonably argued that the solar-flare dose allocation could be set at approximately 100 rem at a 1-percent probability, thus avoiding the added shielding in the shelter which this mission model requires. However, a generally conservative approach was used for this study.

Further contribution to the problem of exposure criteria comes from the disagreement in the technical community regarding allowed dose. Arguments have been voiced ranging from use of industrial standards to allowing doses as high as 1000 rem per year. No universally accepted set of criteria exists. In this study, as in many others dealing with nuclear systems, shielding mass is highly significant and the establishment of firm criteria substantially at variance with those used herein would change results and alter conclusions.

The power system may be landed on the lunar surface up to 6 months before it is brought into operational status. During the preoperational storage period, the lunar base presumably will be unoccupied and the crew will arrive at the base prior to the power system's being brought to full power. The initial startup of the powerplant will be scheduled for the lunar day in order to minimize problems with thermal conditioning of the system.

For the purpose of maintenance, repair, and redundancy studies, it was assumed that, if the nuclear power system fails, there will be a backup emergency power system to permit withholding a decision for 14 days as to aborting the lunar-base mission. The backup power system will have the capability of assuring survival of the crew but will not necessarily permit continuance of any experiments. Therefore, the maximum allowable downtime of the power system is 14 days. The power system should have the capability for restart during the lunar night. It was further assumed that a 2-day cooldown period with the reactor subcritical would be employed prior to manned repair activities. This procedure substantially reduces gamma-shielding requirements.

Surface mobility vehicles are assumed to be available at the lunar base for purposes of exploration, experimentation, aid in various maintenance and repair tasks, aiding an astronaut in distress should he become stranded somewhere on the lunar surface, and other purposes. Two lunar scientific survey modules (LSSM) (ref. 11) and one large mobile exploration vehicle (ref. 12) were assumed. For off-loading and radiator deployment tasks, the large vehicle can be modified by mounting an onboard crane or other device.

In the absence of any measurements or other available data concerning the density and composition of the lunar surface material, it was assumed that the material is an anhydrous [1] sandstone, rocklike surface constituted mainly of silicon dioxide. A density of 1.6 gm/cm^3 was assumed when the lunar material is used in the form of block or bricks.

The evidence obtained from approximately 3 weeks of operation with the Surveyor I spacecraft indicates that the visible spacecraft surfaces show no noticeable covering of dust that might be caused by either lunar surface ejecta or electrostatic charges on the lunar surface. Consequently, it was assumed that no significant covering of lunar material will collect on any external surfaces of the power system or on any of its auxiliary structures during the mission.

The lunar thermal environment used as a guideline for this study is specified in reference 13. The basis for the meteoroid environment is given in reference 14. This reference was used to obtain a working curve of single-thickness aluminum for various probabilities of no puncture. For application to the lunar mission, the product of area to be protected and time is multiplied by 0.5 to account for shielding by the Moon.

REACTOR AND SHIELD

The present SNAP–8 S8–DR core with 211 elements has been operated for a 10 000-hour

[1] The shielding effectiveness of soil is sensitive to hydrogen content; for conservatism, none was assumed.

test at power levels up to 600 kilowatts and would be adequate for a 1-year lifetime for reactor power levels up to about 800 kWt.

A reactor core larger than the S8–DR would provide greater capability. The larger core can be achieved by increasing the number of fuel-moderator elements and the length of the S8–DR core. A 20-inch-long core made up of 241 fuel-moderator elements, which could be produced by a minimal design change from the present S8–DR core, provides a significant increase in performance margins of the reactor system. The reflector thickness and control drum diameter have been reduced in order to reduce the shielded volume. The design and performance characteristics of the reference reactor are shown in table 3. This reactor core design was approved by the AEC as the reactor design for the lunar-base reactor power systems for the purposes of the subject study. The outlet NaK temperature from this core is approximately 1300° F, and at 600 kWt the reactor has a design lifetime of approximately 20 000 hours.

Two shielding concepts were investigated for the power system integration concepts studied. The baseline concept was a 4π shield design integral with and completely surrounding the reactor (fig. 2). The gamma-ray shield is composed of tungsten and the neutron shield of LiH. A tungsten shield in the shape of a hat was placed around the power conversion system containing the primary loop. The purpose of this shield was attenuation of the gamma-ray

TABLE 3.—*Reference Reactor Design and Performance Characteristics*

Design characteristics

Item	Value
Number of fuel elements	241
Active fuel length, in	20.2
Vessel outside diameter, in	10.2
Fuel material	$U\text{–}ZrH_x$
Uranium loading, wt percent	10.5
Hydrogen content, $N_H \times 10^{22}$	6.3
Fuel element diameter, in	0.560
Element separation, mils	30
Hydrogen barrier material	SCB–1
Cladding material	Hastelloy N
Core vessel material	316 SS
Coolant	NaK–78
Control drum diameter, in	4.0
Reflector material	BeO
Poison material	B_4C

Performance characteristics

Item	Value		
Power, kW	400	600	1000
Outlet temperature, °F	1300	1300	1300
Coolant temperature rise, °F	200	200	200
Design lifetime, hr	~26 000	~20 000	~12 000
Coolant flow rate, lb/sec	9. 0	13. 5	22. 5
Pressure drop, psi	0. 34	0. 75	2. 08

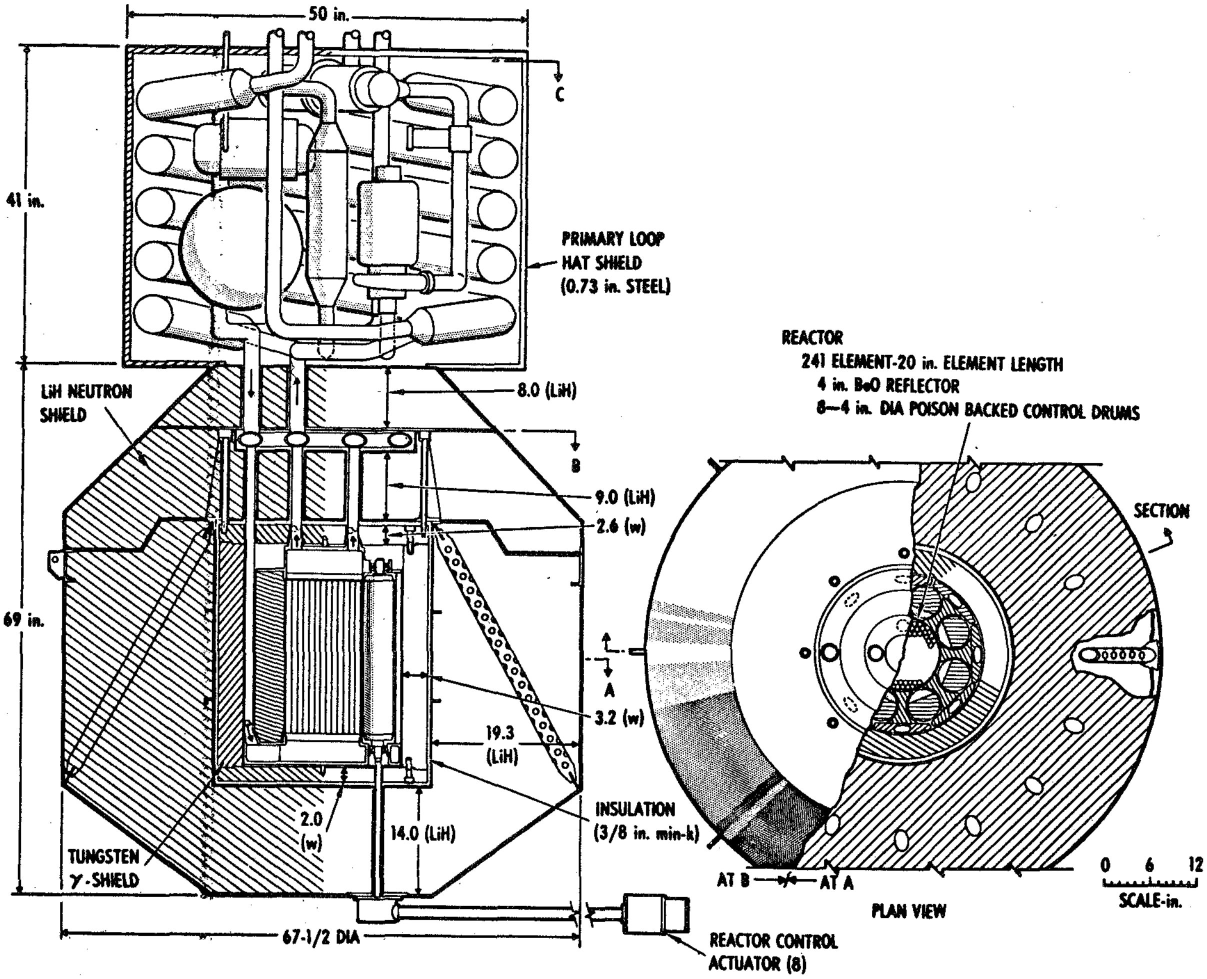


FIGURE 2.—Lunar-base reactor shield assembly. SNAP–8 mercury Rankine system.

radiation from the radioactive NaK and from possible fission products in the primary NaK loop, both during operation and during maintenance and repair after shutdown. Figure 2 shows the design concept.

The other concept was an "off-loaded" mode, with the reactor assembly removed from the LLV and buried in a hole prepared in the lunar surface. Reactor burial to a sufficient depth reduces the radiation dose rate at the surface to acceptable levels for the power conversion system during reactor operation and for the astronauts after power system shutdown by virtue of the shielding effect of the lunar soil. However, additional shielding is required between the reactor and primary loop to reduce the radiation to the primary loop components to acceptable levels. The design for the off-loaded concept provided this added shielding as part of the reactor and primary loop package.

INTEGRATION CONCEPTS

Three concepts for integration of the SNAP–8 mercury Rankine system were developed: integral, deployed radiator, and off-loaded. All concepts employed the SNAP–8 cycle shown in figure 3. For the mercury Rankine system there was no advantage in radiator deployment, since adequate radiator area was

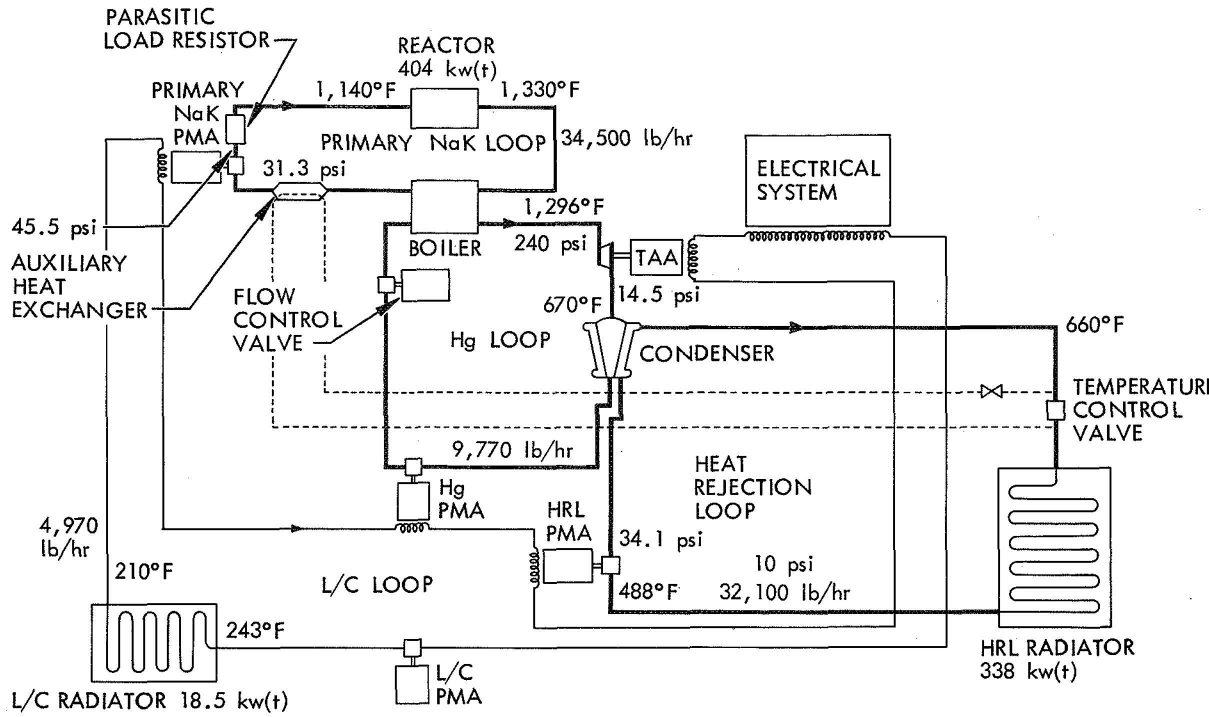


FIGURE 3.—Baseline SNAP-8 power system.

Performance summary	
Net reactor input to PCS, kWt	404
Net electrical output (BOL), kWe	40
Net electrical output (EOL), kWe	35
HRL radiator heat rejected, kWt	338
L/C radiator heat rejected, kWt	18.5
Available pressure drops	
HRL radiator, psi	18
L/C radiator, psi	15

available with the integral mode in accordance with payload envelope dimensions employed. Radiator deployment was studied in view of its potential application to a high-output SNAP-8 and the thermoelectric and Brayton systems. Two techniques were considered: flexible tubing and assembly and welding of radiator panels. Investigation of potential techniques for semiautomatic welding of tubing and pipe joints by astronauts on the lunar surface indicated that highly reliable welding probably could be perfected. There is comparatively little experience with flexible tubing in liquid metal systems; it was felt that the thin-wall nature of flexible-tubing designs would present leak hazards, and therefore the welding approach was selected. This selection was conditional, since integral concepts were chosen as preferred modes for all systems.

The off-loaded SNAP-8 concept allows delivery of two complete systems (two reactors, etc.) on one Saturn V logistics flight, as a result of greatly reduced shielding mass and reduced separation distance. However, the estimated assembly and setup work required three suited astronauts working 6 hours a day for 17 days. Therefore, the off-loaded concept was rejected in spite of its attractive mass characteristics.

The selected SNAP-8 integral configuration is shown in figure 4. To increase the assurance of mission success, redundancy is incorporated by connection of two complete power conversion systems to the primary loop. The boilers are in series in the primary loop, and this loop contains a standby NaK pump. There are two lubrication and coolant loops; each can cool both pumps in the primary loop and can operate with either power conversion system.

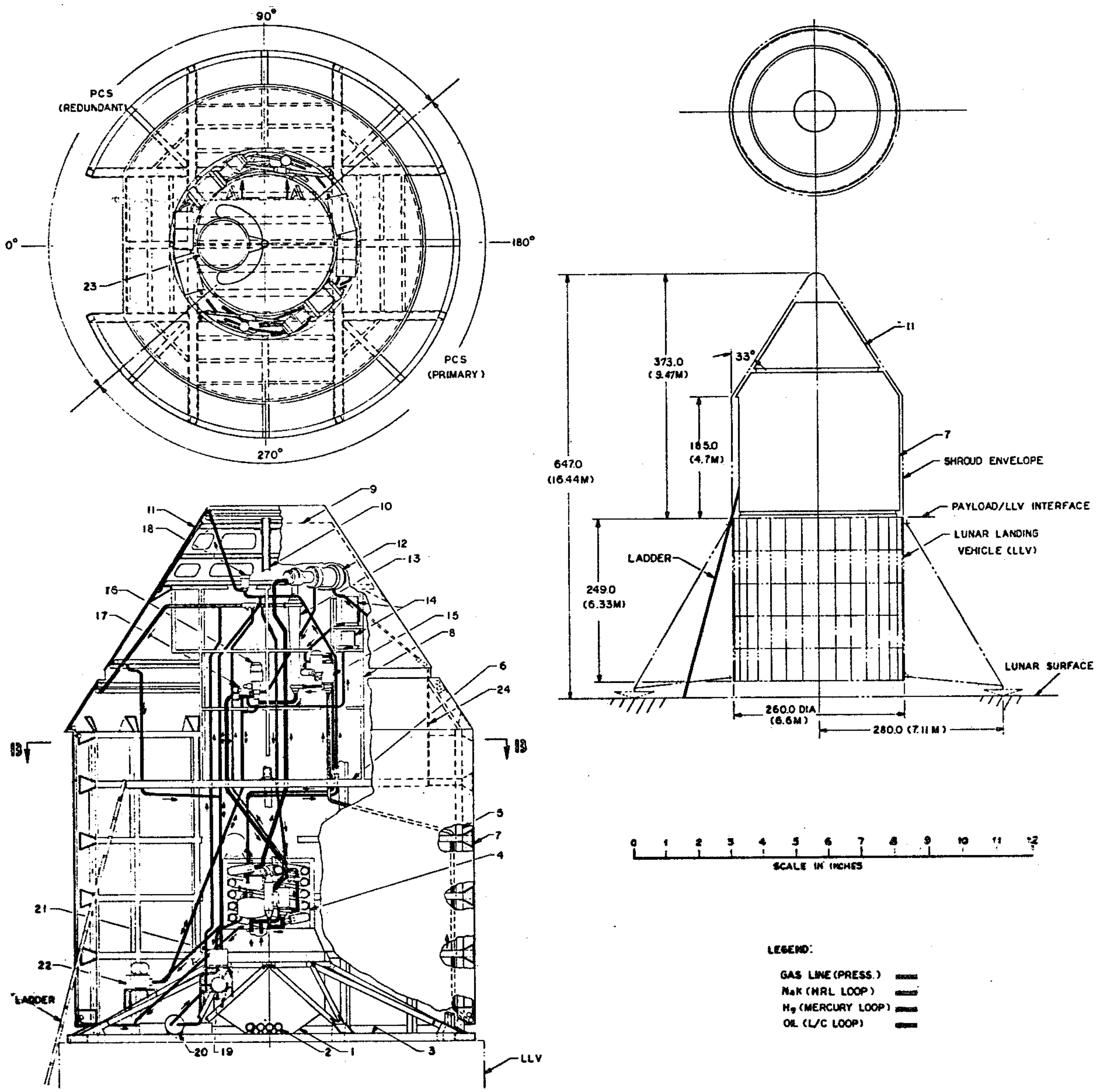


FIGURE 4.—Detailed configuration of SNAP–8 concept selected.

1. Reactor and shielding
2. Reactor control motors
3. Lower walkway
4. Primary loop and shielding
5. Tubular structure integral with HRL radiator
6. Upper floor
7. HRL radiator
8. Tubular truss structure
9. Sheet metal structure
10. Pole for basket
11. L/C radiator integral with structure
12. Turbine alternator assembly
13. Condenser
14. Electrical equipment
15. NaK-pump motor assembly
16. Mercury pump
17. Flow control valve
18. Pump, oil (L/C loop)
19. Pressure sphere (L/C and HRL loop)
20. Reservoir assembly (NaK)
21. Reservoir assembly (oil)
22. Injection system (mercury)
23. Basket
24. Insulation
25. Thermal blanket
26. Aluminum sheet
27. AL extrusion with STL tube insert
28. Weld

The two independent heat-rejection loops share the same radiator fins. Crew access and a movable basket are provided in order to facilitate manned maintenance and repair during down periods.

The electrical control subsystem would be transported to the lunar surface in one of the crew shelters. Since the shelter must be environmentally controlled during storage, this arrangement avoids providing environmental control for this equipment in the powerplant during a storage period. During setup operations, the electrical package is placed on the lunar surface about 75 feet from the powerplant. This distance satisfies thermal control requirements and locates the package conveniently for maintenance access.

The compact converter thermoelectric reactor power system is schematically shown in figure 5. Before the configuration of this powerplant was determined, parametric studies were made of weight and radiator area required versus power delivered for a compact converter (lead-telluride) version and a direct-radiating (silicon-germanium) version. Both systems were limited by available radiator area (integral design) to about 20 kWe delivered to the base. Deployed radiators would increase the power capability by about 5 kWe, but the added power was believed not justified because of the reduction in mission success assurance which would be incurred by the use of deployed radiators; therefore, an early choice of integral design was made. The compact converter system was selected by the AEC in preference to the direct radiating system largely because its greater materials efficiency required 40 percent less reactor power than did the latter at a slightly reduced temperature; this former system thereby provided much greater reactor lifetime potential. The thermoelectric system design is shown in figure 6. A high degree of inherent redundancy is provided by eight independent converter and heat-rejection loops; therefore, manned access is provided only to reactor control devices and control electronics located around the periphery of the base of the system (fig. 7).

The Brayton system schematic is shown in figure 8 and the integrated design in figure 9. Again, an integral design was chosen, although deployed radiators could have provided additional power capability. Two power conversion loops are provided for redundancy. The working fluid is a helium-xenon mixture and

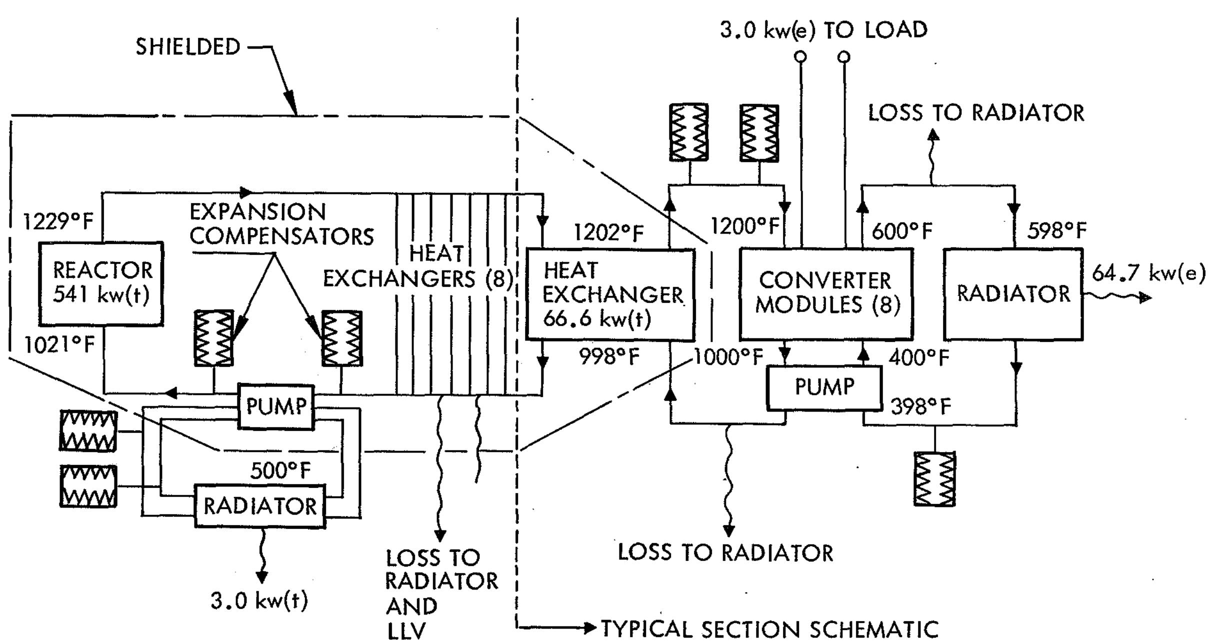


FIGURE 5.—Flow diagram of SNAP–8 compact converter thermoelectric power system.

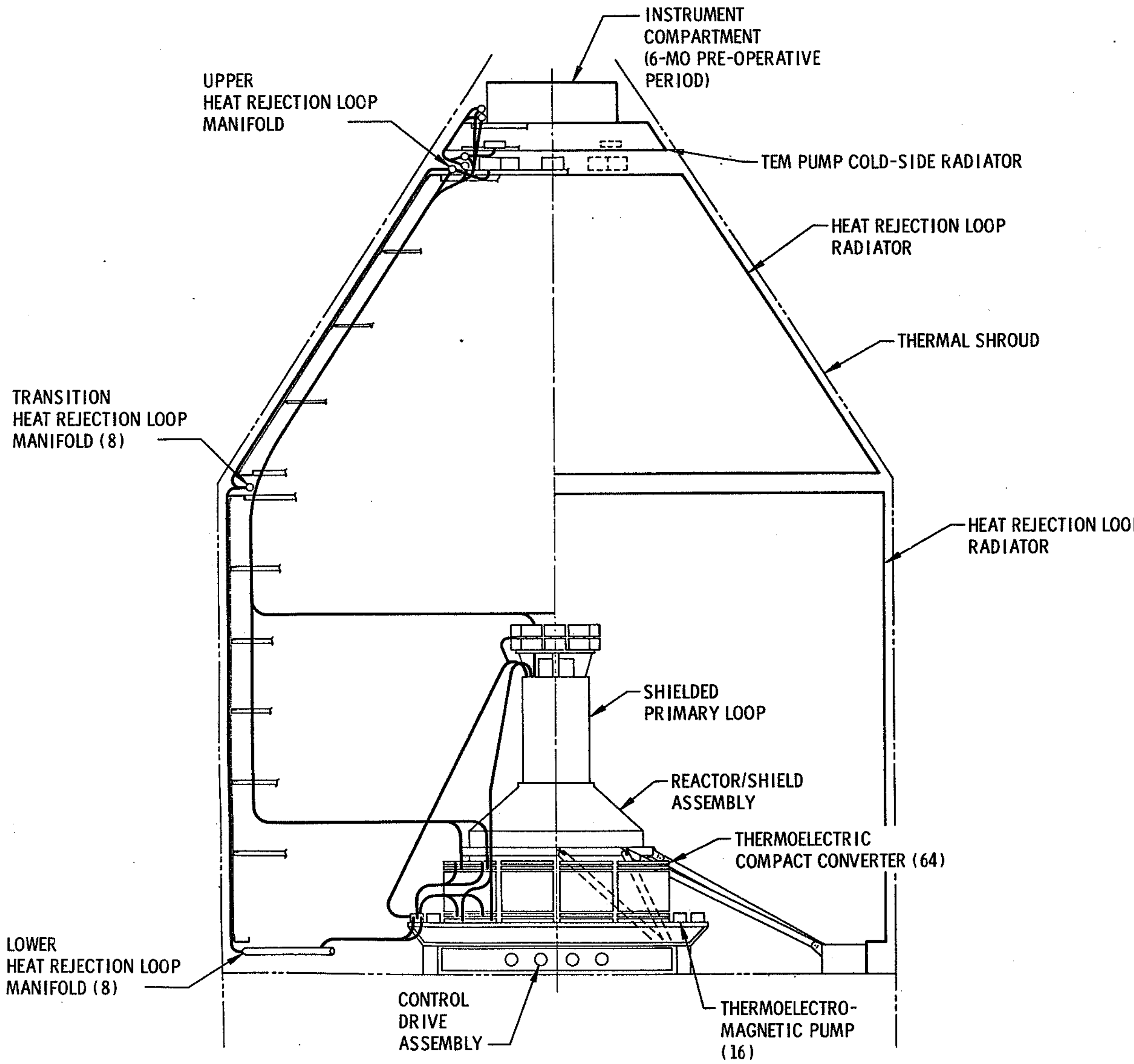


FIGURE 6.—Integral compact converter configuration.

the system employs a gas flow radiator and thus avoids the thermal control problems of a liquid metal radiator. A radiator bypass control valve is used for regulating power. The Brayton cycle runs with comparatively low radiator temperatures and the result is high sensitivity to the lunar thermal environment; power output would increase about 100 percent during the lunar night without this control.

WEIGHT AND PERFORMANCE

Performance parameters and weights of the powerplants are summarized in table 4. Performance parameters for the deployed-radiator and off-loaded version of the mercury Rankine system were the same as those for the integral design, except for masses, which were 31 600 pounds and 29 030 pounds, respectively, and separation distance for the off-loaded system,

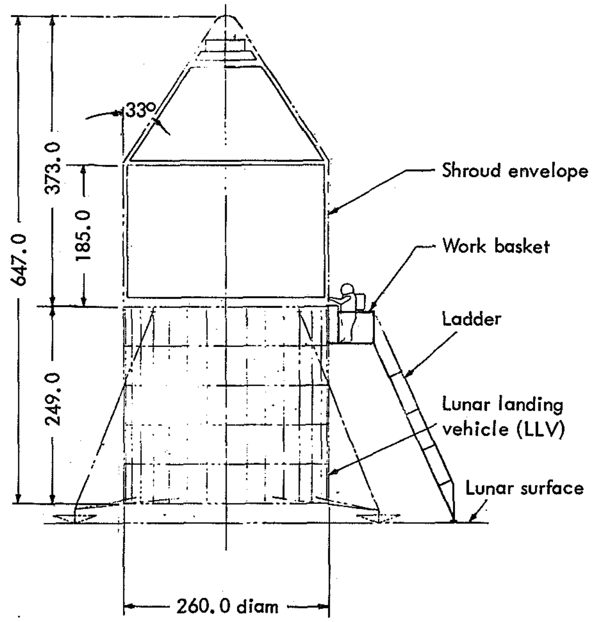


FIGURE 7.—Maintenance and repair access to thermoelectric system.

which is 900 feet. Note that the mass of the off-loaded system includes two complete powerplants; each powerplant includes only one power conversion system.

REDUNDANCY AND MAINTENANCE AND REPAIR

The technology with which this study dealt is not sufficiently mature to allow meaningful reliability analyses of the conventional nature. Nonetheless, reliability considerations were necessary in order to attain appropriate concepts for system redundancy. The technique applied was a combination of engineering judgment and comparative analysis. For example, it was decided to provide two power conversion systems connected to a single primary loop for the mercury Rankine system. The interface between the primary (reactor heat removal) loop and the secondary (power) loop is the boiler. Hot NaK from the reactor transfers heat to boiling mercury in a shell-and-tube boiler. One potential failure mode is a boiler leak, wherein the primary loop could become contaminated with mercury and cause permanent reactor shutdown (mercury is a strong neutron absorber). A potential solution would be placement of the boilers in parallel in the primary loop, with shutoff valves. However, this would require a sensor in order to detect very low levels of mercury contamination and zero-leak NaK valves, neither of which is considered to be within the near-term state of the art. Therefore, this solution was rejected and the boilers were placed in series; the result is a simpler system but one requiring a high-integrity boiler, such as a double-containment design.

This approach also led to selection of two power conversion systems connected to a single primary loop for the Brayton system and to eight power conversion modules and heat-rejection loops for the thermoelectric system. For the mercury Rankine system, substantial effort was also invested in analysis of the switchover problem which arises in the event of an unexpected failure of one of the power conversion systems. The normal startup procedure for the mercury Rankine system is fairly complex and occupies several hours. The principal tradeoff was between a "quick restart" in which an immediate startup of the standby system would be employed, with no change in reactor power level, and a shutdown and subsequent restart of the standby system. This is a very complex problem which would require a transient thermal and dynamic analysis for proper resolution. No definitive final conclusions were drawn. However, the following factors were considered important:

(1) Certain kinds of failure can cause a rapid loss of capability of removing heat from the reactor. Probably the worst case is a failure of the operating primary loop NaK pump or of the turboalternator which provides its drive power. Somewhat less severe would be loss of the mercury pump.

(2) In the event of such failures, the reactor must be protected from overheating. Some combination of auxiliary heat removal, quick response startup of the standby primary loop NaK pump (if required) on auxiliary power and reactor power reduction, will be necessary to provide adequate protection.

(3) It may be necessary to provide a reactor

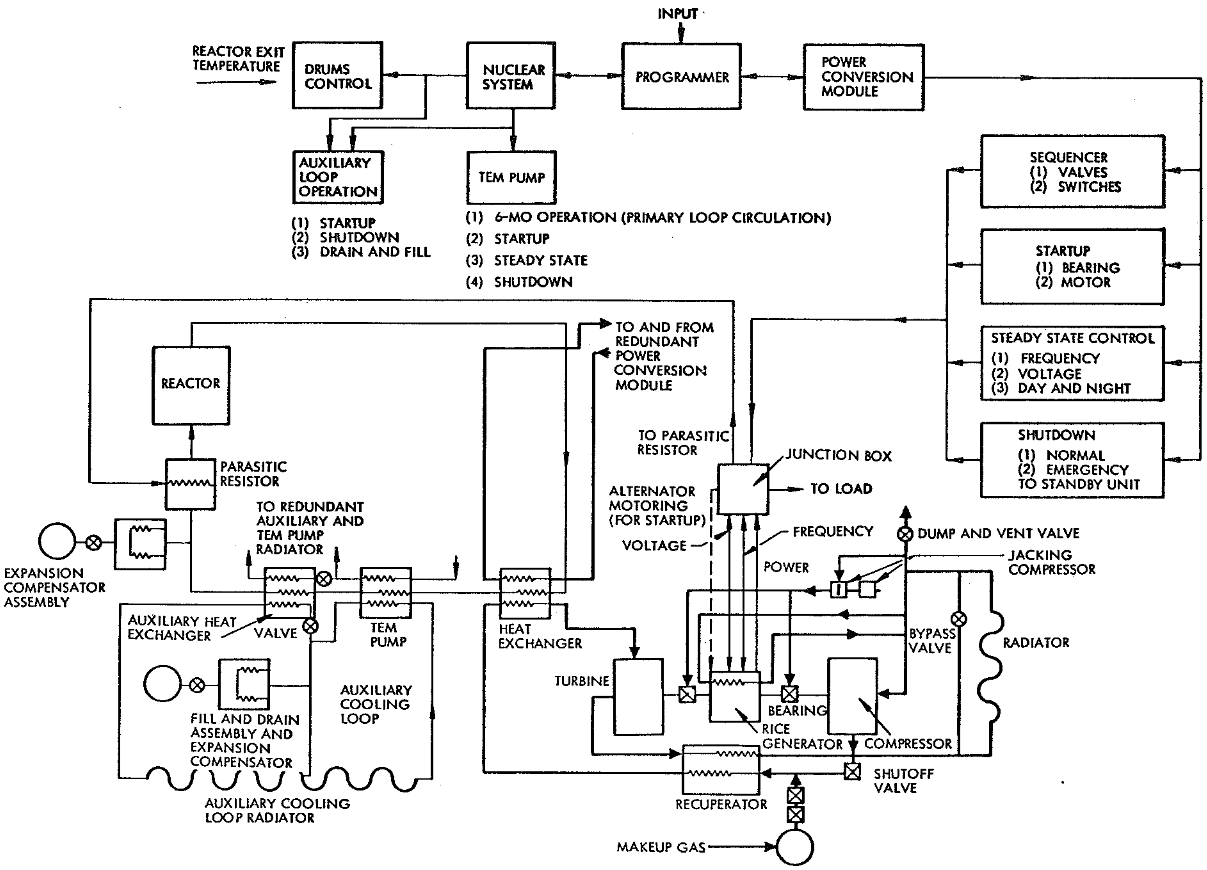


FIGURE 8.—SNAP-8 Brayton system flow diagram.

scram capability. However, this should be avoided (in favor of use of the normal control drum drive), if possible, since scram circuits and controls are responsible for a large proportion of inadvertent shutdowns of operating reactor systems.

(4) If restart is to be delayed, thermal protection for the heat-rejection and lube-coolant loops must be provided in the event that shutdown occurs during the lunar night.

The conclusion was reached early in the study that manned maintenance and repair of minor maintenance items would be mandatory for maximum mission success assurance. This requires provision of manned access to the system (after a 2-day cooldown period). Once manned access has been provided, the additional provisions required for major maintenance and repair are relatively minor. Major maintenance of repair implies replacement of a component, which would require opening a liquid or gas flow loop. Although assurance of success of such an operation is somewhat doubtful, it serves as a backup to a backup (redundancy of design) and is therefore justifiable. Some specific points are:

(1) Maintenance or repair involving opening the primary loop or removing any reactor shielding is considered unfeasible.

(2) Investigation of potential welding techniques indicated that semiautomatic techniques employing either TIG or EB welding attachments, which would be set up in position by the astronaut, could be developed with a high assurance of producing good welds.

(3) Maintenance and repair operations would be restricted to the lunar day. In the event of a shutdown during the lunar night, an attempt would be made to start the backup system and program a repair activity later.

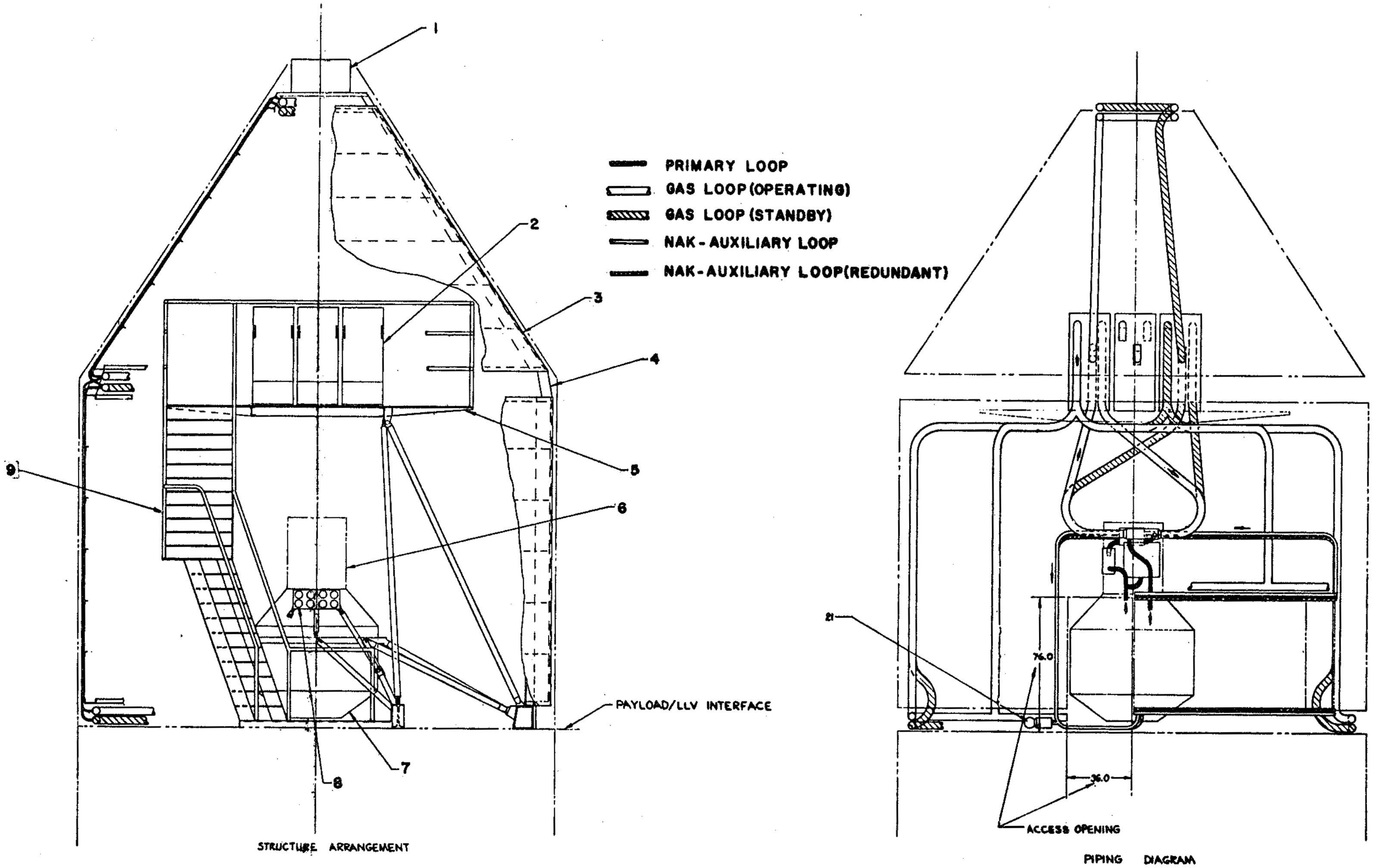


FIGURE 9.—Brayton cycle design.

1. T/M package (used during preoperational storage)
2. Power conversion module
3. Heat exchanger
4. Structure
5. Work platform
6. Primary loop
7. Reactor and shielding
8. Reactor control motor assembly
9. Stairway

TABLE 4.—*Powerplant Performance Summary*

Parameter	SNAP-8 Rankine	Compact converter T/E	Direct-radiating T/E	Brayton
Electric power at base, EOL[a], kW	33	20.4	20.0	25.6
Reactor thermal power, kW	404	541	907	182
Total system mass, lb	[b] 32 880	[c] 27 135	25 836	[d] 21 440
Shield mass, lb	14 000	13 900	13 900	12 500
Total radiator area, ft²	1390	1500	1527	1400
Reactor outlet temperature, °F	1330	1227	1300	1300
Mean radiator temperature (high-temperature radiator), °F	574	498	670	345
Overall thermal efficiency, EOL[a], percent	8.17	3.77	2.2	14.1
Power-to-mass ratio W/lb	1.0	0.75	0.775	1.10
Total radiator area, ft² per electrical kW	43.5	73.5	76.5	54.7
Separation distance, ft[e]	2500	3000	3750	2500

[a] EOL, end of life.
[b] Includes 3723 lb transported with lunar shelter.
[c] Includes 1820 lb transported with shelter.
[d] Includes 1240 lb transported with shelter.
[e] For buried reactor concepts the separation distance is about 900 ft.

(4) Because of the high degree of redundancy provided in the thermoelectric system, provisions were made only for manned access to electrical subsystems and reactor control drum drives; these would not require opening flow loops.

(5) In most cases repair of failed components would be impractical; these components would be discarded and replaced by spares. In no case would a liquid-metal component be taken into a lunar crew shelter.

(6) Time-line estimates indicate that two astronauts could replace a typical failed component, the task including opening the loop and welding in place the spare, in a 6-hour work shift. These time lines are, however, rather uncertain at present, since they have not been confirmed by task simulations.

Potential Modifications to SNAP-8

A number of modifications to the SNAP-8 Rankine cycle system, which are potentially desirable for the manned lunar surface application, were studied. Replacing both NaK pumps in the primary loop with thermoelectric-magnetic pumps or cooling all NaK pumps with NaK rather than with lube oil are desirable modifications. Further study is required in order to determine which of these two modifications is preferred.

OPERATIONAL INTERFACES

One of the most significant operational interfaces is that between the reactor power system and the lunar environment. The principal problem arises during the lunar night when the ambient temperature drops to roughly −250° F. If the powerplant is operating, the waste thermal energy produced suppresses this problem. For the Rankine and thermoelectric systems the heat-rejection temperature is sufficiently high so that changes in the ambient temperature have only a minor effect. As noted, the environmental day-night cycle poses a control problem for the Brayton system.

During storage or downtime periods the night environment (which lasts about 14 days) is cold enough to cause freezing of liquid metal heat transfer agents. Ordinary NaK freezes at 10° F; mercury at, −39° F; and a special NaK-cesium eutectic recently investigated for low-temperature service freezes at about −100° F. It is anticipated, on the basis of laboratory experience, that freezing and subsequent thawing of liquid metals in fluid systems could result in damage, leaks, or burst lines, and therefore such occurrences must be prevented. Several methods were studied; these are listed as follows:

(1) During storage or extended downtime for the Rankine system, liquid metal in the power and heat-rejection loops must be drained into thermally insulated storage vessels, where a few watts of radioisotope heat will prevent freezing.

(2) For all systems, the primary loop can be thermally insulated and maintained liquid by a small radioisotope heater (or by reactor afterheat following a power period). Thermal insulation around the reactor shield must be removed prior to initial startup by an astronaut since the shield is radiatively cooled.

(3) An articulated thermal shroud, remotely actuated, can protect the radiator for short night-down periods of a few hours to a day or so.

(4) The Brayton system concept employed a gas-cooled radiator so that only the primary loop contains liquid metals.

(5) The thermoelectric system could be operated at very low power with the radiator shroud in place during the storage period. This is possible because the liquid metals are circulated by thermoelectric pumps rather than by dynamic pumps (which require electric power) as in the Rankine system.

Crew participation during startup and operation of these systems would be minimal. Some initial installation tasks, such as laying the power cable from the plant to the base and emplacing the power conditioning and control electronics package, is required. These reactor systems have been designed for remote automatic startup and operation and there is no compelling reason for changing this method. Monitoring of key red-line parameters by the crew would be desirable, with override capability provided. Most system measurements would be telemetered directly to Earth.

Crew activities for maintenance and repair were previously discussed in terms of system design and reliability philosophy. Some familiarity with the system by the crew would be necessary. It is likely that most skills required for maintenance and repair would be of a general utility nature applicable to much of the mission equipment for lunar exploration. In the event of a failure, it seems likely that the best approach would be to rely heavily on consultation with appropriate specialists in mission control on Earth. Attempting to give crew members special training in coping with failures, the nature of which is not accurately predictable and the time of which would probably occur many months after the training period, is of dubious value at best.

A variety of methods of simplifying power system operations during preoperational storage, startup, shutdown, and switching to a redundant power conversion system were studied. Within the relatively small effort allotted, the results showed few methods that were significant. More detailed study will be required in order to determine whether the degree of simplification obtainable from potentially desirable modifications is significant.

The only modification considered absolutely essential is the use of a 4π shield around the reactor.

Growth

The SNAP–8 mercury Rankine system appears capable of substantial uprating, should requirements materialize for more power for lunar operations (e.g., processing of lunar resources). Radiator area increases slightly, from 1390 to 1450 ft^2, a size still within the nominal payload envelope. System mass is increased by about 4000 pounds. The power increase comes primarily from increased component efficiency and reductions of parasitic loads.

The other systems are limited with respect to radiator area. The payload envelope employed for this study is not a rigid limit, and more radiator area could be provided for integral system designs. The penalty for doing so is increased sensitivity of the launch vehicle to ascent wind loads and corresponding reductions in launch probability (probably not significant for this mission). The largest payload envelope which has been studied in detail for the standard Saturn V is the Voyager shroud, which was analyzed in connection with Voyager-Saturn V studies. This envelope would increase available radiator area by roughly 1000 ft^2. For the compact converter thermoelectric system, net power could be increased to about 30 kWe, with reactor power of 870 kilowatts and total system mass of 36 000 pounds. For the Brayton system, increased radiator area could be used in order to improve cycle efficiency at constant reactor power and thus provide about 34 kWe; or the system could be scaled up in proportion to the increased radiator area, thereby providing about 45 kWe at a reactor power of 300 kilowatts. System mass does not appear to be a problem, but detailed estimates were not made.

CONCLUDING REMARKS

A related type of nuclear power, radioisotopes, has not been discussed in the present paper. Isotope power (about 70 watts electric) will be used on the Moon to power the Apollo lunar science experiment package which will be emplaced on the Moon by astronauts during Apollo missions. However, isotope power is not likely to be used at the 20-to-30-kWe level because of limitations in the available supply. At this power level, reactor power has another significant advantage over isotope power; the nuclear fuel in a reactor is essentially nonradioactive prior to startup. Isotope heat sources, although much easier to shield than is a reactor, are highly radioactive and present launch hazards. These hazards are quite manageable at power levels in use today but become more difficult at high power.

There seems little doubt that reactor power systems based on technology under development today could be developed for practical operation as the electric generating plant of a lunar outpost. Packaged reactor power is used today in remote regions such as the Antarctic. The expense of conducting lunar operations will place a great premium on powerplant reliability and lifetime. A year of operational life is about the minimum usable, and 3 to 5 years would be desirable. The lunar crew can contribute to this goal by maintenance and repair activities, but a mature technology base is required.

The following conclusions can be derived from this study:

(1) Reactor power is the preferred energy source for lunar exploration missions wherein extended (more than 6-month) operations on the lunar surface will require power levels of 15 kWe or greater.

(2) Missions can be designed so that failure of the power system will not cause loss of crews, but termination of the missions after such failure is implied. The cost of such missions will place a great premium on assurance of power system operation for its design life. This assurance can best be provided by combination of technology maturity, redundancy, and provision for manned maintenance and repair.

(3) Technology presently under development—the SNAP–8 reactor and any of the three power conversion systems analyzed—is capable of meeting presently visualized mission requirements for lunar surface operations.

(4) It would be premature to make a choice now or in the near future as to the preferred power conversion concept. The thermoelectric concept at present appears to offer the greatest assurance of success, but this is partly due to its comparatively greater technological maturity. The thermoelectric system's greatest weakness is its relative inability to provide growth to higher power levels. In this regard, the Rankine system excels. Although it is not anticipated at present that power levels much in excess of 25 kWe will be demanded by lunar surface operations, some missions analysts (but not the authors of the present paper) are enthusiastic about the eventual potential of lunar resource utilization. If they are proven correct, power demands in the neighborhood of 100 kWe will occur.

(5) In the case of the SNAP–8 mercury Rankine system, several modifications were identified (some only tentatively) which would improve mission success assurance. Notable among these was a double-containment boiler. The use of thermoelectric-magnetic TEM pumps in the primary loop also appears promising.

(6) Design concepts employing deployed radiators, or off loading of the system with attendant manned surface operations burdens, do not provide performance gains commensurate with their operational problems and degradation of mission success assurance. Integral designs are therefore strongly favored.

This last conclusion is somewhat dependent upon a ground rule of this study, that shielding advantage of local lunar terrain was not to be available. In the writers' opinion this is a valid ground rule; however, it is a disputable point. If the powerplant were to be located in a local depression (i.e., small crater), radiation dose to the base crew and perhaps shield mass could be reduced. Off loading of an integral system (this does not imply construction and assembly as did the buried-reactor off-loaded system) would make possible the use of a smaller depression than otherwise and might be advantageous. Note, however, that: (*a*) this implies an off-loading system capable of handling the entire powerplant mass and (*b*) use of a depression will worsen the daytime thermal environment experienced by the radiators.

REFERENCES

1. ANON.: Design Requirements for Reactor Power Systems for Lunar Exploration. Final Rept., Contract NAS8-20377, Lockheed Missiles and Space Co., 1967.
2. GYLFE, J. D.: Reactor and Shield Subsystems for MORL and Lunar Base Powerplants. Paper presented at Intersociety Energy Conversion and Engineering Conf. (Miami, Fla.), Aug. 13–17, 1967.
3. ANON.: Initial Concept of Lunar Exploration Systems for Apollo. NASA CR-39, 1964.
4. ANON.: NASA 1965 Summer Conference on Lunar Exploration and Science. NASA SP-88, 1965.
5. ANON.: Scientific Mission Support for Extended Lunar Exploration. Contract NAS8-20258, North Am. Aviation, Inc., 1966.
6. PAUL, DAVID, 3RD; SHAPLAND, D. J.; AND McLAUGHLIN, J. F.: Synthesis of an Evolutionary Lunar Exploration Plan. AIAA Paper No. 67-865.
7. JOHNSON, R. W., ED.: Lunar Exploration. (Collection of papers.) Astronautica Acta, vol. 12, nos. 5 and 6, 1966.
8. ANON.: Engineering Study of Nuclear Power Plant Lunar Exploration Systems for Apollo. Office of the Chief of Engineers, Contract DA49-129-ENG(NASA)-1A, 1964.
9. ANON.: Design Requirements for Reactor Power Systems for Manned Earth Orbital Applications. Contract NAS1-5547, McDonnell-Douglas, 1966.
10. ANON.: Human Factors and Environmental Control—Life Support Systems, LESA. Contract NAS8-11447, AiResearch Mfg. Div., Garrett Corp., 1964.
11. ANON.: LSSM for AAP. Contract NAS8-20378, Aerospace Systems Div., Bendix Corp., 1967.
12. ANON.: Lunar Surface Mobility Systems Comparison and Evolution (MOBEV). Contract NAS8-20334, Aerospace Systems Div., Bendix Corp., 1966.
13. ANON.: Design Criteria Reference Data Handbook for Lunar Exploration Systems. Vol. I, General Criteria. NASA/MSFC.
14. ANON.: The Near-Earth Meteoroid Environment. NASA TN D-3717, 1966.

RODNEY W. JOHNSON
Office of Manned Space Flight, NASA
Washington, D.C.

A Planning Logic for Exploration and Utilization of the Moon

The present paper presents a methodology for the design of a lunar exploration program. The logic is based upon (1) the recognition of the scientific objectives of lunar exploration as presently identified and (2) the critical and variable staytime requirements for lunar exploration missions. Systems ranging from orbital space flights, limited surface staytime exploration modes, and extended mobility missions to temporary stations and bases are included in the development of the analysis.

The technique is based upon the assumption that, although the program planner cannot quantify either the scientific objectives or the output of a lunar exploration program, it is nonetheless possible to employ quasianalytical techniques to derive semiclosed-form solutions to a mathematical model of a lunar exploration program. This is done by breaking down the scientific objectives and total scientific product of a lunar exploration program into percentages assigned to various exploration systems such as orbital, mobile, and fixed-base systems. Each system is designed to produce a given, assigned output of scientific product for each of the missions making up the flight program. In this manner a payload requirement (weight, volume, or power) can be developed for each mission within each system, and the experiment (and, hence, instrument) requirements can be identified as a function of the scientific questions requiring answers during the exploration program.

By appropriate manipulation of the various parameters making up the model, a series of mathematical expressions are derived which present the elements of the exploration program in a simplified analytical relationship. These expressions are plotted in various forms to depict the significance and interdependence of the variables. Some of the significant results and conclusions of the paper are:

(1) A semianalytical mathematical model of a lunar exploration program can be derived if some rather bold assumptions are made.

(2) The mathematical model can be a useful tool to the program planner in structuring and analyzing various lunar exploration systems designed to accomplish certain fixed scientific objectives.

(3) Problem areas in the development of long-range plans for total lunar exploration can be identified for management using this tool.

(4) Technology development requirements can be identified in broad terms in advance of random detailed studies of various systems and subsystem elements.

The paper concludes that if sophisticated management and organizational methods and techniques are vital to the success of space operations, they are also equally vital to successful planning for space systems and operations. Thus the approach described can be very useful in long-range lunar planning activities.

INTRODUCTION

Perhaps as a consequence of U.S. continued success in space, increased interest in lunar exploration and exploitation is developing and is being stimulated anew by the impending project Apollo, a manned landing on the Moon. Thoughtful persons, Government agencies, and industrial organizations are looking toward the Moon as an object of potentially large opportunity for mankind, that is, an opportunity for improving man's understanding of himself, his Earth-Moon environment, and the universe in general. Thus the manned Apollo landing will not mark the conclusion of another space program, but rather will mark the beginning of a period in which the full potential of the Apollo system to support lunar exploration will be realized.

Interest in lunar exploration, including means and scientific results, leads inevitably to a related interest in lunar bases even though the need and justification for lunar bases is not readily apparent. Space exploration is an expensive enterprise, and the benefits, though real, are not entirely tangible or visible. The most successful space programs are those that are motivated by a demonstrated scientific need within technical and economic constraints.

Such an imperative has not yet been firmly established for lunar bases, and though considered opinion reflects an intuitive conclusion that bases on the Moon will be a justifiable and inevitable end product of our Apollo capability, a reasonable logic for such bases has been slow in developing. The fundamental question, of course, is: How can one determine in advance of the first manned landing if a base will ultimately be necessary or even desirable later in the exploration program, when definitive scientific results upon which to support such a decision are lacking? At the same time, the planner realizes that long lead-times are necessary in order to develop mission and support equipment for a base and that those planning and design factors evolving as logical consequences of the environment should be incorporated into all stages of planning and execution of the project.

This paper is addressed to the problem of planning lunar exploration missions and programs up to and including the establishment of lunar bases. For the analysis presented here, an arbitrary time period of 20 years' active life has been chosen. Other major assumptions are presented in the paper as need for them develops. The planning problem is composed of a number of elements which interact with one another. A somewhat incomplete expression of this problem can be phrased as follows: How should a lunar exploration program comprising a number of discrete systems, each of which must accomplish a finite but indefinite amount of "science," be developed? How long should the system continue to be used, how many missions should be flown within it, and when should it be terminated or upgraded to one having greater capability? Articulated in another way, we want to maximize the efficiency of each system in the proposed program and yet anticipate the required efficiency of each system prior to obtaining a good understanding of what we want to do on the Moon and what the products of our exploratory efforts might be.

Answers to all these questions cannot be presented in this short paper, but it is intended that some insight will be provided into the type, nature, and magnitude of the problems constituting the planning process which will be of significant value during future planning and efforts, and which, if left unanswered, could result in losses of efficiency and scientific return as well as national prestige and resources.

The concepts presented in several of the illustrations were developed by the author during his association with the Missile and Space Division, General Electric Co. As such, permission to use these illustrations is gratefully acknowledged. The reader should understand that they do not represent official or even necessarily current thinking of the National Aeronautics and Space Administration and are used only as representative concepts to support the discussion herein.

WHAT IS LUNAR EXPLORATION?

Exploration can be defined in several ways, though a commonly accepted definition is the survey of new areas or regions, usually previously unexplored, with a desire to determine the environment, map or survey the terrain, and establish references for later missions or surveys. Exploration of the Antarctic regions is a good terrestrial example of this procedure. Lunar exploration differs from terrestrial exploration, however, in that visual and photographic orbital surveys will have been made to some degree prior to surface exploration. Furthermore, sophisticated scientific instruments will be used to supplement visual and photographic data and sample acquisition on the Moon. Early terrestrial explorers were limited by the scientific instruments then available. Expressed in precise terms, orbital and remote sensor surveys of the surface must be included in the term "exploration" when it is applied to the lunar case; thus, manned exploration of the lunar surface will produce fewer of the unexpected elements which marked terrestrial exploration.

Exploration missions involve scientific objectives which can be interpreted as:

(1) Broad, involving
  (*a*) Broad areas
  (*b*) Broad phenomena
(2) Limited, involving
  (*a*) Limited areas
  (*b*) Selected phenomena
(3) Restricted, involving
  (*a*) Specific areas
  (*b*) Specific phenomena

It is emphasized that exploration seeks to extend man's knowledge, primarily in the scientific disciplines. Thus, in order to accomplish exploration, the mission objectives should be directed toward rather well-defined scientific goals involving the testing of hypotheses, specific experiments supporting specific phenomena, and some general experiments involving interrelated phenomena or processes. Certainly one could assemble a polyglot of scientific experiments, totally unrelated and uncorrelated to any scientific goal, but such a matrix would not constitute a balanced and thoughtful program of exploration.

Science is not the only imperative for lunar exploration, however, since space exploration, in general, carries and supports other direct and indirect benefits. It is important to consider the relative importance of science in the total lunar exploration program and to understand what the other elements supporting the program and benefiting from it might be. To the degree that it is possible to define the total benefits deriving from lunar programs, it will be possible to consider them in the total context of the program and thus include them in the planning effort, if not directly at least to some degree indirectly.

The major measures of lunar program effectiveness can be considered to be its contribution to or improvement in—

(1) Scientific product
(2) Military posture
(3) Economic value
(4) Technology development
(5) National prestige

Detailed discussion of the relevance of these factors can be found in appropriate literature; for the immediate purposes it is sufficient to inquire into the question of how these factors can be quantized, and, particularly, to inquire into the magnitude of the scientific product. Informal surveys within NASA indicate that the contributions to total lunar program effectiveness by each of the above factors are approximately as given in table 1. Though it is obvious that an individual may disagree by at least ±5 percent with these indices of effectiveness, they can be used to measure system effectiveness in planning analyses.

TABLE 1.—*Relative Contributions to Program Effectiveness*

Factor	Percent contribution
Scientific product	45
Military posture	15
Economic value	10
Technology development	10
National prestige	20

We have established that scientific goals motivate lunar exploration; therefore, we can call this body of knowledge that we seek Q. The quantity Q can be considered to comprise scientific inquiry into the geologic processes on the Moon, a deeper understanding of the Earth-Moon system, and a look at questions involving the solar system or universe as a whole from the surface of the Moon. Further, since Q is defined some years in advance of the actual missions being accomplished, in particular surface missions, it can be expected that new information regarding the Moon will be derived from unmanned probes and spacecraft during this period. As a result new questions will be posed, and these will constitute an additional increment of inquiry which can be designated Δ.

For the purposes of this analysis, Q is considered to be the 15 questions posed at Woods

Hole plus the 10 additional questions posed in the MIMOSA study.[1] Since Q is not constant with time, dQ is considered to be the increase in Q with time; it should be recognized that the rate of change is probably not linear.

In the same manner, Δ reflects the scientific questions involved in disciplines other than those that are predominantly geosciences and includes astronomy, the biosciences, and physics. Again, dΔ is defined as the time rate of change of increase in Δ; dΔ is probably linear and together with Δ reflects the emphasis resulting primarily from the manned components of the lunar program.

Similarly, α and dα are defined as other interdisciplinary questions and research which are directed toward science performed primarily by the unmanned components of the space program.

Lastly, a term R is introduced which reflects the emphasis of lunar resources in the total program and the contribution made by lunar resources to both mission operations and scientific knowledge.

For our purposes, then, we can say that lunar exploration must produce a body of knowledge k as the scientific product of the program equal to the sum of the above subelements:

$$k=Q+\mathrm{d}Q+\Delta+\mathrm{d}\Delta+\alpha+\mathrm{d}\alpha+R$$

The total lunar exploration program must in turn be supported by (1) scientific equipment and (2) mission equipment. These equipments, of course, require transportation to the Moon and involve (3) logistic systems which are also closely related to and considered a part of the total program. The sum of (1), (2), and (3) defines a general lunar exploration system.

If the foregoing is a valid assumption, then we can also assume that the accomplishment of the lunar exploration program could involve a number of rather distinct phases, each reflecting a different system or combination of mission equipments. We must recognize at the same time that the equipments involved in each system will be composed of new developments, improved versions of earlier models, and possibly hybrid combinations.

HOW CAN A LUNAR PROGRAM BE OPTIMIZED?

The analysis presented in this paper assumes a planning period of 20 years during which time the maximum number of systems which could be developed and flown is taken as five. The systems are designated by the letters L, M, N, O, and P, and each system will be designed to contribute to the total scientific product k. Figure 1 shows how these system alternatives could relate to each other in an ideal program, though it is recognized in the diagram that considerable variation and latitude in system cost, staytime, scientific scope, and time duration of use could and probably will exist.

From the foregoing variables, one can designate a simple lunar exploration program p equal to the sum of all the component systems with each performing (or contributing) a certain percent of k:

$$p=L+M+N+O+P$$

Since the components of k (Q, dQ, Δ, etc.) vary with time, k also varies and L, M, N, O, and P can be defined as operators acting on k with each extracting a certain percent of k. Thus, for time t,

$$\begin{aligned} Lk_L(t_1)&=v(t_1)\\ Mk_M(t_2)&=w(t_2)\\ Nk_N(t_3)&=x(t_3)\\ Ok_O(t_4)&=y(t_4)\\ Pk_P(t_5)&=z(t_5) \end{aligned}$$

where $t_1=t_2\leqq t_3\leqq t_4\leqq t_5$ and v, w, x, y, and z are values strongly dependent upon the scientific and mission equipment payload capability of each system. Required in this simple case are

[1] The 15 Basic Science Questions referred to in this paper are those enunciated by the Space Science Board, National Academy of Sciences, which convened a summer study at Woods Hole during June and July 1965. Reference 1 is the report of that study and contains the 15 questions. During the conduct of a NASA study entitled "Mission Modes and System Analysis for Lunar Exploration" by the Lockheed Missiles & Space Co. (ref. 2), an additional 10 scientific questions were posed. Together, these 25 questions have been expressed as Q in this paper.

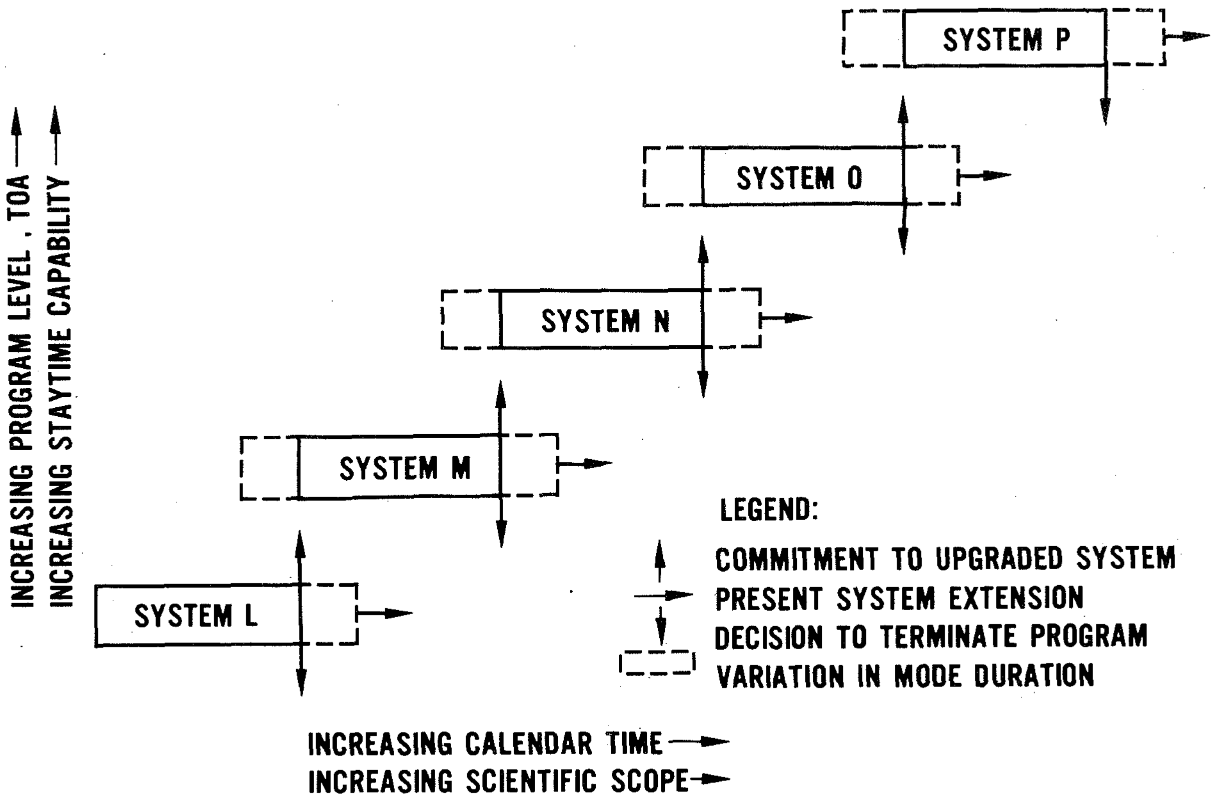


FIGURE 1.—Lunar space exploration mode alternatives.

definition of such considerations as total number of missions in each system, number of missions per year, and the mix of Q and Δ, α, and so on, in each mission.

The central problem in an analysis of this kind is to determine how the various systems should (or could) be individually optimized in terms of cost benefits (effectiveness) so that the total program, whether reflecting a period of 10, 20, or more years' duration, can be similarly optimized with respect to cost benefits. As table 1 demonstrates, the scientific product constitutes close to 50 percent of the program contribution, with the other factors making up the remaining 50 percent. The only valid approach which can be taken in advance of the manned landing is to assume that by optimizing the constituent systems and hence the total lunar program for the benefit of science, the other factors (technology, prestige, economic, and military) will also be benefited to an unknown degree which will be large, though quite probably less than optimum.

By adopting this premise and stressing its essentially intuitive justification, it is possible to design a program which can be used to identify the parameters for the spacecraft, mission, payload, and landing site which bear on and influence the success or failure of the program and which serve to provide insight into the possible payload composition, including experiment and instrument requirements. Figure 1 indicates that each system should reflect an increasing level of scientific scope and staytime capability as the program progresses. These requirements will, in turn, demand increasing program budgetary levels.

In order to permit time structuring of the missions and payloads in the program, it is necessary to establish a relationship between k and the major scientific disciplines of which it is comprised. This was done by an informal survey within NASA from which table 2 was derived. By relating the time sequence of the ordered disciplines to the components comprising k, it is possible to establish a framework upon which to base a program design which includes the percent of k which must be satisfied by each system in the program and the number of missions (flights) necessary to produce the total k for each system. This has been done; the results are shown in table 3.

In this idealized analysis, several assumptions are again apparent. One, the percent k contributed by each system becomes significantly larger as each system is upgraded to a more sophisticated level of capability; and, second, the payload carried per mission is capable of extracting an increasingly larger percent of k. This approach is consistent with the evolutionary growth expected in the spacecraft and launch systems during the lifetime of the program.

Studies directed toward the science to be performed on the Moon from which the definition of the elements composing k, the scientific product, were derived show that the trends indicated by table 2 are consistent with the probable course and scope of lunar science and exploration and can be used to define the systems necessary to support the scientific missions. Candidate-system concepts supporting each system are presented in the subsequent discussion.

A SYSTEM *L* POSIT

System L is considered to be the Apollo and unmanned spacecraft systems which perform missions whose scientific capabilities are primarily directed toward Q, the basic 15 Woods

TABLE 2.—*Ordered Lunar Scientific Disciplines*

Scientific discipline	Subjective—		Numerical—	
	Value	Priority [a]	Value	Priority
Astronomy	Medium-low	Late	3	3
Atmospheric physics	Medium-low	Early	2	1
Bioscience	Medium-high	Early-middle	2	2
Particles and fields	Medium	Middle-late	3	3
Geology	Very high	Early-middle	1	1
Geochemistry	Very high	Early	1	1
Geodesy	Medium-high	Early	2	2
Geophysics	Very high	Early-middle	1	1

[a] "Priority" refers to time frame in exploration period in which major accomplishments could be anticipated.

TABLE 3.—*Idealized Lunar Program Analysis*

Years, cumulative	4	8	12	16	20
Years, incremental	4	4	4	4	4
System	L	M	N	O	P
System description	Apollo and unmanned	SAA	Mobile exploration	Temporary station	Semipermanent base
Percent k	10	12	20	25	33
Cumulative k	10	22	42	67	100
Payload per mission, percent k	2	3	5	5	11
Number of missions	5	4	4	5	3

Hole questions and the MIMOSA questions. Here, the amount of k capable of being produced by each mission is small (2 percent) as shown in table 3. If a total of five missions of Apollo or Apollo equivalence in the case of unmanned or manned orbiter flights is assumed, it can be expected that sample return, remote sensing, and imaging experiments will dominate the payload composition. Staytimes in this case are short, on the order of a few hours for Apollo to a few days for manned orbiter and unmanned systems.

A SYSTEM *M* POSIT

System M can be conceived as a logical extension of the Apollo system whose elements are composed of Apollo and Apollo derivatives. Its mission is envisioned as comprising broad surveys and exploration with time-independent experiments over widely separated areas. The percentage of Q covered in this mission is probably quite large, Δ is probably rather small, and the span of time over which the useful effective lifetime of M is extended is also as long as possible, probably several years or more. The studies conducted with M are directed toward an understanding of the whole body of the Moon and involve such disciplines as geology, geophysics, and geochemistry. Lunar staytimes are also probably quite short, on the order of a few days to a few weeks.

Figure 2 shows an artist's concept of such a system, which might be described as an early lunar pair. Studies show that two Saturn V launches might be required for this system; one launch would land an unmanned shelter carried by the LM truck and would be followed by another launch carrying an Apollo LM taxi which lands the astronauts on the lunar surface. Mission equipments would include a drill capable of drilling to depths of 100 feet and recovering cores for return to Earth. Also carried on the LM taxi would be a small one-man roving vehicle, currently under study, known as a local scientific survey module (LSSM). This roving vehicle would operate within a range of perhaps 5 miles beyond the initial landing point. It will be noted that the vehicle would not contain either environmental control or life-support systems. Portable backpacks are the sole provision for life support with this mobility mode.

Significant contributions to Q can be obtained with this system. These include advancing our understanding of the structure and internal composition of the Moon, learning more of the internal energy regime of the Moon, and studies involving the composition of the lunar surface and processes which act to alter its shape and composition. Missions conducted with this system would involve the placement of fixed instruments at specific sites where time-dependent data are desired and can be obtained by fully automatic instruments. These data might include measurements of heat flow, seismism, gravity, and atmospheric phenomena.

A SYSTEM *N* POSIT

Planning for system N is not as simple as for M, since the mission objectives and scientific studies which are required for this system are constrained by the accomplishments of M in terms of the amount of Q remaining as well as probable increased requirements of Δ on the system.

The mission objectives involve greater areal coverage and are directed toward both selected areas and rather selective phenomena for investigation. As a result, it is not unrealistic to assume that this system will involve a large mix of new developments and second-generation mission equipments. The scientific phenomena of interest during this period, visualized to extend over several years with one or more missions per year, are more time dependent and involve studies in disciplines in addition to the geosciences. These might include the biosciences and supporting studies in astronomy, for instance.

Conceptual studies indicate that this system might also involve two launches of a Saturn V booster per mission. One launch would land an unmanned mobile laboratory and would be followed by an LM taxi carrying two and possibly three astronauts to the lunar surface as shown in figure 3. An additional shelter developed for system M might be available as well in the event that system N spacecraft are landed

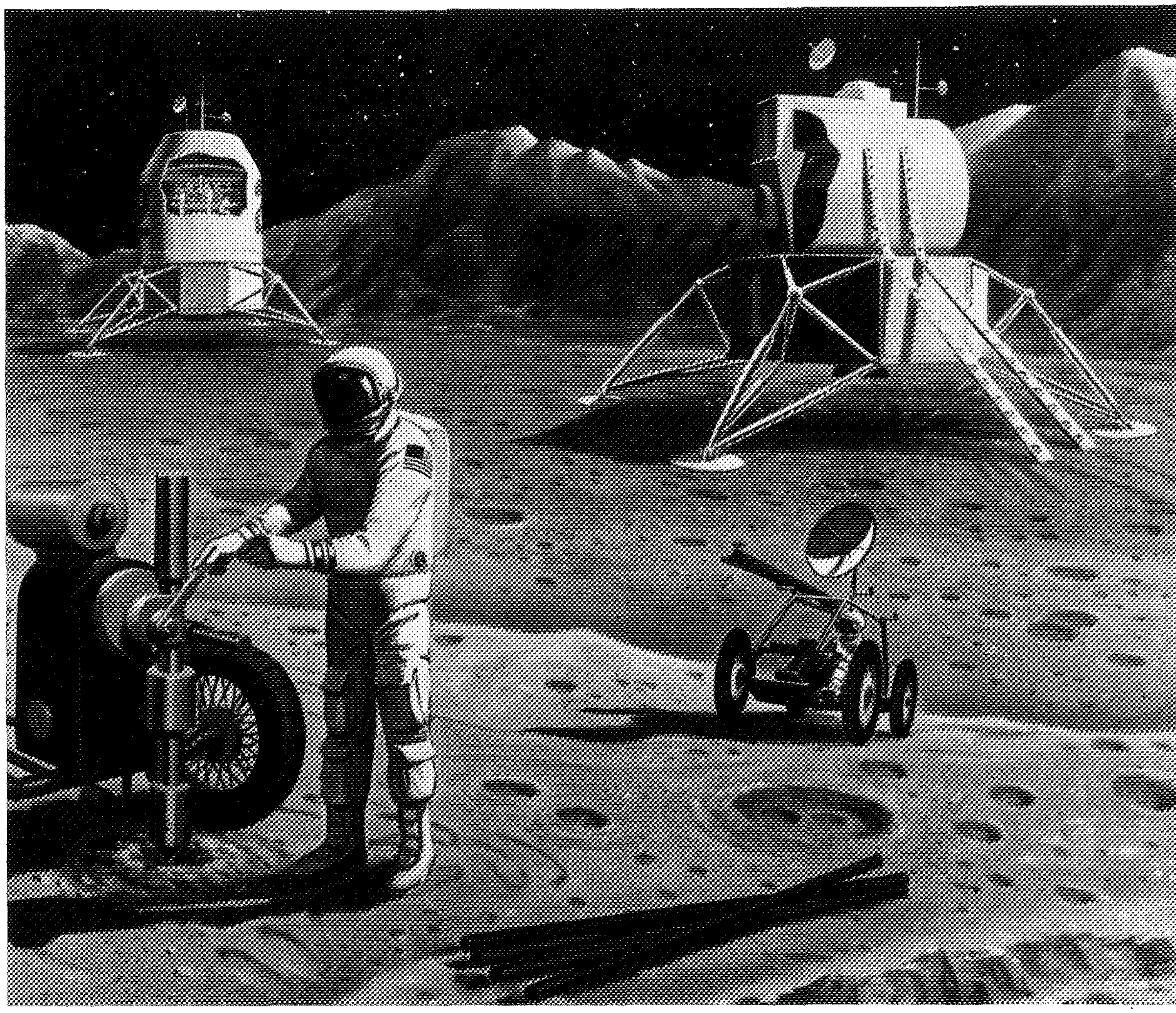


FIGURE 2.—Artist's concept of system *M*.

near a site explored briefly during the lifetime of system *M*. In this case we might be thinking in terms of staytimes of several weeks to several months, during which the mobile laboratory would make extended traverses over the lunar surface. In addition to conducting scientific studies and emplacing scientific equipment, the team would also conduct engineering experiments *in situ* to determine the requirements for more permanent base facilities and to obtain data upon which to base the design of these facilities.

During the lifetime of system *N*, one could reasonably expect that requirements for astronomy and biomedical research would be identified, as would possible lunar resources, and applied science and engineering research needs.

A SYSTEM *O* POSIT

By the time the requirements for system *O* have been identified, the major early requirements involved in *Q* will have been largely satisfied and a rather comprehensive understanding of the Moon, the relationship of the Earth-Moon system, and the history and evolutionary events in the Moon's progression to its present form will have been obtained. Thus the major scientific objectives of this

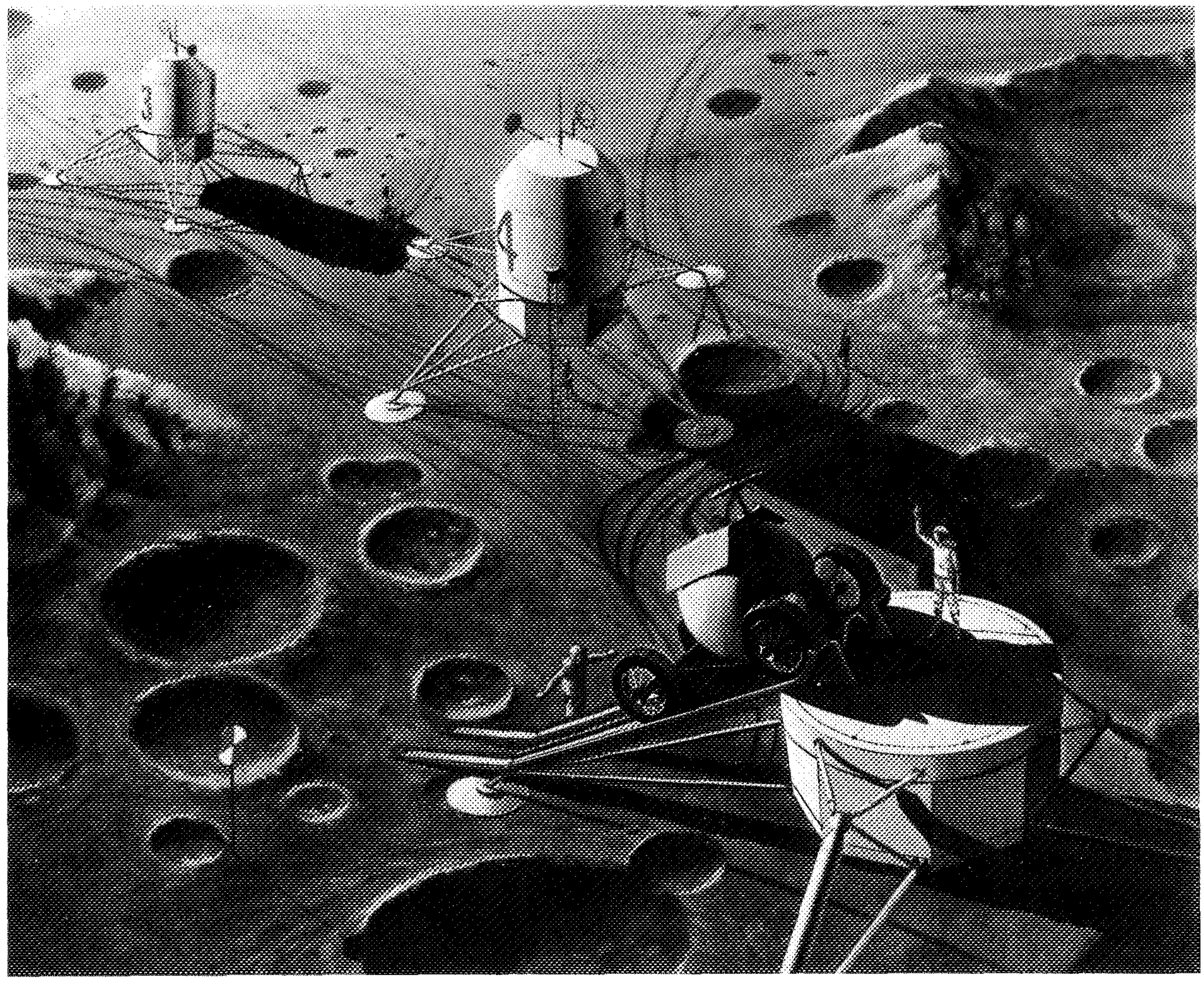


FIGURE 3.—Artist's concept of system N.

system are associated with more restricted areas involving specific sites and specific phenomena which are associated with very time-dependent studies. The scientific experimentation includes a large remaining percentage of Q and a larger percentage of Δ and $d\Delta$ which include small percentages of astronomy and biomedical experiments. In addition, lunar resources R first investigated by system N are given increasing emphasis. These requirements derive from the conclusions reached from k up to this time. Even though systems M and N could be extended and uprated, they are inefficient and inadequate to support the expanded scientific program at this point. As a result, the development of a system composed entirely of newly developed components is needed.

A concept for this system is shown in figure 4. In the left background is a shelter-laboratory for four to six men which has been landed directly on the lunar surface from Earth, and was followed by an improved personnel delivery system lander which transported the astronauts to the site. The manned delivery system might be either direct flight or lunar orbit rendezvous (LOR) depending upon the results of studies currently underway. Later cargo trips have provided additional scientific and mission equipment and an expandable shelter

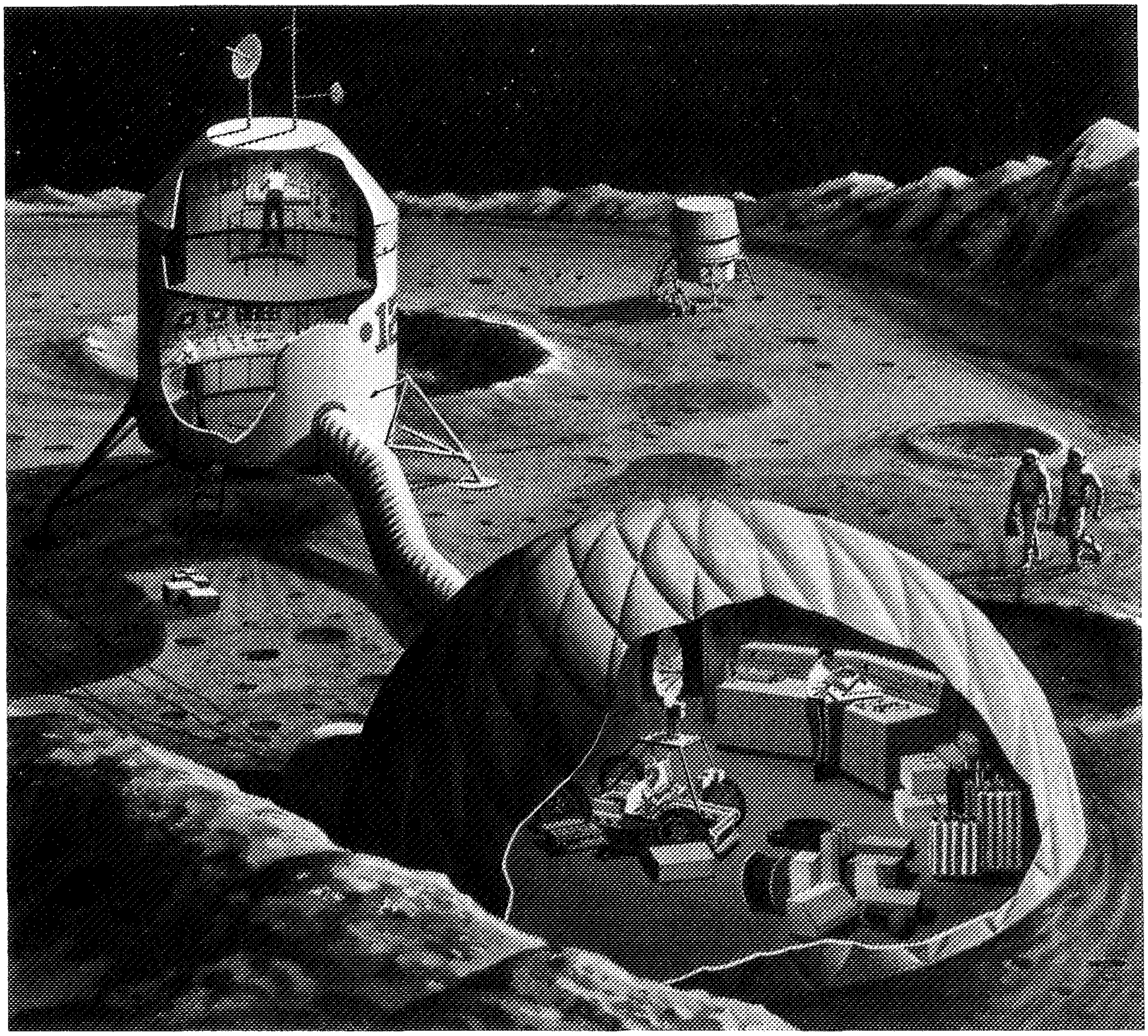


FIGURE 4.—Artist's concept of system *O*.

and maintenance module. Since preceding missions have established that the development of a lunar-base facility at this location is an economically and scientifically worthwhile project, eventual buildup to a large base facility has begun. Stations of this type are envisioned to become practical after development of an efficient unmanned method of landing large payloads directly on the surface. This is considered to be an elementary form of a lunar base. As can be seen, requirements have dictated that it be developed. These requirements are strongly dependent upon man's participation in the effective accomplishment of the mission tasks. Further, these tasks during this phase are strongly time dependent, are varied in scope and complexity, and are relatively immune to preprograming. A fixed base at this site is indicated where man can exploit his advantage on the Moon.

A SYSTEM *P* POSIT

As the requirements for surface staytimes promulgated by increasing emphasis on Δ (astronomy, biosciences, physics) and dΔ in-

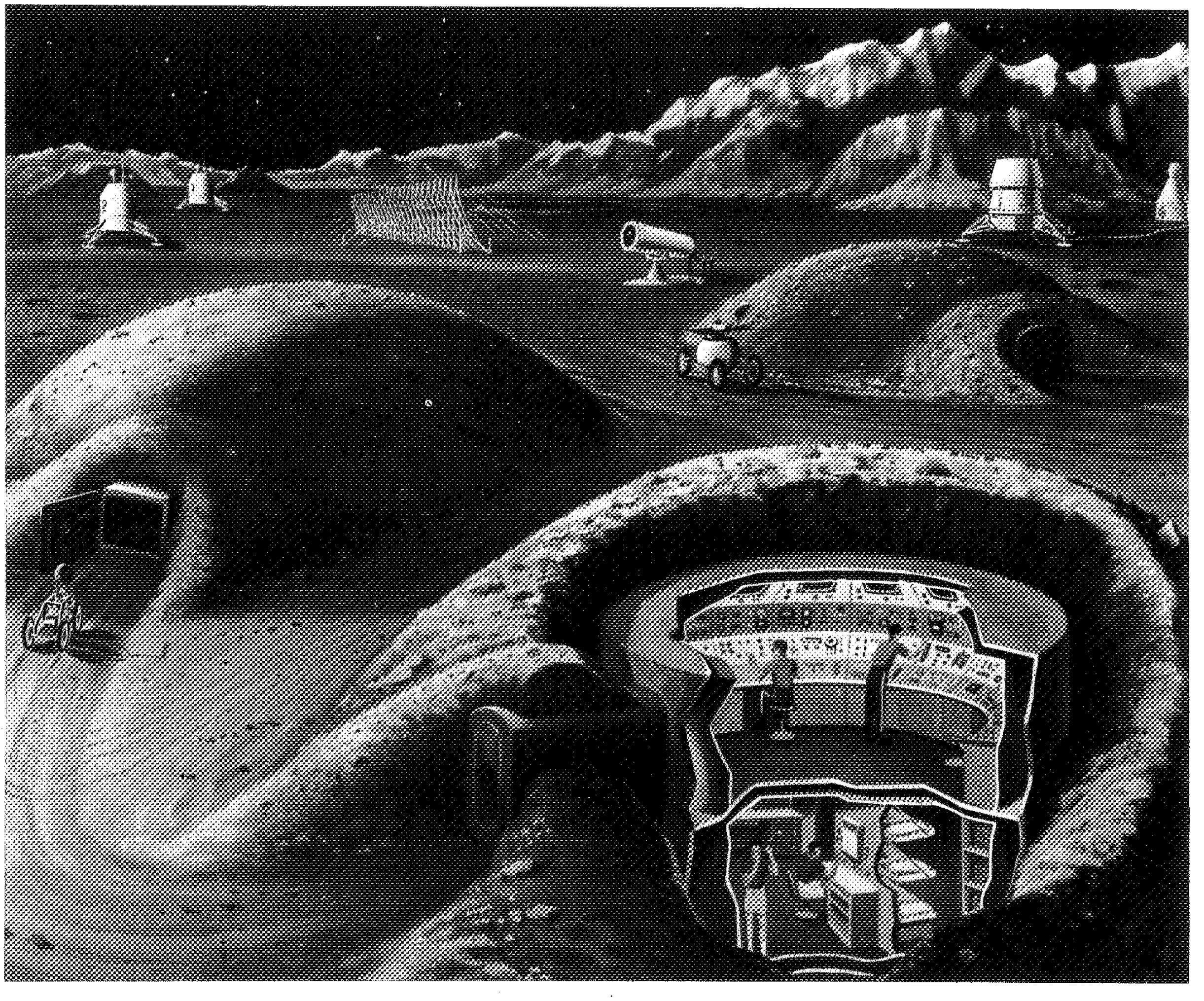


FIGURE 5.—Artist's concept of system *P*.

crease, long-range planning must include studies of concepts similar to that shown in figure 5. This large semipermanent base can accommodate 12 men for periods of a year or more. Furthermore, requirements for exploitation of lunar resources may by this time have been identified, with a parallel impact on increased surface operations capability, staytimes, and manpower levels. At the present time it is difficult to anticipate the evolutionary trend of spacecraft systems which might support a lunar base or to anticipate to what degree there might be new or modified versions of precursor systems.

MISSION PAYLOAD COMPOSITION

As pointed out earlier in this paper, the final step in the analysis is to determine, in terms of the factors making up k, the scientific product, the payload composition for each mission which supports systems L, M, N, O, and P. For the purposes of this analysis, which is an example only, the subdivision of these factors shown in table 4 has been adopted.

If the assumed composition of k is known, the individual payload composition can be defined. In the example used in this paper, this was done on an iterative basis by using a simple proce-

TABLE 4.—*Percentage Composition of* k

Component	Percent composition
Q	46
dQ	6
Δ	22
dΔ	7
α	7
dα	2
R	10

dure. The procedure was based on the expectation that, within each system, the early science would extend and expand that which had preceded it and that science conducted toward the planned useful end of the same system would support more sophisticated systems and science to follow. From a total program standpoint, the priorities of table 2 were followed.

The results are displayed in table 5, where the components of k making up each mission are presented. Note the attempt to introduce more complex science (in terms of k components) during the last phases of each system and the emphasis away from Q late in the program. These expected results are based on the indicated assumptions for the analysis. Having these data at hand makes it possible to plot a graph of the scientific accomplishment of each system in terms of percent of k and its components. Such a graph is shown in figure 6. Notice the emphasis on Q and dQ, the basic scientific questions. This graph demonstrates in a visual way the original premise of this paper, namely, that the logic for the ultimate system, a lunar base (system P), appears at this time to be related solely to the needs of scientific mission objectives which cannot be met by any other system. From a solely scientific view, a lunar base is a requirement only if it is determined

TABLE 5.—*Mission Science Payload Composition*

Variable	System																				
	L					*M*				*N*				*O*					*P*		
Components of k:																					
Q	8					8				10				12					8		
dQ	---					---				2				3					1		
Δ	1					2				3				4					12		
dΔ	---					---				1				2					4		
α	1					2				2				1					1		
dα	---					---				1				1					---		
R	---					---				1				2					7		
Percent k per system	10					12				20				25					33		
Number of missions	5					4				4				5					3		
Q per mission	2	2	2	1	1	3	3	1	1	3	2	3	2	1	3	3	2	3	2	3	3
dQ per mission	---	---	---	1	---	---	---	1	1	---	1	---	1	1	1	1	---	---	1	---	---
Δ per mission	---	---	---	---	1	---	---	1	1	1	1	1	---	1	1	1	1	---	4	4	4
dΔ per mission	---	---	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1	1	2	1	1
α per mission	---	---	---	---	---	---	---	---	---	1	1	---	---	1	---	---	---	---	1	---	---
dα per mission	---	---	---	---	---	---	---	---	---	---	---	1	---	1	---	---	---	---	1	3	3
R per mission	---	---	---	---	---	---	---	---	---	---	---	---	1	---	---	---	1	1	---	---	---
Total k per mission	2	2	2	2	2	3	3	3	3	5	5	5	5	5	5	5	5	5	11	11	11

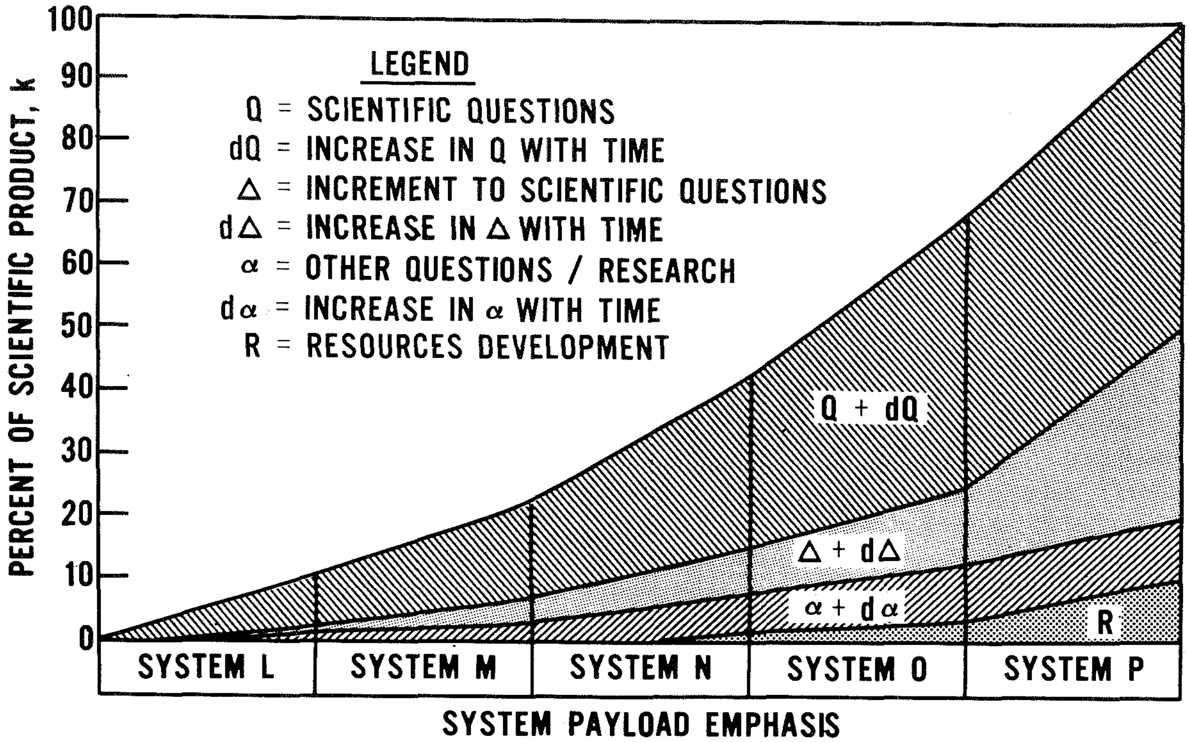


FIGURE 6.—Lunar exploration mode science capability.

that long staytimes at some point on the lunar surface are required to accomplish complex research involving man, time-dependent phenomena, and very sophisticated mission and experiment equipments. It is premature to attempt to define the operational requirements for the base and no attempt has been made in this analysis to do so. If we can sustain the conclusion, however, that a semipermanent base reflects considerably greater scientific contribution, we can at the same time stress that its contribution to technology development is correspondingly greater than that of most other spacecraft systems supporting lunar science and exploration. Many subsystems are involved in the development of a base which may or may not be characteristic of other modes of exploration. Among these are power generation and transmission, communication, and data management.

Power requirements for a base are expected to be much higher than those for systems similar to *N* and *O*. They will probably be met most efficiently by nuclear systems, though missions up to several months or even a year could be supported by solar thermoelectric and solar thermionic power units.

Requirements for communications and data transmission will be very extensive, since the missions will certainly involve links beyond the line of sight. Thus ground and space-based repeaters and groundwave propagation techniques will probably be employed. Since the communication and data systems required for base operations are directly and importantly related to the missions to be performed, the requirements for them must be established on the basis of an integrated exploration and exploitation system. Thus, they must be designed to permit expansion and modification to reflect growth from early systems to the more advanced bases. Furthermore, the load levels will be determined directly by the scientific equipments, both type and number, the data output from them, and the degree of automation of the experiments. Data recording, storage, and transmission, or, in sum, the data management problem looms as one which will require much study and definition in the period of preparation for a base.

SUMMARY AND CONCLUSIONS

An analysis of this kind does not solve problems so much as it serves to make problems more visible. Several of these problems are discussed in the following paragraphs.

The fact that a mission may have to be aborted at any time after its initiation must be recognized. This requires that the more important experiments should be scheduled and flown as early as possible, if all other constraints and considerations are equal. Again, a situation in which the experiment-conducting phase of the mission must be terminated prematurely is a real possibility. In either case, the impact on the program would be either an attempt to repeat the mission, to cancel the payload (and hence its potential contribution to k), or to carry over the payload to subsequent systems in the program. For example, assume a mission failure for one mission in each of systems L, M, and N. If the carryover mode is followed, it derives from figure 2 that a cumulative payload carryover of 10 percent k must be designed into systems O and P to accommodate the loss.

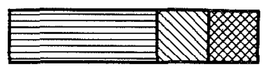
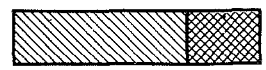
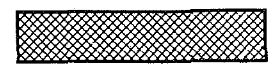
Another vexing problem involves the composition of experiments and instruments in each payload and a determination of what each might contribute to the components of k. Expressed in another way, we must determine the experiments and their related instruments which support the science related to Q, Δ, R, and so on. Again, which experiments and instruments have commonality and what are the common elements? Implications of these considerations on the spacecraft subsystems and on data management are evident.

These problems notwithstanding, a program of systems and missions must be planned and selected together with payloads, experiments, and instruments. This requires that the qualitative objectives of the scientific community be quantified and divided down to a level at which engineering alternatives can be determined and evaluated. Evidently the scientific community will eventually be required to exercise its collective judgment at a more precise level than that of the basic scientific questions. The process of development of a program plan attempts to relate the requirements on the program to the means by which they are accomplished. Considerable study within NASA has produced a much clearer understanding of the means than it has of the specific requirements (as opposed to general requirements), with the result that optimization of the system elements has not been possible. It is evident that, in optimizing for science, mission definition, and payload definition which impact on the systems design must progress much more rapidly than the current trend supposes.

A further remark should be addressed to the components of k, the scientific product of lunar exploration. At the present time the component Q and the influence of these questions in terms of experiments and instruments is quite well understood, as is the time ordering of the experiments continued in Q. This is not true for the other components which relate to such disciplines as astronomy, biosciences, physics, and so forth. Since they, too, will provide a contribution to k (approximately 50 percent according to table 4), they must be defined sufficiently well in terms of basic questions, experiments, and instruments to permit their timely incorporation into the payloads so that their anticipated k value can be extracted from both the individual systems and the total program.

How these other components might impact on the program is displayed by table 6. Note that even during phase I of a total program period, a number of experiments, operations, and engineering tests must be performed to support both operations and science during later phases. Unless the requirements in disciplines such as astronomy and bioscience are defined early in the planning period and incorporated into the early phases of the operational period, those activities required to support more involved and complex missions later in the program will not be done and

TABLE 6.—*Lunar Science Program Trends*

Component	Scientific-economic benefits	Socio-humanistic benefits	Scientific benefits
Phase	I—Early	II—Intermediate	III—Optimum
Major emphasis	Geosciences	Biosciences	Astrosciences
Disciplines	Geological Geophysical Geochemical	Biological Biomedical Physiological	Astronomy Applied science Engineering science
Experimentation program.	 Phase I support Phase II support Phase III support	 Phase II support Phase III support	 Phase III support
Purpose	Directed toward understanding Earth-Moon system	Directed toward understanding man	Directed toward understanding man's environment

delays, possible fractional payloads, and suboptimum utilization of the spacecraft systems will result. That the simple version of a lunar exploration planning logic presented here is only one of many possible forms and directions which the exploration of the Moon may take is acknowledged. Those interested in participating in this type of analysis may wish to insert their own numbers into the mission variables and may also choose to define the systems in a variety of alternate ways. One caution should be expressed, however: The plan should be structured to permit maximum effective utilization of the Apollo system derivatives and should be consistent with sound scientific objectives and reasonable measures of cost effectiveness.

Last, it must be emphasized that the analysis presented here is empirical in nature. It is hoped that it will prove possible to develop a generalized closed-form mathematical program planning model having application to programs other than lunar exploration.

If sophisticated management and organizational methods and techniques are vital to the success of space operations, they are also equally vital to successful planning for space systems and operations. Thus the approach described can be very useful in long-range planning activities such as lunar exploration and orbital space stations.

REFERENCES

1. ANON.: Space Research: Direction for the Future. Part I: Planetary and Lunar Exploration. Space Sci. Board, Natl. Acad. Sci.
2. ANON.: Mission Modes and System Analysis for Lunar Exploration. Lockheed Missiles & Space Co.

324-954 O—69——12

Page intentionally left blank

L. L. MORGAN
Lockheed Missiles & Space Co.
Sunnyvale, Calif.

RODNEY W. JOHNSON
NASA Headquarters
Washington, D.C.

Improved Lunar Cargo and Personnel Delivery Systems

INTRODUCTION

Lunar research and exploitation will require larger quantities of cargo and more available manhours than will be required by early exploration. Freedom of movement of personnel to and from the lunar surface and maximum cargo delivery per launch are required to maintain necessary economies. These requirements coupled with the large area of the lunar surface make landings anywhere on the surface very desirable.

In order to define the optimum candidate transportation systems, NASA has directed studies through the "Improved Lunar Cargo and Personnel Delivery System Study" (ref. 1), which has the objective of detailed conceptual design of two pairs of transportation systems: early and advanced. Each pair consists of a personnel delivery system and a cargo delivery system.

In this study two principal flight modes for personnel delivery were investigated: Lunar orbit rendezvous (LOR) and direct flight. The LOR mode, as shown on the left in figure 1, is basically the same as the Apollo flight mode, with the exception that surface staytimes of up to 90 days were investigated. Staytimes in this range require that the command and service module (CSM) remain unmanned and dormant in lunar orbit for 90 days and that the lunar module (LM) remain unmanned and dormant on the lunar surface for 90 days. The delivery of three men can be achieved with this system.

The other principal personnel delivery mode under consideration has been termed "direct flight." In this mode the Earth return stage, with a command module and its service support, is landed on the lunar surface for direct return to Earth. This latter flight mode can be seen to be of considerable merit when we consider the significance of the illustration in the center of figure 1. When a landing site is located at latitudes off the lunar equator, an extended staytime results in the landing site moving out of the plane of the orbit; this requires a plane change for pickup of the LM ascent stage except at the times of intersection of the landing site and the orbit plane. The direct-flight mode eliminates the requirement for large plane changes and, hence, fuel expenditures in accomplishing the rendezvous and docking maneuvers.

Another mode of personnel delivery considered was the "pickup" method. In the pickup mode four men make the translunar flight; three men land in the LM, and one man returns to Earth. The return of the three men is accomplished by a subsequent launch, with one man performing the translunar flight and landing of an unmanned LM followed by pickup of the three men and Earth return. This personnel delivery system was not included in the final phases of the study since its advantages were outweighed by its disadvantages.

Large-cargo delivery must be accomplished by unmanned direct flight. The direct-flight mode selected was initial brake into a lunar orbit followed by descent to the landing site. The lunar parking orbit is utilized to increase

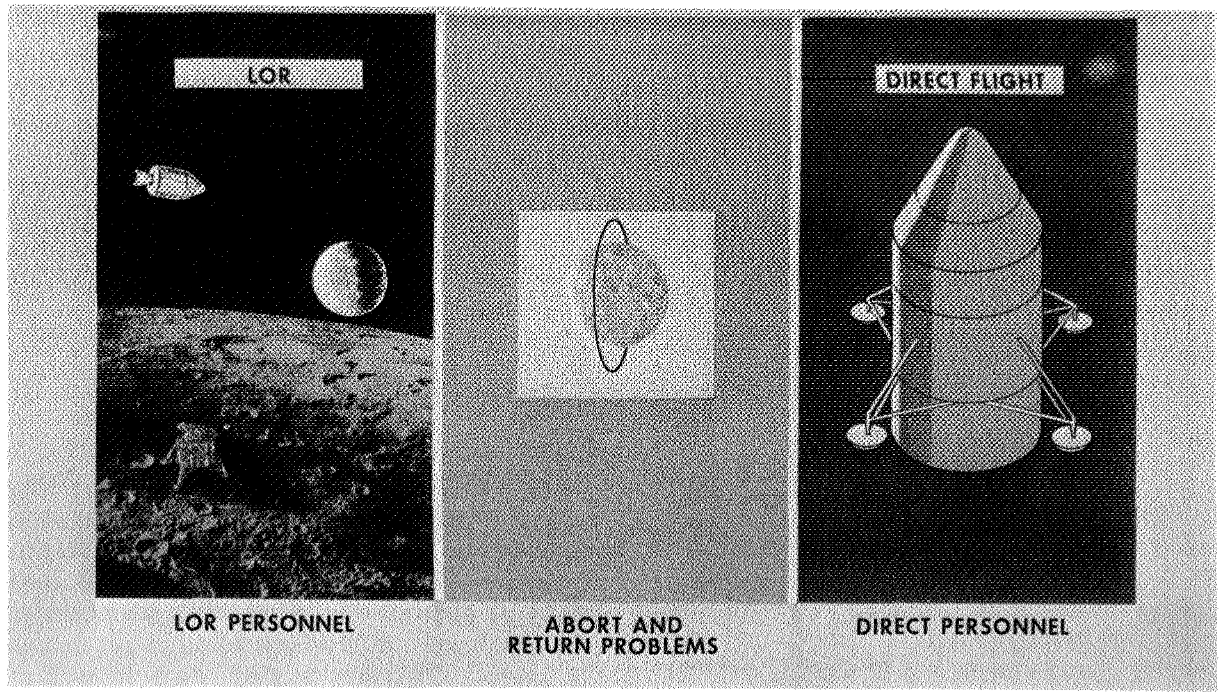


FIGURE 1.—Personnel delivery flight modes.

the accuracy of landing and safety and reliability of delivery.

Possible modes of evolution of lunar transportation systems are shown in figure 2. The development of a single-stage cargo vehicle allows evolutionary use of the stage over a long time period. This stage could be utilized for early missions by combining with an intermediate launch vehicle as the third stage, and later with the Saturn V as a fourth stage. This same stage may be stacked using one stage as a lunar-orbit braking stage and one as a landing stage for direct delivery of personnel or cargo with a 180-day dormancy capability.

The initial phases of the study program, shown in table 1, included consideration of six propellants, N_2O_4/50–50, LO_2/LH_2, LF_2/LH_2, $FLOX/CH_4$, OF_2/MMH, and LF_2/NH_3, in parametric investigations of LOR, direct-flight personnel delivery, and direct cargo delivery. A matrix of transportation systems was established and individual stages were configured and sized for applicable propellant loadings. Mass summaries were compiled by selecting point designs, utilizing applicable design loads, and performing relatively detailed analyses.

By use of these stage point designs, launch vehicle requirements were determined for the delivery of three, four, and six men by the LOR flight mode for staytimes of 14, 28, and 90 days. A standard velocity budget was used in these evaluations. All of the stages in set A employ the same propellants. In set B, the service module and LM descent stage were modified to correspond with the indicated propellants. For set C, only the descent stage was modified. The change in propellants for the service module, set D, represents the less difficult modification in that only one stage is affected, and structural envelopes are compatible.

The direct-flight personnel systems were evaluated for single-stage and two-stage delivery to the lunar surface. Here, too, all the stages in set A employ the same propellants. The stages making up set B have the indicated propellants in the Earth-return stages. These Earth-return stages are delivered by LO_2/LH_2-powered lower stages.

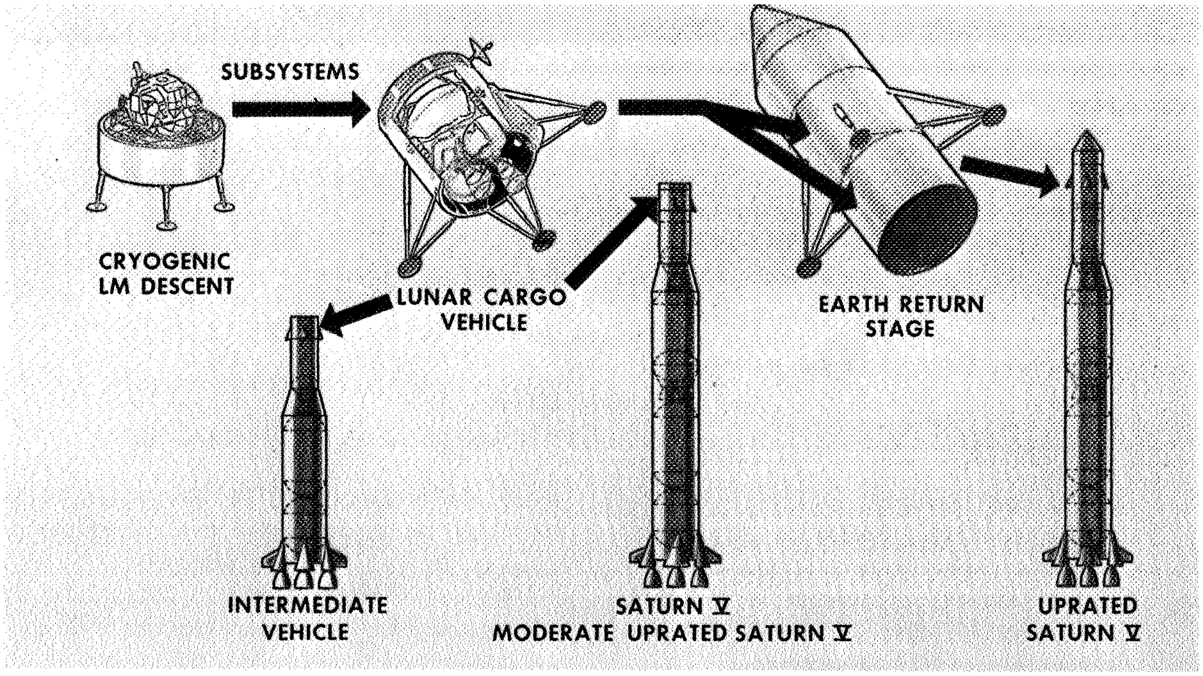


FIGURE 2.—Evolutionary usage of a multiapplication stage.

TABLE 1.—*Parametric Study Candidates*

Candidate propellants	Transportation system	Set	Stage	Resulting number	Variations	Total number cases examined
N_2O_4/50–50	LOR personnel	A	All stages		3, 4, 6 men 14, 28, 90 days.	108
		B	Service module LM descent.	2		
		C	LM descent	1		
		D	Service module	5		
LO_2/LH_2, LF_2/LH_2.	Direct personnel	A	All stages; 3 stage	11	3, 4, 6 men 14, 28, 90 days.	198
		B	Earth return; 2 stage	11		
$FLOX/CH_4$, OF_2/MMH, LF_2/NH_3.	Direct cargo	A	2 stage	6	3 ELV	38
		B	1 stage	6		
		C	LM truck	2		

The parametric data for the direct-flight cargo stage were iterated by assuming launch-vehicle capabilities and determining the resultant cargo delivery by use of a standard velocity budget.

The conclusions drawn from these parametric studies are shown in table 2. Note that the delivery of three men with 90-day dormancy by the LOR method may be accomplished with the present Saturn V if all of the current Apollo stages are changed to space-storable propellants or if the service module (SM) and

TABLE 2.—*Conclusions From Parametric Studies*

LOR personnel delivery—3 men, 90-day dormancy
Within Saturn V capabilities if—
All stages: space-storable propellants
Service module and LM descent: cryogenic propellants
Saturn V upratings required:
All stages N_2O_4/50-50, ~15 percent uprating
SM space-storable or cryogenic: max. 10 percent uprating
Direct personnel delivery—6 men, 180-day dormancy
All stages: N_2O_4/50-50, ~100 percent uprating
LO_2/LH_2 braking and landing stage: satisfactory (~60 percent)
Earth-return stages: LF_2/LH_2 or space storable
Direct cargo delivery
Single-stage cargo-delivery capabilities are only approximately 5 percent less than those of two-stage

LM descent are changed to cryogenic propellants. If the existing Apollo LM propellants (N_2O_4/50-50) are employed, a Saturn V uprating of approximately 15 percent is required. Changing the service module propellants results in a lesser launch-vehicle requirement.

Retaining the propellants in the present Apollo LM systems in direct-flight stages requires at least a 75-percent uprating of the Saturn V capability to deliver six men with 90 days' dormancy. The combination LO_2/LH_2 for the braking and landing stages greatly improves performance and appears to give results comparable to those of other propellant combinations. Earth-return stages require very good mass fractions, and LF_2/LH_2 or space-storable propellants appear to be attractive for this purpose.

Evaluation of the direct cargo delivery also indicated comparable performance between space-storable propellants and LO_2/LH_2. This appears to result principally from the attractive mass fractions of space-storable propellants, accompanied with moderately good specific impulses, and the excellent specific impulse of LO_2/LH_2 with less attractive mass fractions. Earth-storable propellants (N_2O_4/50-50) result in much poorer performance. An unexpected and very significant finding was that single-stage cargo delivery was comparable with two-stage delivery, which indicates that only one stage needs to be developed with only minor payload penalty (approximately 5 percent).

On the basis of these results, 14 transportation systems were selected for refined analysis, as indicated in figure 3. The selected stages and spacecraft design concepts were refined by increasing the depth of the subsystem analyses and by considering all factors influencing the masses and subsequent performance indices.

A number of factors were considered in the selection of the candidate systems for detailed analysis. An evolutionary development analysis was used to reduce the number of candidates by identifying promising "building-block" stages which exhibited the maximum potential for evolutionary growth. A propellant selection analysis was conducted to determine the most suitable fuel/oxidizer combinations for the selected building-block stages. For each potential stage, two factors were considered: (1) how the stage would be used in the early system and (2) how it could be used, within the imposed limitations, in an improved system.

The selection of propellants for the systems studied was the result of investigation of the status of engine programs, availability of propellants, safety considerations, and a number of other related factors. As a result of these investigations, the following propellants (other than present Apollo LM propellants) were selected: LO_2/LH_2 and $FLOX/CH_4$, both a cryogenic and a space-storable propellant. LF_2/LH_2 was examined in the Earth-return stage for advanced personnel delivery. From these refined analyses and a reconsideration of related factors such as engine availability, four systems were selected for conceptual design. These are enclosed in boxes in figure 3 and consist of:

(1) LOR systems for delivery of three men

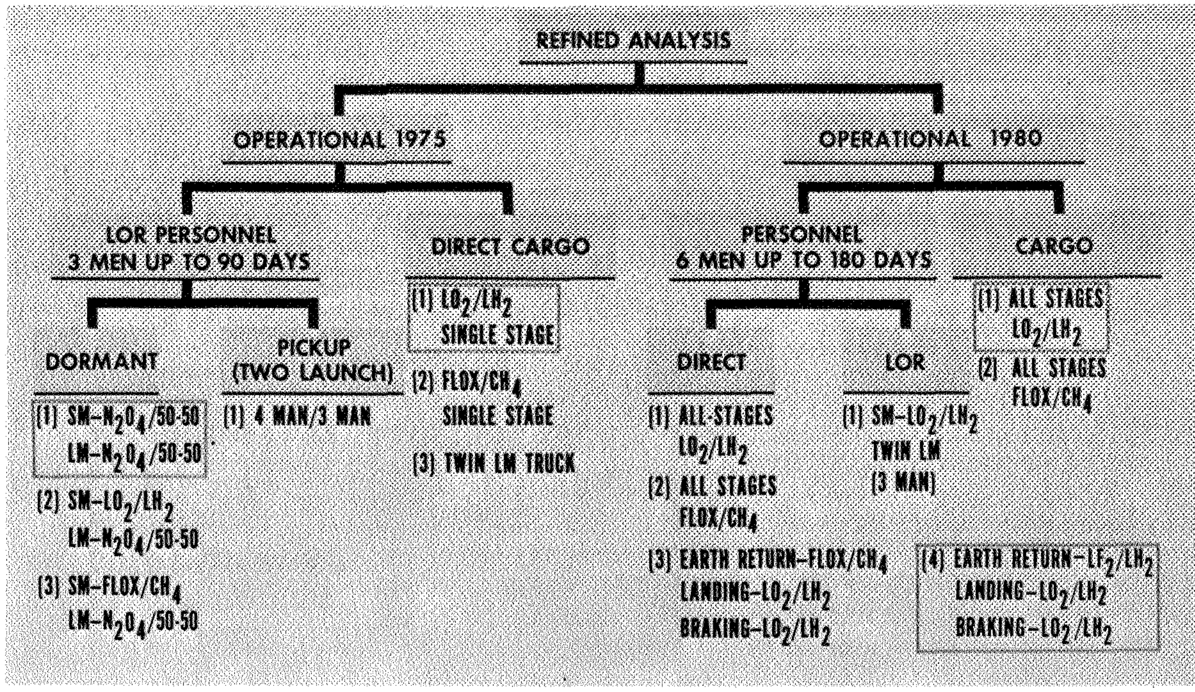


FIGURE 3.—Transportation systems selected for refined analysis.

with 90-day dormancy using N_2O_4/50-50 propellant in all stages and utilizing present Apollo LM derivatives.

(2) Direct lunar cargo stage consisting of a single LO_2/LH_2 stage.

(3) Direct personnel system for the delivery of six men with a dormancy of 180 days.

(4) Direct cargo system utilizing the braking and landing stage of the direct personnel system.

PERSONNEL DELIVERY—OPERATIONAL 1975

The primary purpose of the detailed investigation of personnel delivery systems was to establish launch-vehicle requirements to permit sizing of the direct cargo stages. Baseline weight stagements and design data for the standard Apollo system were provided by NASA. The CSM was examined for configuration changes required to allow for an unmanned 90-day dormancy in lunar orbit and for delivery of a three-man LM.

A basic assumption in achieving the 90-day dormancy was that the subsystems could be developed to satisfy the required lifetime with no appreciable increase in present equipment weight. This appears feasible, since there is a minimum of rotating equipment in the CSM. Modifications to the command module are relatively minor as shown in figure 4. The major factor is qualification of equipment for the 90-day operating period. The command-module internal pressure is maintained at 0.5 psia during the dormant period.

The major modification to the service module is in the electrical power system. The fuel-cell reactant requirement of 2150 pounds requires utilization of bay 1 for the storage of hydrogen. Development programs are in progress to increase the lifetime of fuel cells and to allow shutdown and restart. For these reasons, only three fuel cells were considered necessary, with one operating at reduced power during the dormancy period.

The primary propulsion propellants are increased by the mission requirements, and storage can be accomplished by increasing the length of the propellant tanks. The plumbing arrangement remains basically unchanged. During the

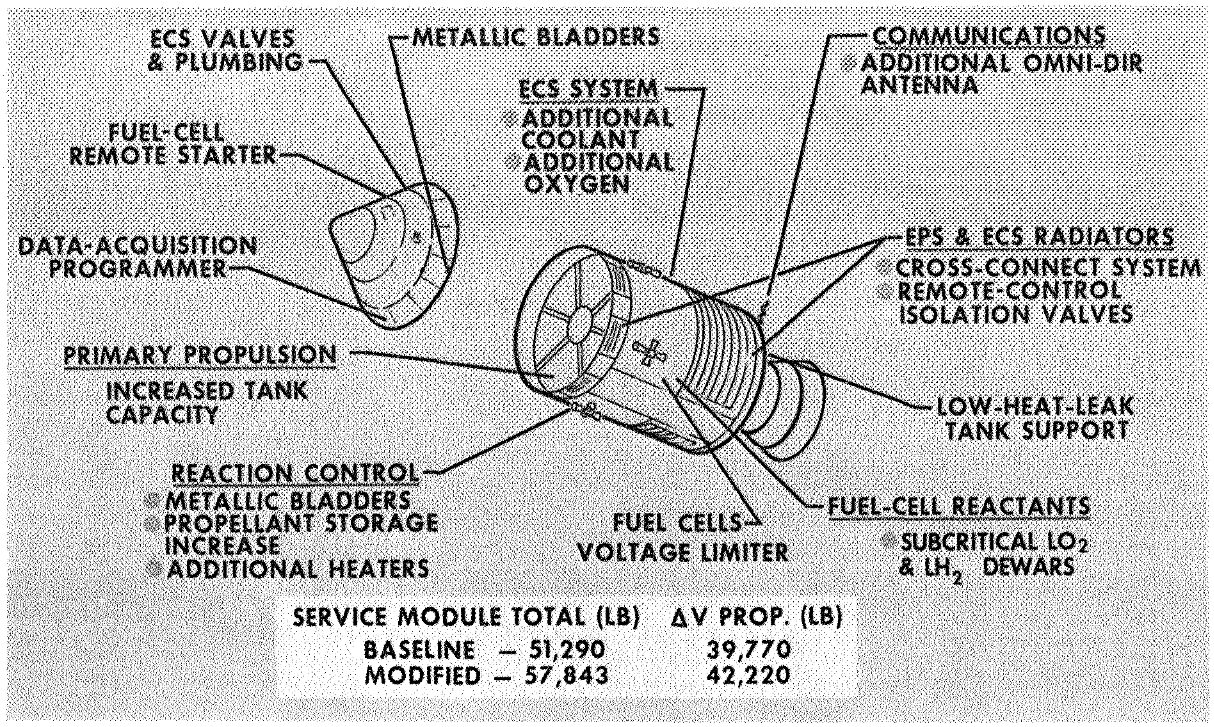


FIGURE 4.—Summary of modifications to CSM.

90-day orbital dormancy of the CSM, the systems essentially constitute an unmanned lunar satellite; it is required only that the vehicle subsystems be protected. The approach is summarized in figure 5.

Spin stabilization was found to be the best method of assuring maintenance of required radiator temperatures. The selected mode at this time entails maintaining the vehicle longitudinal axis nominally perpendicular to the vehicle sunline and allows a deviation of up to a 20°, half-cone angle. Nulling the 20°, half-cone angle is accomplished by a two-impulse maneuver that restores the vehicle centerline to the original angular momentum vector. Since the deviation is principally a result of fuel sloshing, the analyses indicated that, at the low spin rates examined, the propellant required for 90 days increases as the spin rate is increased. A spin rate of 0.3 to 0.5 rpm has tentatively been selected which requires some 150 pounds of reaction-control propellant.

With the exception of the thermal-control system, the internal measuring unit is shut down during the dormancy period. Gyros are employed for attitude determination. The S-band command receiver is left on, together with the antenna steering circuit. Earth communications and/or control are established on command or by programmer.

Attitude control would be required only for correction of spin stabilization. Heater power can be supplied continually. In the event of a nozzle freezeup, heater power can be increased to restore the nozzle prior to use.

As previously mentioned, only one fuel cell is required during the dormant period. This allows switching of cells, and therefore lower lifetime requirement per cell. Freezing of radiators is marginal in the lunar shadow, and some deliberate heat addition could be necessary.

Modifications required for the LM ascent stage are principally related to provisions for the third man, as shown in figure 6. They are:

(1) *Crew provisions.*—An additional suit,

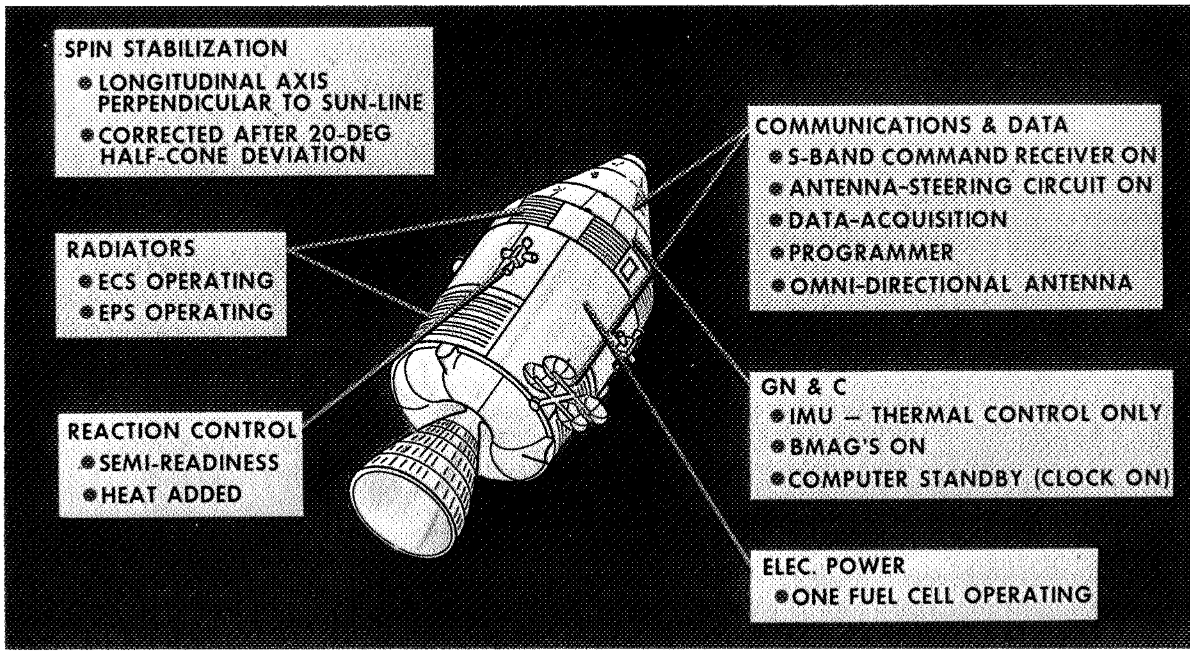


FIGURE 5.—Orbital dormancy of CSM.

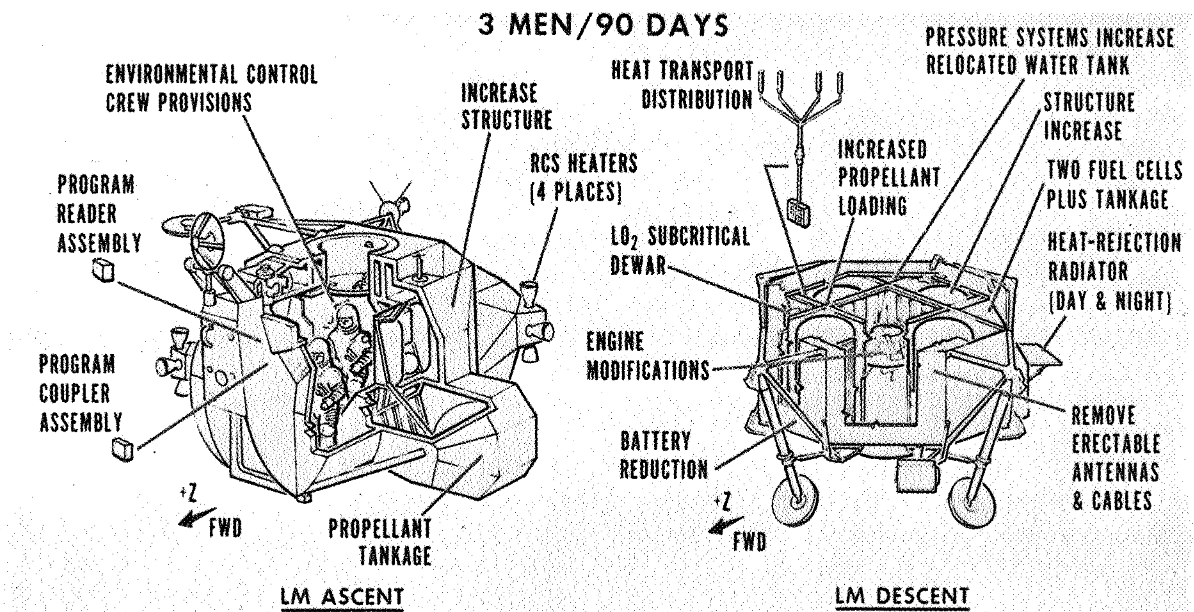


FIGURE 6.—Summary of modifications to LM for three men with 90-day dormancy.

planetary life-support system, restraints, and other equipment must be provided for the third crewman.

(2) *Environmental control subsystem.*—A controlled cabin pressure of 0.5 psia must be maintained during the quiescent period to reduce

deterioration of materials. Heat rejection can be accomplished with a radiator during the quiescent period. The radiator would be relatively small (15 ft^2), being sized to prevent freezing during lunar night. The water evaporator would be used for heat rejection during occupancy. Water and oxygen requirements are not significantly affected.

(3) *Electrical power subsystem.*—The ascent energy requirements should not require significant change. Batteries would be used.

(4) *Reaction control subsystem.*—The existing subsystem can be used; propellant lines near the nozzles will freeze unless purged. Heaters should be provided for this region for warmup prior to use.

(5) *Structures and propulsion.*—Additional meteoroid shielding may be necessary. The propellant loading must be increased to approximately 5700 pounds.

The modifications of the LM descent stage are also indicated in figure 6 and consist principally of:

(1) *Electrical subsystem.*—Batteries would be used for descent. Fuel cells must be added for the quiescent period. Only one is required, since the power requirements are lower than the capacity of single cell; however, two were included for redundancy. The cabin can be heated by a reflux condenser that draws heat from the fuel cells.

(2) *Structures and propulsion.*—The propellant loading must be increased to approximately 20 600 pounds. This could be accomplished by employing ellipsoidal tank bulkheads and increasing the length of the cylindrical section of the tank.

The launch-vehicle capability requirements were established by use of a standard velocity budget supplied by NASA Marshall Space Flight Center; the composition is shown in table 3. All expendables necessary for a normal 14-day lunar mission were considered left on board the CSM in all performance evaluations. However, it was considered realistic to assume that expendables associated with the 90-day dormancy would be either consumed or dropped prior to leaving lunar orbit, and this was considered in the evaluation of the launch-vehicle requirement.

TABLE 3.—*Summary of LOR Personnel Delivery Mission Requirements for Operational 1975 Personnel System*

Requirement	Weight, lb
Translunar injected weight	112 200
SLA jettison	3 850
Midcourse propellant	730
Lunar orbit insert propellant	29 318
Total weight in lunar orbit	78 300
Total weight LM with men	38 380
LM rescue propellant	2 489
Weight at lunar departure	35 660
Inject propellant	9 578
Midcourse propellant	103
Final burnout weight	25 980

CARGO DELIVERY—OPERATIONAL 1975

The early cargo stage was designed in considerable detail. Maximum use was made of existing hardware and techniques that are within the present state of the art. Minor sacrifices in performance were made where necessary to utilize proven systems and techniques to keep development costs minimal. The availability of the RL–10 engine, which could be modified to provide a suitable engine for direct cargo delivery, makes LO_2/LH_2 stages very attractive.

In developing the mission profile for the time period contemplated, achievement of the highest possible landing accuracy with minimum degradation of payload was considered to be of prime importance. Use of a lunar parking orbit contributes appreciably to the accuracy of a landing; Earth tracking is of maximum effectiveness when several orbits are made prior to lunar descent. The Apollo flight mode involves braking into a lunar orbit at approximately 80 nautical miles. The LM then performs a Hohmann transfer down to an elevation of approximately 50 000 feet, where the engines are restarted for final descent.

Several objectives were considered in selecting a flight mode. These include:

(1) Use of a lunar orbit

(2) A velocity budget not differing greatly from that of Apollo

(3) Minimizing number of burns
(4) Effective line of sight to landing point at initiation of burn or shortly thereafter

Minimizing the number of burns results in a significant weight saving of propellant. In addition, a number of operational problems could be eliminated if the 1-hour Hohmann transfer were omitted.

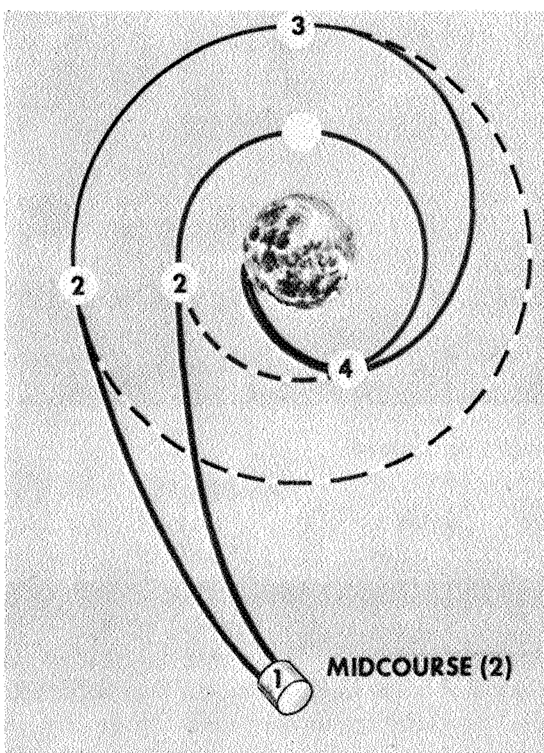
The selected flight mode is indicated in figure 7. Lunar-orbit injection is into a 100 000-foot orbit. Error analyses indicate that this maneuver can be performed with a maximum altitude error (3 sigma) of approximately 16 000 feet. Descent from 100 000 feet after several orbits is accomplished by use of a single burn. The early cargo stage is above the horizon at initiation of burn. A 10° line of sight to the landing point is achieved at an altitude of approximately 85 000 feet (using the two 20 000-pound-thrust RL–10 engines). The resulting velocity budget is slightly lower than the Apollo budget and produces comparable performance.

The selected early cargo stage concept as shown in figure 8 presents several attractive features:

(1) Maximum utilization of existing hardware
(2) Structural efficiency
(3) Simplicity
(4) Accessibility
(5) Flexibility

The stage has been designed to utilize a modified RL–10 engine with either a 57:1 area ratio or a 150:1 area ratio to allow growth in engine performance.

The external shell is made of eight honeycomb panels of equal size. The shell is reinforced with internal rings which serve the multipurposes of external shell stiffening, assistance in propellant tank support, and landing-gear backup. The meteoroid shield is located



		STANDARD APOLLO m/sec (ft/sec)	SELECTED m/sec (ft/sec)
1	MIDCOURSES	21 (68)	21 (68)
2	LUNAR ORBIT INJECTION	972 (3,189) 80 NM	984 (3,227) 100,000 FT
3	DESCENT HOHMANN TRANSFER	30 (97)	
4	DESCENT	2,203(7,228) FINAL DESCENT	2,171 (7,121) SINGLE BURN

FIGURE 7.—Selected direct cargo delivery flight mode.

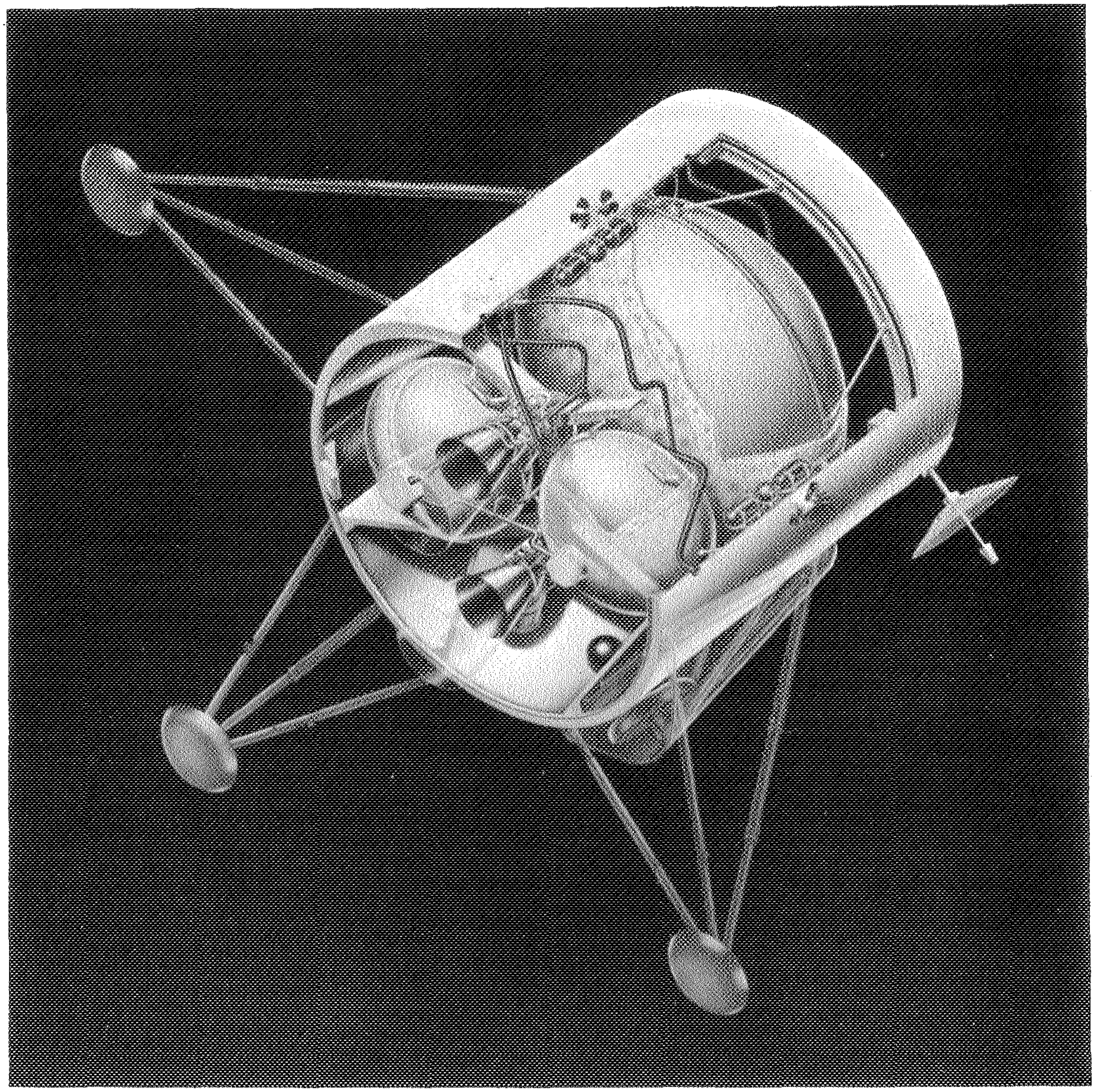


FIGURE 8.—Early direct cargo stage concept.

inside the shell and is attached to the inner edge of the rings.

The liquid-hydrogen and liquid-oxygen tanks are of 2219 aluminum and are supported with fiber-glass struts. The struts are attached to Y-rings in the tanks with most of the weight in the system concentrated in the liquid-oxygen tanks. The selected support system distributes the load effectively and efficiently to the shell.

Each propellant tank is insulated with multilayer insulation consisting of thin, crinkled, double-aluminized Mylar radiation shields with Tissuglas spacers and is applied in blankets. Areas which might leak gas into the insulation are covered with fiber-glass structure which is vented past the insulation. The thermal protection system is sufficiently effective to permit an entire translunar flight without propellant boiloff.

The reaction control system is located in four modules in the region between the liquid-hydrogen and liquid-oxygen tanks. The space-qualified modules from the Apollo service module are used.

The Saturn V instrument unit is capable of providing the major portion of the astrionic functions if it is attached to the cargo stage and taken to the lunar surface. The alternative to this is integrated stage astrionics. By using the Saturn V instrument unit, however, costs can be appreciably reduced, though the payload loss is approximately 1000 pounds more than with integrated astrionics. Additional equipment must be added to supplement the instrument unit. The landing radar is the same as that used on the LM and is located in the aft region.

The landing gear is relatively small, considering the vehicle size. It is folded on the exterior of the vehicle during launch and is covered by a fairing.

In figure 9, some of the existing hardware applications are shown:

(1) The current RL–10 engine can be modified to the required capabilities. This was a major factor in the selection of LO_2/LH_2 as propellant.

(2) As previously discussed, the modification and use of the Saturn instrument unit is attractive, since no major developments are necessary. The Apollo fuel cells and reactant storage tankage could be utilized.

(3) The flow-rate and pressure requirements of the components in the pressurization system and the propellant feed system are compatible with valves and regulators that have been used on other stages utilizing the RL–10 engine.

(4) The thermal-protection system has been tested on full-size tanks and found to be satisfactory. Lockheed has made sufficient tests to assure that the insulation system is flight qualified.

Typical results from the landing-gear stability studies are presented in figure 10. The stability angle is defined in the illustration as the point where the overturning moment exceeds the restoring moment. Note that the vehicles become unstable rather rapidly with decreasing landing-gear radius.

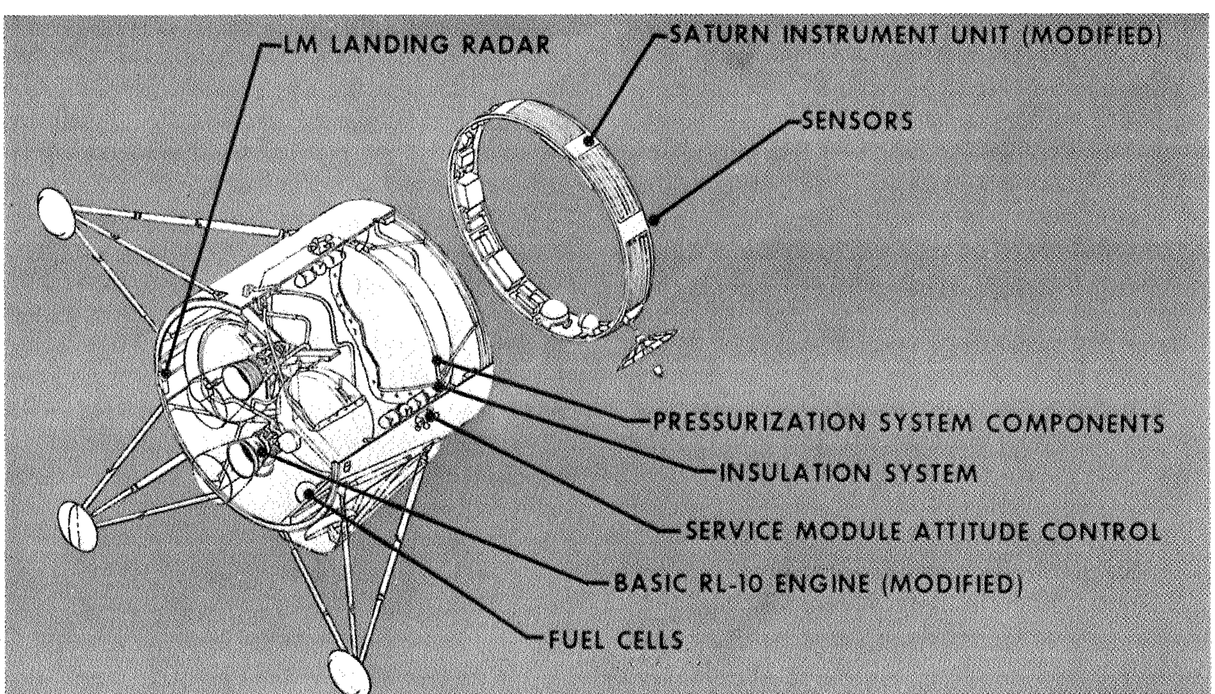


FIGURE 9.—Existing hardware utilization.

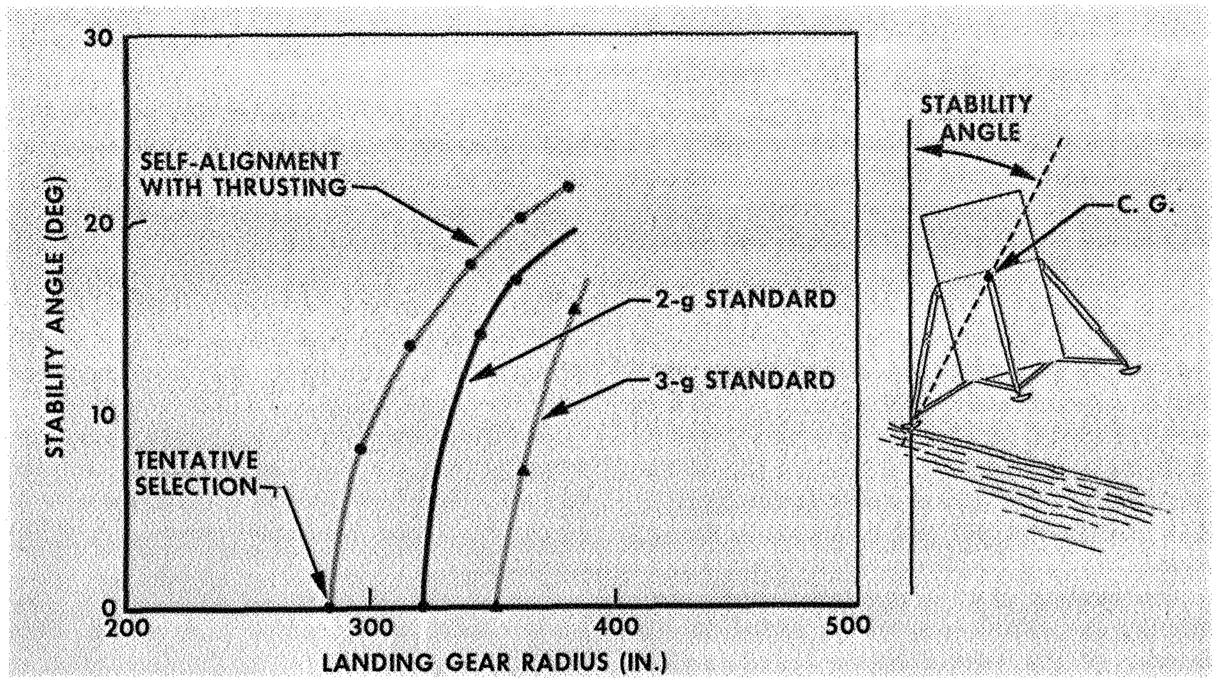


FIGURE 10.—Typical landing gear stability results.

The landing-gear radius selected during the study was 280 inches. The design incorporates a self-alining gear that strokes with almost zero load if only one leg touches until two opposing legs touch; all legs are then stiffened, and honeycomb crushing begins. The addition of reaction control thrusting downward after primary-engine cutoff assists in assuring stability. These active methods could result in additional reduction in landing-gear weight and radius in future stages.

Several observations from the studies made to date are of interest:

(1) An increase in the height of the center of gravity does not rapidly affect the stability. (Example: for an increase of 20 inches, stability angle increases by only 3°.)

(2) The lower the crushing g in the main strut, the greater the stability for a given radius.

(3) Increasing the tension-carrying capacity of the secondary struts appears to decrease stability.

(4) Horizontal velocity may be the largest contributor to instability.

Experience in evaluating thermal-protection systems and pressurization has indicated that simplified methods (such as summing insulation and boiloff to obtain minimum weight) are not sufficient for the evaluation of a high-performance insulation system for multiburn missions. An evaluation technique was tailored for this particular mission.

Detailed thermal analyses have been performed on the stage design by using computer techniques to obtain the heat input as a function of the insulation weight and throughout the mission time. Nominal thermal insulation conductivities were varied; in addition, the computer program considered variation with temperature. The resulting information is used to produce a weight index (or weight penalty) which consists of—

(1) Insulation weight
(2) Vented propellant
(3) Tank weight
(4) Pressure gas quantity
(5) Pressure gas subsystem
(6) Residual gas

An example of the information which was obtained is shown in figure 11. In the illustra-

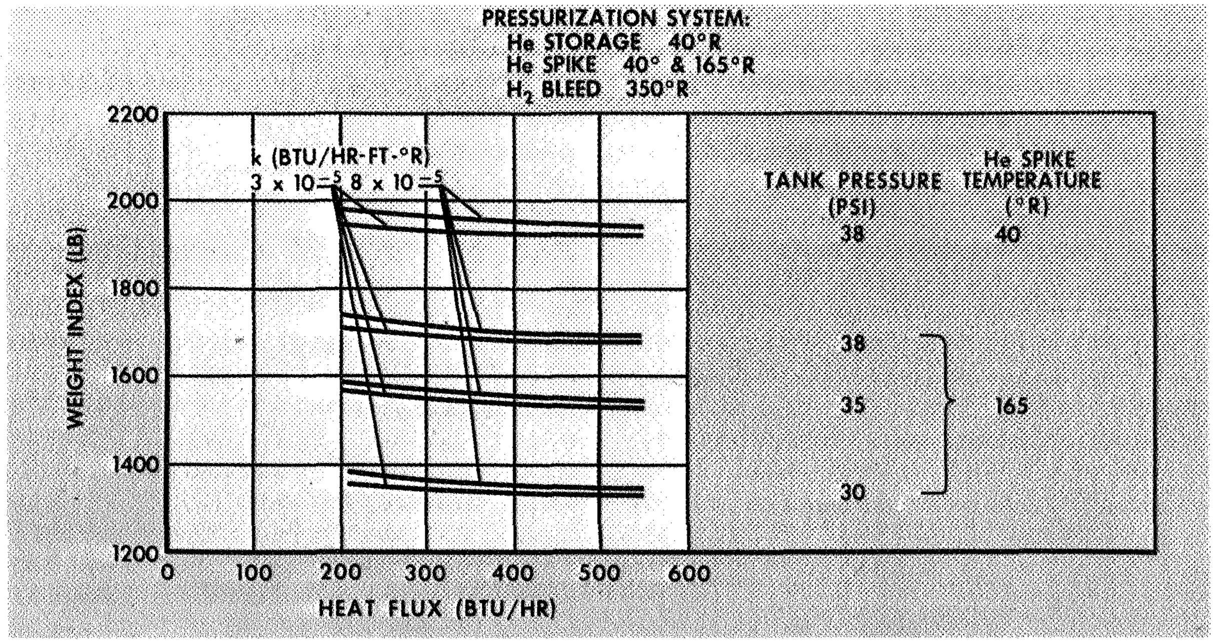


FIGURE 11.—Typical insulation/pressurization optimization results for LH_2 propellant tank.

tion, helium is used to prepressurize the liquid-hydrogen tank, and gaseous-hydrogen engine bleed is used for run pressurization of the liquid hydrogen. Estimates of stratification during ground hold and ascent have indicated that a minimum tank pressure of 35 to 40 psia may be required during the period when ullage pressure relief is not possible. Also, using the tankhead start of the RL–10 makes it desirable to have a higher tank pressure for better performance. These factors force the tank pressure up so that minimums do not occur in the curves; in addition, the effects of insulation thermal conductivity are relatively small. Heat input to the propellant from pressurization gas is on the same order of magnitude as heat input through the insulation. Pressurization gas weight is reduced by an increase in tank vapor pressure because the required pressurant weight is only the amount necessary to increase the pressure from the vapor pressure to the operating pressure.

As a result, an insulation thickness of approximately 0.3 inch is now considered to be a reasonable value. Subsequent evaluations and possibly a different pressurization system may increase this thickness. If the engine NPSP could be held from 2 to 4 psia, the insulation thermal conductivity can be degraded and still give satisfactory performance with the pressurization system under the ground rules for the data shown here.

A number of terminal guidance possibilities exist; these include:

(1) Lunar surface beacon
(2) Optical comparison (area correlation)
(3) Radar comparison (area correlation)
(4) Tracking and updating

A beacon-assisted landing is most advantageous, but the questions concerning delivery and placement of the beacon raise difficulties. If the beacon is not available from a previous landing, it may be delivered by a separate launch or by being landed from the orbiting early cargo stage. The location of the beacon must be established from Earth tracking. A beacon tracker will be added to the guidance and navigation system of the early cargo stage and will furnish relative range, range rate, and angular rate of the line of sight to the beacon. This information would be used to update the inertial system. Altitude and lunar-surface velocity data from landing radar will complete the system.

The use of automatic image (area) correlation offers a possible technique for precision landing. This guidance technique requires previously obtained photographs of the lunar surface surrounding the selected landing site. The reference photographs are stored in the correlator, and during final descent optical images are obtained in real time and compared with the reference images to determine vehicle position. Vehicle guidance would be inertial, with position correction used to improve terminal accuracy.

The same area correlation technique may also be used with a radar imaging sensor. Reference images would be constructed from previous radar mappings of the lunar surface. Two problems accompany this approach: (1) radar reference images may not be available, and (2) low resolution and low frame rates inherent in the radar system would reduce guidance accuracy.

The reduction in landing-point dispersion through the use of an altimeter and beacon tracker is clearly indicated by the 3-sigma dispersion shown in table 4. The altimeter function would be provided by the landing-radar FM/CW beam, which has an altitude-measuring capability of from 10 to 25 000 feet. As shown, the beacon tracker may be used to provide high-accuracy location guidance. However, a lunar-surface velocity sensor is necessary to insure a soft and stable landing. This sensor is provided by the landing radar FM/CM three-beam velocity sensor.

The unified instrumentation unit (UIU) will be located atop the early cargo stage as shown in figure 12. It will consist of the basic instrument unit (in operational configuration) with modifications and additions of existing, flight-proven components. The UIU will be capable of performing all required astrionics functions from Earth launch to soft lunar landing. Thus, the UIU will perform all guidance and navigation, stabilization and control, measurements and telemetry, command and communications, sequencing, and inflight checkout functions during all phases of the mission; that is, during launch, injection, midcourse corrections, braking, and soft lunar landing. The philosophy is to use the basic set of inertial sensing and computing equipment provided by the operational instrument unit, and to add auxiliary sensing equipment as required by the various phases of the mission.

The additional equipment shown in figure 12 would be utilized as follows:

(1) *Guidance and control:*

(*a*) Solar sensor: OAO or Surveyor type—provides a vehicle inertial reference direction.

(*b*) Star tracker: OAO or Surveyor type—provides a second vehicle inertial reference direction.

(*c*) Horizon sensor (lunar): determines direction of lunar local vertical as the

Table 4.—*Terminal Guidance Error Comparison*

Mode	3σ landing dispersion,[a] m (ft)		
	Downrange	Cross-range	Altitude
IMU only	820 (2700)	1460 (4800)	1400 (4600)
IMU with altimeter	820 (2700)	1460 (4800)	~0
IMU with altimeter and beacon	[b] ~150 (~500)	[b] ~150 (~500)	~0

[a] Top value given in meters; bottom value in parentheses, in feet.
[b] Principally error in beacon location from Earth tracking.

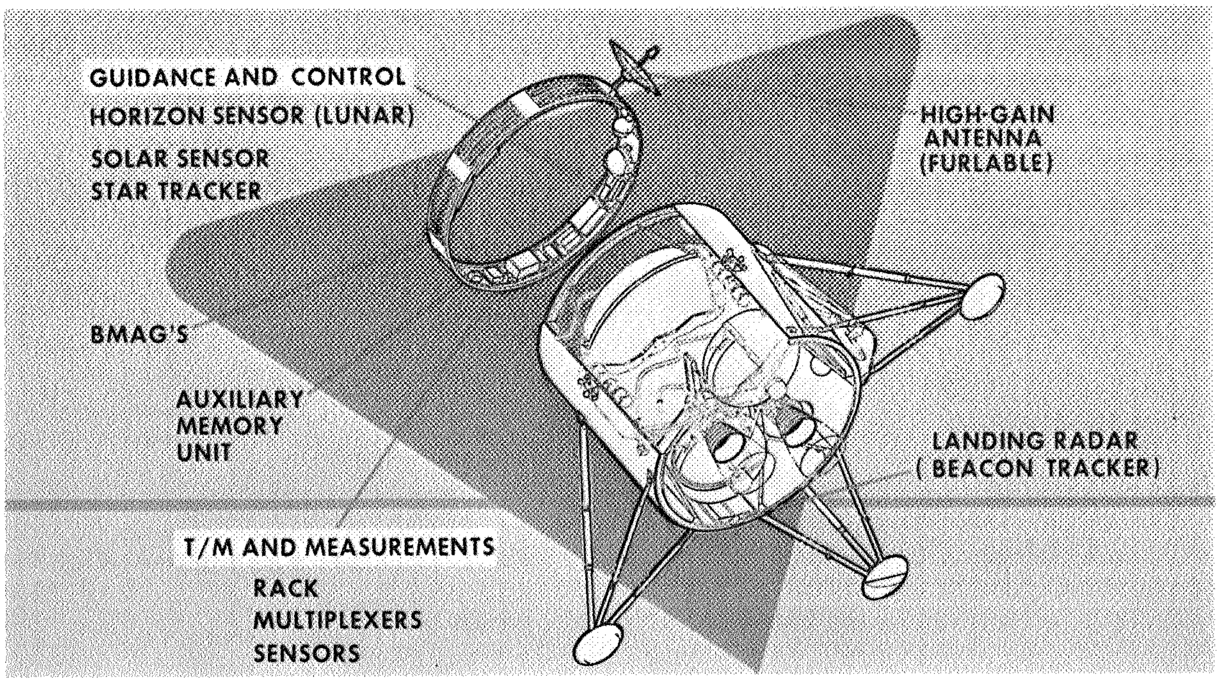


FIGURE 12.—Selected astrionic approach.

vehicle approaches the Moon. This is required for position updating using either a beacon tracker, derived data, or area correlation data.

(*d*) Body-mounted attitude gyros (BMAG): SCM type—provides an attitude reference for midcourse and terminal attitude orientation when the ST–124 inertial platform is caged.

(*e*) Auxiliary memory unit (AMU): used to provide additional program storage for the launch-vehicle digital computer.

(*f*) Landing radar (LR): Ryan LM type—provides altitude and velocity inputs to the LVDC for the terminal descent phase from about 50,000 feet to touchdown.

(2) *Telemetry and measurements.*—Measuring racks, a multiplexer and a remote submultiplexer are required to accommodate the increase in the number of measurements to be made, specifically of the parameters that would be monitored on the early cargo stage. These items are used on the basic Saturn instrument unit.

(3) *Communications.*—A high-gain, steerable S-band antenna is required for communication with Earth at midcourse and lunar distances. A Lockheed 6-foot parabolic reflector antenna that is furlable, with two-axis steering, is the recommended antenna.

PERSONNEL AND CARGO DELIVERY—1980

In the time period of 1980 and beyond, it is a reasonable assumption that Earth-launch-vehicle capabilities will have appreciably increased, and delivery of personnel by the direct-flight mode should be possible.

The direct personnel mode, shown in figure 13, employs the command module and an Earth-return stage which can be supported by a service adapter. The Earth-return stage has been designed to employ LF_2/LH_2 propellant.

For comparison purposes, two approaches were taken. An optimized system was evaluated on the basis of minimum launch-vehicle capability, as shown in the illustration. The second mode considered was based on using the early cargo stage as a braking and landing stage. Since the stage is required to sustain

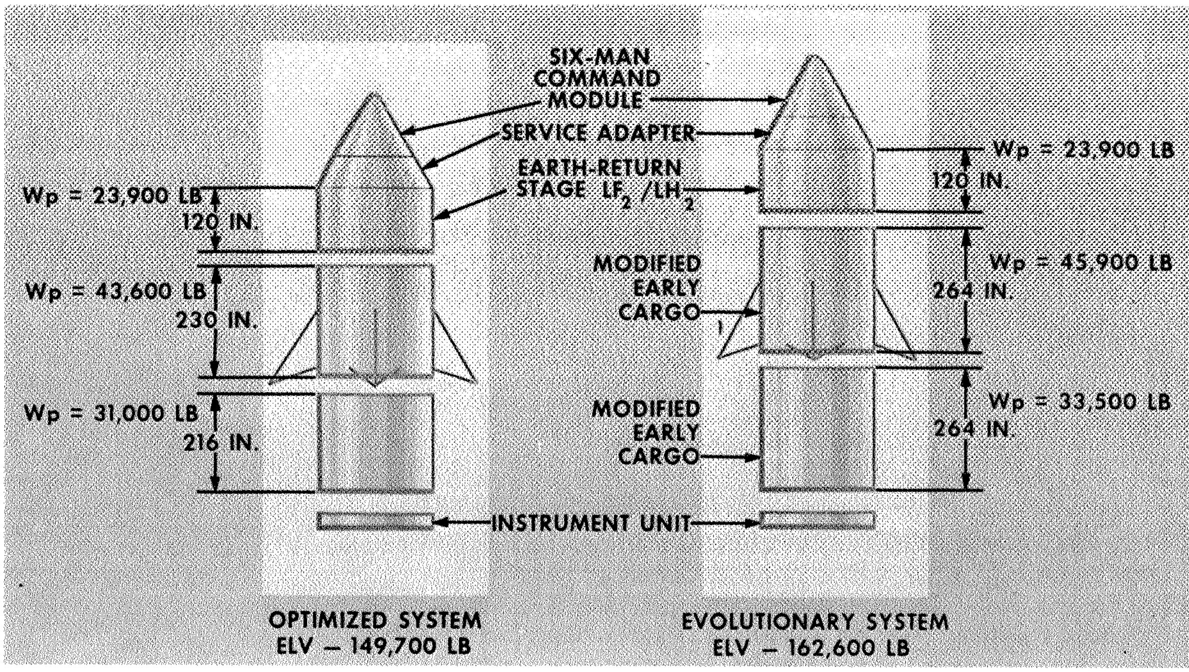


FIGURE 13.—Direct personnel delivery concepts.

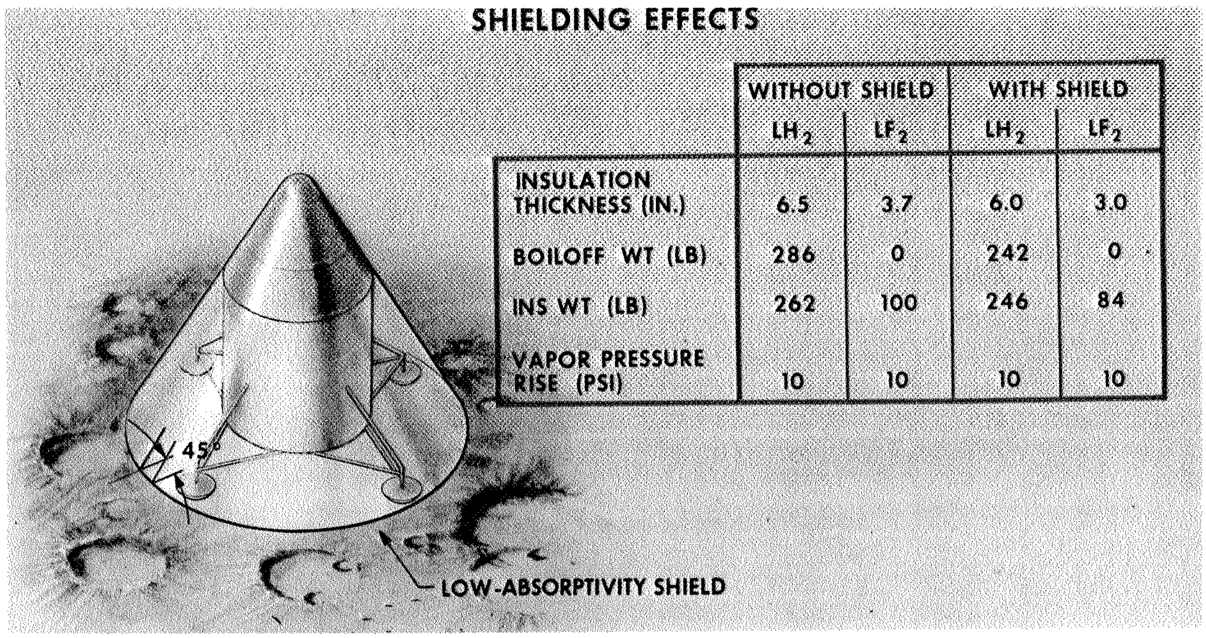
more axial loading and larger bending moments, the shell weight is increased, even though attitude control can be removed from the breaking stage.

The studies indicate that the direct command module, which must accommodate six men, can be constructed from the components of the present Apollo command module. Further, Lockheed-sponsored studies indicate that this could be accomplished using refurbished command modules. In order to provide volume for the extra three men, the approach was to lengthen the pressurized cabin, thus increasing the diameter of the command module. The service adapter between the Earth-return stage and the command module houses the fuel cells and reactant supply, environmental control system (including radiators and expendables), S-band deployable antenna with associated electronics, and vehicle status sensing instrumentation.

The Earth-return stage remains on the lunar surface from the time of touchdown to time of departure. Its function is to provide direct return to Earth, with or without an intermediate lunar parking orbit. A lunar parking orbit was assumed in the studies reported here. The basic stage design adopted was identical with that previously discussed for the early cargo systems. The vehicle has been designed with two liquid-fluorine tanks and two liquid-hydrogen tanks. The tanks are supported between the shell and honeycomb shear panel cross-beams by fiber-glass struts. Since thermal protection is of major importance, the tanks are insulated with multilayer insulation in the same manner as for the early cargo stage.

The thermal protection system should be optimized so as to contribute to increasing the net vehicle performance capability. Propellant boiloff, a component of the thermal protection system, is a weight that must be landed on the lunar surface, but does not have to be lifted off from the surface. Therefore, in tradeoff studies, optimum insulation thickness trades off in a different manner than does boiloff, and a seemingly large boiloff does not cause penalties as large as might be indicated. In the case of fluorine, used in this particular mission, no venting is required if the bulk liquid is occasionally mixed.

One concept for achieving lower heat rates by utilizing a solar reflective shield is illustrated in figure 14. The shield was designed to be placed at an angle of 45° to the vertical vehicle. The thermal-analyzer program was run with and without the shield. An $\alpha/\epsilon = 0.36/0.94$ of the vehicle surface without the shield was utilized; this corresponded to that of an ultra-



	WITHOUT SHIELD		WITH SHIELD	
	LH_2	LF_2	LH_2	LF_2
INSULATION THICKNESS (IN.)	6.5	3.7	6.0	3.0
BOILOFF WT (LB)	286	0	242	0
INS WT (LB)	262	100	246	84
VAPOR PRESSURE RISE (PSI)	10	10	10	10

FIGURE 14.—Thermal analysis of Earth-return stage.

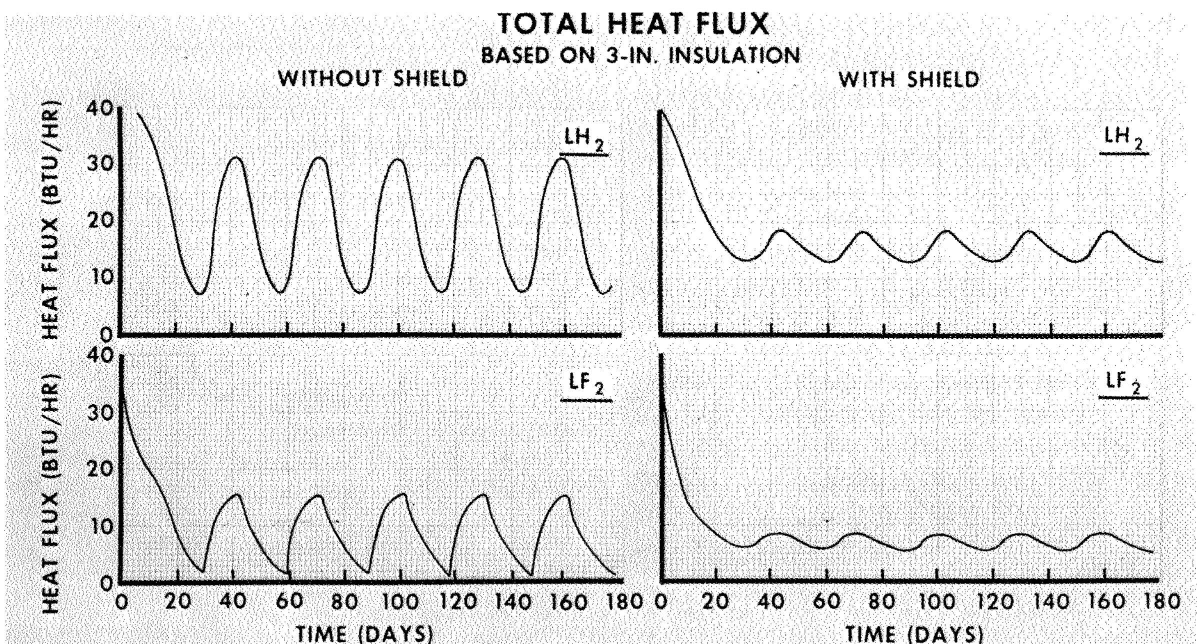


FIGURE 15.—Earth-return stage heat flux variation on lunar surface.

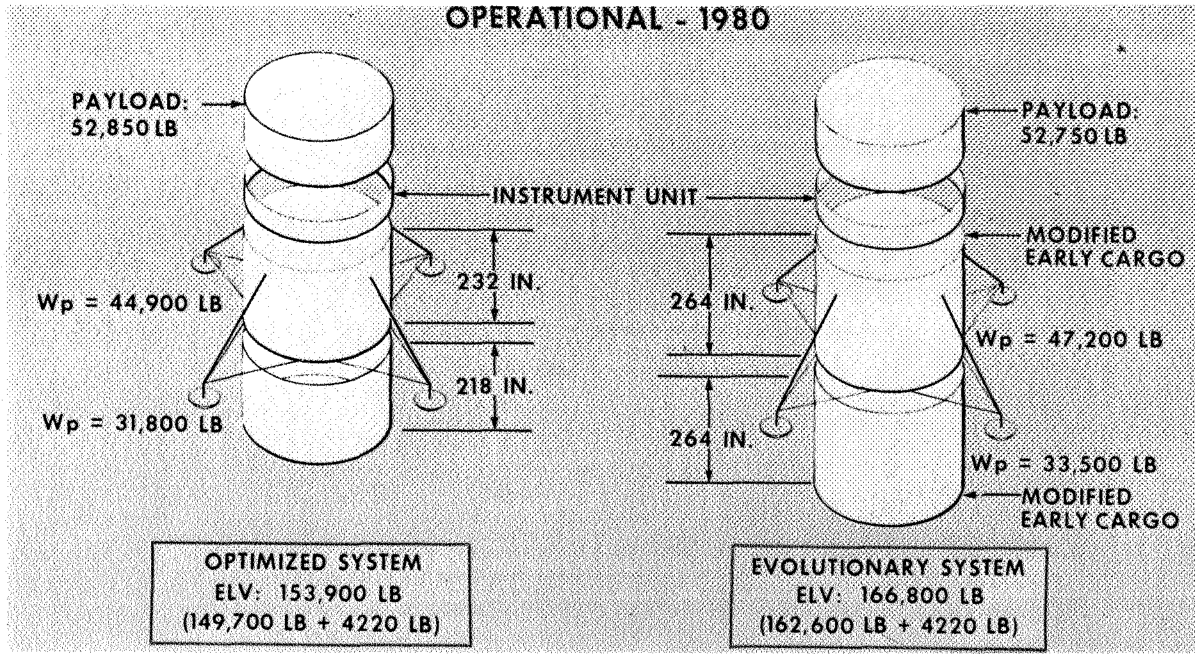


FIGURE 16.—Advanced two-stage cargo delivery.

violet degraded thermal point. With the shield, a value of $\alpha=0.94$ was used on the vehicle, and an $\alpha/\epsilon=0.06/0.4$ was used for the shield. Use of the shield would result in a reduction of the total heat flux by more than 20 percent. The effects on the heat flux produced by a shield on the Earth-return stage are shown in figure 15. The shield tends to dampen the amplitude of the heat flux, but the integrated total heat input is lowered by only about 20 percent.

In this study the personnel delivery system launch-vehicle capability has been used as the basis for determination of the cargo delivery launch-vehicle capability; when this is done these capabilities may be adjusted, depending on the location of the instrument unit. In the evaluation of the advanced cargo delivery, the instrument unit was moved to the forward end of the cargo stage, and a corresponding adjustment in capability was made as presented in figure 16.

As explained in the discussion of the advanced personnel delivery systems, the optimized-system and evolutionary-system approaches were taken in the evaluation.

TABLE 5.—*Summary of Transportation System Performance*

Item	Weight, lb
Personnel (operational 1975); 3 men, 90-day dormancy	
Launch-vehicle requirement	112 200
Cargo (operational 1975); single stage	
Based on ELV	112 200
Delivered payload	35 140
ΔV propellant	60 000
Personnel (operational 1980); 6 men, 180-day dormancy	
Launch-vehicle requirement:	
Optimized	149 700
Evolutionary	162 600
Cargo (operational 1980)	
Delivered payload:	
Optimized	52 850
Evolutionary	52 750

SUMMARY

The performances of the transportation systems are presented in table 5. The early personnel delivery requirement appears to be consistent with expected capabilities of early Saturn V product improvement. The resulting cargo delivery capability is very significant. Each of these results may be considered to be conservative, and performance in excess of that shown can be expected.

One of the most important considerations shown by the study is that of the simplicity and ease of development of the early cargo stage. This follows primarily from the fact that the subsystems previously discussed are developed or are in an advanced state of development.

Finally, the study has provided a logical approach to obtaining a direct cargo delivery capability by 1975, with growth potential to a direct personnel delivery system. The payload and volume requirements for lunar exploration and exploitation can be supplied by an economical upper stage for which existing hardware and technology are available at very modest cost.

REFERENCE

ANON.: Improved Lunar Cargo and Personnel Delivery System Study. Contract NAS 8-21006, Lockheed Missiles & Space Co.

Page intentionally left blank

ROBERT S. NOVOSAD
Martin Marietta Corp.
Denver, Colo.

Integration of Expected Extraterrestrial Resources Into the Design of Space Transportation Systems

An evaluation of the benefits derived from the utilization of lunar materials as propellants for space systems is based on a logistics study. Various methods and opportunities to supply the materials required by a space program at various locations in space are examined. These include a number of different propellants with several sources and manufacturing processes as well as modes of delivery. The requirements are resolved into launch requirements from Earth and are used as a basis for comparing the alternatives that may be available. The paper integrates the results of previous mission analyses with logistics studies and treats a number of cases, some of which are shown to be promising.

INTRODUCTION

Potential value of lunar material as a source of propellant for space transportation systems is a function of three unknowns:

(1) The resources available on the Moon.

(2) The transportation system that will use the propellant.

(3) The space program of the era during which it first becomes feasible to use lunar material.

In view of the unknowns, any plan made today to exploit lunar material will probably be wide of the mark. However, it is not too early to explore the possibilities, because these can justify and guide the exploratory phase of the lunar program in which we find ourselves today. The Moon's geological history is quite different from that of the Earth, and as a consequence materials suitable for propellant manufacture are apt to differ greatly from material from Earth. Some possibilities are:

(1) Crater bottoms and caves near the poles of the Moon could be very cold, and deposits of ice, solid carbon dioxide, ammonia, etc., could have collected there. There is also the possibility of large permafrost areas containing subsurface ice.

(2) Pockets of helium produced as a radioactive decay product could occur in the interior.

(3) Water of crystallization might be present in certain materials.

(4) Volcanos may still be active, and emissions of water, ammonia, hydrogen sulfide, etc., could supply needed raw materials.

(5) Minerals that do not occur naturally on the Earth might be a suitable propellant source. Metallic compounds, for example, could be better than water as a source of hydrogen.

(6) Basaltic-type materials, whose presence is indicated, could be processed.

(7) Many surface rocks appear highly porous, and the voids are most likely filled with gases (ref. 1).

In view of the uncertainties, this paper will treat many possibilities and will indicate the circumstances under which use of lunar propellant sources will become profitable. In making effectiveness evaluations of propulsion systems based on extraterrestrial resources, one must account for—

(1) Propulsion performance as calculated from specific impulse, structure factors, boiloff, and fuel transfer requirements.

(2) Materiel requirements that support manufacture, storage, and transportation of the propellant to the point in space where it will be used. Production efficiency will depend heavily on the quantities produced.

(3) Facilities to support personnel that include materials, transport, and erection.

(4) Cost of recovery of the propulsion system and the propellant tanks used in delivery from lunar sources.

Methods for evaluating Earth-based systems treat these items independently. This cannot be done here because the most likely benefit comes from lowering the transportation cost listed under (2) above. This must be traded off against degraded values in almost all the other categories. It will also be seen that the possible benefits are highly dependent on the types and numbers of space flights. Therefore the evaluation will be done in the context of a number of scenarios depicting possible space programs of the future.

Much background information on the subject is given in references 1 to 9.

MISSION DESCRIPTIONS

The analysis will be made in the context of two basic space missions with variations given of each. The first is a manned planetary voyage with the spacecraft assembled in Earth orbit. We are not too concerned with what happens at the destination planet or with the details of the spacecraft or its payload. We are concerned with—

(1) The weight breakdown of the space transportation system

(2) Propellants that can be provided from lunar sources and the associated operations.

(3) Assembly and logistic weight burdens.

The other basic mission is the establishment of a lunar base and its resupply. The possibility of using lunar resources for the propulsion of a shuttle is to be investigated and compared with a wholly Earth-based propellant supply.

Much attention will be paid to the method of analysis, and it is convenient to treat both missions in terms of a single framework. Therefore, consider a mission composed of the following maneuvers (see fig. 1):

1. A launch from the Earth's surface E delivering a payload to a rendezvous point R.
2. A launch from the Earth's surface E to the lunar surface L.

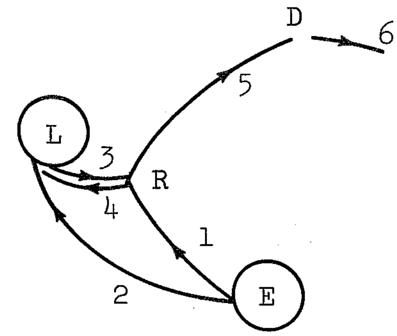


FIGURE 1.—Schematic of maneuvers.

3. Transportation of supplies (propellant) from the lunar surface L to the rendezvous point R.
4. Return from the rendezvous point R to the lunar surface L.
5. A flight from the rendezvous point R to the destination D, which would be either the vicinity of the planet or a return to Earth.
6. A further maneuver (possibly capture by the planet).

In reference 2, it was shown that the cislunar libration point is well suited for the rendezvous point R, and the high-orbit rendezvous to be treated herein can be considered to take place at this point.

The following notation will be used:

N	The maneuver number, $N=1, 2, 3, 4, 5, 6$
W_{PN}	Weight of payload on maneuver N
W_{PRN}	Weight of propellant on maneuver N
W_{VN}	Weight of vehicle (dry) on maneuver N
W_{TN}	Weight of propellant tanks (dry) on maneuver N
W_{BN}	Weight of burden on maneuver N; a part of W_{PN} (the burden consists of tools and supplies needed for an assembly operation performed after the maneuver)
W_{FN}	The final weight of system after maneuver N; $W_{PN}+W_{VN}$
K_N	The ratio $W_{VN}/W_{PRN}=(W_{FN}-W_{PN})/W_{PRN}$
K'_N	Ratio W_{TN}/W_{PRN}

$H_{1,5}$ Ratio W_{B1}/W_{PR5}

a Rate of propellant manufacture needed to supply this mission divided by the rate of propellant manufacture needed to supply all users

M Weight of mining and processing equipment needed to produce propellant

b Logistic requirements needed for propellant manufacture divided by logistic requirements needed for all activities of the base

L Weight of all logistic requirements of the lunar base (so bL is the weight prorated to propellant manufacture)

ΔV_N Change in velocity requirement by maneuver N

I_{SPN} Specific impulse of propulsion system used in maneuver 4.

We shall use set theoretic notation as follows:

$P3 \cap PR5$ that part of the payload P of maneuver 3 that is propellant PR for maneuver 5.

Then the compositions of the transportation systems used on the maneuvers have the appearance shown in figure 2.

The payload weights to be delivered are:

Type	Frequency, mo/yr	Payload, lb
Planetary	1	200,000.
Lunar shuttle	12	28,000 to Moon. 3,000 to Earth.

The planetary payload is an average derived from many studies of a Mars capture mission, and the lunar shuttle is intended to supply a 30-man base.

In figure 2, note that the payload for maneuver 1 is composed of—

(1) Part of the payload $P4$ for maneuver 4
(2) The burden $B1$ (assembly expendables)
(3) The vehicle (dry) for maneuver 5
(4) The payload for maneuver 5

The horizontal separation of the payload of maneuver 2 indicates that the vehicles $V3$ and $V4$, the mining and processing equipment M, and the logistic resupplies L are to be shared with missions other than the one under consideration.

We are faced with some 77 parameters or variables, of which 16 are input parameters and the others are to be calculated. In view of the uncertainty as to resource availability, the many alternative routes that the national space program may follow, and the technology of the era, a narrative encompassing all the situations worthy of analysis would fill a book. Instead of this, table 1 is presented as an overview of the factors influencing the missions (and, hence, influencing the input parameters, which for present purposes describe the mission).

In the same way, table 2 takes the place of a description of all the parameters, their significance, and how their values may be influenced by the inputs.

The analytic methods are a combination of straightforward space flight mechanics, some algebra, and logistic computations. Considerable use was made of the relations derived in reference 2 for the flight mechanics and in reference 3 for the logistics.

Maneuvers 3, 4, 5, and 6 are analyzed with the use of the rocket equation. For maneuver 5, for example, the weight of the initial system

$$W_{15}=W_{F5} \exp (\Delta V_5/gI_{SP5}) \tag{1}$$

Then

$$W_{PR5}+K_5W_{PR5}+W_{P5}=(K_5W_{PR5}+W_{P5}) \exp (\Delta V_5/gI_{SP5})$$

where

$$K_N=(W_{FN}-W_{PN})/W_{PRN} \tag{2}$$

and so

$$W_{PR5}=\Phi(5)W_{P5} \tag{3}$$

where one uses the abbreviated notation

$$\Phi(N)=\frac{\exp (\Delta V_N/gI_{SPN})-1}{1+K_N-K_N \exp (\Delta V_N/gI_{SPN})}$$

Requirements for maneuver 6 are calculated in exactly the same way. When velocity requirements are given in terms of hyperbolic excess speeds, the charts in reference 2 can be used.

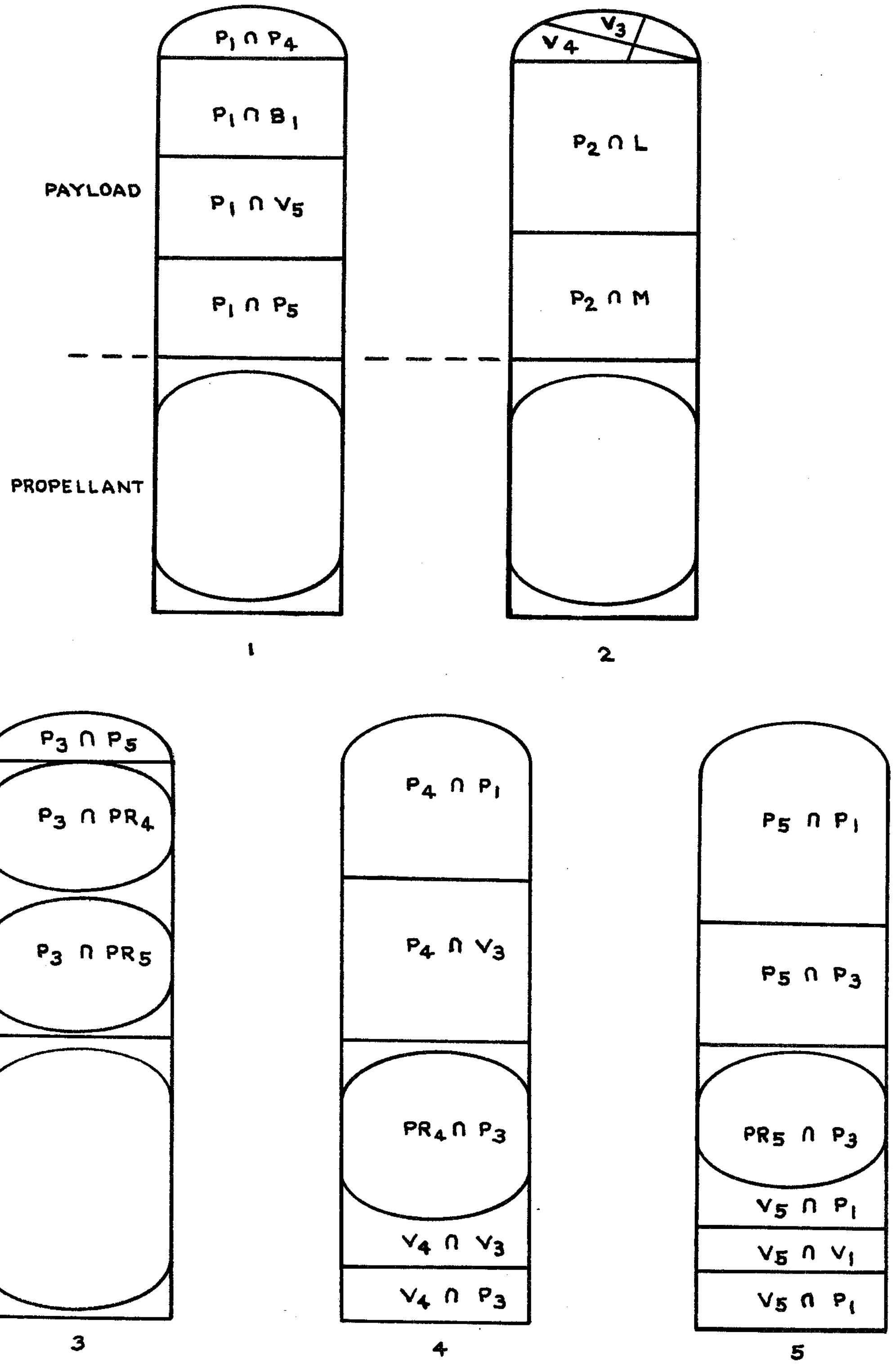


FIGURE 2.—Payload distribution.

TABLE 1.—*Input Parameters*

Uncertainty	Parameters	Symbols	Remarks
Space program level of activity.	Mission-dependent factors.	W_{P5}	Large value for ambitious manned planetary mission, additional maneuvers.
		ΔV_1 to ΔV_6	Depends on rendezvous point, destination, lunar launch site, etc. Large for fast missions.
	Space-program-dependent factors.	a	Small if resource is used widely in addition to use for propellant by this mission.
		b	Small if propellant manufacture is small part of total lunar effort.
		M	Increases with rate of propellant production. Large for difficult or inefficient processes. (Silicate reduction).
		L	Increases with size of lunar base.
		W_{P4}, W_{P5}	Increases with size of lunar base.
Era during which mission takes place.	Propulsion technology.	I_{SP1} to I_{SP5}	Large for a variety of nuclear developments. Small for low-performance propellants such as H_2O, NH_3.
	Design	K_1 to K_5; K_3', K_4' K_5'	Small for efficient design, advanced materials. Large for nuclear systems, artificial gravity.
	Mining and processing technology.	M	Small for efficient processes of fluid handling as opposed to solids. Make use of vacuum. Depends strongly on resource availability. Small for automated processes.
	Space operations	$H_{1,5}$	Small for efficient assembly, propellant transfer.
Resource availability.	Mining and processing technology.	M, b	Small for readily available, readily usable materials.

TABLE 2.—*Mission Parameters*

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
W_{P1}	Payload weight	1	Relates to number of space vehicle launches required.	Choice of R, W_{P4}, assembly needs.	(15)
W_{P2}	Payload weight	2	Relates to number of space vehicle launches required.	Prorating among lunar base activities; processing and mining weight M.	(13)
W_{P3}	Payload weight	3	Focus of study	Propellant needs at R; Moon-to-Earth traffic rate.	(4)
W_{P4}	Payload weight	4	Tank recovery lunar transport.	Structural efficiency; base resupply rate.	(5)
W_{P5}	Payload weight	5	Scopes mission	Mission objectives; payload delivered to destination.	Input
W_{PR3}	Propellant weight	3	Tradeoff variable	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(8)
W_{PR4}	Propellant weight	4	Recovery penalty	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(7)
W_{PR5}	Propellant weight	5	Focus of study	Transportation system I_{SP}, ΔV, boiloff, leakage, cooldown.	(3)

TABLE 2.—*Mission Parameters*—Continued

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
W_{F3}	Final weight (dry)	3	Weight delivered to *R* from Moon.	Degree of automation, propellant transfer methods.	
W_{F4}	Final weight (dry)	4	Shuttle system weight landed on Moon.	Degree of automation, propellant transfer methods, tank structure.	
W_{F5}	Final weight (dry)	5	Mission effort	Payload, structural efficiency, propellant density, insulation.	
W_{I3}	Initial system weight	3	Launch weight from Moon.	Propellant requirements of final mission manuevers.	(1)
W_{I4}	Initial system weight	4	Moves back to Moon.	Lunar shuttle, tank recovery scheme.	(1)
W_{I5}	Initial system weight	5	Orbital launch weight.	Fixed by mission and choice of transportation system, boiloff.	(1)
K_3	Empty vehicle to propellant ratio.	3	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	(2)
K_4	Empty vehicle to propellant ratio.	4	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	
K_5	Empty vehicle to propellant ratio.	5	Accounts for structural weight.	Design efficiency, propellant density, max. acceleration, insulation engine size.	(2)
W_{B1}	Weight used in assembly at *R*.	1	Part of Earth liftoff weight.	Assembly methods, degree of modularity.	
K'_4	Ratio of propellant tank weight to propellant weight.	4	Determines payload for maneuver 3.	Design, propellant density, insulation.	(4)
K'_5	Ratio of propellant tank weight to propellant weight.	5	Determines payload for maneuver 3.	----------	(4)
$H_{1,5}$	The ratio W_{B1} to W_{PR5}.	1	Payload on 1 can be related to propellant on 5.	Assembly operations at *R*	(15)
a	The ratio of propellant used in this mission to all propellant produced by the base.	----------	Prorates mining and processing equipment.	Level of lunar-base activity using resource, other missions using resource.	(13)
b	Logistic requirements ratio propellant production to total.	----------	Prorates logistic weights transported to Moon.	Overall lunar activity; manpower required for propellant production.	(13)
M	Weight of supplies sent to Moon.	2	Weight delivered to Moon.	Type of production process, rate of production.	(12)
L	Weight of supplies sent to Moon.	----------	Weight delivered to Moon.	Lunar-base activity	(13)
ΔV_1	Change in velocity	1	Energy requirement	Assembly point *R*	Input
ΔV_2	Change in velocity	2	Energy requirement	Location of lunar base *L*	Input
ΔV_3	Change in velocity	3	Energy requirement	*R* and *L*	Input
ΔV_4	Change in velocity	4	Energy requirement	*R* and *L*	Input
ΔV_5	Change in velocity	5	Energy requirement	*R* and mission final destination *D*.	Input

TABLE 2.—*Mission Parameters*—Continued

Symbol	Represents—	Maneuver	Significance	Influenced by—	Equation
I_{SP1}	Specific impulse	1	Determine propellant weight.	Propulsion system technology.	Input
I_{SP2}	Specific impulse	2	Determine propellant weight.	Propulsion system technology.	Input
I_{SP3}	Specific impulse	3	Determine propellant weight.	Type of resource available	Input
I_{SP4}	Specific impulse	4	Determine propellant weight.	Type of resource available	Input
I_{SP5}	Specific impulse	5	Determine propellant weight.	Type of resource available	Input

The payload for maneuver 4 includes the vehicle for maneuver 3 and the payload of maneuver 3 contains the tanks and propellant for maneuver 4. Consequently a pair of simultaneous equations must be solved. Consider first the case where the tanks carrying propellant for maneuver 5 are not returned to the Moon but become part of vehicle $V5$.

$$W_{P3}=W_{PR4}+W_{T4}+W_{PR5}+W_{T5}=(1+K_4')W_{PR4}+(1+K_5')W_{PR5} \quad (4)$$

where

$$K_4'W_{PR4}=W_{T4}$$

Also

$$W_P=W_{T3} \quad (5)$$

Using the rocket equation again

$$W_{PR3}=\Phi(3)W_{P3}=\Phi(3)[(1+K_4')W_{PR4}+(1+K_5')W_{PR5}]$$

and assuming $K_4'=K_5'$ (i.e., the same structure factor for the two maneuvers)[1]

$$W_{PR3}=\Phi(3)(1+K_4')(W_{PR4}+W_{PR5}) \quad (6)$$

and if the tanks carrying propellant for maneuver 5 become part of vehicle 5

$$W_{PR4}=\Phi(4)W_{T3}=K_3'\Phi(4)W_{PR3} \quad (7)$$

Then substituting equation (7) into equation (6) and setting $K_3'=K_4'$.[1]

[1] This assumes that the ratios of tank to propellant weights are the same for maneuvers 3, 4, and 5; this is not a bad assumption since the propellants are the same in each case.

$$W_{PR3}=\frac{\Phi(3)(1+K_4')}{1-(1+K_4')K_3'\Phi(3)\Phi(4)}$$

$$W_{PR5}=\frac{(1+K_3')\Phi(3)\Phi(5)}{1-(1+K_3')K_3'\Phi(3)\Phi(4)}W_{P5} \quad (8)$$

If the tanks carrying propellant for maneuver 5 are returned to the Moon (and the propellant is transferred to other tanks), instead of equation (5), we have $W_{P4}'=W_{T3}+W_{T5}$, and, instead of equation (7), we have, using W_{PR3}' as the new propellant for maneuver 3,

$$\begin{aligned}W_{PR4}'&=\Phi(4)(W_{T3}+W_{T5})\\&=\Phi(4)(K_3'W_{PR3}'+K_5'W_{PR5})\\&=K_3'\Phi(4)(W_{PR3}'+W_{PR5})\end{aligned} \quad (9)$$

Setting $K_3'=K_4'$ and $\Phi(3)=\Phi(4)$ (the return trip has the same ΔV, I_{SP}, and K factor), we get instead of equation (8)

$$W_{PR3}'=\Phi(3)(1+K_3')\frac{1+K_3'\Phi(3)}{1-(1+K_3')K_3'\Phi(3)}2$$

$$W_{PR5}=[1+K_3'\Phi(3)]W_{PR3} \quad (10)$$

which is a convenient form because we intend to calculate W_{PR3} prior to W_{PR3}'.

If additional payload W_{P4} is delivered on maneuver 4 in addition to the return of tanks W_{T5} and the shuttle W_{V3}, equation (10) becomes

$$W_{PR3}''=\frac{\Phi(3)\{(1+K_3')[\Phi(4)(K_3'W_{PR5}+W_{P4})+W_{PR5}]+W_{P3}\}}{1-\Phi(3)\Phi(4)K_3'(1+K_3')} \quad (11)$$

The propellant requirements for maneuvers

3, 4, and 5 can now be expressed in terms of the payloads to the destinations. Relations between propellant manufacturing rates and mining, basing, and processing weights are given in reference 3. In order to use these charts to calculate the weight of material to be delivered to the Moon, two things must be done:

(1) Total requirements for propellant must be translated into rates of production.

(2) Production rates must be prorated to various requirements.

These depend on the ability and cost of storing propellant and the total activity at the lunar base. Instead of attempting to solve these problems, we introduct the notation a, M, b, and L listed in table 2 and then treat these terms parametrically.

Then the payload for maneuver 2 becomes

$$W_{P2}=aM+abL+c(W_{V3}+W_{T4})$$

where

$c=1\div$the number of uses of the vehicle used in maneuver 3

The relations in reference 3 are linear, so by introducing a proportionality constant J to relate propellant production to weight of equipment used to produce that propellant and by introducing a constant K to relate propellant production to logistics requirements, we get

$$\begin{aligned} J(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})&=M \\ K(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})&=bL \end{aligned} \tag{12}$$

where $\overline{W}_{PR3}$ denotes the yearly rate of propellant consumed by maneuver 3. Then

$$W_{P2}=a(J+bL)(\overline{W}_{PR3}+\overline{W}_{PR4}+\overline{W}_{PR5})+c(W_{V3}+W_{T4}) \tag{13}$$

Instead of using the rocket equation to determine the initial weight (weight at launch), we use performance curves for the launch vehicle, in this case the Saturn V, to determine the number of launches required. Using the lunar logistics vehicle on top of the Saturn V, 28 500 pounds can be landed on the Moon (ref. 4). Therefore dividing W_{P2} by 28 500 gives the number of launches required. Fractional launches make sense in this context because we assume other lunar activities that would use up the additional payload capacity. The number of Saturn V launches used on maneuvers 1 and 2 to be ascribed to the missions are:

$$N_2=W_{P2}/28\,500 \tag{14}$$

A lunar landing vehicle other than the one envisioned gives a different constant as a divisor. The consequence will be discussed later.

The payload of maneuver 1 consists of the mission payload, the vehicle used in maneuver 5, and the weight burden needed to carry out the assembly operations at the rendezvous point R. This is given by

$$\begin{aligned} W_{P1}&=W_{P5}+W_{V5}+W_{B1}+W_{P4}=W_{I5}-W_{PR5}+W_{B1}+W_{P4} \\ &=W_{P5}+K_5W_{PR5}+H_{1,5}W_{PR5}+W_{P4} \\ &=[1+(K_5+H_{1,5})\Phi(5)]W_{P5}+W_{P4} \end{aligned} \tag{15}$$

The Saturn V can deliver about 100 000 pounds to the cislunar libration point. If this point is chosen for the rendezvous point R, the number of Saturn V launches required for maneuver 1 is

$$N_1=W_{P1}/100\,000$$

However, W_{P4} should not be ascribed to the planetary mission, so that the number of Saturn V launches to be assigned to this mission is

$$N_1=(W_{P1}-W_{P4})/100\,000$$

SCOPE

One purpose of this paper was to treat cases other than those already appearing in the literature and to give something more specific than a parametric treatment. Therefore these propellants were considered:

Liquid hydrogen-oxygen-chemical:
$I_{SP}=444$ sec
Methane-nuclear:
$I_{SP}=400$ sec
Ammonia-nuclear:
$I_{SP}=400$ sec

Water-nuclear:

$I_{SP}=300$ sec

Helium-nuclear:

$I_{SP}=600$ sec

Hydrogen-nuclear:

$I_{SP}=830$ sec

The methane and ammonia yield values of I_{SP} that are close and overlap in some cases depending on the temperature of the reactor (ref. 5); therefore, they were treated as one case. The water-nuclear system proved to be inferior for the planetary mission and was not investigated in depth.

The planetary mission had two versions, a slow and a fast trip with the following velocity requirements:

(1) Slow: two impulses with V_∞ of 0.1 EMOS each

(2) Fast: two impulses with V_∞ of 0.15 EMOS each

The propellant for the return trip was considered part of the payload of the final maneuver. No essential difference would occur if the total excess velocity V_∞ (0.2 EMOS, slow, and 0.3 EMOS) were partitioned in different ratios between the two impulses.

The departure from Earth was considered in three modes:

(1) HO, departure from a high orbit, specifically the cislunar libration point.

(2) LO, departure from a low circular orbit, specifically a 250-kilometer altitude.

(3) EO, departure from an eccentric orbit, specifically a 60×1.1 Earth radii ellipse.

Rendezvous of the lunar and Earth originating stages was assumed to take place in the departure orbits. This poses operational difficulties in the EO case. However, the penalty paid for rendezvous at the cislunar libration point and transferring the entire transportation system into the elliptic orbit is not too large. Figure 3 illustrates the three alternate Earth departure orbits.

The lunar mission was treated in three versions in which—

(1) The lunar shuttle and Earth shuttle rendezvous at the cislunar libration point

(2) The shuttles rendezvous in low Earth orbit

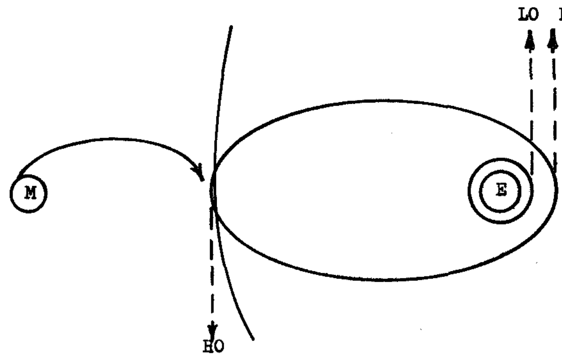


FIGURE 3.—Orbital launch modes.

(3) One shuttle operates between the Moon's surface and the Earth's surface

Version (2) was ruled out as too wasteful of propellant and version (3) was used mainly with the no-lunar-material baseline mode.

Four processes for obtaining propellant were considered:

(1) Oxygen by silicate reduction (refs. 3 and 8).

(2) Hydrogen and oxygen from electrolysis of permafrost water (ref. 3).

(3) Hydrogen and oxygen from pure water (ref. 3).

(4) Ammonia, methane, water, or helium from a gas drilling operation perhaps supplemented with a nuclear underground blast to open up the rock.

In order to carry out the analysis outlined in the previous section, values of J and L are needed. These were derived from 1-, 2-, and 5-year equipment lifetime from charts given in reference 3 as shown in table 3.

Benefits from the 5-year life of equipment are limited by a maximum of 2-year life of the powerplant fuel elements. Figures 4 to 6 give the processing equipment weight as a function of propellant production rates. If the propellant is used at the production, the process must be represented by a point below the broken 45° line shown in these figures. If the propellant must be transported prior to use, the point must lie considerably below the 45° line. The values for L in table 3 represent the resupply requirements for 1 year, in pounds.

TABLE 3.—*Processing Coefficients*

Process	Coefficient, lb/lb/yr, for—			[a]L, lb
	J (1 yr)	J (2 yr)	J (5 yr)	
1	1.06	0.51	0.48	27 000×NM[a]
2	.78	.40	.33	27 000
3	.45	.22	.19	27 000
4	.31	.16	.13	27 000
5	.017	.008	.003	27 000

[a] NM=number of men used in process.

RESULTS

Table 4 shows the propellant requirements for different versions of the planetary mission. Weight is given in kilopounds. The departure from low orbit was set up to calculate direct Earth supply only and has been omitted from several of the versions which apply to lunar refueling. As expected, the hydrogen-nuclear system provides the best performance.

By using totals given in table 4 and the relations in figures 4 to 6, we can calculate equipment weights that must be delivered to the Moon if we use the various propellant manufacturing processes. Results are shown in table 5 with the equipment sized to take care of the mission versions indicated.

A summary of the lunar-shuttle mission propellant weights is given in table 6 for the cislunar rendezvous mode only when this proved superior to the other modes. Again the hydrogen-nuclear propulsion is superior, but, of course, the processing penalties have not

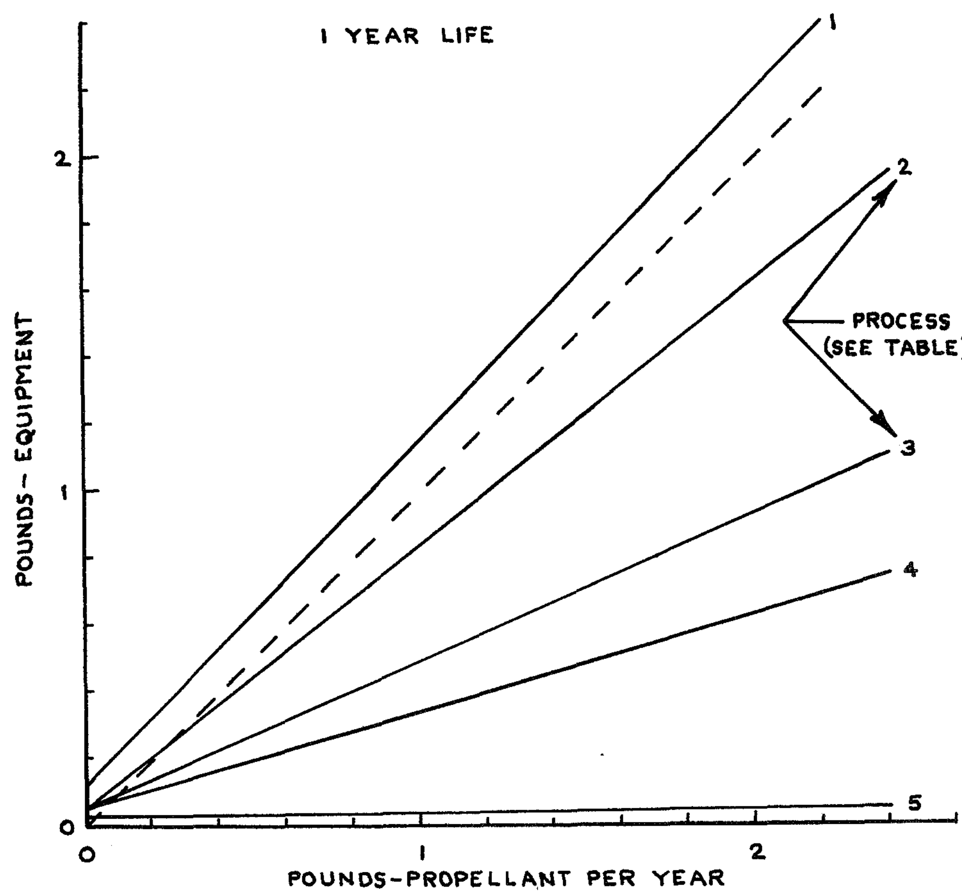


FIGURE 4.—Processing equipment weight against propellant weight for 1-year equipment life.

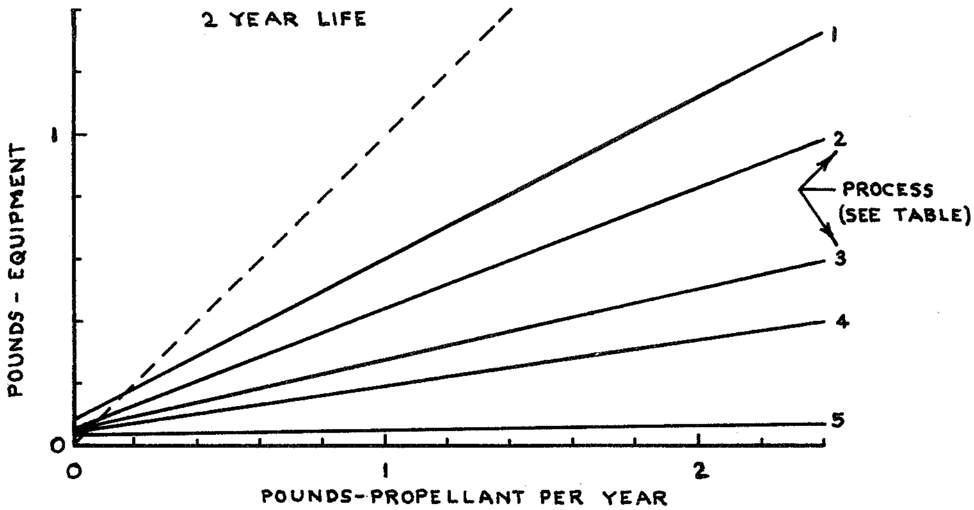


FIGURE 5.—Processing equipment weight against propellant weight for 2-year equipment life.

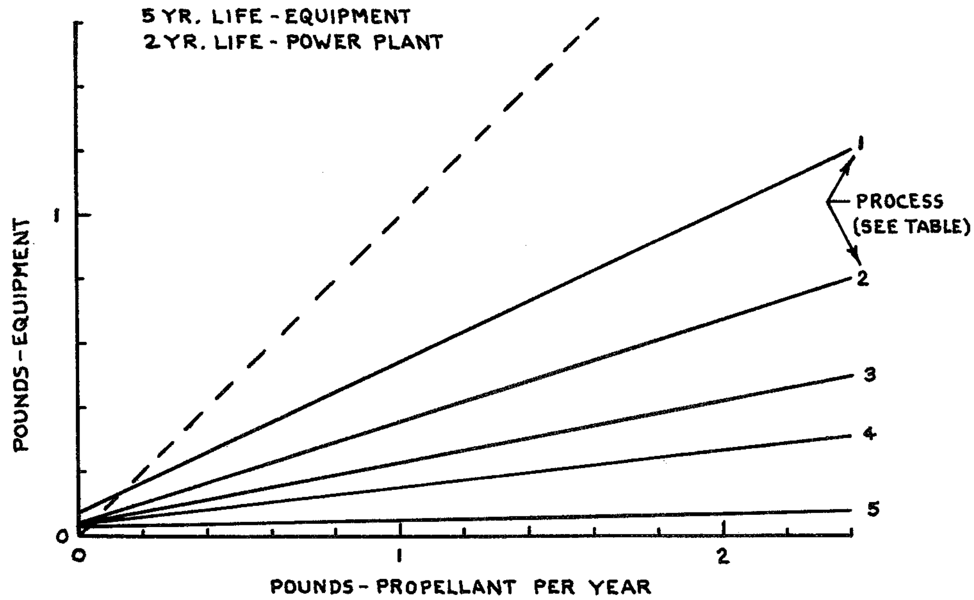


FIGURE 6.—Processing equipment weight against propellant weight for 5-year equipment life.

yet been included. Using figures 4 to 6, we get the equipment weights shown in table 7. The figures in parentheses under the column labeled "5-yr life" represent the number of Saturn V flights needed to deliver the equipment. In addition to the number needed for delivery of equipment, 4.6 Saturn V flights are needed per year to deliver payload from the Earth to the rendezvous point *R*.

Lunar supply is most beneficial to large-scale

324-954 O—69——14

TABLE 4.—*Propellant Consumption for Different Versions of the Planetary Mission*

Version	Propulsion	Trip	Orbit	Consumption, klb				
				W_{PR6}	W_{PR5}	W_{PR4}	W_{PR3}	Total
1a		Slow	HO	143	267	309	21	740
1b			LO	143	520	--------	--------	--------
1c			EO	143	40	231	23	437
1d	H_2-O_2 chemical	Fast	HO	278	812	867	50	2006
1e			LO	985	--------	--------	--------	--------
1f			EO	130	515	51	974	--------
2a	CH_4 nuclear	Slow	HO	171	330	500	42	1053
2b			EO	171	54	362	36	623
3a		Slow	HO	106	305	214	30	645
3b	He nuclear		EO	106	33	112	17	225
3c		Fast	HO	172	390	296	38	887
3d			EO	172	83	211	31	499
4a		Slow	HO	72	97	63	3	256
4b			EO	72	16	47	3	--------
4c	H_2 nuclear	Fast	HO	108	215	116	6	445
4d			LO	108	258	--------	--------	--------
4e			EO	108	41	50	5	204

TABLE 5.—*Equipment Weights Needed To Supply Planetary Mission Propellant*

Mission version	Propellant used, lb	Propellant process	Equipment weight per year, W_{P2}, lb [a]		
			1-yr life	2-yr life	5-yr life
1a	0.740×10^6	1. Si reduction	0.90×10^6 (31)	0.48×10^6 (17)	0.44×10^6 (15)
		2. 25 percent H_2O	.65	.34	.28
		3. 50 percent H_2O	.38	.22	.18
		4. 100 percent H_2O	.27	.16	.13 (4.5)
1c	.437	4. 100 percent H_2O	.17	.10	.08
1d	2.006	4. 100 percent H_2O	.63 (22)	.33 (12)	.27
1f	.974	4. 100 percent H_2O	.33	.18	.14
2a	1.053	5. Gas drill	.045 (1.6)	.030	.024
3a	.645	5. Gas drill	.037	.026 (1)	.022
3c	.877	5. Gas drill	.041	.029	.023

[a] Numbers shown in parentheses in selected cases give the number of Saturn V flights needed to move the indicated weight.

operations and in particular is not too favorable to the planetary mission when no lunar shuttle mission is flown. Therefore, combining the monthly lunar shuttle flight with a yearly planetary flight, the propellant consumption is given in table 8 by combining the totals from tables 4 and 6. The version 1*a*+1 shown in table 8 combines totals from mission version 1*a* from table 4 with totals in line 1 from table 6, etc. Again equipment weights are calculated with the aid of figures 4 to 6.

In order to point up the relative merits of

TABLE 6.—*Lunar Shuttle Propellant Consumption*

Mission version	Propulsion	Consumption, klb				
		W_{PR5}	W_{PR4}	W_{PR3}	Total	Total×12
1	H_2-O_2 chemical	6.5	20.4	20.9	47.8	574
2	CH_4 nuclear	7.1	25.3	31.4	63.8	765
3	He nuclear	5.3	13.6	10.6	29.5	354
4	H_2 nuclear	3.4	8.8	2.9	15.1	181

TABLE 7.—*Equipment Weights for Propellant Used by Lunar Shuttle*

Mission version	Propellant used per yr, lb	Propellant process	Equipment weight per yr, W_{P2}, lb		
			1-yr life	2-yr life	5-yr life
1	0.574×10^6	1	0.71×10^6	0.38×10^6	0.34×10^6 ([a]8.7)
		2	.50	.27	.22 ([a]5.6)
		3	.30	.17	.16 ([a]4.1)
		4	.21	.12	.10 ([a]2.5)
2		5	.040	.027	.023 ([a].59)
3		5	.032	.024	.022
4		4	.029	.022	.021

[a] Number of Saturn V flights per year needed to deliver equipment.

selected mission-propellant manufacture combinations, the number of Saturn V flights required for the missions has been plotted in figure 7. The labels on the bars in figure 7 are explained below. The first number indicates the production process as given in table 3. The second number in a pair below indicates equipment life; for example, (4,5) connotes 5-year life for 100 percent H_2O propellant process.

Slow planetary:
- (0,–) Earth supply, LH_2, LOX chemical propulsion
- (1,1) Silicate reduction
- (4,5) Electrolysis of water, 100 percent water
- (5,2) Gas drill, helium nuclear propulsion

Fast planetary:
- (0,–) Earth supply, LH_2, LOX chemical propulsion
- (0,–) Earth supply, H_2, nuclear propulsion
- (4,1) Electrolysis of water, 100 percent water
- (4,2) Electrolysis of water, 100 percent water
- (5,2) Gas drill, helium nuclear

Lunar supply:
- (0,–) Earth supply, lunar lander, LH_2, LOX
- (0,–) Earth supply, lunar shuttle, LH_2, LOX
- (1,5) Silicate reduction
- (2,5) Electrolysis of water, 25 percent permafrost
- (3,5) Electrolysis of water, 50 percent permafrost
- (4,5) Electrolysis of water, 100 percent water
- (5,5) Methane, nuclear, gas drill

Lunar supply plus slow planetary:

TABLE 8.—*Total Propellant Consumption and Process Equipment Weight*

Mission versions	Propellant used, lb	Propellant process	Equipment weight per year, W_{P2}, lb		
			1-yr life	2-yr life	5-yr life
1*a*+1	1. 31×10[6]	1. Si reduction	1. 5×10[6]	0. 76×10[6]	0. 70×10[6]
		2. 25 percent H_2O	1. 1	. 56	. 46
		3. 50 percent H_2O	. 64	. 34	. 29
		4. 100 percent H_2O	. 43	. 23	. 19
1*c*+1	1. 01	1. Si reduction	1. 6	. 60	. 54
		2. 25 percent H_2O	. 84	. 43	. 36
		3. 50 percent H_2O	. 50	. 28	. 23
		4. 100 percent H_2O	. 34	. 19	. 15
1*d*+1	2. 58	1. Si reduction	3. 0	1. 5	1. 4
		2. 25 percent H_2O	2. 2	1. 1	. 92
		3. 50 percent H_2O	1. 3	. 67	. 57
		4. 100 percent H_2O	. 85	. 45	. 37
1*f*+1	1. 55	1. Si reduction	1. 75	. 88	. 80
		2. 25 percent H_2O	1. 3	. 66	. 53
		3. 50 percent H_2O	. 75	. 40	. 34
		4. 100 percent H_2O	. 50	. 27	. 21
2*a*+2	1. 82	5. Gas drill	. 061	. 038	. 027
2*b*+2	1. 39	5. Gas drill	. 053	. 035	. 026
3*a*+3	1. 0	5. Gas drill	. 045	. 030	. 024
3*b*+3	. 58	5. Gas drill	. 037	. 026	. 022
3*c*+3	1. 25	5. Gas drill	. 050	. 032	. 025
3*d*+3	. 85	5. Gas drill	. 042	. 028	. 023
4*a*+4	. 44 ([a]3. 9)	4. 100 percent H_2O	1. 36	. 76	. 60

[a] Water processed to get required H_2.

(0,–) Earth supply, lunar lander, LH_2, LOX
(0,–) Earth supply, lunar shuttle, LH_2, LOX
(3,5) LH, LOX 50 percent permafrost, shuttle, libration rendezvous
(3,5) LH, LOX 50 percent permafrost, shuttle, eccentric rendezvous
(1,5) LH, LOX silicate reduction, shuttle, eccentric rendezvous
(1,5) LH, LOX silicate reduction, shuttle, eccentric rendezvous
(2,5) Methane, nuclear, libration rendezvous
(4,5) H_2 nuclear, 100 percent water, libration rendezvous

It can be seen that some lunar propellant schemes compare favorably with a direct Earth supply, and some unfavorably. If a nuclear propulsion system using liquid hydrogen as a propellant is developed, no advantage can be seen for lunar propellant, at least for a one-shot planetary mission similar to that which has been considered here. If the planetary craft is recoverable and can be resupplied with resources from the destination planet, the situation may reverse itself (see ref. 2). The most favorable cases using helium or methane should be compared to an Earth-based nuclear system using hydrogen as a propellant inasmuch as the technology is the same. Here, as can be seen from figure 7, the comparison is slightly favorable to the lunar source of propellant for the fast planetary mission.

For the lunar supply mission and the combined lunar supply and slow planetary missions, the comparison is much more favorable to the lunar propellant schemes. This is due to the use of much of the propellant at the Moon

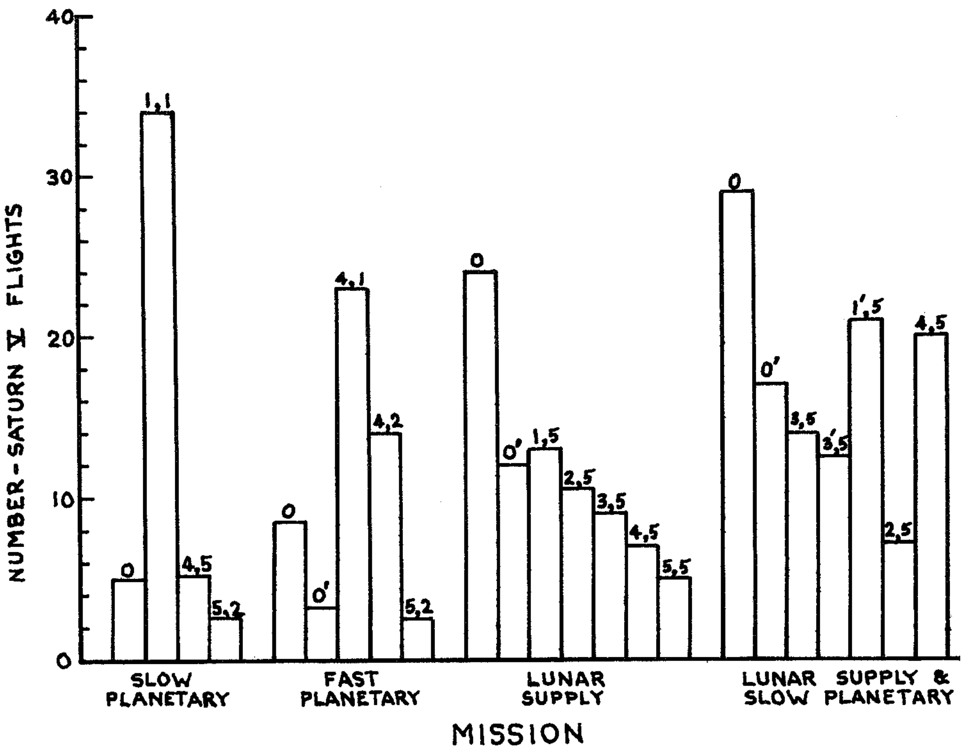


FIGURE 7.—Chart of Saturn V launches required.

and the resulting savings over transporting propellant from the Earth.

In conclusion, we return to the position stated in the introduction; namely, that too many uncertainties exist to decide at this time for or against the use of lunar resources for propellants. However, there are promising situations that could evolve as shown by the preceding analysis. Future planning for lunar exploration and exploitation should keep these situations in mind.

REFERENCES

1. O'KEEFE, JOHN; AND SCOTT, RONALD F.: Chondritic Meteorites and the Lunar Surface. Science, vol. 158, no. 3805, Dec. 1, 1967, pp. 1174–1176.
2. GILLESPIE, ROLLIN W.: Impulse Propulsion Gains Resulting From "Free" Retanking of Propellants on Various Orbits and Stations at the Earth, the Moon, Mars, and Venus. Proc. Third Working Group on Extraterrestrial Resources Annual Meeting (San Antonio, Tex.), 1964.
3. PAUL, DAVID, III: Economic Analysis of Extraterrestrial Propellant Manufacture in Support of Lunar Exploration. Advanced Systems Office, R&D Operations, Marshall Space Flight Center, NASA, Nov. 15, 1965.
4. WAGGONER, E. E.: A Comparison of Two Candidate Lunar Logistics Systems for Apollo Saturn V LLV and LEM Truck. MTP–FP–63–3, Marshall Space Flight Center, NASA, Dec. 1963.
5. BEHM, HANS J.: Results of the Ranger, Luna 9, and Surveyor 1 Missions. J. Astronaut. Sci., vol. XIV, no. 3, May 1967, pp. 101–111.
6. COLE, DANDRIDGE M.; AND SEGAL, RONALD: Rocket Propellants from the Moon. Astronaut. and Aeronaut., Oct. 1964, pp. 56–63.
7. CORLISS, WM. R.: Propulsion Systems for Space Flight. McGraw-Hill Book Co., Inc., 1960.
8. ROSENBERG, S. D.; GUTER, G. A.; AND ROTHENBERG, M.: Requirements for On Site Manufacture of Propellant Oxygen From Lunar Raw Materials. Proc. 3d Annual Meeting, Working Group on Extraterrestrial Resources (San Antonio, Tex.), Nov. 19, 1964.
9. SHOTTS, REYNOLD Q.: Systems for Lunar Mining. Tech. Rept. no. 24, School of Mines, Ala. State Exp. Station, Univ. of Alabama, Jan. 1968.

Page intentionally left blank

SAMUEL P. ALTMAN
General Electric Co.
King of Prussia, Pa.

Cislunar (or Earth) Swingby for Interplanetary Missions

Cislunar swingby is the basic trajectory profile which initiates heliocentric flight from the Earth-Moon system by inception from cislunar space so that the spacecraft swings close by Earth prior to injection into its interplanetary orbit. In the present paper, the energetics of this Earth swingby are compared by means of parametric curves for the four alternative options of flight inception from a highly eccentric elliptic orbit about Earth, the cislunar libration point L_1, a lunar orbit, or the lunar surface.

In a previous paper, Gillespie compared the energetics of rockets launched directly into heliocentric space from the cislunar libration point with those of rockets launched from low circular orbits about the Earth. In this present paper, it is shown that, for a given payload, the fuel mass expenditure for perigee departure from a highly eccentric orbit about Earth is almost one-half that required for launching directly from the cislunar libration point. In both cases it is assumed that the rocket is refueled by reusable tanker rockets.

A comparison of the energetics for cislunar swingby (from lunar orbit), direct transfer, and planetary swingby (from low, circular, terrestrial orbits) shows that cislunar swingby alone offers fuel savings of about 50 percent over the other two profiles. In this comparison, only an outbound leg of heliocentric flight was considered. Additional savings could be realized by the combined use of cislunar and extraterrestrial planetary swingby profiles for a complete interplanetary flight.

It is indicated that the launch window for cislunar swingby will be significantly wider than that for direct or planetary swingby flight. For the last three options described, the launch opportunities occur in "sidebands" which are distributed over the launch window as a function of the lunar period.

INTRODUCTION

The vehicle staging design of an interplanetary spacecraft is principally determined by the onboard fuel mass required for all maneuvers from inception of outbound interplanetary flight until termination of inbound flight at terrestrial orbit or surface landing. Significant fuel savings may be provided by means of planetary swingby (see ref. 1) during interplanetary flight. In addition, considerable fuel economies may be realized by effective refueling within the Earth-Moon system prior to inception of the outbound interplanetary flight. Gillespie (ref. 2) has compared the energetics of rockets launched directly into heliocentric space from the cislunar libration point, with rockets launched from low circular orbits about the Earth. In general, Gillespie has demonstrated that refueling modes within the Earth-Moon system are very advantageous and enable the design efficiency of the interplanetary vehicle staging to be impressively increased. Refueling may occur from the Moon, assuming the availability of lunar resources by lunar-surface operations, or from the Earth. The availability of the Apollo system for the retanking capability offers a realistic basis for the immediate and planned use of trajectory profiles using refueling prior to inception of the interplanetary flight.

Study of the dynamic principles behind planetary swingby and cislunar retanking indicates that a significant increase in fuel savings is generally realized by flight inception from cislunar space, remote from the Earth's surface, after refueling so that the interplanetary vehicle swings close past the Earth for injection then into heliocentric orbit. Aside from the increased efficiency of the rocket energetics, the attendant flight characteristics and subsequent system-design objectives appear quite favorable in several major aspects. This cislunar (or Earth) swingby for interplanetary missions is explored briefly in this paper by description and discussion of its outstanding performance characteristics. The realizable fuel savings are estimated as a function of the alternative and selectable classes of flight inception point, which may be located at various stable dynamic sites in cislunar space.

Cislunar swingby past Earth for launch into heliocentric orbit may be provided, as shown schematically in figure 1, from any one of four options of flight inception points:

(1) Perigee of a highly eccentric Earth orbit
(2) Cislunar libration point
(3) Lunar orbit
(4) Lunar surface

Refueling at the cislunar libration point or in lunar orbit might be provided from Earth or the Moon. Flight from the lunar surface would best utilize refueling from lunar resources, whereas refueling on the highly eccentric Earth orbit could be provided from Earth, from a cislunar-libration-point station, or even from the Moon.

The subsequent heliocentric flight in interplanetary space after cislunar swingby may be either direct to the target planet (or asteroid) or by extraterrestrial planetary swingby.

The assistance of my colleague, Josef S. Pistiner, in the preparation of this paper is gratefully acknowledged.

ROCKET ENERGETICS

The study of the complete interplanetary flight may be conducted in two discrete and successive "legs": outbound to the target planet (or planets) and return, if required. In this paper, for brevity, only the outbound leg is discussed, so that the available parametric tradeoffs are demonstrated. The outbound leg can be considered in two discrete steps:

(1) The rocket energetics within the Earth-Moon system until transition into the desired heliocentric orbit.

(2) The heliocentric transfer energetics from the point of Earth-Moon system injection into heliocentric orbit, until capture (propulsive or atmospheric), or fly by the target planet.

The rocket energetics for cislunar swingby out of the Earth-Moon system (step (1) above) from each of the four alternative inception points are presented in figures 2 and 3, in parametric form, for specific impulse $I_{sp}=444$ seconds. Comparable sets of parametric curves may be generated for other realizable values of specific impulse. The parametric format for mass-ratio tradeoff used in figure 3 is Gillespie's concise method (ref. 2) of presenting energetics working curves for system synthesis and evaluation.

With all four cases, the required velocity increment and the remaining mass (expressed in percent of initial mass) are plotted against hyperbolic excess speed in EMOS (i.e., units of Earth-mean-orbital-speed), where 1 EMOS =29.8 km/sec. Note that these working curves are dissociated from staging design variations, since the remaining mass includes the onboard fuel left after injection into heliocentric orbit, the basic rocket staging, and the payload. Tradeoff between fuel, staging, and payload of the remaining mass can then be separately evaluated and optimized.

The total velocity increment for each alternative inception of cislunar swingby was determined in accordance with the equations given below:

(1) From Earth-orbit perigee:

$$\Delta V \equiv \Delta V_{\oplus \male} = \sqrt{Ve_2 + V_{\mathrm{HBEV}}{}^2} - V_{\mathrm{swby}} \qquad (1)$$

where

Ve	parabolic escape velocity from Earth $=(2r_{\oplus}/R_{\oplus})^{1/2}$
V_{HBEV}	hyperbolic excess velocity = (heliocentric transfer injection velocity) − (Earth's mean heliocentric velocity)
V_{swby}	Earth swingby velocity $\equiv V_P$
$R_{\oplus}$	Earth's spherical radius

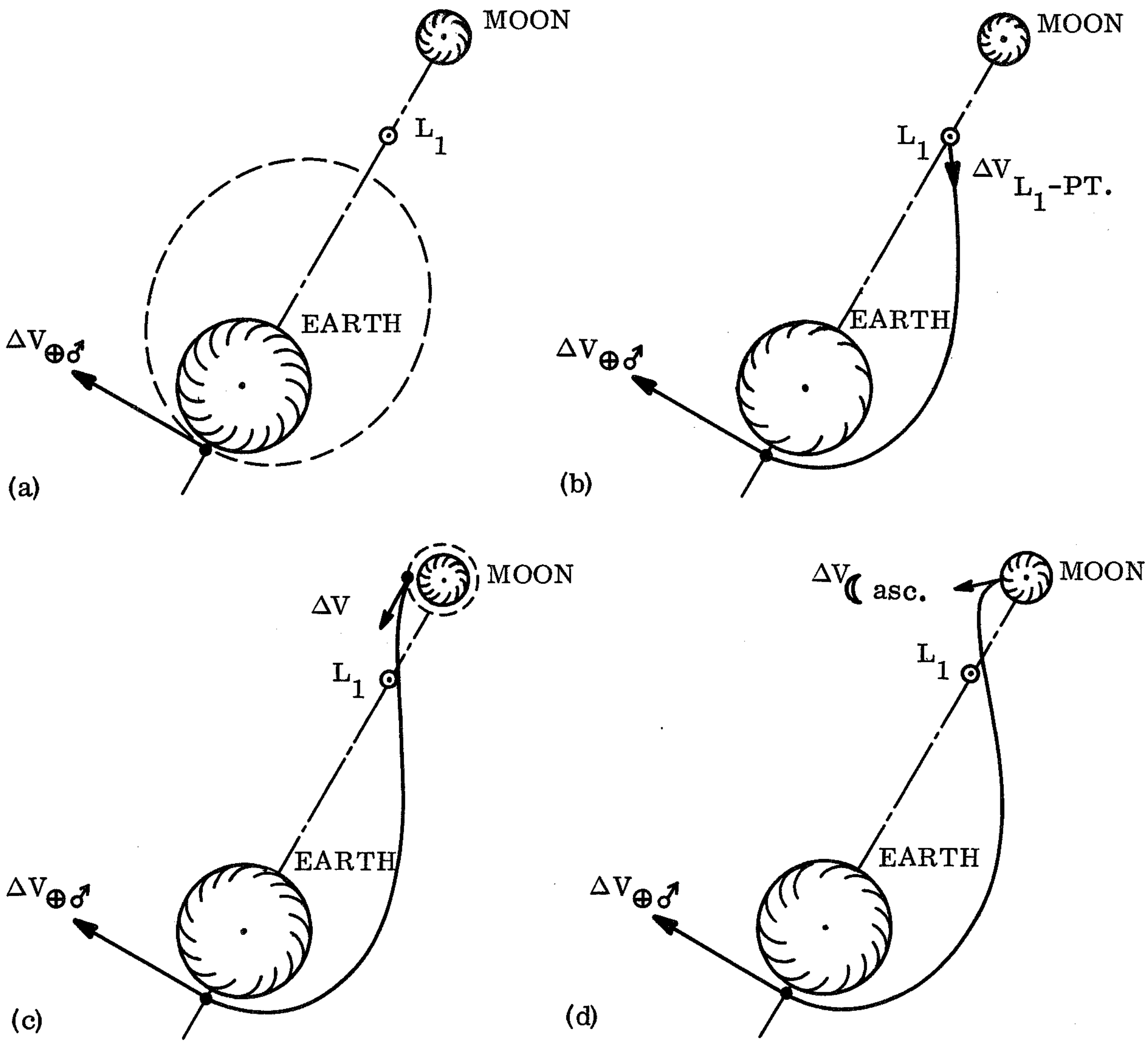


FIGURE 1.—Options of cislunar swingby inception (schematic only).

(*a*) Departure from perigee of highly eccentric orbit about Earth.
(*b*) Departure from cislunar libration point L_1.
(*c*) Departure from lunar orbit.
(*d*) Departure from lunar surface.

(2) From cislunar libration point L_1:

$$\Delta V_2 = \Delta V_{L1-PT} + \Delta V_{\oplus\male} \quad (2)$$

where

ΔV_{L1-PT} velocity increment to leave L_1 to swing by Earth, approximated by the apogee velocity V_A of the highly eccentric Earth orbit

(3) From lunar orbit:

$$\Delta V_3 = \Delta V_{☾} + \Delta V_{\oplus\male} \quad (3)$$

where

$\Delta V_{☾}$ velocity increment needed to leave lunar orbit to swing by Earth, approximated by the difference between the lunar escape velocity and the lunar orbital velocity $= V_{☾e} - V_{☾c}$

(4) From lunar surface:

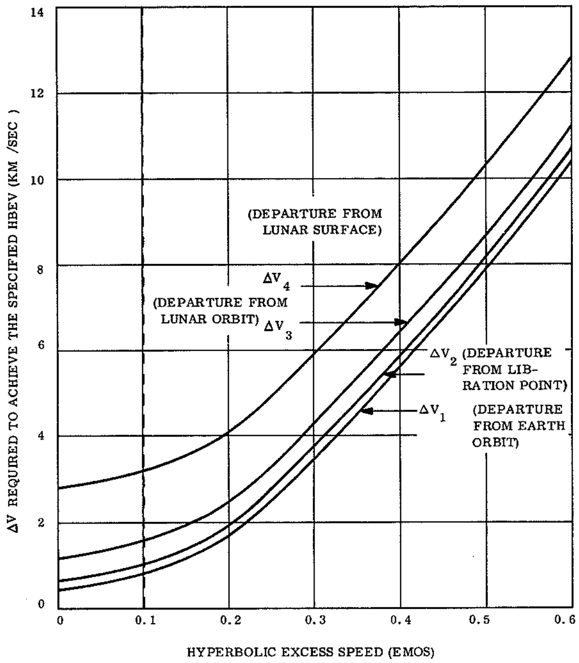


FIGURE 2.—Required velocity increments for alternative cislunar swingby options. $I_{sp}=444$ seconds.

$$\Delta V_4 = \Delta V_{\text{☾}asc} + \Delta V_{\oplus\text{♂}} \quad (4)$$

where

$\Delta V_{\text{☾}asc}$ velocity increment to ascend from the lunar surface to swing by Earth, approximated by the lunar escape velocity $V_{\text{☾}e}$

These velocity increment equations approximate the actual fuel expenditure, by use of the conventional conic approximation of impulsive transition of a spacecraft from the gravisphere domain of one force center into that of a second force center. The Earth orbit for perigee inception (case (1)) was selected as a highly eccentric orbit which lies realistically within the terrestrial gravisphere. The definitive orbital data are as follows:

- r_A orbit apogee, 300×10^3 km
- r_P orbit perigee, 6.7×10^3 km
- a orbit semimajor axis, 153.35×10^3 km
- e orbit eccentricity, 0.956

In swingby inception from the cislunar libration point L_1 (case 2), the velocity increment to leave the libration point was approximated by the apogee velocity ($V_A=0.24$ km/sec) of the highly eccentric Earth orbit, in order to assure a reasonable transit time from inception until swingby. In cases (3) and (4), the velocity increments for injection into cislunar flight to Earth swingby were approximated by use of the lunar escape velocity, since the hyperbolic velocity may vary for different lunar orbital altitudes and Earth swingby altitudes. In general, the actual additional velocity will vary from about 0.21 to 0.25 km/sec, depending upon the hyperbolic velocity to be attained on cislunar departure.

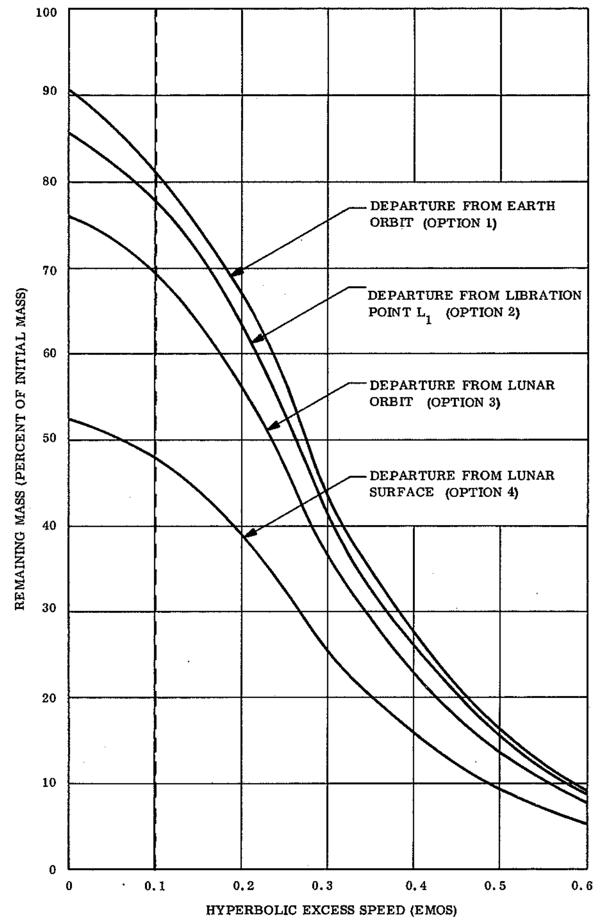


FIGURE 3.—Remaining mass ratio for alternative cislunar swingby options. $I_{sp}=444$ seconds.

Nonideal losses such as with finite-time thrust or with nonoptimal deviations from ideal flight parameter values will entail added losses which characterize the attainable efficiency of a given spacecraft system design. However, these losses and the above approximations do not affect the basic parametric variation of the energetics for the various Earth swingby modes available.

Obviously, departure from the highly eccentric Earth orbit is most advantageous and necessitates the smallest velocity increment to enter heliocentric orbit (fig. 2) so that the remaining mass is maximum (fig. 3). At zero hyperbolic excess speed, the relative ratios of remaining mass fractions are

$$m_1:m_2:m_3:m_4=1.75:1.65:1.45:1$$

These relative ratios are valid over the complete range of hyperbolic excess speed shown. Two salient features are evident:

(1) A very large penalty is imposed for lunar-surface launch, whereas all other inception point profiles lie within a much narrower envelope.

(2) The mass expenditure for Earth-orbit departure is only 0.64 of that for libration point departure.

The heliocentric velocity required upon exit from the Earth-Moon system will be determined by the transfer orbit for rendezvous with the target planet. In general, the heliocentric transfer orbit which requires the least total fuel expenditure between given endpoints (i.e., Earth at the time of departure and the target planet at the time of spacecraft arrival) is determined as the smallest positive real root of an eighth-order polynomial with constant coefficients (refs. 3 and 4). That is, all possible solutions of minimum-fuel heliocentric transfer orbits can be presented in parametric form. It can be visualized that Earth swingby will enable a lower total fuel expenditure than that of the corresponding direct transfer provided by heliocentric transfer from a terrestrial close circular orbit. Moreover, Earth swingby enables even a smaller fuel requirement than that with planetary swingby. As a simple example indicative of this favorable tradeoff, let us consider the corresponding velocity increments required for outbound flight by direct, planetary swingby and cislunar swingby (from lunar orbit) modes for transit to and propulsive capture by Mars. Direct and cislunar swingby are based upon standard opposition conditions of heliocentric transfer, whereas planetary swingby utilizes Venus en route to obtain the representative results reported in reference 5. All other definitive conditions are as follows:

Lunar circular orbit altitude =161 km (100 miles)
Terrestrial circular orbit altitude=300 km (186 miles)
Martian circular orbit altitude =800 km (496 miles)

The outbound transit data are as shown in table 1. Note that two different sets of standard opposition and Venus swingby are presented; these illustrate the tradeoff between trip time and total velocity increment ($\Sigma\Delta V$). In general, cislunar swingby requires about 50 percent of the velocity increment for either direct or Venus swingby, with a trip time almost the same as for direct transfer. Note that this heliocentric transfer requires about 0.1 EMOS to enter heliocentric space, as indicated by the broken vertical lines in figures 2 and 3.

TABLE 1.—*Velocity Increments for Alternative Basic Trajectory Profiles*

Flight mode	Trip time, days	$\Delta V_{LV\oplus}$, fps	$\Delta V_{AR♂}$, fps	$\Delta V_{outbound}$, fps
Direct	460	12 365	11 555	23 920
Outward Venus swingby	680	14 095	11 165	25 260
Direct	420	13 200	15 240	28 440
Outward Venus swingby	500	14 090	13 760	27 850
Cislunar swingby	Standard +3	3 444	11 395	14 839

Of course, the Earth and planetary swingbys could be combined to provide remarkable total fuel savings with almost the same trip time as for planetary swingby alone. It is noteworthy that computer study of planetary swingby solutions can be expedited by analytic approximation of this flight mode by a three-impulse orbital transfer optimization as shown in reference 6. In this reference, analytic formulation and partial reduction for solution of the three-impulse transfer optimization was accomplished. In planetary swingby, the gravity potential influence of the swingby planet (such as Venus) could be effectively approximated as the intermediate (or second) impulse. This analytic aid to mapping of the solution field can expedite future swingby studies, especially of hybrid swingby profiles (i.e., cislunar followed by planetary swingby). Significant reductions in solution running time can be expected.

INFLUENCE OF ORBITAL PLANE INCLINATION

Since the planets and other major bodies within the solar system lie in different orbital planes inclined to the ecliptic, the nonplanar (or three-dimensional) nature of the actual interplanetary transfer must be considered in evaluation of the energetics for heliocentric trajectories. The inclination to the ecliptic of the major bodies of immediate interest are as follows:

Body	Orbital plane inclination, deg
Mercury	7.00
Venus	3.38
Earth	0
Mars	1.85
Jupiter	1.31
Saturn	2.49
Earth's Moon	5.15

In view of the relatively large scalars of interplanetary transfer velocities, these inclinations can cause significant differences in fuel expenditure for accommodating maneuvers, even though the inclination angles appear to be small. However, the orbital inclination of the Moon may be employed to advantage in reducing or eliminating the nonplanar fuel penalty. Of course, the time of trajectory inception must be properly selected in order to utilize this inherent capability of cislunar transit within the Earth-Moon system in the course of Earth swingby.

Note that Earth swingby by inception from a highly eccentric Earth orbit need not necessarily occur within the plane of Earth-Moon system rotation, since the Earth orbit could be inclined to it, if desirable or realizable from the available launch and range facilities.

LAUNCH WINDOW AND FLIGHT OPPORTUNITIES

In general, spacecraft mass limitations upon the permissible fuel expenditure impose a severe operational constraint upon the launch window. This critical constraint results in the restriction, for current system capabilities, of interplanetary missions to a few crucial "opportunity years." It is eminently desirable to be able to "open the launch window" for mission launch from the Earth (or Earth-Moon system).

The cislunar swingby would obviously enable this launch window problem to be alleviated by virtue of the fuel savings indicated by the parametric curves and examples of the preceding sections. However, the cislunar swingby has another effect upon the launch window because of the recurrence of launch opportunity with lunar period. That is, direct and planetary swingby launch windows are principally determined by the Earth-orbit period and the relative phasing between planetary ephemerides, whereas the cislunar swingby window is determined principally by the lunar period and the relative phasing between planetary ephemerides. The structure of the launch window is shown schematically in figure 4, which presents the tolerance in delay time at any given launch opportunity as a function of the launch time. That is, a characteristic tolerance band for timing of launch into heliocentric orbit is available at each launch opportunity. Note that the delay tolerance is of the order of minutes, whereas the total width of the apparent launch window is of the order of months.

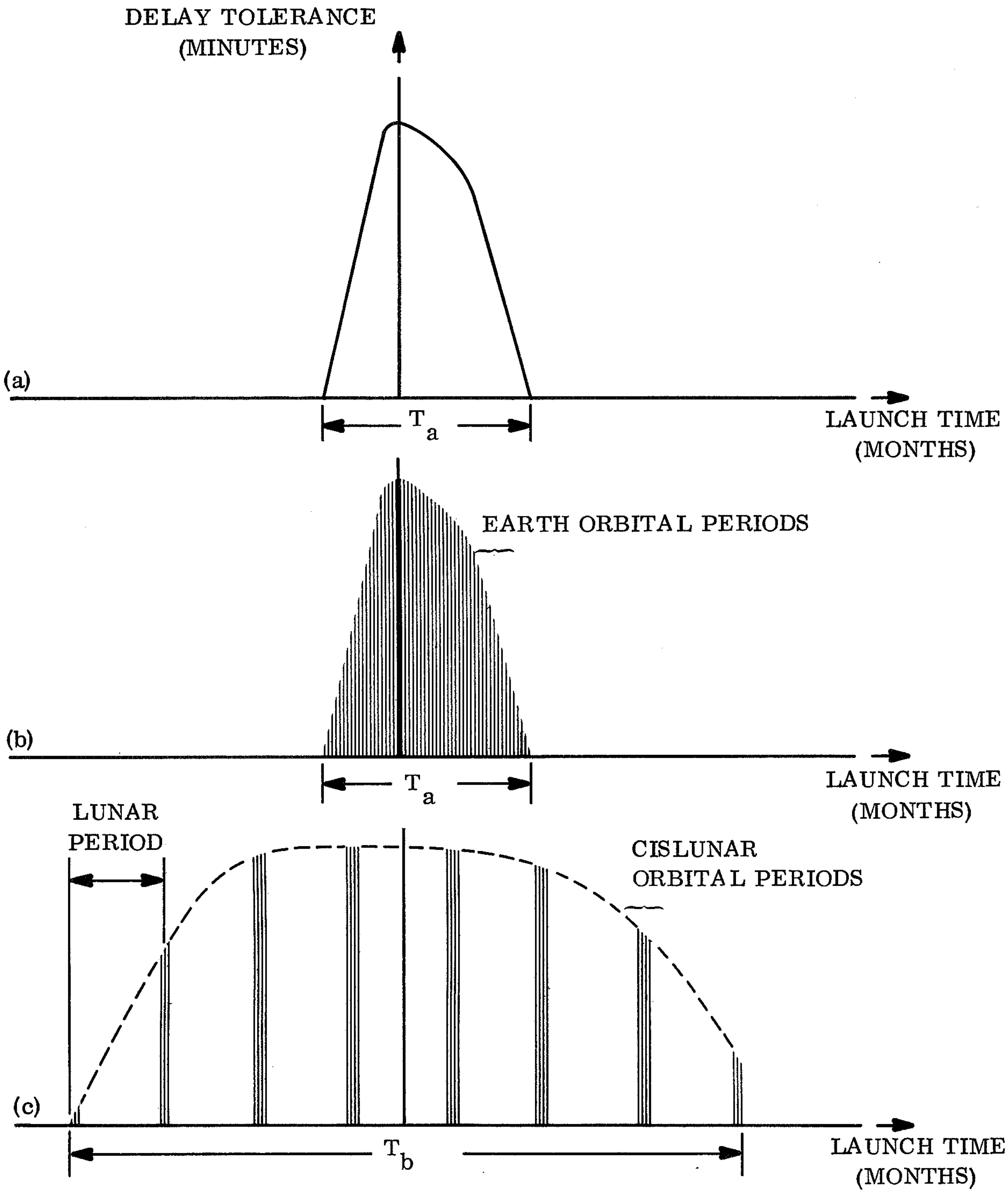


FIGURE 4.—Structure of launch window (schematic only).

(*a*) Apparent launch window; direct or planetary swingby.
(*b*) Actual launch window; direct or planetary swingby.
(*c*) Actual launch window; cislunar swingby, cases 2 to 4.

Figures 4(*a*) and 4(*b*) describe the launch windows for direct and planetary swingby in schematic form. As shown in figure 4(*a*), the "apparent" launch window is defined by the envelope of actual launch opportunities. The actual opportunities will recur with Earth-orbit period, as shown in figure 4(*b*); that is, the launch opportunities (presented discretely along the abscissa) are separated from one another by the period of the Earth orbit from which launch occurs, in the order of hours. The launch window for cislunar swingby is shown schematically in figure 4(*c*) to the same relative scale of launch time. The major "sidebands" of launch opportunities recur with the lunar period, whereas the discrete opportunities may occur at any time within them. It is estimated that the cislunar swingby spreads the envelope or timespan of launch opportunities in the relative ratio of $T_a:T_b$ as shown schematically in figure 4, and with the periodic recurrence pattern indicated in figure 4(*c*).

The delay tolerance for cislunar swingby appears to be about that for direct and planetary swingby, as indicated by the ordinate values of figure 4. However, brief consideration suggests that the cislunar swingby delay tolerance might be significantly larger. Of course, the dynamic model is more complex and analytical knowledge of the variational characteristics of the useful classes of cislunar orbits must be extended in order to determine this trajectory characteristic conclusively.

SYSTEM DESIGN AND MISSION OPERATIONS

The flight performance characteristics of a trajectory profile must fulfill the requirements of the available space system designs and mission operations. In addition to favorable energetics, flight time, and launch windows, Earth swingby has several other attractive aspects.

Earth approach and swingby for subsequent injection into heliocentric orbit will occur within Earth's planetary test range, which consists of the extremely accurate command and operations complexes (tracking stations, operations control center, etc.) used for space missions. The solid base of the space program is the Apollo system complex and missions. In general, the Apollo system and operations will be available and proven for hyperbolic approach phases within the near future.

In particular, the most sensitive system design performance and operations problems encountered in cislunar swingby will necessarily have been solved in the Apollo mission. Moreover, the operational experience and procedures will be almost directly applicable to the interplanetary mission with the cislunar swingby profile. The Apollo guidance and control system will solve the critical guidance and control requirements of swingby around Earth. Although the high approach velocity requires great control accuracy, swingby will be extra-atmospheric and can be carried out under optimum system conditions of ground tracking and joint onboard/ground control of injection into heliocentric orbit. Moreover, a number of alternative abort options would be available well at the start of the complete trajectory so that system and crew recovery will be possible with minimal risk or hardware loss.

The transport system, payload instruments, and tests can be exercised as the spacecraft approaches Earth for subsequent swingby and injection into heliocentric orbit. Consequently, prior calibration of all onboard subsystems with the actual working instruments is possible at the beginning of the long interplanetary flight. Any observed deficiencies can then be corrected by the operations team (on the Earth and/or onboard) prior to arrival at the target planet. In particular, the experiment scenario of the Earth swingby test exercise of payload operations can yield invaluable evaluation criteria for subsequent data processing and reduction of the target-planet observational data.

The selection of the inception point for the interplanetary flight leg will be determined by the costs, risks, and many design considerations for the given mission. The spectrum of design characteristics implied by each of the four alternative options is sufficiently broad to enable the selection and optimization of an effective system for various missions.

SUMMARY

The four alternative options of the cislunar (or Earth) swingby trajectory profile for interplanetary flight have been compared briefly by means of parametric curves of the energetics for departure from the Earth-Moon system. While the fuel expenditure for flight inception from the lunar surface is significantly greater than for the other three inception options, the use of perigee departure from a highly eccentric elliptic orbit about the Earth is most favorable. Refueling may be accomplished in the neighborhood of apogee, either from the Earth, a cislunar libration station, or the Moon.

Fuel savings of about 50 percent over direct transfer or planetary swingby alone are indicated with cislunar swingby from lunar orbit (option 3) and subsequent direct heliocentric flight. Additional savings by the combined use of cislunar and planetary swingby profiles could be realized.

The inclination of the orbital plane of the Earth-Moon system to the ecliptic may be advantageous in minimizing the spacecraft energetics, provided the required endpoint conditions for heliocentric transfer in three-dimensional space can be realized.

The launch-window envelope and opportunities have been described as functions not only of the relative phasing between the planetary ephemerides (of the Earth and target planet), but also of the period of the Moon about the Earth. In general, the timespan of the Earth swingby window will be significantly greater (than that of direct or planetary swingby flight) with more frequent discrete launch opportunities, although they occur only within sidebands of lunar periodic frequency. However, heliocentric injection from a highly eccentric terrestrial orbit will depend upon the spacecraft's orbital period rather than on the lunar period about the Earth.

REFERENCES

1. Ross, S. E.: Trajectory Design for Planetary Mission Analysis. Recent Advances in Space Flight Mechanics, vol. 9. AAS Sci. and Technol. Ser., AAS Pub. (Tarzana, Calif.), 1966, pp. 3–43.
2. Gillespie, R. W.: Impulse Propulsion Gains Resulting From "Free" Retanking of Propellants on Various Orbits and Stations at the Earth, the Moon, Mars, and Venus. Proc. 4th Annual Meeting, Working Group on Extraterrestrial Resources (Air Force Acad., Colorado Springs, Colo.), 1965.
3. Altman, S. P.; and Pistiner, J. S.: Analysis of the Orbital Transfer Problem in Three-Dimensional Space. Progress in Astronautics and Aeronautics, vol. 14. Academic Press (New York), 1964, pp. 627–654.
4. Sun, F. T.: Some Analytical Characteristics of the Optimum Two-Impulse Orbital Transfer Under Arbitrary Terminal Conditions. Paper no. 67–584, AIAA Guidance, Control and Flight Dynamics Conference (Huntsville, Ala.), Aug. 1967.
5. Deerwester, J. M.; and D'Haem, S. M.: Systematic Comparison of Venus Swingby with Standard Mode of Mars Round Trips. Paper no. 62–27, AIAA 5th Aerospace Sciences Meeting (New York), Jan. 1967.
6. Anon.: General Solution of the Three-Impulse Optimization Problem. Rept. DIN67SD4318, Spacecraft Dept., Gen. Elec. Co., June 20, 1967.

Page intentionally left blank

ERNST A. STEINHOFF
Air Force Missile Development Center
Holloman Air Force Base, N. Mex.

Importance of the Use of Extraterrestrial Resources to the Economy of Space Flight Beyond Near-Earth Orbit

INTRODUCTION

During the 1961-to-1966 period, the Working Group on Extraterrestrial Resources devoted its main efforts to analyzing the economy of space flight with the use of extraterrestrial resources, and during the last 2 years the American Astronautical Society as well as the Institute of Aeronautics and Astronautics have begun to devote special sessions to problems associated with the potential use of extraterrestrial resources and/or dealing directly with the subject. In October 1968, the XIXth International Congress of Astronautics will hold special sessions in New York, N.Y., which also will deal with this timely subject.

During the XVIIIth International Congress of Astronautics, Prof. Fritz Zwicky of the California Institute of Technology presented a very impressive lecture on this subject, and, more recently, Prof. Donald Menzel, Director Emeriti of the Harvard Astronomical Observatory, called the attention of the scientific community to apparently obvious indications of water action having taken place in the remote past on several locations on the Moon. These described phenomena can be clearly seen on recent lunar orbiter pictures. In a recent private communication, Prof. Harold C. Urey of the University of California at San Diego also supports this view. These interpretations can have considerable bearing on the work done by the Working Group and could be of far-reaching influence on the future course of space flight. Those who have followed the work of this group will remember the frequently stated fact that support of extraterrestrial space flight and the logistics of manned stations on the Moon or in interstellar space will require that more than 90 percent in weight of all vital logistic supplies will consist of water or its derivations, if we plan to use oxygen and hydrogen as fuels.

Another subject recently discussed more frequently in space-flight-related meetings is the quest for utilization of the extraterrestrial environment for commercial and industrial uses in addition to research objectives. Many processes performed on Earth are subject to limitations as a consequence of our particular Earth environment. To achieve particular objectives, man has artificially changed his environment, for instance, to make these commercial objectives more efficient or more economic at a cost. However, our state of technology and the celestial body we happen to live on sometimes do not permit us to duplicate environments on Earth with great economy; we could achieve them more easily in space or on the surface of celestial bodies within reach of our Earth by space flight.

A third observation I would like to make is that space flight at the present cost level will not become attractive to many of the proposed uses, particularly those which entail commercial uses, much beyond the ones recognized as economically feasible. Substantial reduction in space flight cost would attract many new uses into the "orbit" of commercial utilization of space flight. These uses in themselves would tend to reduce space-flight cost because of the increased volume of space flight and the factors involving reaction to cost as a function of volume and time.

The following remarks will be devoted to the various possibilities and factors which could involve, or result in, increased economy of

324-954 O—69——15

space flight and the promotion of commercial ventures making industrial or other use of extraterrestrial resources and environments. These remarks are based on my own past work, on work of members of the Working Group or of contributors to it, and on more recent independent observations and contributions, which have resulted as a consequence of our growing storehouse of knowledge of the cislunar and lunar environment.

DEFINITION OF EXTRATERRESTRIAL RESOURCES

Extraterrestrial resources can be considered resources which can maintain space flight and human life in space and on extraterrestrial bodies without Earth-derived logistics. In other words, self-contained exploration, operation, and settlements, as, for example, on the Moon, and maintenance of traffic and logistics between different extraterrestrial bodies without continuing logistics from Earth, would require extraterrestrial resources. But we can define this term even more broadly. Physical phenomena can be considered extraterrestrial resources, too, if they permit us to conduct processes or operations which would be more difficult or less economical to achieve in the natural Earth and Earth atmosphere environment, such as lowered or disappearing gravity, wide spectrum of radiation level, varying degree of vacuum, extreme temperature environment, or potential or kinetic energy levels difficult to achieve from Earth.

These resources could be:

(1) Indigenous raw materials to produce fuel and life support.

(2) Indigenous raw materials to support construction and operation on the Moon.

(3) Raw materials of value and qualities to be furnished from extraterrestrial resources to the Earth.

(4) Environmental conditions difficult to achieve on Earth as, for example, lack of gravity, different radiations or lack of radiations, and degree of achievable vacuum.

(5) Natural radiation spectra and propagation phenomena not directly available on Earth.

Of the consumables, water and oxygen require the highest support level in weight to maintain human life in extraterrestrial space. Since oxygen is the major weight component of water (approximately 87.5 percent), availability of water alone could reduce logistic requirements to support life by almost 90 percent. Oxygen and hydrogen, a highly effective fuel and oxidizer combination for chemical rocket motors, could be supplied from water and thus this logistic percentage would be increased far above the 90-percent point.

More recently, many proposals have been made to use extraterrestrial environment for manufacture of products which would be difficult to produce on Earth because of high-gravity effects, not low enough vacuum, the need to add or remove heat at high rates economically, or the need to provide conditions of peculiar radiation or absence of it. If the product is of sufficiently high value with respect to its weight or volume when the cost of transportation is included, it may pay to have it produced outside the terrestrial environment. In turn, if transportation cost to extraterrestrial space is low enough, the candidates potentially capable of taking advantage of this environment may increase to such a magnitude that use of space for commercial purposes may become increasingly attractive and eventually self-supporting. Prof. Zwicky, in his paper given during the XVIIIth International Astronautical Congress, made an eloquent case for using the Moon as a resource for fuel and life support by using minerals of expected high abundance to produce fuel and life-supporting oxygen.

THE CASE FOR THE PRESENCE OF WATER IN THE MOON AND THE INNER PLANETS

Prior to unmanned lunar landings and lunar orbital flights, the prevailing theory of the composition of the lunar crust and the lunar interior was based mainly on the assumption that the Moon, being a part of the system of the inner planets of the solar system, would have to have a distribution of elements similar to that found on Earth. If this is true, one then could expect that water, which is not now observable on the surface of the Moon, could possibly have played a role in the lunar past or could be expected to be found in the form of water of crystallization or hydration within the rocky material of the surface and interior of the Moon and even might be found in underground lunar deposits in the form of liquid water or as permafrost, particularly in areas which have surface temperatures permanently below freezing level. Presence of liquid water could be particularly expected if volcanism has been active in the lunar past or is present even at this time, or if interior temperatures, due to compression and possibly radioactivity, reach levels required to start dehydration of the rock material (300° to 1400° C).

Analysis of the alpha-scattering experiment used on Surveyor V after its lunar landings, as recently reported by Dr. Newell of NASA and his team and, particularly, by Dr. Anthony Turkevich of the University of Chicago, shows preliminary results of composition of surface rocks (table 1) similar to that observed on rock samples of the Earth. This confirms the expectation of there being approximately the same relative abundance of elements as there are on Earth. This scientific achievement can be considered as one of the greatest in human history. Even if this fundamental experiment to obtain the chemical composition of the lunar surface material reflects the composition of only a very thin surface layer and does not give insight into the composition of the rocks of the crust below, in which case much of the information might be based on meteoritic dust spread over the Moon's surface, but not originally from the Moon, this achievement loses none of its significance. Another characteristic of this experiment is that it cannot disclose or detect the presence of hydrogen, which is necessary to prove presence or certainty of water within the Moon. A determination of the relative abundance of water has to be derived by indirect means of rather high uncertainty.

TABLE 1.—*Chemical Composition of the Lunar Surface at Surveyor V and VI Sites (Preliminary Results)*

Element	Atoms, percent, found by—	
	Surveyor V	Surveyor VI
Carbon	<3	<2
Oxygen	58 ±5	57 ±5
Sodium	<2	<2
Magnesium	3 ±3	3 ±3
Aluminum	6.5±2	6.5±2
Silicon	18.5±3	22 ±4
Calcium	13 ±3 (Calcium and Iron)	6 ±2
Iron		5 ±2

Before I come to another observation, which may point to presence of water at some point of time in the history of the Moon, I would like to present two figures originally published by NASA which compare abundances of elements represented in terrestrial rocks to that obtained on the surface of the Moon as exhibited by the alpha-scattering experiment of the Surveyor V (figs. 1 and 2). Dr. Gault's interpretation, as published in the preliminary results of the Surveyor mission, postulates that the lunar-surface material as presented by the alpha-scattering experiment is best interpreted to consist of a general basaltic composition. This confirms the prediction of Dr. Jack Green, who has been a distinguished speaker to the Working Group in the past. Proof of presence of basaltic material, confirmed in parallel to the alpha-scattering experiment by a magnetic properties test and a proton-scattering test, points to the fact that, within the interior of the Moon, rock material of ultrabasic type has reached temperatures necessary to drive water of crystallization or hydration out, but in some cases or locations the temperature was not sufficient to melt the original rock material. I would not postulate at this time whether such melting took place as a result of mechanical heat generation caused by impact of large meteors (which possibly resulted in the existing maria), whether it is a direct consequence of internal heat generation (independent of heat of impact), or whether it was a consequence of the original source of the material not being of the Moon at all.

Prof. Donald Menzel, in his paper presented to the last technical conference of the AIAA at Anaheim, Calif., in October 1967, showed a number of specific surface features of the Moon, which, according to his interpretation, can only be caused by liquid erosion by water

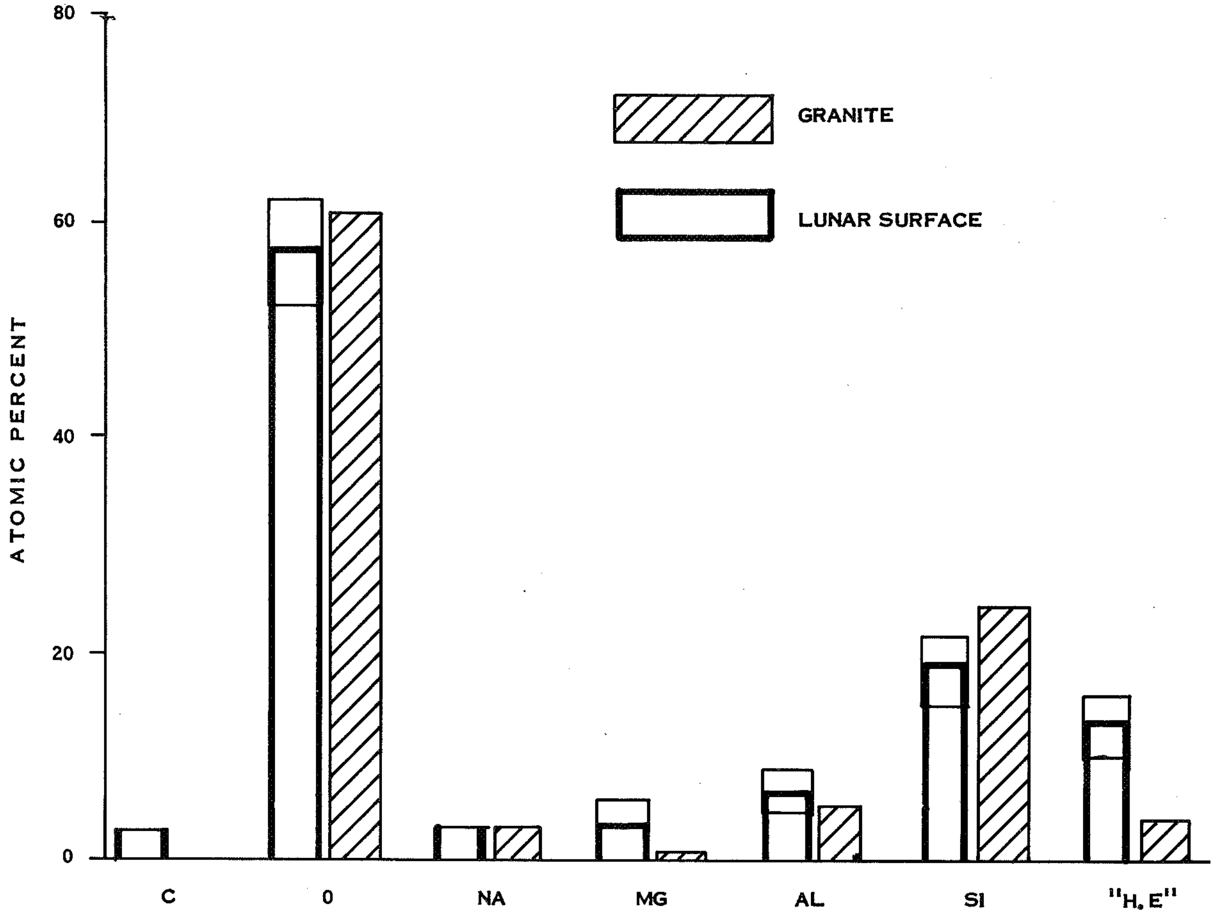


FIGURE 1.—Abundance of elements found in terrestrial granite and that of elements found on lunar surface by alpha-scattering experiment of Surveyor 5.

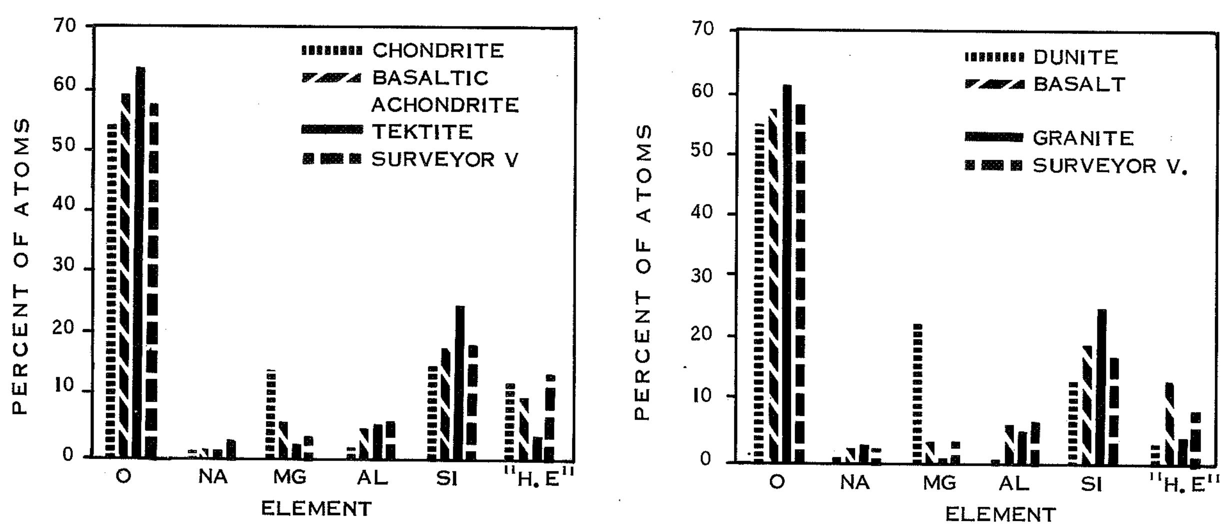


FIGURE 2.—Abundance of elements found in various terrestrial rocks and that of elements found on the lunar surface by alpha-scattering experiment of Surveyor 5.

or by a medium having similar properties. These erosion features are distinguished by their meandering tracks, which begin mostly near a crater's fractured wall and continue toward lower territory as they gradually fade out. Figure 3 is a picture of such a case taken by Lunar Orbiter V. Pictures obtained from Gemini missions show similar erosion features on the surface of the Earth caused by water erosion in desert areas (fig. 4). Both Dr. Urey and Dr. Menzel agree that these features point toward active water erosion sometime in past lunar history and to the distinct possibility that, in spite of the apparent barrenness of the surface, underground liquid water storage exists. Dr. Menzel goes even further in his conclusions and postulates that, under the assumption of relative abundances of cosmic elements on the Moon, the Moon ought to have had an atmosphere in its distant past and evidence of this should turn up in future observations on the Moon itself. These

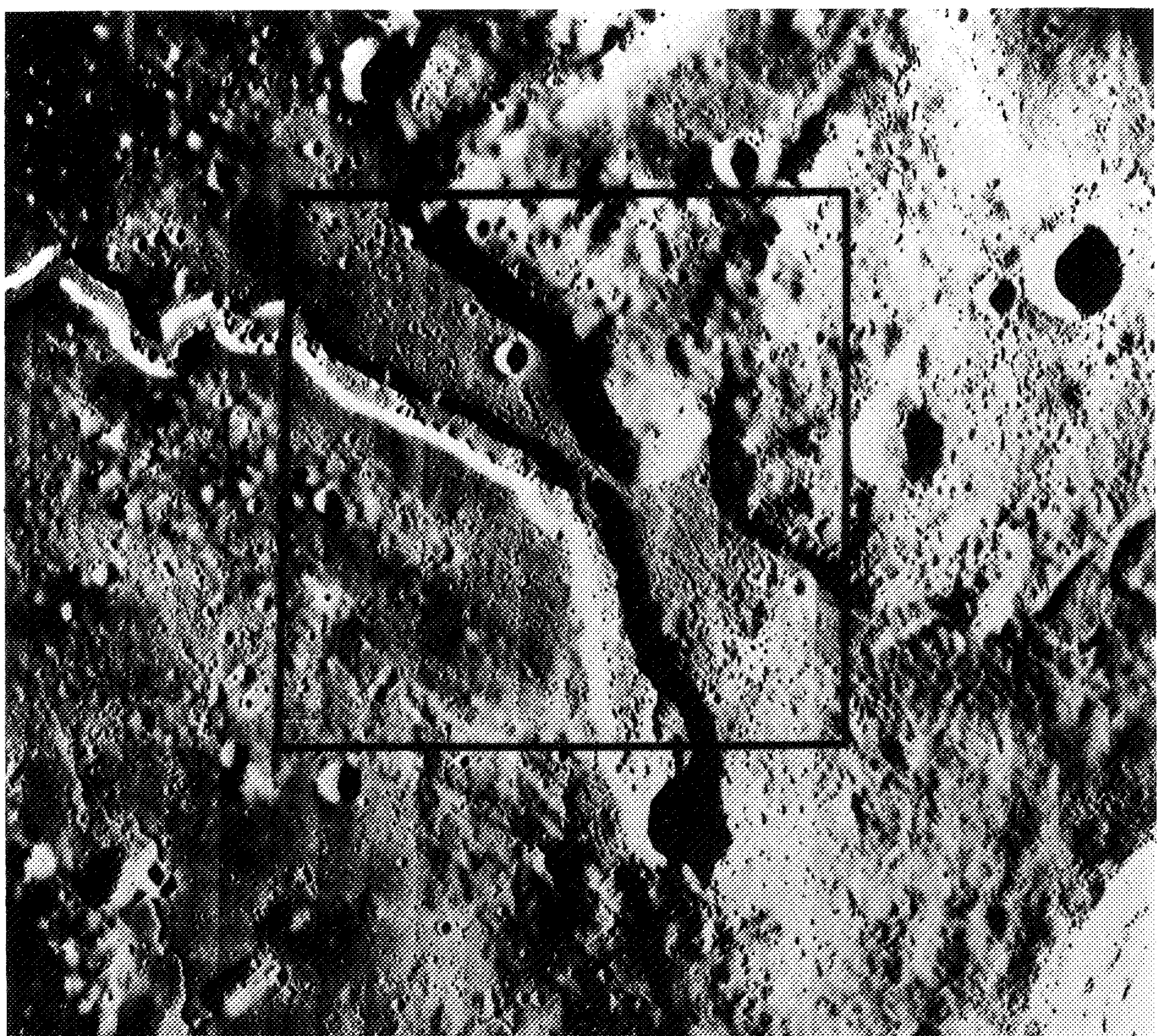


FIGURE 3.—Lunar Orbiter V picture showing erosion on surface of the Moon.

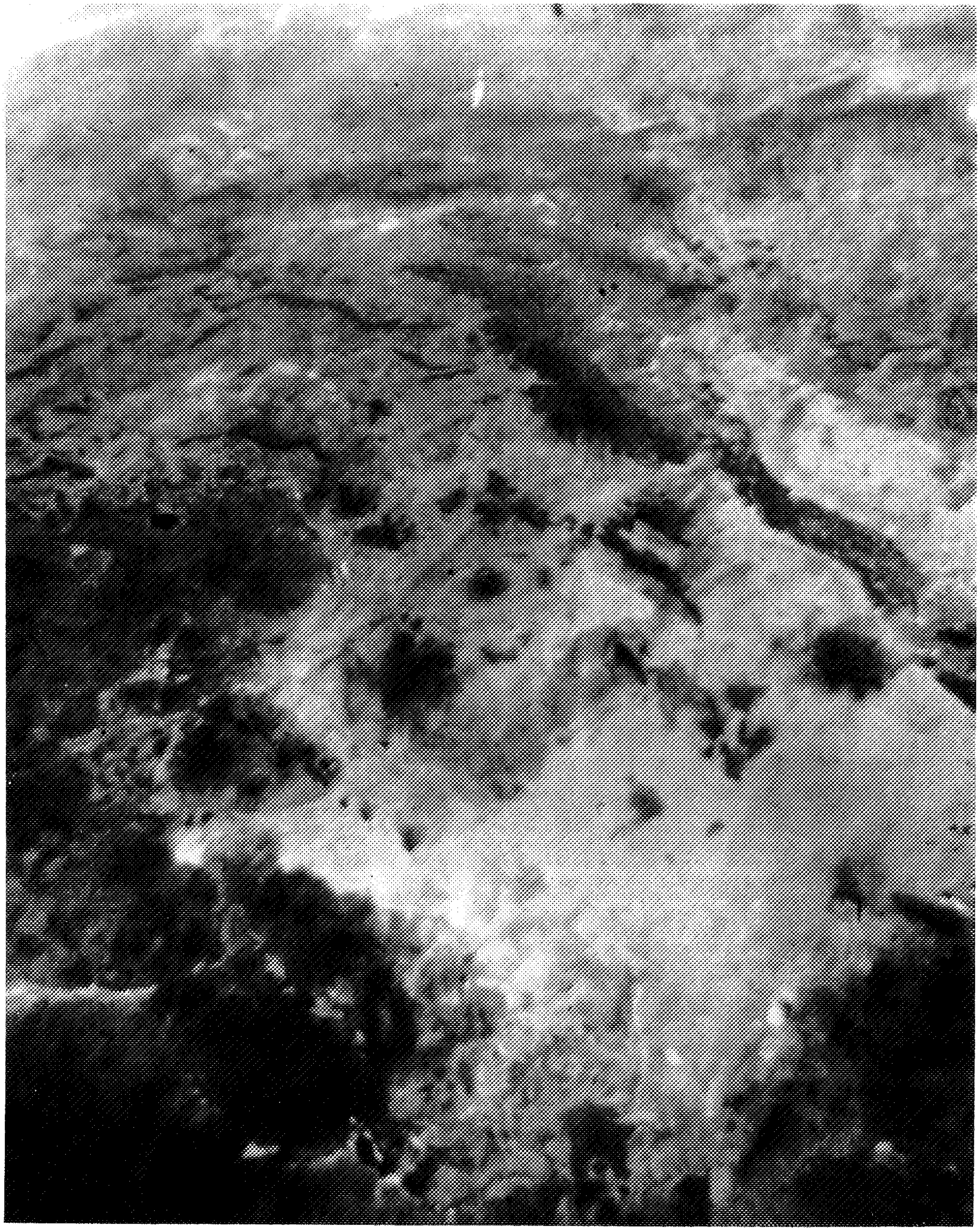


FIGURE 4.—Gemini picture showing erosion on surface of the Earth.

thoughts and conclusions are not too much different from those presented in the past years by Dr. H. Strughold and this author.

EFFECT OF INDIGENOUS FUEL SOURCES ON SPACE TRANSPORTATION

The problem of producing fuel and oxidizer on the lunar surface or on a planetary surface from the indigenous raw materials has been studied in the past, and a number of processes have been developed or proposed as conceptional approaches, which are derivatives of industrially known processes, but take into account the particular operational and environmental peculiarities of extraterrestrial application.

Since transportation costs to a lunar or planetary location are very high as compared with the specific cost of establishment, operation, and maintenance of an industrial chemical plant and its manpower for conventional Earth use, the design has to reflect extremely low-weight construction, long life, minimum-type preventive maintenance, resistance to wear, and a very high degree of automation to save operating manpower. Installation and assembly are other areas requiring a very high degree of sophisticated engineering, so that final assembly can be accomplished at the extraterrestrial destination with a minimum of manpower and equipment. Use of construction materials with properties now on the fringes of our technology may be cheaper in total cost, including transportation, emplacement, and long-term operation, than those that current chemical-plant construction technology and practices may be able to provide; therefore, a considerable amount of advanced engineering and fabrication research will be required. Waste disposal from the manufacturing site may also cause problems which in the case of fabrication on the Earth are easily surmountable although frequently bothersome, but under extraterrestrial environment and extreme shortage of manpower may become important factors to deal with. Here, the magnitude of the problem is directly proportional to the yield of waste as compared with the useful yield and, in the case of fuel, to the inverse specific impulse produced per pound of fuel.

If pure water is the raw material, the case of no waste would be the optimum case, while for a raw material of 1 percent extractable water content, the waste would have 100 times the weight of the product and possibly between 30 and 100 times the volume of the useful yield. This ratio can become a problem as to waste disposal, difficult to handle with a minimum of physical labor, and requiring considerable analysis of engineering solutions and many other aspects, as, for example, the cost per construction man-hour or assembly man-hour involved to complete the plant to turnkey conditions. A value of $15,000 per man-hour was arrived at from studies of one such example. Depending on the details of the assembly and duration of the job, this number may fluctuate in a wide range around this value. Studies done in my office by members of my staff indicate that, given a lunar source for fuel, the amount of fuel needed to maintain a certain level of space-flight activity between Earth orbit and lunar surface, broken down into two traffic sections (Earth orbit to lunar orbit and lunar orbit to lunar surface), shows advantages for lunar-based systems (fig. 5). One can see immediately that a substantial advantage for the lunar-based system extends in the case of the round-trip-payload mode to between 1000 and 2000 nautical miles above the Earth, and in the case of the one-way-payload empty-return mode down to 300 nautical miles. In this mode, it appears that Earth-launch payload fractions never show an advantage. For example, assume that 1-million-pound vehicles are launched from the surface of the Earth and from the lunar surface. The Earth-based system will deliver approximately 3.9 percent of its launch weight as payload, or 39 000 pounds. Using the same level of technology, the lunar-based system on the other hand will deliver 6.5 percent, or 65 000 pounds, to the 300-nautical-mile Earth orbit.

While fuel per pound produced on the Moon will be more expensive than that produced on the Earth, the implication of the lunar supply permits one to break down operations into individual traffic sections and achieve an optimum traffic pattern so that the space-

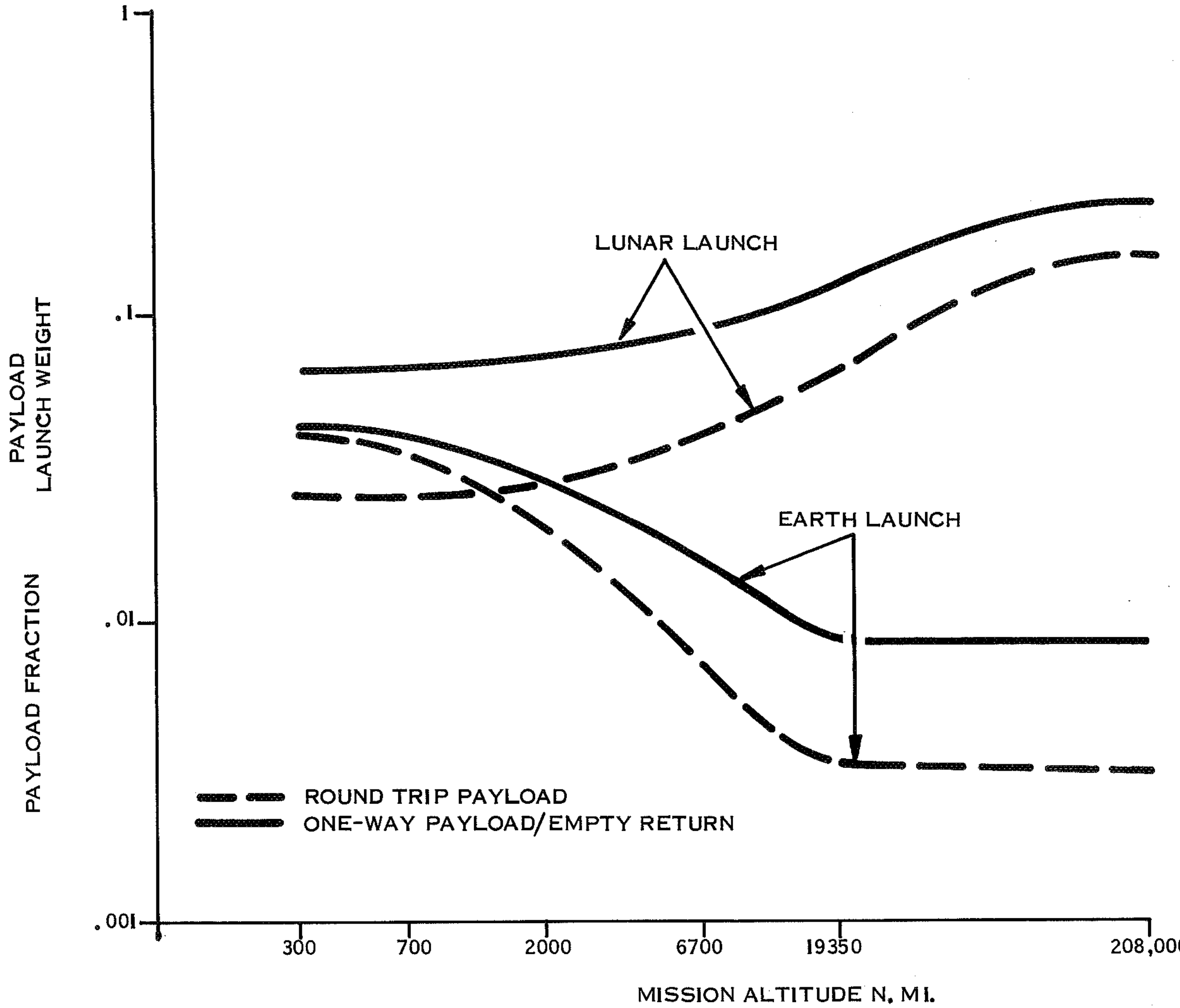


FIGURE 5.—Earth-surface and lunar-surface launch payload fractions against mission altitude.

flight system can be designed as a fully reusable system permitting hundreds or thousands of round trips with little cost of maintenance and spare parts, as soon as the used powerplants are designed for a high reuse level. In such a use pattern, currently employed stages, as, for example, the Saturn S–IVB and S–II, show spectacular payload weight fractions, even unmodified from their standard configuration. Since thrust-to-weight fractions for the Earth-orbit-to-lunar-orbit shuttle can be considerably smaller than 1 and, meantime, the failure caused by reduced power setting can already provide considerable extension of lifetime without major engine redesign, an approach to using already existing hardware, modified in orbit, may be the easiest way to convert space-flight operations using fully expendable components gradually to a pattern of increasing reuse of components.

Such a space-flight pattern, when introduced, could be supplied with fuel from lunar resources and could provide an extraterrestrial transportation system of potential economic superiority as a function of productive plant sophistication. When such a system is analyzed, the yield of the extraterrestrial raw material and plant operating cost associated with this yield become tradeoff factors. To obtain a complete Earth surface to lunar surface round-trip system, the transportation system's final link from Earth surface to Earth orbit and return to Earth surface has to be considered and its operating cost determined. If the Earth-lunar section cost level is low as compared with the per pound cost of transportation from Earth surface to Earth orbit, design and development of a reusable link between Earth surface and Earth orbit terminal system of improved economy may eventually lead to a trend of increasing space-flight economy and would eventually result in an increased use of space traffic to Earth orbit and to the Moon for research, industrial, and commercial reasons. Although achievement of space operations for commercial purposes beyond the current practical cases (Comsat, Intelsat, weather satellites, possibly navigation satellite use for commercial air and ship traffic use, conventional TV satellites, and near-future educational satellites for transcontinental TV transmission) may take decades, introduction and increased use of more economic reusable sections in our space traffic pattern may accelerate commercial uses to less than a decade if systematically made the objective of our military and civilian space plans.

If one, for instance, would salvage S–II and S–IVB stages in orbit and perform overhaul and preventive maintenance on these from an orbital space station, these stages could be refueled in Earth orbit and lunar orbit and fly back and forth between these two terminals. The lunar-orbit terminal (a second orbital space station such as these have been proposed for the Apollo Applications Program) could be established and serve as a support base for vehicles returning from the Moon. These could be parked on the lunar-orbit terminal, receive preventive maintenance, and be reused; this would obviate the need to bring in new ones from Earth for every lunar landing. In this case, only the lunar landing module would need to be brought from Earth.

With the establishment of a small fuel-generation plant, supplied with electric energy from nuclear electric plants, as, for example, SNAP–50, fuel could be produced first for the sole purpose of returning lunar excursion modules (LEM's) to lunar orbit, and obviate the need to bring new LEM's from the Earth to the Moon. Since the LEM has a greater payload capability than has the lunar return vehicle, a new capability of return payloads begins to take shape. Increasing the fuel-plant capacity further could then lead it to provide an increasing percentage of the return fuel for S–II and S–IVB stages from lunar orbit to Earth orbit. Excess fuel arriving from the Moon in Earth orbit could be stored at the Earth-orbit terminal and be used to refuel outbound trips whenever possible; the need to bring fuel to Earth orbit from the Earth itself would be further reduced and the payload capability of the Earth surface to Earth orbit transportation system would be further increased.

Before this stage of operation is achieved, there could be an interim case in which instead of fuel and oxidizer, only water would be brought from Earth to the Earth orbit terminal, and there the water would be dissociated and liquefied for use as fuel by using spent S–II stages attached to the Earth orbit terminal as fuel storage tanks. Only a minimum of conversion equipment, including a space nuclear electric plant, would be required. The lunar orbit terminal could be similarly equipped, thus the operation could first start with water brought in from Earth and later, with water extracted or mined from the Moon. The next step would be to dissociate water directly on the Moon and thereby supply the fuel for the return to orbit of LEM's and lunar return vehicles. Payload of the LEM's could be lunar water to be converted to fuel in lunar orbit. Those familiar with the components of the Apollo system will agree that such a bootstrap-type expansion of our space-flight capability would considerably widen our space-flight horizon.

Work done by and for the NASA Marshall Space Flight Center under the Mimosa Study and work done by Dr. Howard Segal deals with the use of Apollo components beyond that of the original Apollo concept and is extremely promising as to increasing economy of space flight. Some of the thinking of Dr. Segal should be reviewed here. In the lunar orbit rendezvous mode, this combination can deliver 5750 pounds of return fuel and 2410 pounds of cargo to the lunar surface from lunar orbit. If fuel were available from sources on the Moon, the 5750 pounds of fuel could be replaced by payload (total payload, 8160 pounds). One could return not only the ascent portion of the LEM to lunar orbit, but also the complete original landing vehicle, which carried the LEM; it would carry not only payload on its return flight, but also fuel for the next landing on the Moon. Dr. Segal has investigated the possibility of returning it to Earth orbit along with the command module. With these two vehicles, one could maintain two levels of shuttle operation between lunar surface and orbit. Figures 6 and 7, which describe the Segal case, show a 2- to 3-man-crew rotation case and a 5- to 6-man-crew rotation case, respectively, with the associated objectives of a return to lunar orbit or to Earth orbit.

One interim approach which could be expected to reduce Earth logistics by a factor of approximately 2.3 would be an approach which would use lunar rocks which were recently proven to exist on the Moon by Surveyor V. Dr. Rosenberg in 1964 investigated the use of silicate rocks, which are rich in oxygen (e.g., $MgSiO_3$) and which were expected to be abundant on the Moon, to provide oxygen for life support and as oxidizer for use in rocket and extraterrestrial surface vehicle propulsion. Figures 8 to 10 describe the process he used, which is within the state of the art of chemical manufacturing. In order to get the process started, an initial supply of methane is needed, which is recycled in the process. The product is water, but this water needs to be dissociated to recycle the hydrogen into the process. If methane, hydrogen, acetylene, ammonia, or other fuels could be found on the Moon and can be easily collected, dissociated to H_2, and liquefied, no further resupply from Earth would be needed.

As an insight into the yield of the process, it takes 29 pounds of lunar rock to produce 8.33 pounds of oxygen, a yield of approximately 28.8 percent. However, at the site of the first lunar base, where according to recent surface material analysis (fig. 2) rocks rich in O_2, Si_2, and Mg should be found, one cannot expect that raw materials providing the above fuels or similar fuels to go with the oxygen would also be available. A long time may pass before raw materials for these companion fuels may be

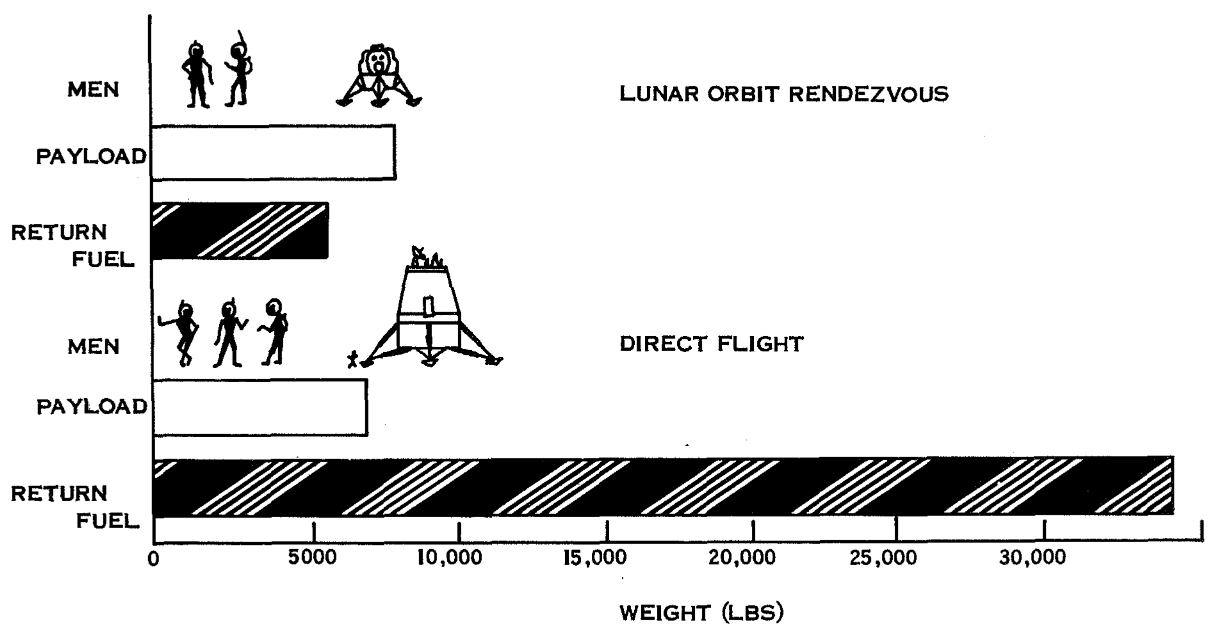


FIGURE 6.—Return fuel requirements for 2- and 3-man-crew rotations.

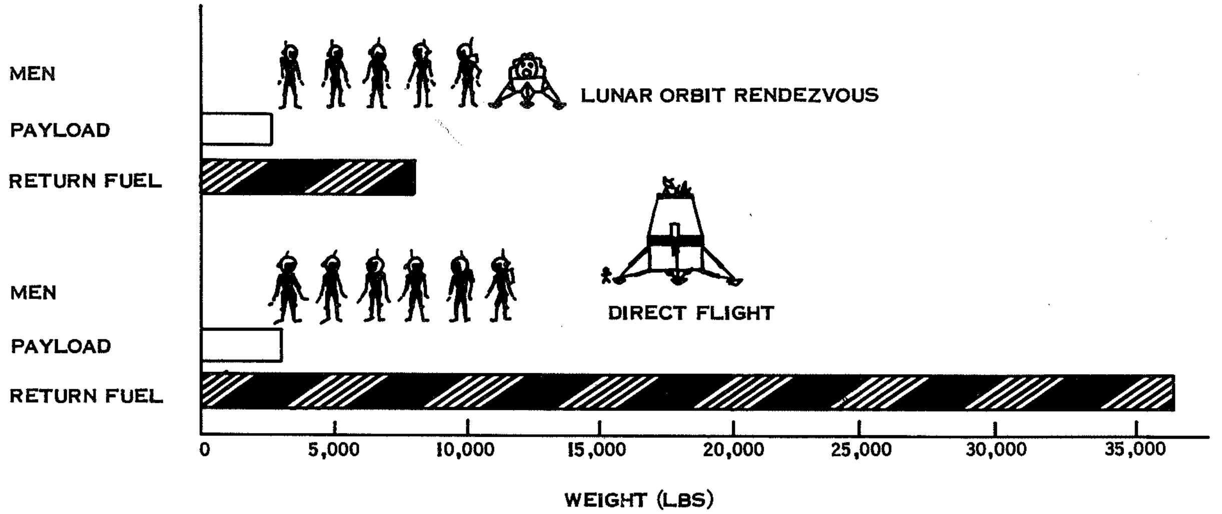


FIGURE 7.—Return fuel requirements for 5- and 6-man-crew rotations.

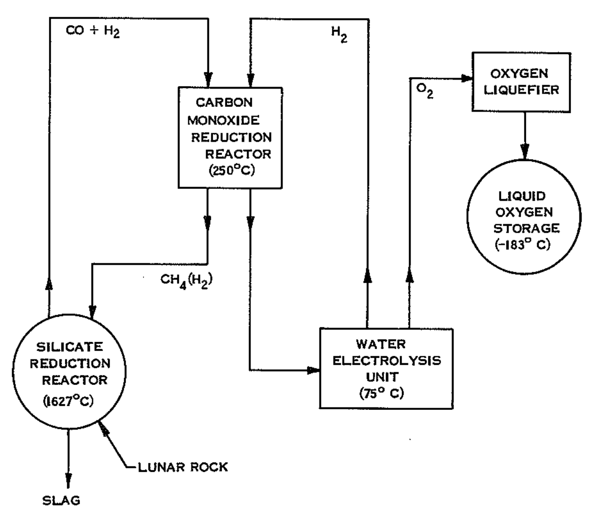


FIGURE 8.—Simplified flow sheet for Aerojet carbothermal process.

found. I think that the prospect of finding water in minable form may be better.

However, this process could be the second step in a bootstrap buildup of space-flight capabilities. The first step would not be to bring oxygen and hydrogen separately as fuels, but would be to bring water to Earth and lunar orbit and eventually to the lunar surface and to dissociate and liquefy it there. Packaged nuclear electric powerplants could be used to dissociate it and radiators could be used to reject excess heat to cosmic background in order to liquefy its components. After starting Rosenberg's process, one need bring only half the amount of weight in methane instead of water to the lunar location. Methane packs more than twice as much H_2 per pound than water does and one would dissociate hydrogen from methane instead of from water. This means that for return flights from the Moon, if there is an oxygen supply there, a weight only half that of water would have to be ferried in from Earth; and carbon gas would be left on the Moon as an extra bonus for further use as a fuel. One can see that this approach has the potential of cutting fuel logistics on the lunar base by better than half. This possibility points up the need for further analysis of other possibilities of processes and compounds which have still higher H_2 yields but have a high enough specific density to reduce the transport volume further.

While the weight factor of 1 to 9 between hydrogen and water is attractive, the low density of even liquefied hydrogen gas requires storage volumes and structural tank weight fractions which might be impractical as an avenue toward the final goal of independence from Earth logistics with current space system components used as reusable carriers. Then, if water as a compound is found in minable

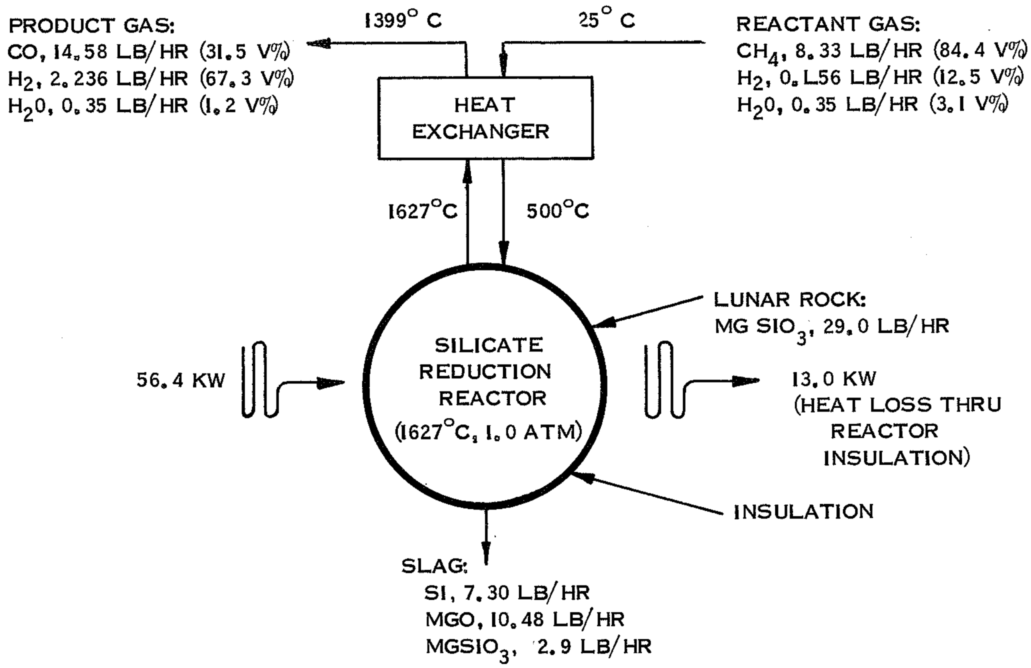


FIGURE 9.—Silicate reduction reactor section; values based on oxygen production of 6000 pounds per month.

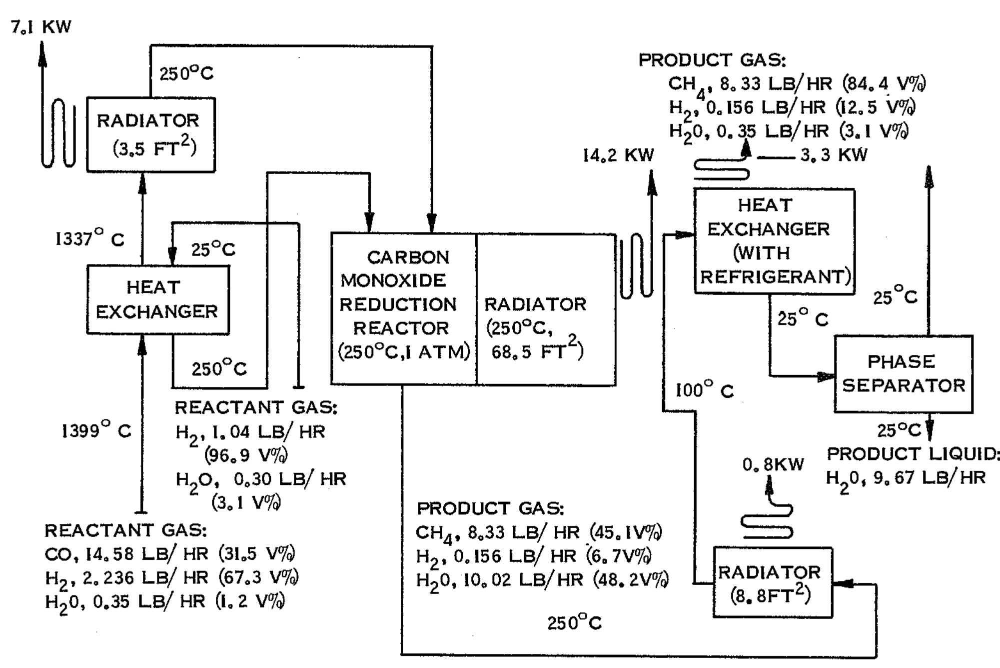


FIGURE 10.—Carbon dioxide reduction reactor section; figures based on oxygen production of 6000 pounds per month.

and processable qualities, the Rosenberg process could be replaced by more efficient processes involving extraction and dissociation to obtain LO_2 and LH_2. Every one of the described steps would reduce the logistic requirement and lead to a higher degree of economy and independence from Earth. For a while, these processes could be used parallel to each other until the less efficient one can be replaced by a proven and more efficient process.

A next step could be the establishment of a third space terminal at one of the lunar libration points which would serve as a point of departure for interplanetary missions which would be supplied with fuel first from Earth and later from the Moon.

RECOMMENDATIONS FOR AND MODEL OF A SPACE TRANSPORTATION SYSTEM

From the preceding discussion, we can conclude that a partly reusable transportation system which should include landing at and establishment of a lunar orbital terminal as well as a surface terminal can be considered well within the realm of possibilities of current technology and planned vehicles. If this proposed approach is to be used, however, it must be included in our national space plans and implemented as we go along in using the Saturn V system to expand our space capabilities. The real step forward toward a highly economic Earth-surface to Earth-orbit system would come when this part of the space transportation link would be made at least partly recoverable and would use components which are part of existing or near-future aerospace systems, as far as either components or technology of these systems are concerned. The current limited number of annual space launches of NASA and the Department of Defense does not justify the early replacement of the current nonreusable space launch systems, and a desire for their replacement would not find strong support in either camp. However, thoughts have been advanced throughout the scientific community for gradually improving subsystems which eventually would prepare the way toward more economic space flight, including at least partial reusability of space vehicles. One item that could pave the way is a fully recoverable reentry vehicle with a capability of launching and returning from orbit a large payload weight (40 000 to 60 000 pounds per flight). The other possibility would be to develop a mobile reusable space-launch platform, using horizontal takeoff and landing on existing military runways as needed. Several approaches for such a launch platform, good for the range from subsonic launch speed to hypersonic launch speed, have been advanced by the scientific community and by industry. Although one can obtain higher payloads per pound of takeoff weight by going to high separation speeds, there is much indication that degree of reusability, level of preventive maintenance, cost of initial development, test, and procurement, and the technological risks and uncertainty involved would make such an approach a long-leadtime approach and could be detrimental to the level of cost effectiveness needed to effect space-launch cost favorably even with high launch numbers. Use of the lower speed spectrum from the range of high subsonic to low supersonic transport speeds provides interesting possibilities besides furnishing a reduction in technological risk, and could turn out to be economically superior to other advanced solutions. Further scrutiny, however, may place a higher ΔV burden on the upper stage or stages or require the reentry vehicle to have a limited ΔV capability of its own. The interim stage or stages would use conventional space launch systems technology.

This approach, if jointly undertaken by DOD and NASA, could first lead to a space rescue system which would be desirable as a point of departure and as a means of rapid access to low Earth-orbit targets, independent of inclination and ephemeris, as well as to space stations. For the latter, the space rescue system could serve as a crew rotation vehicle. Since it initially uses a subsonic space-launch platform, it would not involve major advances in space technology and would require only the typical leadtime of a development within current state of the art for design and construction or modification of aircraft and rocket boosters. It, therefore, could be available within less than a decade, if such an approach would become part of a national program.

Even if the military side of our national space effort would gain only a rescue, crew rotation, and in-space maintenance capability out of this approach, since the takeoff site would be independent of the ephemeris data of the target orbit and could be land based on one of our military bases—a big step forward in enhancing industrial and research utilization of space might possibly result. Increased industrial utilization of space then would tend to increase progressively the annual number of space launches, and so, in turn, make reusable space systems increasingly more attractive as compared with currently uneconomic systems.

One may witness a similar situation in early air transportation, where improvements in military aircraft spawned greater commercial use and, in turn, produced other military aircraft improvements. If this element of mutual interaction had been missing, the progress of aviation would have been less dramatic than it has been. This story may be repeated again in space flight if we as a nation look at those elements of progress which are affected by a high degree of mutual support between commercial and military use aspects.

On the basis of the preceding discussion, one could recommend that a vigorous national program be established to study the adaptability of the subsystems of all of our current space-launch and spacecraft systems from the aspect of their usefulness as reusable components of a new system. The study should include:

(1) Establishment of Earth- and lunar-orbit terminals made up mainly of spent S–IVB and S–II stages and equipped so that they can be used to house personnel, shop facilities, and fuel storage appendices.

(2) Reuse of lunar landing and rendezvous modules as reusable shuttles between lunar surface and lunar orbit.

(3) Use of S–II and S–IVB's which have been modified so that they become optimum for shuttles between Earth orbit and lunar orbit on a reusable basis.

(4) Augmentation of the current space-launch vehicles by an Earth-surface to low-Earth-orbit partially reusable system, in which the first stage would be a horizontal-takeoff, horizontal-landing aircraft of subsonic ($M = \leqq 0.9$) or low-supersonic second-stage launch speed ($M=2.7$ to 3.0). The second stage should be a hydrogen-oxygen-fueled expendable rocket stage and should be augmented by the already proposed moderate ΔV (approximately 5.0 fps) fully recoverable upper (third) stage of a 40 000- to 60 000-pound payload capability. In the event a mach 2.7 to 3.0 first stage is used, it could be possible to lay out the third-stage capability so that all of the second stage reaches orbit and all expensive major components could be recovered again with the third, fully land-recoverable, stage after disassembly of the second stage at the orbital terminal. The tanks of the second stage could be salvaged for orbital fuel storage and other purposes. This possibility is based on LH_2–LO_2 as standard fuel for these missions and would be more difficult to achieve if use of LH_2–LF_2 were planned.

With liquefaction and dissociation capabilities for water, it is visualized that by equipping these terminals with nuclear electric powerplants, water rather than fuel could be brought to orbit and converted to fuel there; this would save transport volume and insulation during ascent through the dense Earth atmosphere. With this capability, return fuel should be dissociated in lunar orbit, and the lunar reusable shuttle system inaugurated to establish service between the lunar-orbit terminal and lunar surface.

The next step could be the establishment of a lunar oxygen extraction plant, as proposed by Dr. Rosenberg, which provides interim oxygen supply. If now the water is replaced by CH_4 to be brought in from Earth, the S–II and S–IVB stages could be flown back to Earth orbit using H_2 fuel derived from CH_4 and oxygen supplied from the Moon. It is quite obvious that this approach increases cargo capabilities both ways and could lead to industrial exploration and possibly exploitation of commercial uses in Earth and lunar orbits as well as on the lunar surface.

With progressing lunar-surface exploration and growth of our selenographical knowledge, sources for lunar water may now be established and the mining technology projected which will be needed to convert it from either water of hydration, permafrost, or subselenian water to liquid oxygen and hydrogen. I have presented only a gross layout of these possibilities. By a closer analysis, one will find that there exist a number of interim steps, in which newly achieved capabilities will, as they reach their eventual maturity and capacity, gradually relieve the earlier modes of operation.

Contributions of the members of the Working Group toward the approaches sketched in this treatise may go a long way toward increasing U.S. space-flight capabilities and space-flight contributions to this Nation's welfare and future stature. Some of the recent spectacular findings of U.S. lunar landers and orbiters have confirmed earlier postulations of our group and brought many of the technical thoughts advanced by its members closer to reality than the majority of the scientific community would have believed possible. The fact that the major professional societies pay increasing attention to this area by including it in their session programs testifies to the importance which our work may achieve in our Nation's space operation and exploration objectives. Timely inclusion of these presented possibilities in advanced technology plans would aid this work in remaining in the forefront of progressive space technology and provide the means to advances which would otherwise be difficult to achieve.

Page intentionally left blank

FRITZ M. G. HOLMSTROM
School of Aerospace Medicine
Brooks Air Force Base, Tex.

Observations Made at a High-Altitude High-Latitude Manned Facility

INTRODUCTION

From 1963 to 1965 the Arctic Aeromedical Laboratory, a facility of the U.S. Air Force Systems Command's Aerospace Medical Division, conducted an active research and development program in conjunction with the Geophysical Institute of the University of Alaska and the U.S. Army Arctic Test Center which resulted in the establishment and operation of a small field station at 4 160 meters (13 650 feet) near the summit of Mount Wrangell, Alaska. Mount Wrangell, located at 62° N, 144° W, is a minimally active vol-

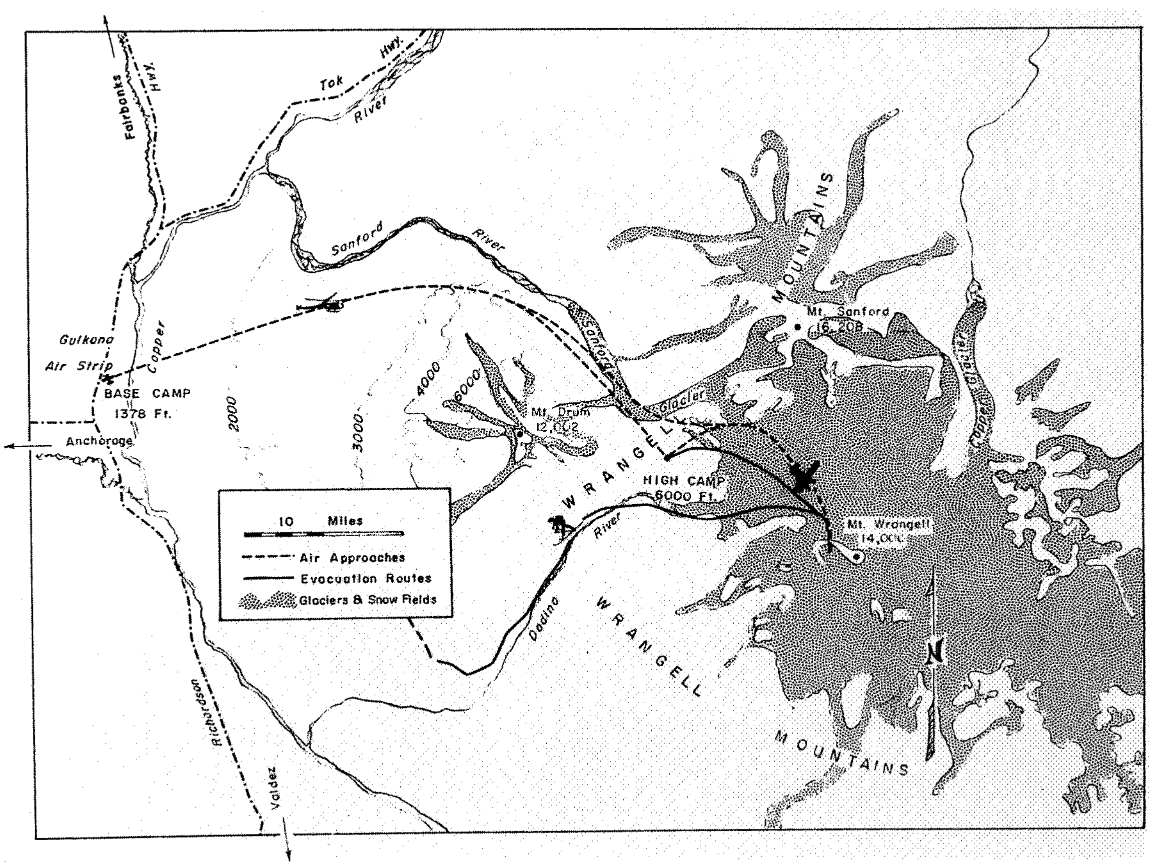


FIGURE 1.—Contour map of Mount Wrangell area showing location of base camp, temporary high camp site, summit, and connecting air route.

324-954 O—69——16

cano with a large, relatively flat, plateaulike top which measures about 5 by 3.5 kilometers (figs. 1, 2, and 3). It is covered with a perennial snow and icefield at an altitude high enough to be approximately at the dry-snow line. The icefield is essentially unbroken except for a small crater, which produces modest amounts of steam and hydrogen sulfide, and for several ridges, some of which are kept ice free by the presence of volcanic heat. In the summer of 1964, a specially insulated, prefabricated shelter measuring 16 by 24 feet was assembled on the largest of these ice-free ridges (figs. 4 and 5). The structure was designed to trap and hold heat from the underlying warm ground. Since its erection the structure has remained comfortably warm without the use of supplemental heat regardless of outside temperatures. This building was utilized for several weeks as the living quarters for a working party in the late summer of 1964 and served as the laboratory work and support area for several research and work teams who used the facility in the spring and summer of 1965 (figs. 6 and 7). The present paper reports on certain psychophysiological responses observed in station personnel and on selected temperature and barometric pressure measurements made during this period.

Sincere thanks are expressed to Dr. C. S. Benson for his suggestions concerning the feasibility of using trapped volcanic heat; to D. L. Chauvin, the supervising construction engineer; and his fine team of Geophysical

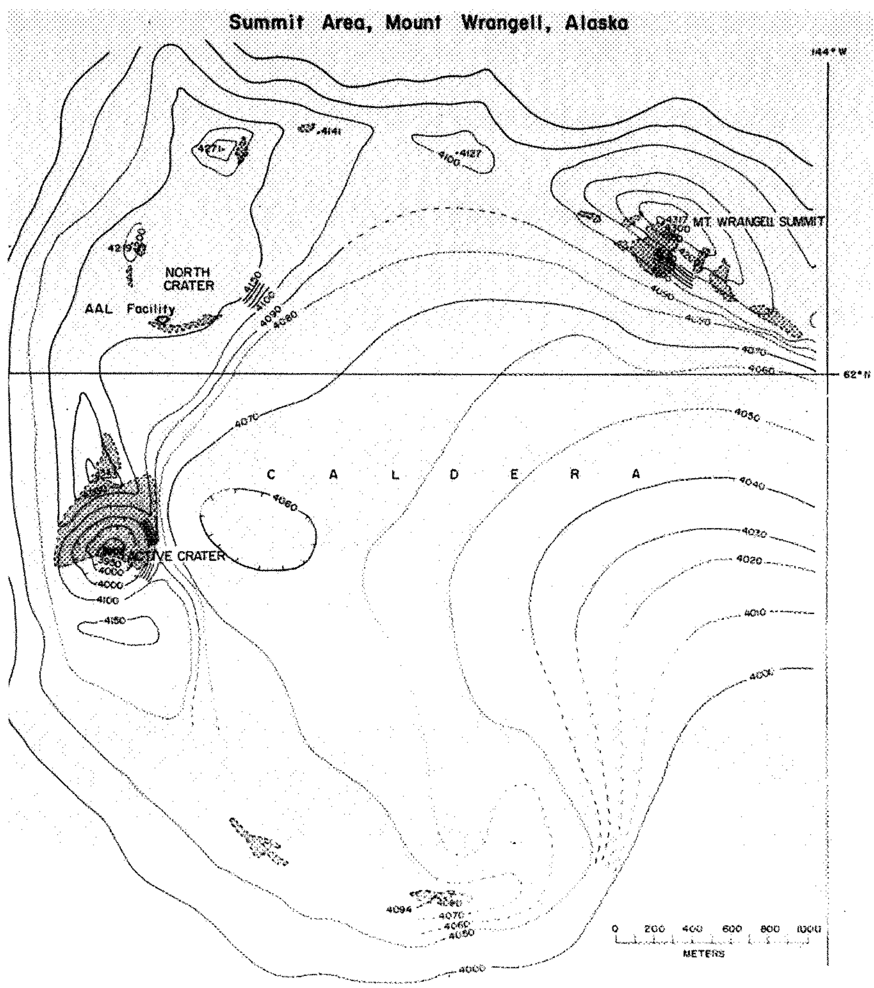


Figure 2.—Contour map of summit area, Mount Wrangell, Alaska.

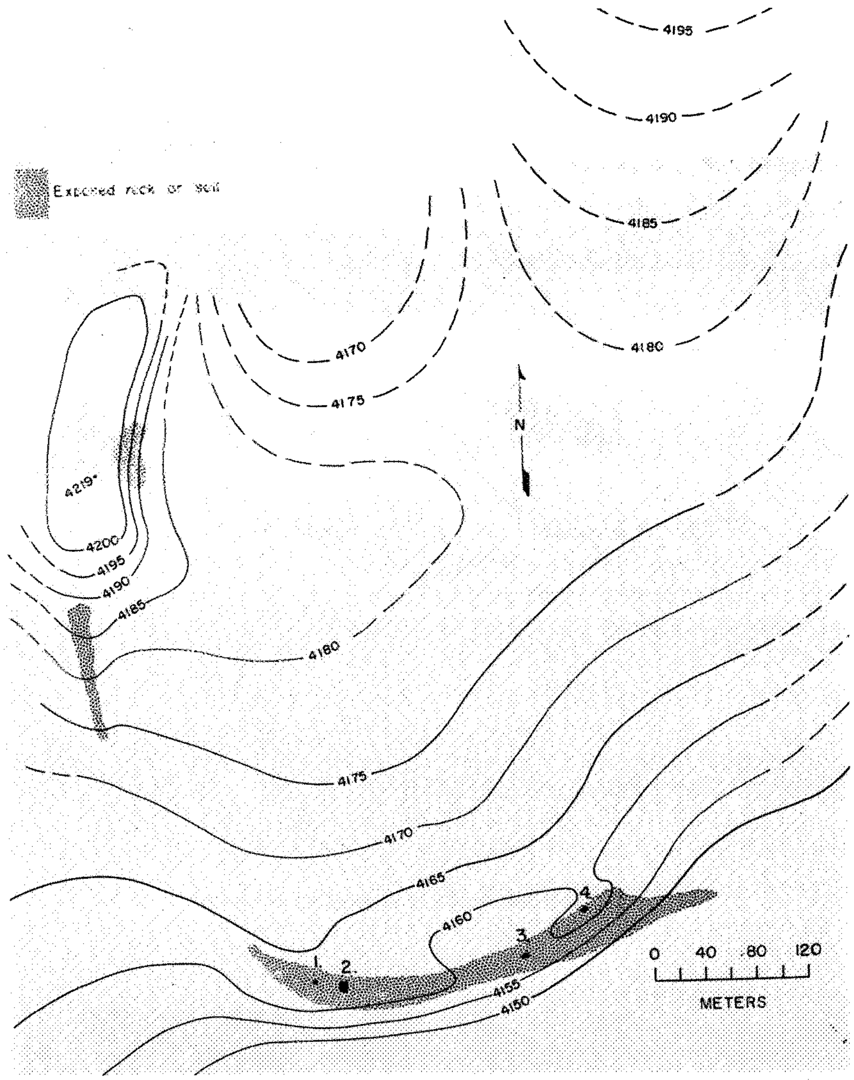


FIGURE 3.—Contour map of research facility area on Mount Wrangell.
1. Storage and generator building.
2. Main building.
3 and 4. Huts from 1953–54 (of possible use in emergency).

Institute personnel; to Dr. C. J. Eagen, Capt. J. Ray, J. Schuman, and the others of the Arctic Aeromedical Laboratory staff who participated both as subjects and observers; and to the outstanding airlift support provided by the U.S. Army Arctic Test Center, the U.S. Air Force Alaskan Air Command, and J. Wilson, owner of the Wilson Air Service in Gulkana, Alaska.

ADAPTATION OF PERSONNEL

A total of 37 different individuals participated in the establishment and initial operation of the facility and in the follow-on research program. Of this number, 28 individuals, varying in age from 20 to 53 years, remained on location for more than 1 day and are included in the analysis. Their average stay

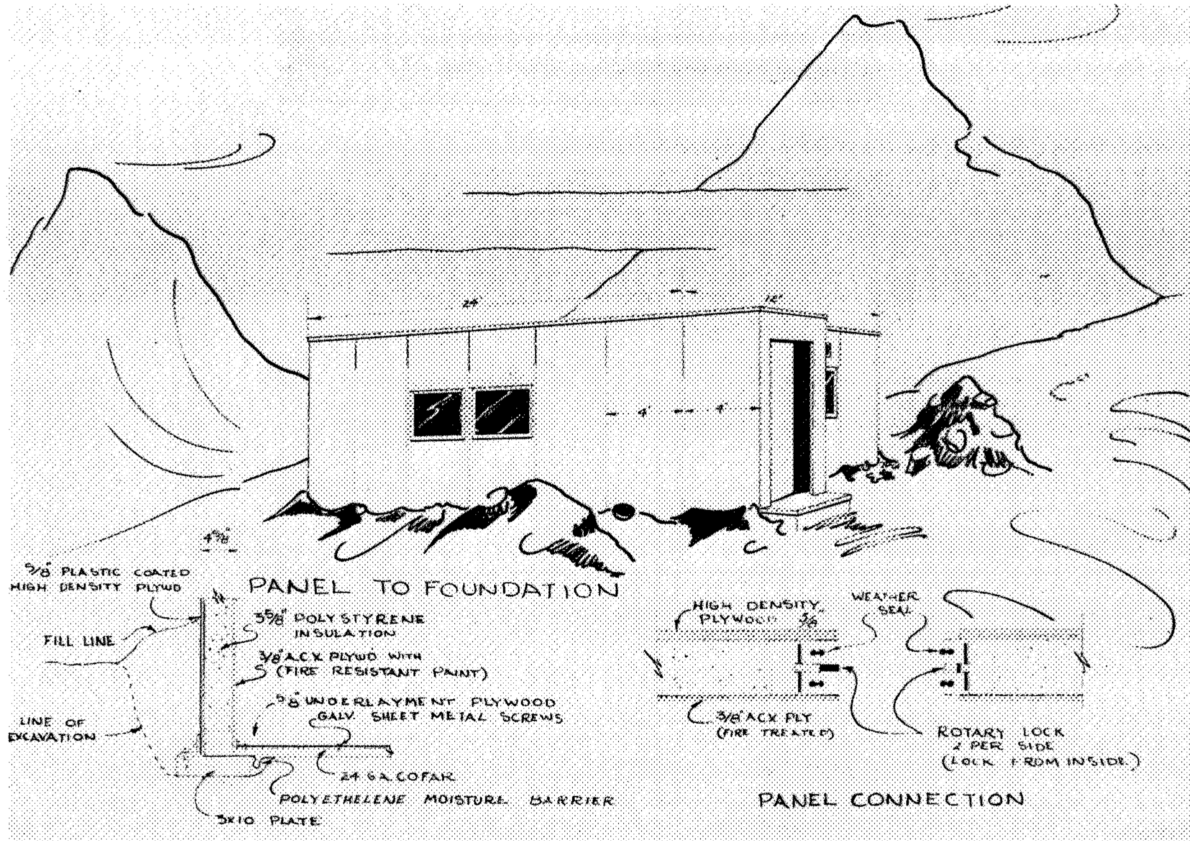


Figure 4.—Schematic of laboratory structure.

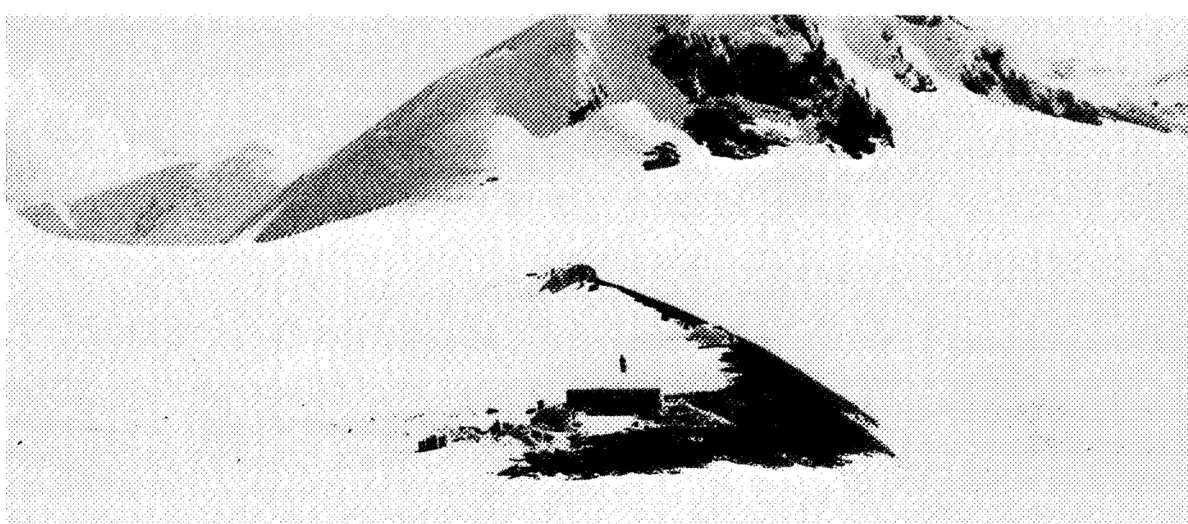


Figure 5.—Aerial view of ice-free ridge with laboratory facility in foreground. Small structures visible at far end of ridge are Jamesway huts erected by Geophysical Institute in 1953–54 to support a cosmic-ray research program.

FIGURE 6.—Mount Wrangell research facility showing laboratory facility on the left, generator hut on the right, and bivouac area in left foreground.

FIGURE 7.—Interior view of laboratory building. Special egress window is open.

was 14 days, so they received a protracted exposure to the combined stress of altitude, cold, and work. Because the remoteness of the site and an aggressive work program placed a premium on maintaining physical fitness, the health and operational effectiveness of all personnel were observed and recorded. These observations are of practical interest inasmuch as they offer substantial evidence that, contrary to popular belief, it is the older, more mature male and not necessarily the young individual who is better able to adapt effectively to the rigors of life in the Arctic at an altitude of 4160 meters.

Physiological Environment

Table 1 summarizes the physiologically significant environment data. Like all high mountains, Mount Wrangell exhibits reduced barometric pressures, low temperatures, high winds, and capricious storms. During the period of this study the barometric pressure as measured at the facility (altitude, 4160 meters) was most frequently observed to be at or about 450 mm Hg, with variations from a high of 457 to a low of 429 mm Hg. Since most of the site activities reported were conducted from July to August 1964 and March to June 1965, the very low temperatures associated with the long arctic night were not observed. Daytime environmental temperatures varied from a high of −5° C on the warmest days to −25° C on the coldest. Nighttime temperatures generally averaged 1° to 6° C colder. High winds and severe storms with blowing snow were common and wind velocities were estimated to be in excess of 75 knots on several occasions.

Participants

The participants were divided into three teams as described in table 2. The construction group, team A, consisted of civilian contract employees from the Geophysical Institute of the University of Alaska. Team B, the research group, was comprised solely of U.S. Air Force personnel. All individuals in teams A and B worked hard at altitude. Team C was a research and support group whose members generally engaged only in light work. It included U.S. Air Force personnel and personnel from the Geophysical Institute as well as one participant from the U.S. Army, one from the University of Hawaii, and one from Oxford University in the United Kingdom.

TABLE 1.—*Environment Characteristics Observed at Mount Wrangell Research Facility*

Characteristic	Value		
	Max	Min	Av
Altitude:			
Meters	--------	--------	4 160
Feet	--------	--------	13 650
Barometric pressure:			
MB	608	572	600
mm Hg	457	429	450
Daytime temperature:			
°C	−5	−25	−18
°F	23	−13	0
Wind, knots	75+	0	10
Length of day, hr	22	12	19

TABLE 2.—*Age Distribution of Participants as a Function of Activity*

Age	Number of subjects with primary activity of—			Total
	Hard work		Light work	
	Team A	Team B	Team C	
20 to 24	1	3	2	6
25 to 29	2	1	4	7
30 to 34	1	0	4	5
35 to 39	2	2	1	5
40 plus	1	1	3	5
Total	7	7	14	28

All participants underwent baseline physical examinations including chest X-ray, 12 lead electrocardiograms, and blood indices. No abnormalities were noted. None of the participants were altitude acclimatized at the time of their ascent to Mount Wrangell. As a matter of fact, only 3 of the 28 had ever lived previously at altitude long enough to acclimatize. For the rest, the present experience was their first.

Only seven individuals, the members of team B, were known to be in excellent physical condition. They had trained daily in cross-country runs, ski reconnaissance patrols, and other types of graded exercise for 5 months prior to ascent. Repeated testing using the method of Johnson et al. (ref. 1) as described by Consolazio, Johnson, and Pecora (ref. 2) classified all of them as highly fit. The rest of the participants made no special effort to train or otherwise improve their fitness. The military members of group C, when tested in the same way, all fell into the lowest category of fitness. Group A was not tested. (The foregoing information was obtained from a personal communication from Dr. C. J. Eagen.)

Quality of the Experience

Nearly everyone spent a substantial number of waking hours in the open. With the exception of a few members of the support groups who slept in the facility structure where the temperature averaged from 23° C (70° F) to 29° C (80° F), all personnel lived in standard four-man mountain tents and slept in arctic sleeping bags placed on air mattresses. Clothing was the standard arctic military issue supplemented by lightweight down-filled parkas and pants. The basic diet, unrestricted with respect to quantity, was the standard military K-ration supplemented, when logistically feasible, by fresh bread, meat, fruits, and vegetables.

Transportation between base camp and the summit was accomplished by aircraft, the total ascent usually taking less than an hour. Immediately on arriving, the participants undertook a full work schedule. In the case of the construction crew, team A, the initial task was to excavate a foundation for the laboratory building and also unload incoming materials as they arrived. For example, six men working almost continuously were able to excavate and move an estimated 4.6 cu m (cu yd) of volcanic ash and sand weighing about 7250 kilograms (8 British tons) in the first 15 hours on location, in addition to unloading several tons of supplies and materials from incoming aircraft. They continued their heavy work at a lesser rate for the next 4 days until all major assembly activities had been completed. Similarly, the seven men in the physically fit team B worked hard from the onset; they set up a bivouac area on their first day and initiated a preplanned program of ski patrols, climbing activities, and calisthenics on the following day. By way of contrast, most members of group A engaged in a comparatively undemanding work regimen; they limited their activity to setting up and operating research equipment and conducting general station-keeping tasks.

The close presence of a volcanic crater intermittently venting modest quantities of visible steam and small amounts of hydrogen sulfide gas, which was also the source of occasional tremors as masses of snow and ice on the crater rim would melt, loosen, and audibly tumble to the bottom of the cone, continually reminded each participant that he was indeed living on the edge of a volcano. Although the probability of a substantial unheralded eruption was judged to be negligible, the possibility of such an event could not be completely discounted (ref. 3). Thus, the participants were subjected to a unique whole-body stress based not only on a physiologically demanding environment but also on a series of psychological loads which included the problems of small-group living in a location remote from outside help, where work and exercise schedules had to be tailored to fit the immediate weather, and a quiet volcano exerting its own background effect.

Observations

For the first several hours after arrival at 13 650 feet, nearly all subjects reported a transient sense of elation. Within 4 to 24 hours slightly more than one-half of the individuals were affected by symptoms of altitude sickness occurring in varying degrees of severity: Headache, shortness of breath, general weakness, loss of appetite, nausea, and sometimes vomiting. However, only a few were disabled enough to restrict job performance.

A rating scale of from 1 to 4 is used to assess the operational effectiveness of each of the 28 individual participants, the assessment being based on general work performance rather than on the degree of symptomatology. (See table 3.) A subject is judged fully effective and

TABLE 3.—*Classification of Operational Effectiveness*

Classification	Degree of effectiveness
1	Fully effective.
2	Marginally effective.
3	Temporarily ineffective.
4	Ineffective.

rated as 1 if no symptoms were reported, if activity was not consciously limited by dyspnea or weakness, and if assigned tasks were performed appropriately. A rating of 2 suggests marginal effectiveness and indicates that the subject had overt signs and symptoms of acute altitude disease perhaps for as long as several days, but the capacity to work, exercise, and perform general duties as assigned was not noticeably compromised. Group 3 is composed of subjects probably best described as temporarily ineffective because they required intermittent bedrest for time periods ranging from hours to days. Although these subjects were not a major burden since they could take care of their personal needs, they were physically unable to perform part of their assigned duties in a predictable manner. However, all recovered in place and became effective within a week. Subjects rated as 4 are termed ineffective because they were so severely incapacitated by nausea, vomiting, headache, and weakness that immediate evacuation to base camp was clearly indicated.

Tables 4 and 5 show the variation in operational effectiveness of the Wrangell subjects. On inspection it is evident that the maintenance of operational effectiveness is somewhat proportional to age with young men under 25 years of age being most vulnerable to significant impairment and failure, while similarly exposed men in their thirties and forties remained comparatively effective. As a matter of fact, the data might even be interpreted as suggesting that it is the combination of youth and hard work that is most likely to cause disability, while in the more mature subjects physical work at altitude seems therapeutic.

TABLE 4.—*Operational Effectiveness at 4160 Meters Shown as a Function of Age*

Age	Number of subjects for effectiveness rating—				Total
	1	2	3	4	
20 to 24	1	------	3	2	6
25 to 29	2	1	3	1	7
30 to 34	1	4	------	------	5
35 to 39	5	------	------	------	5
40 +	3	1	1	------	5
Total	12	6	7	3	28

Effective Performance at Altitude

Thresholds for Altitude Tolerance

It is believed that the observed decreases in operational effectiveness were primarily related to acute altitude sickness in most instances. Altitude sickness derives from hypoxia which in turn is a function of the decreased partial pressure of oxygen found at altitude. Table 6 presents a spectrum of operationally applicable hypoxic thresholds as a function of altitude. The performance of athletes such as long-distance runners is reduced by 5 to 7 percent at 2134 meters (7000 feet) (ref. 4). Psychomotor function is impaired by acute exposure to altitudes above 3048 meters (10 000 feet), and for this reason military fliers are required to breathe supplementary oxygen when that altitude is exceeded during flight. However, given time, complete acclimatization appears possible in most healthy individuals up to an altitude of 4752 meters (15 000 feet). Above that altitude, sometimes termed the "threshold of incomplete compensation," men born at sea level fail in substantial numbers to adapt successfully to prolonged exposures. The maximum threshold for permanent residence is very well defined at 5334 meters (17 500 feet) (ref. 5). The Mount Wrangell field station strategically located at 4150 meters (13 615 feet) is thus within the range that should be fully compensable for most

TABLE 5:—*Operational Effectiveness at 4160 Meters as a Function of Age*

Age	Fitness	Number of subjects for effectiveness rating [a]				Total
		1	2	3	4	
20 to 24	Fit			(1)	(2)	
	Less fit					2(4)
	Unknown	(1)		2		
25 to 29	Fit			(1)		
	Less fit	1		2		4(3)
	Unknown	(1)	1		(1)	
30 to 34	Fit					
	Less fit		2			4(1)
	Unknown	(1)	2			
35 to 39	Fit	(2)				
	Less fit					1(4)
	Unknown	1(2)				
40+ [b]	Fit	(1)				
	Less fit					3(2)
	Unknown	1(1)	1	1		
Total subjects		3(9)	6(0)	5(2)	0(3)	14(14)

[a] Numbers in parentheses indicate subjects who engaged in hard labor; others refer to subjects engaged in light work.

[b] 4 of the 5 subjects in the 40+ group were younger than 44; the fifth was a hard-working, 53-year-old member of team A.

healthy people but is nevertheless high enough to provide a severe degree of hypoxic stress.

Effect of Age

The effect of aging on changing the responsiveness of man to physical stress usually takes the form of a gradual and progressive loss of physiological reserves. It becomes evident in the third or fourth decade of life to a degree sufficient to compromise performance in those physical activities which require both reasonably long-term, high-energy outputs and quick reaction times. By analogy, it would seem that the most fundamental of the physiological stresses—namely, exposure to high terrestrial altitudes with its reduction in inspired oxygen—should be tolerated better by the young adult than by an older person. This viewpoint is probably accepted a priori by most individuals and has support in the literature. For example, it has been reported that at 4000 meters (13 120 feet), younger subjects acclimatize better and sooner (ref. 6) and at 2896 meters (9500 feet) older people are more severely affected by symptoms of altitude sickness than is the average fit young man (ref. 7).

Insofar as the 28 subjects in this study represent a reasonable sample of the general American population of military age, the data in table 4 indicated that probably the reverse is true; namely, a man in his late twenties, thirties, and early forties performs more effectively at altitude than does a younger person. This is not an anomalous finding but has been substantiated to some degree by the observations of others. Mountaineers have long appreciated the fact that it is the person in his thirties, and not necessarily the very fit young man in his late teens or early twenties, who makes the best high-altitude climber. Nevison (ref. 8), in reporting on the Hidden Peak expedition in the Himalayas in 1958, observed that it was the two oldest members of the party who were able to make the highest ascent. Hellriegel, medical director of the Cuero del

TABLE 6.—*Operationally Significant Reaction Thresholds to Altitude Showing Critical Location of Mount Wrangell*

Threshold	Altitude		Atmospheric pressure, mm Hg	P_{O_2},[a] mm Hg	PA_{O_2},[b] mm Hg
	Meters	Feet			
Normal function	0	0	760	159	102
Significant reaction	3048	10 000	523	110	61
Mount Wrangell:					
Average	4160	13 650	450	94	51
Max	----------	----------	457	95	52
Min	----------	----------	429	90	46
Incomplete compensation	4572	15 000	429	90	46
Highest permanent residence	5334	17 500	387	81	43
Acute exposure, lethal	6706	22 000	321	67	30

[a] P_{O_2}, partial pressure of atmospheric oxygen.
[b] PA_{O_2}, partial pressure of alveolar oxygen.

Pasco Corp., which conducts mining operations in the high mountains of South America, has noted, in a personal communication, that the degree of disability suffered by miners recruited from the lowlands and newly arrived at altitudes of 3658 to 4663 meters (12 000 to 15 300 feet) appears to be age specific and closely parallels the Wrangell experience as presented in table 4. Bowerman (ref. 9) stated that among track athletes training at 2133 meters (7000 feet), the more youthful the competitor, the less adjustment in 15 to 20 days. McFarland, in a study of more than 200 men varying from 18 to 70 years of age who were acutely exposed for 2 hours to a 4267-meter (14 000-foot) altitude in a low-pressure chamber (ref. 10), found heart rates of older men to be slower than those of the younger. In addition, the older subjects appeared to have fewer complaints and were less susceptible to fainting and collapse. Folk (ref. 11), using Mosso's original data, showed that young men aged 18 to 19 years exposed for 3 days to 4559 meters (14 957 feet) at the Regina Margherita Hut in the Italian Alps had substantially higher heart rates than did older men between 22 to 50 years, but that the older men had higher respiratory rates. Hall et al. (ref. 12), in evaluating the effectiveness of potassium chloride to modify altitude sickness, transported 20 Indian Army soldiers varying in age from 18 to 30 years from a sea-level location to 5782 meters (17 000 feet) within a 24-hour period. None had a history of previous altitude acclimatization. All subjects suffered to some degree from acute altitude sickness during the 4 days at altitude, and it was concluded that the drug was ineffective. However, when Hall's original data are evaluated in terms of the degree of disability as determined by incapacitation requiring bedrest (see table 7), an age effect is uncovered which shows that men over 20 years of age apparently are less affected than are younger men. Luft (ref. 13), in a series of low-pressure-chamber studies, found a remarkable age-related difference in tolerance to acute exposures of 7500 meters (24 600 feet) with men between the ages of 25 and 40 years having a time of useful consciousness about 2 minutes longer than the average time of 6 minutes 8 seconds recorded for subjects between the ages of 20 and 25 years. Finally, the observation that high-altitude pulmonary edema, an uncommon but serious complication of acute sickness, seems to have a higher incidence in young people is not inconsistent with the general thesis that performance at altitude improves with age (ref. 14).

There is no convincing explanation for the age-related altitude effect. In the case of

TABLE 7.—*Estimated Effectiveness of 20 Indian Army Soldiers Exposed for 5 Days to 5782 Meters in the Himalayas*

[Estimates based on a review of Hall's original data to determine length of time subjects in each age category were confined to bed because of illness]

Age	Number of subjects requiring—			
	No bed	Bed <1 day	Bed >1 day	Total
20	0	4	1	5
20 to 24	3	2	5	10
25 to 30	2	2	1	5
Total	5	8	7	20

mountaineers, part of the answer may be found in previous training and motivation. The older man is presumably willing to accept the discomfort and anxiety associated with exposure and work at altitude secure in the knowledge, based on the firsthand experience of the past, that the situation is tolerable. On the other hand, one cannot completely discount the possibility that the older mountaineer does better because his acclimatization processes, having been previously exercised, are more effectively mobilized and thus minimize the severity of altitude sickness. The observation of Pugh (ref. 7), when he was referring to successive ascents to altitude, is very much to the point because he notes that most of the people he knows who have personal experience would say they had less trouble the second time. He said he would certainly claim for himself that he had less trouble, although his ceiling is lower now that he is getting older. Perhaps this phenomenon can be considered evidence of a biological memory which, once established, promotes successful patterns of acclimatization to subsequent exposures. Considerations of previous training and exposure, important though they may be to mountaineers, are not believed to be important factors in the present study, since only 3 of the 28 subjects had previously lived at altitude. However, it is interesting that one of these, a 33-year-old member of team A, volunteered the information that his second exposure, which followed his first by about 9 months, was much more tolerable.

The possibility of a relationship between maturity and the qualities that promote operational effectiveness cannot be discounted. Maturity in a physiological sense occurs at about age 26 in males and age 21 in women (ref. 15). With respect to altitude tolerance, the Wrangell data suggest that males have a critical point (perhaps a kind of "setpoint") at about age 25 which tends to divide the ineffectives from the more effective. The observations of Luft and the analysis of Hall's data as presented in table 7 seem consistent with such a conclusion. Although the temporal coincidence observed between physiological maturity and setpoint age cannot be considered cause and effect, evidence of a setpoint phenomenon in females of an appropriate age would tend to be confirmatory. Unfortunately, few references are to be found on this matter. Harris et al. (ref. 16) observed that girls of college age when compared with men experienced less shortness of breath, chest tightness, and so forth, at 4300 meters (14 110 feet) and Ravenhill (ref. 17) in referring to altitude sickness felt that women suffer less than men.

Physical Fitness

Fitness refers to the efficiency with which physical work can be performed. A highly fit person requires less energy to perform a physical task than does someone in poor condition. Presumably the fit person, because of training, has not only greater skill and dexterity but also more efficient metabolic processes and should be better able to tolerate altitude. Our data on fitness are inadequate since the status of less than one-half of the subjects is defined. In even those the applicability of the fitness test used is open to question. Table 5 presents the available evidence which compares operational effectiveness as a function of fitness and age. In this connection, Dr. C. J. Eagen, resident scientist for the Wrangell effort, found no significant differences between the fit and less fit as a result of their exposure in his report on body weight changes in teams B and C (ref. 18).

Cold Exposure

The possibility that living and working in subfreezing temperatures may affect altitude adaptation deserves consideration. Exposure to cold induces a diuresis with loss of fluids and electrolytes to cause a reduction in plasma volume and hemoconcentration. However, cold also causes a general peripheral vasoconstriction which not only serves to insulate against heat loss but also reduces the size of the vascular bed and thus adjusts one to the reduced blood volume. The extent to which such physiological changes altered the adaptability of our subjects is not known. However, since no pertinent evidence implicating age as a factor in cold tolerance has been found in the literature, it is assumed that the impact of cold, if any, should fall equally on all participants.

Day-Night Cycle

The long summer day is one of the most striking characteristics of the Earth's polar regions. At the latitude of Mount Wrangell there is little or no darkness for the best part of several weeks before and after the summer solstice. Although a long day of this kind has a potential for disturbing the inborn circadian cycle and thus affecting health and efficiency, it was not an important factor in this study. Each of the subjects had been at the same or at higher latitudes for weeks to years before moving to the summit and had already adopted his activities to the usual 24-hour day independent of the hours of daylight. There was no essential change in work and sleep schedules at the laboratory station.

Psychological Factors

Of all the variables that influence behavior in a practical situation, only a few can ever be incorporated in any series of laboratory tests. At best then, laboratory experiments only approximate real life and incorporate a potential for error since important interactions may not be observed. The Wrangell location is not a structured laboratory setting. The knowledge that unpredictable, potentially destructive, unrestrainable natural forces are underfoot and operative provides an emotional test bed that cannot be duplicated in any laboratory and may represent a reasonable terrestrial approximation to the kind of psychological stress implicit in an extraterrestrial location.

Reactions to stress include fear, anxiety, depression, tremors, speech disturbances, increased muscle tension, altered cognition which can impair performance, and physiological changes related to autonomic nervous-system stimulation. Because stress reactions may also mimic the symptoms of altitude sickness, the degree to which the Wrangell subjects were stressed by location, independent of altitude, cannot be accurately determined. That such a stress was operative and caused the evacuation of at least one subject is quite clear. The subject, a motivated, physically fit, 21-year-old man, had been an unofficial leader during the months of preascent training; he had consistently tried to improve his own performance and had urged the rest of the group to do the same. Several days before ascent he underwent an obvious change in mood and became depressed and anxious. He was allowed to ascend with his group. His first action upon arrival at the summit was to walk to the laboratory building, spread out his sleeping bag, lie down, and immediately complain of headache, weakness, nausea, and anorexia. He resisted all offers of assistance and refused to be encouraged until he was evacuated a day and a half later. He recovered quickly on returning to base camp.

In spite of this instance, the general performance of most subjects exceeded expectations. Living in isolated togetherness, the subjects maintained good individual and group discipline, remained strongly motivated to perform well, and were responsive to broad general guidance from base camp. There was no evidence of the so-called "breakaway" phenomenon that has been reported in certain long-term underwater habitation studies which feature a strong control and command function from the surface (ref. 19), perhaps because our groups had the primary responsibility of scheduling their own activities on location so that they could take advantage of weather and events so as best to accomplish their established objectives in the time which had been allotted.

Summary of Adaptation Data

The Wrangell data strongly suggest that altitude tolerance in males when measured in terms of the effective performance of physical labor, reconnaissance ski patrolling, and general responsiveness to a disciplined group regimen is related to age. Others have made observations consistent with such a conclusion at altitudes as low as 2133 meters (7000 feet) (ref. 9) and as high as 7500 meters (24 600 feet) (ref. 13). An age effect has been observed in people of different ethnic origins; for example, European and American Caucasian mountaineers (refs. 7 and 8), Indian soldiers, and Latin American miners. The effect seems to be essentially independent of cold, of prior altitude acclimatization, and possibly of physical fitness. Psychological stresses enhanced by the essential autonomic nervous instability of the young are undoubtedly important.

ENVIRONMENTAL VARIABILITY

Barometric Pressure

Changes in barometric pressure with pressures ranging from 572 to 608 millibars have been observed on Mount Wrangell. While part of this variability is attributable to local meteorological conditions, by far the major influence is seasonal as shown in figures 8 and 9. Pressure changes of this magnitude, particularly at altitude, are physiologically significant. For example, a subject at the Wrangell station who is at a tapeline altitude of 4160 meters (13 650 feet) and therefore assumes that he is at a pressure altitude of 604 millibars may, in the worst case, be exposed to a pressure altitude of only 572 millibars. Thus, from a physiological viewpoint, he is really exposed to an altitude of 4572 meters (15 000 feet). The effect of barometric pressure changes primarily related to latitude becomes evident if the situation at 4160 meters (13 650 feet) on Mount Wrangell is compared with that at the same tapeline altitude at 28° N on Mount Everest. In the worst case, calculated on the basis of the data extrapolated from figure 8, an Everest subject would be at a pressure altitude of 606 millibars or 4136 meters (13 570 feet) and, by comparison, would enjoy a substantial physiological advantage.

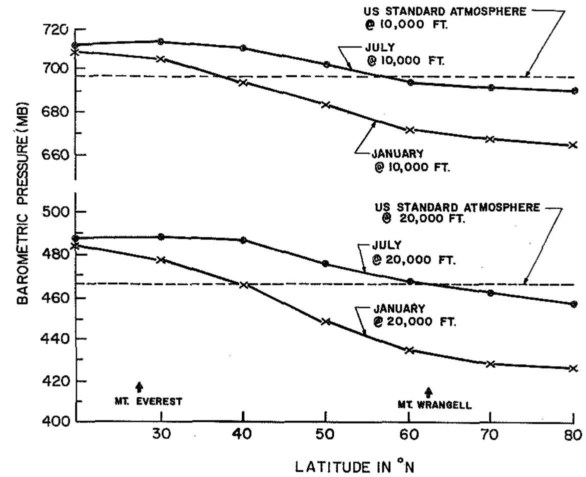


FIGURE 8.—Variation in barometric pressure as a function of altitude, latitude, and season compared with U.S. standard atmosphere (ref. 21). Latitudes of Mount Wrangell and Mount Everest are shown.

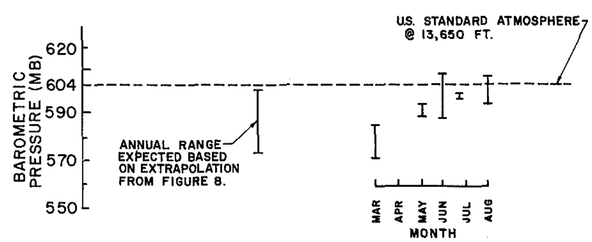


FIGURE 9.—Range of barometric pressures observed at Mount Wrangell by month and annual expected range based on an extrapolation from figure 8. Data from Bingham and Benson (ref. 23) and unpublished Arctic Aeromedical Laboratory observations.

The reasons for the seasonal and latitude barometric pressure effects have been discussed by others (ref. 20). The latitude effect is related to the axial rotation of the Earth which produces an equatorial bulging and polar flattening of the Earth's atmospheric envelope as a function of angular velocity and the Earth's diameter. The seasonal effects are related to the changes in thermal inputs to the atmosphere from solar radiation as a function of the 22° axial inclination of the Earth.

324-954 O—69——17

Air Temperature

The mean average temperature at the Wrangell station is −20° C (ref. 21). Figure 10 shows the temperature lapse rate as a function of season. These readings are free-air temperatures recorded from an aircraft during ascent from the base camp. It is evident that temperatures at the summit have a relatively narrow range when compared with the wide seasonal excursions seen near sea level only a short distance away.

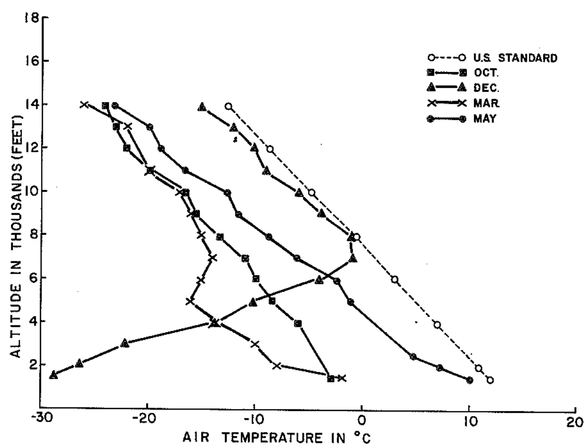


FIGURE 10.—Temperature profiles as a function of altitude and season in the Wrangell area. Measurements made from an aircraft flying from Gulkana, Alaska (altitude, 1500 meters), to the Wrangell summit 50 miles away. Temperature lapse rate according to the U.S. standard atmosphere is shown for comparison. Data collected by Benson, Wilson, and Holmstrom.

Ground Temperature

Mount Wrangell's attractiveness as a location for an arctic altitude station is related in part to the availability of usable ground heat in the region of the ice-free ridge. A reconnaissance study performed in 1961 by Benson (ref. 21) provided the basic data. (See fig. 11.) The ash comprising the main body of the ridge was identified as typical Pacific rim andesites. The thermal gradient in the ridge was found to be 0.30° cm^{-1} down to a depth of 1 meter. Calculations performed in 1963 (ref. 22) showed the heat flux to be sufficient to maintain a 16- by 24- by 8-foot structure with an uninsulated floor and 4-1/2-inch-thick insulated walls and roof at an interior temperature of 20° C in the face of an external temperature of −40° C. Since its erection in 1964 the present structure has, in fact, remained warm, fairly dry, and stably located in its original position. The enormous logistical advantage of being able to draw on an unlimited thermal source for warming an arctic building in a remote location can be best appreciated by those with some experience in the polar regions.

During construction, three dial thermometers reading from 0° to 100° C were mounted in the plywood floor to measure ash temperatures below the building as shown in figure 12. During the period of occupancy substantial temperature variations were seen; they rose on occasion to the boiling point of water (84.7° to 86.4° C, depending on barometric pressure) at rates as high as 4.5° C hr^{-1}. (See fig. 13.) Bingham and Benson (ref. 23) have observed that the temperature rises correlate well with decreases in barometric pressure and explain it on the basis of Elder's steaming ground model. They feel that the temperature effect, although operative in the whole ridge, is accentuated in the ash under the structure probably because the hut, acting as a seal, prevents the free escape of water vapor to the outside.

In addition to the main ice-free ridge, there are other evidences of volcanic heat such as a modest crater, several small, hot areas scattered around the rim of the caldera, and one area of several hundred square meters of red clay formed by the hydrothermal alteration of the rock in the area. The temperature of the clay surface ranges from warm to hot to the touch, with temperatures as high as 86° C having been measured. Blue-green algae tentatively identified as a *Phormidium* have been observed growing on the warm surface. Unfortunately, no systematic biological study of this or any of the other ridges has been undertaken, although such an effort might prove very interesting, particularly if the results could be compared with similar studies from other mountainous areas such as the warm spots on Mount Erebus (altitude 4023 meters (13 200 feet)) at 77° S.

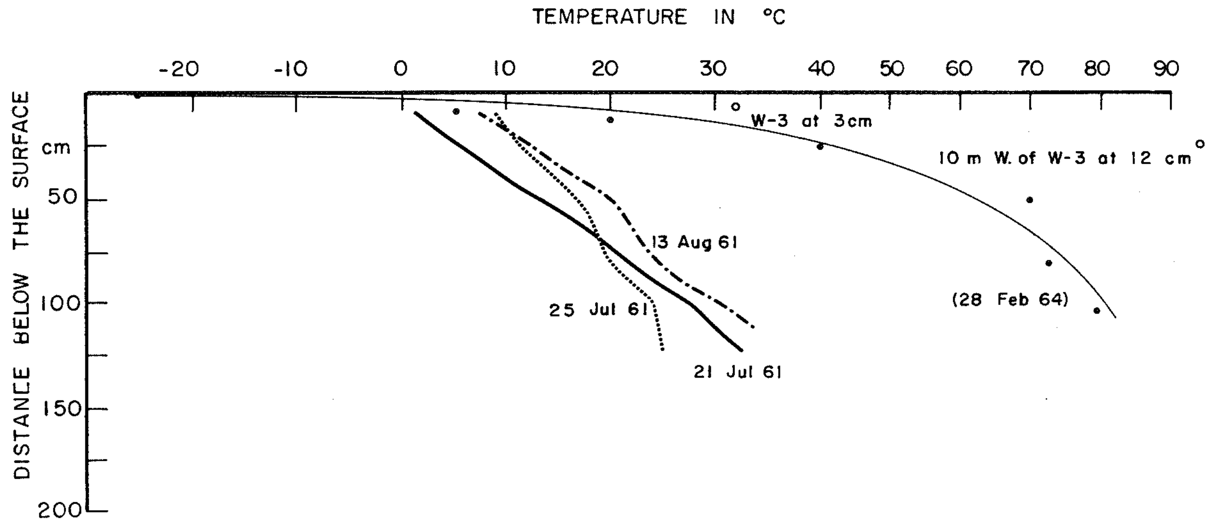


FIGURE 11.—Temperature gradient in ice-free ridge. 1961 data from Benson (ref. 21) 1964 data collected by Bingham and Wilson.

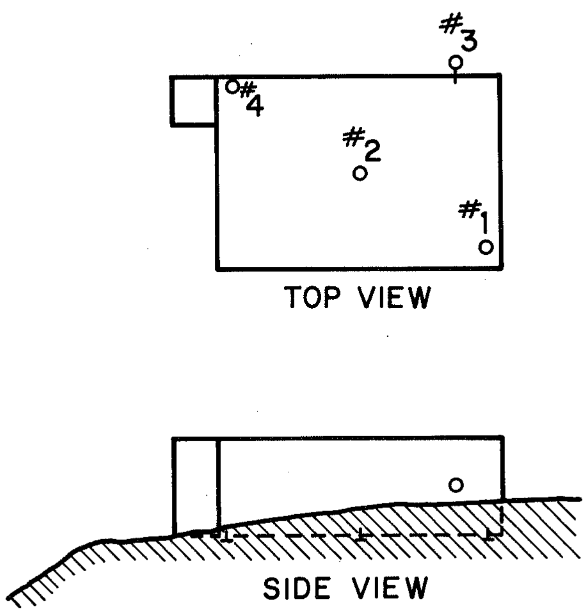


FIGURE 12.—Floor plan showing location of thermocouples used to measure ground-floor temperatures. Thermocouple 3 was located outside, next to wall of hut, and measured free-air temperature.

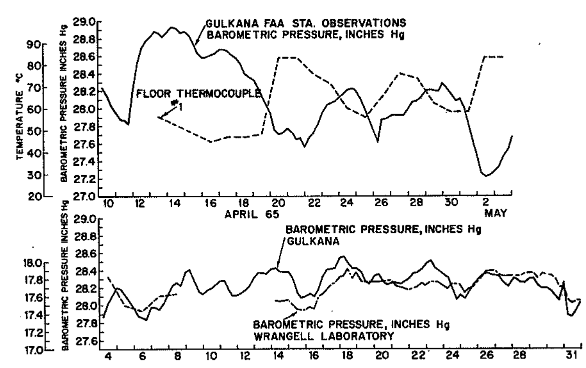


FIGURE 13.—Comparison of barometric pressures. Data collected by personnel from Geophysical Institute, U.S. Army, and U.S. Air Force. (*a*) Comparison of barometric pressures as measured at Gulkana with subfloor ground temperatures at laboratory building. Mount Wrangell pressures were not made during this time. (*b*) Comparison of barometric pressures at Gulkana and at Mount Wrangell showing the close correspondence in direction and extent of changes.

APPLICATION TO EXTRATERRESTRIAL ACTIVITIES

The Wrangell summit is one of the world's unique locations. It has the polar day; temperatures well below freezing; a massive, relatively flat, permanent snow field and icefield; a small volcanic crater; and an ice-free ridge productive of ground heat which can be trapped in useful quantities with a minimum of effort. The yearly ambient temperature range is about half as great as that in the valley lowlands 50 miles away. Barometric pressures are much lower than those ordinarily expected at such an altitude. It is remote yet logistically acceptable.

The establishment of a small facility on the Wrangell summit provided an unusual opportunity to observe several fundamental interactions of man and his environment. In the first of these, the impact of the multiple environmental and psychological stresses on the subjects appeared to have been greater than a simple sum of the parts. Thus, the Wrangell experience accentuated and uncovered a naturally occurring age-specific relationship to altitude tolerance. This is an important observation which relates to the selection and training of planetary pioneers as well as to lunar and planetary station operations. It suggests that a man in his thirties is innately superior to a younger man, a superiority probably related, at least in part, to physiological factors and independent of the processes of self-selection incidental to time. It also provides a model for the broad human response that might be seen should a degradation in the station life-support system result in a modest reduction in internal pressure and oxygen tension. Second, the significance of certain physical phenomena becomes evident only after the environment has been "stressed" by the works of man. Figure 10 shows the ground-temperature gradient as measured February 28, 1964, to be very steep when compared to earlier measurements. It was incidentally observed at the time that a thin surface layer of ash was frozen in the area. However, it was only after the ground-temperature effect under the shelter had been observed and evaluated that the abnormally steep gradient noted in 1964 could be appreciated as a variation having meteorological rather than volcanological significance. Finally, the Wrangell observations focus attention on season and latitude in determining physiologically important atmospheric characteristics in the world's high places, considerations which might also be important should an extraterrestrial location be found which possesses a sensible atmosphere.

From a logistic point of view, the use of ground heat proved to be a major operational asset. The same general principle may well apply in long-term manned extraterrestrial efforts as applies to the utilization of locally available natural resources. Although the Wrangell ridge is only a small thermal island in a vast, lifeless desert of snow on an Arctic mountaintop, when compared with other Arctic mountain sites it represents a preferred location for a manned station because of its usable heat stores. Preferred locations may also exist on otherwise forbidding extraterrestrial bodies. In defining them, the availability of local energy sources such as ground heat may well be an important criterion, in which case the observations already made at Wrangell represent only a beginning.

REFERENCES

1. JOHNSON, R. E.; BROUHA, L.; AND DARLING, R. C.: A Test of Physical Fitness for Strenuous Exertion. Rev. Canad. Biol., vol. 1, 1942, pp. 491–503.
2. CONSOLAZIO, C. F.; JOHNSON, R. E.; AND PECORA, L. J.: Physiological Measurements of Metabolic Functions in Man. McGraw-Hill Book Co., Inc., 1963.
3. FORBES, R.: Activity State of Mt. Wrangell. Rept. Geophys. Inst. Univ. of Alaska, 1965.
4. PUGH, L. C. G. E.; AND OWEN, R.: Report of Medical Research Projects into Effects of Altitude in Mexico City, 1965. British Olympic Assoc. (London), 1966. Cited by Balke B.; Daniels, J. T.; and Faulkner, J. A.: Training for Maximum Performance at Altitude. Exercise at Altitude, R. Margaria, ed., Excerpta Medica Foundation (The Netherlands), 1967.
5. MCFARLAND, R. A.: Anoxia: Its Effect on the Physiology and Biochemistry of the Brain and on Behavior. The Biology of Mental Health and Disease, Milbank Memorial Fund, ch. 22. Paul B. Hoeber, Inc. (New York), 1952, pp. 335–355.
6. ASAHINA, K.; IKAI, M.; OGAWA, S.; AND KURODA, Y.: A study on Acclimatization to Altitude in Japanese Athletes. Schweiz. Z. für Sportmedizin, vol. 14, 1966, pp. 240–245. Abstract in Aerospace Med., vol. 38, 1967, p. A–92.
7. PUGH, L. C. G. E.: Metabolic Problems of High Altitude Operations. V. Nutritional Requirements for Survival in the Cold and at Altitude, Proc. Symposia on Arctic Biology and Medicine. Lucile Vaughn, ed., Arctic Aeromed. Lab. (Fort Wainwright, Alaska), 1965, pp. 335–339.
8. PUGH, L. C. G. E.: Metabolic Problems of High Altitude Operations. V. Nutritional Require-

ments for Survival in Cold and at Altitude, Proc. Symposia on Arctic Biology and Medicine. Lucile Vaughn, ed., Arctic Aeromed. Lab. (Fort Wainwright, Alaska), 1965, pp. 331–332.

9. BOWERMAN, W. J.: Preliminary Report on 1967 Olympic Development Program. Summary sheet—USA Olympic Develop., Sept. 1967.

10. MCFARLAND, R. A.: The Effects of Oxygen Deprivation (High Altitude) on the Human Organism. CAA Tech. Develop. Rept. 11, Govt. Printing Office (Washington, D.C.), 1941.

11. FOLK, G. E., JR.: Introduction to Environmental Physiology, 215. Lea & Febiger (Philadelphia, Pa.), 1966.

12. HALL, W. H.; BARILA, T. G.; METZGER, E. C.; AND GUPTA, K. K.: A Clinical Study of Acute Mountain Sickness. Arch. Environ. Health, vol. 10, 1965, pp. 747–753.

13. LUFT, U. C.: Altitude Tolerance. German Aviation Medicine—World War II, vol. I, Govt. Printing Office (Washington, D.C.), 1950, p. 310.

14. HULTGREN, H. N.; SPICARD, W. B.; HELLRIEGEL, K.; AND HOUSTON, C. S.: High Altitude Pulmonary Edema. Medicine, vol. 40, 1961, pp. 289–313.

15. JOBSIS, F. F.: Basic Processes in Cellular Respira, tion. Handbook of Physiology, vol. 1, sec. 3, Respiration, ch. 2, W. O. Fenn and W. Rahn-eds., Am. Physiol. Soc. (Washington, D.C.), 1964, p. 67.

16. HARRIS, C. W.; SHIELDS, J. L.; AND HANNON, J. P.: Acute Altitude Sickness in Females. J. Aerospace Med., vol. 37, 1966, pp. 1163–1167.

17. RAVENHILL, T. H.: Some Experiences of Mountain Sickness in the Andes. J. Tropical Med. Hygiene, vol. 16, 1913, pp. 313–320.

18. EAGEN, C. J.: Body Weight Changes in Man at Altitude. Proc. Fourth International Biometeor. Congr. (New Brunswick, N.J.), Swets & Zeitlinger (Amsterdam), 1966.

19. BOND, G.: Undersea Exploration—Sea Lab. II. Lecture to Operational Aeromedical Problems Course, USAF School of Aerospace Med. (Brooks AFB, Tex.), Jan. 18, 1968.

20. KATZ, ISREAL: Structures of the Terrestrial and Extraterrestrial Atmospheres. Ann. N.Y. Acad. Sci., vol. 140, art. 1, 1966, pp. 49–60.

21. BENSON, C. S.: Reconnaissance Snow Studies on Mt. Wrangell, Alaska. Geophys. Inst. Univ. of Alaska, 1963.

22. PEEL, E. M.: Mt. Wrangell High Altitude Research Station Feasibility. Rept. No. 1, contract AF 41(609)-2200, Geophys. Inst. Univ. of Alaska, 1964.

23. BINGHAM, D. K.; AND BENSON, C. S.: Ash Temperature Variations on Mt. Wrangell, Alaska. To be published.

Page intentionally left blank

MARVIN F. CLARKE
General Electric Co.
Philadelphia, Pa.

Underwater Simulation of a Lunar-Surface Traverse

This paper is a summary presentation of some of the work accomplished by the Missile and Space Division of the General Electric Co. during the past 18 months. Particular emphasis is placed upon its possible significance with respect to man's capabilities and limitations when he first attempts to walk on the lunar surface.

As a supplement to the basic analytical approach toward determining the problems which man will encounter when he makes this first lunar walk, the General Electric Co. has developed underwater simulation techniques which provide insight into some of the specific problems to be expected and potential means to resolve or ameliorate such problems. The underwater simulation techniques are based upon the crew performance of simulated mission tasks in a partial-gravity or zero-gravity condition when a specially designed backpack is used to provide life support and space-suit pressurization and to maintain constant volume displacement of the underwater subject. The backpack also provides recorded measurements of key biophysical parameters.

A simulated lunar traverse was made over an 80-foot course on the bottom of the bay at the General Electric Co. Underwater Test Facility. Two different subjects in pressurized space suits in a simulated ⅙-gravity condition were used. Both subjects demonstrated their inability to walk purposefully under these conditions. The addition of a walking staff as a mobility aid made traverse of the simulated lunar terrain possible though still difficult.

INTRODUCTION

When man first lands upon the Moon and leaves his spacecraft to explore the lunar surface, he will be faced with many conditions never before experienced. One of the most significant of these new conditions will be the reduced gravity field on the lunar surface. Because of the smaller size of the Moon with respect to the Earth, the gravity field at the lunar surface is only 0.165 of that field present at the Earth's surface. Thus a man's weight on the surface of the Moon will be approximately one-sixth of his weight on Earth. This is also true for his spacecraft and for all of the equipment and experiments which he brought with him.

This apparent reduction in weight on the Moon as compared with similar weights on Earth has led to many interesting speculations as to man's potential physical capabilities on the lunar surface. In general, it has been assumed that since man developed his muscles in an Earth environment he would be capable of a greatly increased physical performance on the Moon where his weight would be much less than that which he normally experienced on Earth.

Since man is so adaptable to new situations and environments, it is quite possible that he will eventually move across the lunar surface in great leaping strides, but it appears likely that he will first have to learn to walk. The reasons for this become apparent when one considers the physical parameters involved. Although a man's weight appears to be less on the surface of the Moon, his absolute mass has not changed. Thus, if we consider a man who is trying to move in a horizontal line on the lunar surface, it will require just as much force to start, stop, or turn at a given rate as it did on Earth. Similarly, the momentum he will develop (and the velocity, since his mass is constant) is a function of the force times the time applied, or the total impulse. Thus, if he jumped straight up, he would leave the surface at a velocity similar to that on Earth, but, because of the lower gravity on the Moon, he would go much higher and would remain in the air much longer than he would on Earth. This timing change is one of the factors which will make it difficult at first for an astronaut to walk on the Moon.

When a man walks on the Earth, he not only leans forward but also rocks from side to side as he swings one leg after the other and shifts his weight from one to the other. The combination of these movements, properly timed in a coordinated sequence, takes a while to learn. It is reasonable to assume that, if the time constants varied significantly, as they would if the man were trying to walk on the lunar surface instead of on Earth, man may, and probably will, have difficulty when he first tries to walk on the Moon.

The above analogy is a greatly oversimplified case, but it serves a useful purpose by highlighting a particular part of the total problem which may be a potential source of trouble when man first tries to walk on the Moon. There are obviously many such potential trouble sources involved in the physical locomotion of a space-suited astronaut over the lunar surface and his performance of all the varied man/machine tasks involved in space voyage and lunar exploration and experiment activities.

Crew/system performance in manned space systems under partial-gravity and zero-gravity conditions can be investigated using an underwater simulation technique. It provides one of the more useful and cost-effective methods of empirically answering fundamental questions related to human performance and the development of equipment needed to optimize man's performance in space.

FACILITIES

In order for the General Electric Co. to put into operation a facility to accommodate large existing structures (such as the Saturn S–IVB workshop) on a timely economic basis, it was imperative that a natural site be selected. High capital expenditures and long leadtimes ruled out the possibility of constructing a large tank facility. Furthermore, a natural site was desired which would provide a relatively unlimited growth possibility.

Mandatory requirements for the facility were:

(1) Adequate space for whole task simulation which would accept a minimum 55-foot-long by 22-foot-diameter structure with growth possibilities.

(2) Clear water for ease of vision and to facilitate underwater photography.

(3) Calm water to facilitate surface operations and to minimize underwater currents and disturbances.

(4) Warm water (minimum 78° F) to permit year-round operations with efficiency and comfort.

(5) Ready access to aerospace and industry centers and to support services.

After a careful review of available locations, Buck Island, the site of a former U.S. Navy UDT training area near St. Thomas, V.I., was chosen. Buck Island provides a cove approximately 700 feet in diameter with a sandy bottom. The cove is sheltered on the lee side of the island from the predictable easterly trade winds. The water is warm and clear throughout the year, and sufficient light is available for good underwater photography. The maximum tidal variation is less than 1 foot. The Buck Island site is sufficiently remote from St. Thomas to discourage curiosity seekers but still not so far away as to cause operational problems.

The underwater test area of the General Electric Co. is located within a sheltered cove of approximately 10 acres on the western side of Buck Island. This island is located 4 miles off the south coast of St. Thomas, the most populous of the Virgin Islands, and near the entrance to the harbor of Charlotte Amalie, the largest city in the islands.

As shown in figure 1, the water depth in the primary simulation area is 28 to 29 feet and there are additional test areas surveyed in the 15- and 20-foot ranges. The cove floor in these testing areas is composed of white sand. It is quite level and relatively free of rocks and marine life. Water temperature is a rela-

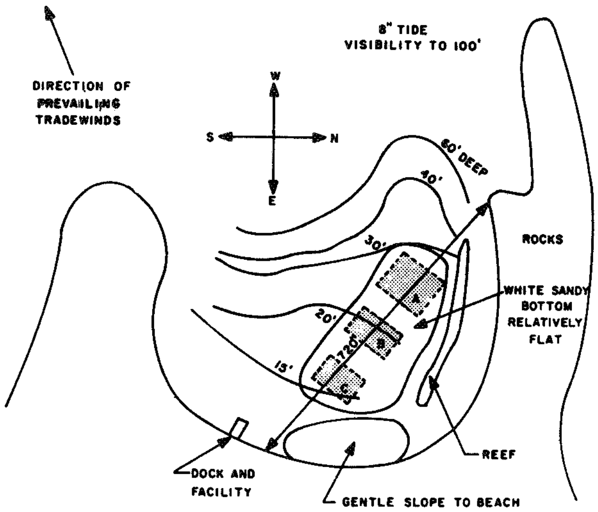


FIGURE 1.—Schematic diagram of the General Electric Co. underwater test facility at Buck Island, V.I. *A*, 28-foot test area; *B*, 20-foot test area; *C*, 15-foot test area.

tively constant 78° to 82° F. Underwater visibility approaches 100 feet permitting detailed underwater photography without the need of artificial light under most conditions.

An operations building has been constructed on the foundation of an old concrete pier approximately 300 feet from the primary underwater test area. This structure, with dimensions of 12 by 20 feet, contains the monitoring, recording, diving, and medical equipments, general office space, and comfort facilities. A covered access deck extends around three sides of the building with a boat dock attached to the west side facing the testing areas. A platform extends into the water from the dock to permit ready access to the water for both test personnel and pressure-suited test subjects. The building is lighted and air conditioned and draws its power from two 3000-watt gasoline generators located on the roof.

A hexagonal observation platform located 40 feet from the primary simulation area permits direct viewing of test operations and provides for above-water photography through its six Plexiglas windows located below the waterline. A safety work platform was installed over the primary simulation area. Figure 2 shows the

FIGURE 2.—General Electric Co. underwater test facility site.

relative locations of the operations building, the observation platform, and the primary test area.

Boats are available as required to transport personnel and equipment to and from the site. A close working relationship has been established with a local machine shop which is capable of providing speedy fabrication of experimental hardware.

Continuous communications are maintained with the main island of St. Thomas through leased radiotelephone lines provided through the Virgin Islands Communications Corporation. Onsite communications are provided by walkie-talkie units as required.

Although present experimental plans do not require the use of extensive quantities of classified material, arrangements have been made for the protection and safeguarding of any such material that may be required. Arrangements have been made for storage of classified items at the U.S. Coast Guard Station, Charlotte Amalie, St. Thomas.

UNIQUE SUPPORT EQUIPMENT

The changes in lung volumes when a diver inhales and exhales result in changes in his total water displacement and hence in his buoyancy. In order to maintain a constant partial-gravity simulation and, even more important, to maintain a neutral buoyancy to simulate zero-gravity conditions, it was necessary to develop a compensatory breathing apparatus to eliminate these changes.

The General Electric backpack shown in figure 3 was developed for this use. In addition, it also provides the following functions:

(1) Closed respiratory system with carbon dioxide removal and automatic replacement of oxygen consumed.

(2) Space-suit pressurization at selected pressures from 0 to 4 psig above ambient.

(3) Sensing and recording of physiological data such as—

Electrocardiogram
Respiratory rate
Respiratory volume
Oxygen consumption
Deep body temperature

The closed respiratory system has three major advantages over an open-type system:

(1) It eliminates bubbles.

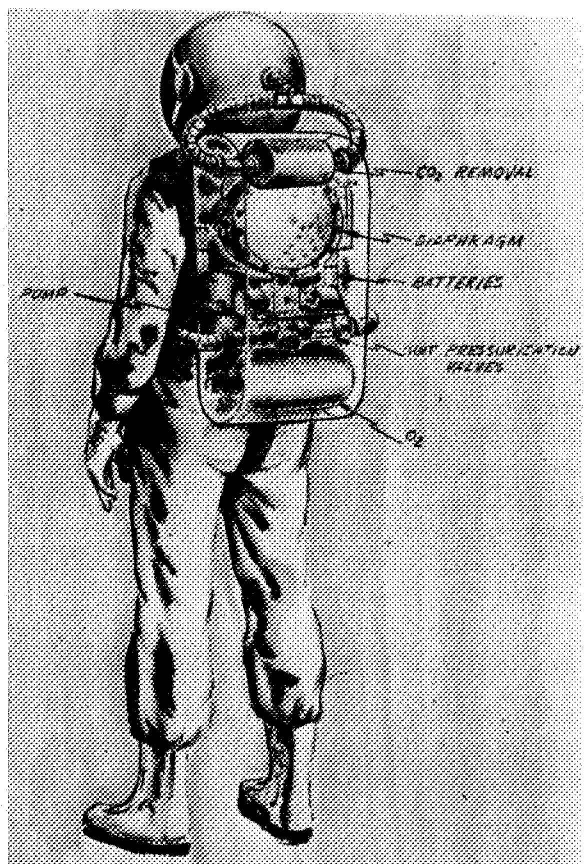


FIGURE 3.—General Electric Co. neutral buoyancy and life-support backpack for underwater simulation of zero-gravity conditions.

(2) It eliminates the cyclic rise and fall of the test subject as a result of inspiration and expiration.

(3) It provides a larger test time between bottle changes, since only the oxygen consumed metabolically need be carried.

Physiological data recorded in the backpack provides a basis for estimating the energy output required to accomplish a given task. The data to be taken include respiration rate, tidal volume, body temperature, electrocardiogram, and oxygen consumption; of these, oxygen consumption is considered to be of primary importance. The signals from these physiological transducers are recorded directly on a Gemini-type biomedical tape recorder which is incorporated into the backpack.

The backpack incorporated a system for pressurizing the space suit so that tests could be conducted with a pressure-suited subject. A water pressurization system was selected for space-suit use in underwater simulation for the following reasons:

(1) An air-pressurized suit must be brought to neutral buoyancy by distributing weights over the suit surface. These weights (of the order of 100 to 200 pounds, depending on the subject and suit size) are difficult to install so that the test subject is truly neutrally buoyant in any orientation and impose a safety hazard should the suit lose its pressure.

(2) Air leaks from air-pressurized suits cause distracting bubbles and provide orientation cues to the test subject.

(3) If the test subject, in water, works in an inverted position (head down) in an air-pressurized suit, he will experience the same effect as if he were hanging by his feet on land because the air pressurization level is constant throughout the suit.

(4) Changes of depth will cause variations in an air-pressurized suit delta pressure and will require the addition or venting of air from the suit.

ORBITAL WORKSHOP SIMULATION

Operation of the presently conceived Apollo Applications Program (AAP) orbital workshop requires extended and complex astronaut performance after orbit insertion. The astronauts' tasks will include passivation of the Saturn S–IVB spent stage, transfer of equipment from its launch location through an airlock and into the spent-stage hydrogen tank, and erection and operation of this equipment. Implicit in these tasks are basic requirements for electrical, hydraulic, and mechanical connection; operation of controls, hatches, fasteners, and restraint systems; and the controlled transport of large pieces of equipment through relatively long distances and large volumes.

The tests conducted by General Electric Co. in the winter of 1966–67 were primarily exploratory and attempted to develop guidelines for crew performance and equipment design. They did identify basic problems, either of a human or an equipment performance nature, which need further understanding and which must therefore be simulated more completely in the future. The exploratory tests conducted included the following:

(1) Hydrogen tank cover removal

(2) Installation and evaluation of mobility aids

(3) Transfer of large bulky equipment

(4) Erection of an experiment console

(5) Erection of primary partitions

At the time these tests were being planned, the AAP orbital workshop configuration in orbit was similar to that shown in figure 4. A cutaway of this configuration model is shown in figure 5. An underwater test structure with this configuration was built of aluminum rings and screen wire, in full scale, and implanted at the Buck Island test facility. Mounted on a supporting bed which rests directly on the level sandy cove bottom, the underwater test structure (fig. 6) is a full-scale geometric duplicate of the—

(1) Saturn S–IVB spent stage

(2) Equipment section (forward of the LH_2 tank)

(3) Adapter section (to the SLA panel joint)

(4) Airlock and docking adapter

(5) Pertinent task equipment and mobility aids

Measuring 22 feet in diameter by 52 feet in overall length, the simulator shell is a skeleton

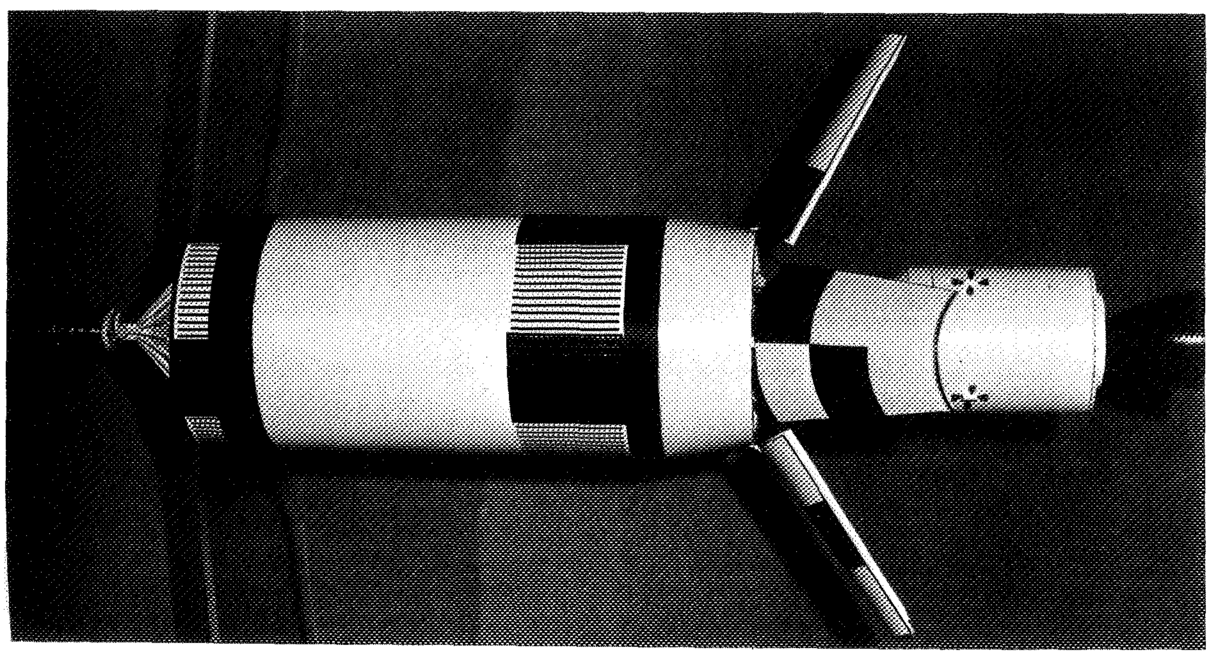


FIGURE 4.—AAP orbital workshop (late 1966 orbital configuration).

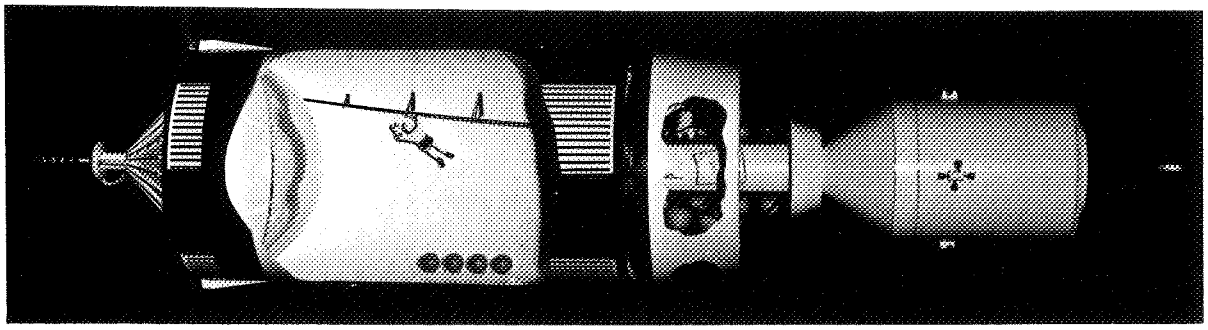


FIGURE 5.—Cutaway view of the AAP orbital workshop (1966 orbital configuration).

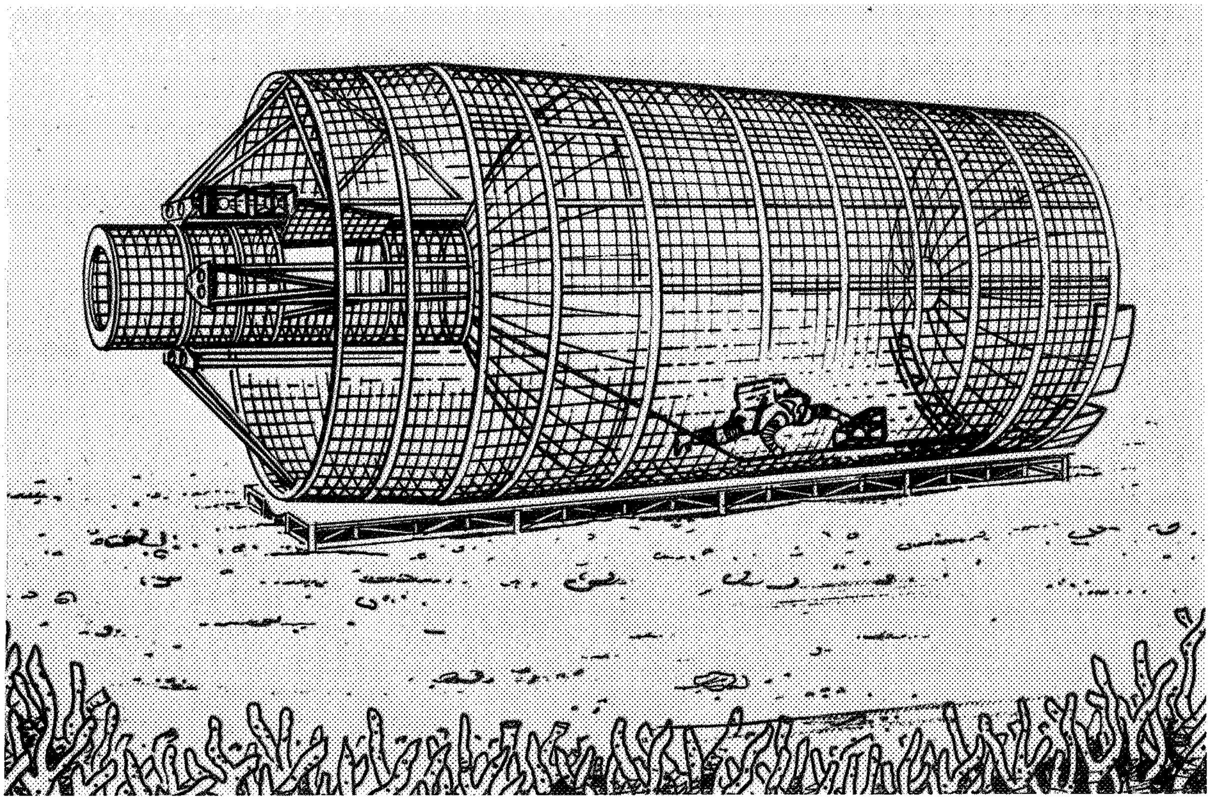


FIGURE 6.—Underwater simulation mockup of the AAP orbital workshop as used by General Electric Co. in 1966–67 tests.

framework of aluminum rings and stiffeners covered with a 4- by 4-inch grid of wire mesh protected from corrosion by a high-visibility, yellow-plastic-base marine paint. Total weight is 7500 pounds. The open design was dictated by the nature of the work, which required maximum exposure for photographic records, test direction, observation by safety divers, solar illumination, and minimum resistance to water motion in the event of turbulence.

The task simulations were planned around the actual tasks which will have to be performed in order to passivate the Saturn S–IVB spent stage and to activate and inhabit the orbital workshop after it is in orbit. Specific tasks were devised around the equipment involved.

Saturn S–IVB Spent Stage

The hydrogen tank, enclosing a volume in excess of 10 000 ft^3, constitutes a major portion of the structure. Included in this item are the three largest internal items which would help or hinder test subject activity within this chamber:

(1) A 34-foot-long propellant utilization probe

(2) An LH_2 vent pipe

(3) Six 23-inch-diameter helium storage spheres

Also included for use in attaching mobility aids, compartmentizing partitions, and consoles are the 112 NASA-type equipment attachment fittings preinstalled in the liquid hydrogen tank of this S–IVB.

In the compound curvature area, where the LH_2 and liquid-oxygen tanks join, are four boattail extensions on which are mounted hardware simulating:

(1) Chilldown pump

(2) LH_2 feed line and antivortex screen

(3) LH_2 chill return

(4) LH_2 fill line and diffuser

As part of the experimental task sequence, these units must be sealed before final pressurization and habitation in the spent-stage LH_2 tank.

Airlock

The airlock is basically a tunnel connecting the Apollo command module to the S–IVB spent stage (SA 209 configuration). This unit measures 65 inches in diameter by 15½ feet long, and follows the design originally proposed by McDonnell Aircraft Co.

Mobility Aids and Task Equipment

The mobility aids provided were, in general, polypropylene rope with quick-connecting clips located at predetermined intervals. Polypropylene, being less dense than water, tended to overcome the clip weight and thus effectively made these aids neutrally buoyant to transport to their positions.

In addition, a three-section telescoping rod was constructed to traverse the distance between the forward-dome manhole and the closest attachment points. After it is extended to its 15-foot length, it is locked in position, and a clip mounted at the forward end secures it to one of the equipment attachment fittings.

The console was simulated by a skeleton framework of aluminum to minimize drag, polyurethane was bonded to the inside of the framework to provide neutral buoyancy, and a Plexiglas sphere of appropriate size was suspended within the framework and allowed to fill with water to provide the necessary mass equivalent.

For tasks such as fastening the console and removing the chilldown pump, appropriate tools are provided, including blade- or socket-type drivers, a ratchet wrench, cam-actuated sealing plugs, blind flanges, and numerous other items. Several types of tethers are provided to determine their usefulness. These included wrist or waist attachment loops and Velcro loop and pile on the tool belt. An equipment storage container was also provided.

The Saturn S–IVB stage was chosen as a basic simulation tool when the Buck Island program was first conceived. The rationale behind this decision was twofold: (1) by using the S–IVB, whole task simulation of a large structure could be demonstrated for the first time; and (2) realistic operations and task ground rules concerning an established ongoing space project could be provided. The requirements for crew operations in the S–IVB orbital workshop are far more complex than those established for space missions to date. For the first time, the astronaut is required to perform assembly, erection, checkout, and maintenance and repair tasks which will have long-range applications to the future development of the U.S. space-flight program.

In order to prepare the S–IVB spent-stage hydrogen tank for shirtsleeve occupation, a passivation sequence must be accomplished which includes the sealing of potential leak points at the common bulkhead. The astronaut must translate from the airlock down into the hydrogen tank and thence to the LH_2 chill pump inlet. The top portion of the pump inlet must be removed and replaced with a blind flange which is bolted in place. The astronaut must then translate to the fuel feed

324-954 O—69——18

line, remove the antivortex screen, and install an expandable plug in the feed-line opening. He must then translate to the LH_2 chill return line, install an expandable plug, and then translate to the LH_2 fill line and diffuser, unbolt the diffuser, and insert an expandable plug in the fill line, and then return to the airlock. The task is accomplished with the astronaut in a pressure suit and with the use of ordinary handtools.

The elemental task steps and times to complete are shown in table 1.

TABLE 1.—*Stage Passivation Task Results*

Subtask	Measured times for simulated task, min	Projected times for actual task, min
Insert plug in LH_2 feedline, actuate and lock handle	0.5	1
Realine cover over opening in antivortex screen and secure with 3 screws	5	5
Translate to LH_2 chill return	.5	.5
Remove expandable plug from stowage container	.5	1.5
Insert expandable plug in LH_2 chill return, actuate handle, and lock	.5	1
Translate to LH_2 fill line and diffuser	.5	.5
Remove 4 bolts holding diffuser in position	3	3
Remove diffuser and place in stowage container	.5	.5
Remove expandable plug from stowage package	.5	1.5
Insert expandable plug into fill line, actuate handle, and lock	.5	1
Translate to airlock via mobility aid	.5	1.5
Total task time	35.5	70

The following conclusions were derived from observations of subjects, safety divers, and the test conductor:

(1) The task elements proved to be quite repetitious and, as a result, boring.

(2) Reactionless power tools or ordinary power tools would have cut down the time needed to perform the tasks but could in no way be considered mandatory.

(3) Some form of quick-release tether system is mandatory at each work site.

(4) Fixed mobility aids are required for personnel transfer.

(5) The task was accomplished with reasonable ease and resulted in little fatigue. Access to all fasteners was adequate.

(6) Properly designed tool and equipment restraints and containers are mandatory.

(7) Projected time to complete task in orbit without using power tools is 70 minutes. The use of power tools to remove the 46 bolts on the antivortex screen cover would probably cut this time to 42 minutes. (The simulator had only six bolts.)

(8) Optimum translational velocity appeared to be on the order of 1 ft/sec or less.

LUNAR-SURFACE TRAVERSE

An underwater simulation of a lunar-surface traverse was accomplished at the Buck Island test facility in early 1967. An 80-foot-long course was selected at the bottom of the bay which included various degrees of surface roughness, slope, and texture such as might be encountered on the Moon. In addition, the course included a fixed ladder which the astronaut must ascend and descend as a part of the course to simulate his exit and reentrance to the Lunar Excursion Module. The simulated lunar traverse task included moving 80 feet over the different types of surface, climbing up the ladder and descending again, and return to the starting point.

The test subjects were ballasted by the addition of lead weights to simulate the 1/6 g on the Moon. This was accomplished by weighing them, fully equipped, in air, then weighing them again immersed in the sea, and adding weights to their harness until the 1/6 g negative buoyancy was achieved.

The two primary test subjects used for these tests were a test pilot and an athlete. Both were experienced scuba divers and both had had extensive previous experience in underwater simulation both with and without the backpack.

The lunar-traverse task was first performed using the backpack but no space suit. The test subjects were suitably weighted. Under these conditions, the test subjects were able to traverse the course without undue difficulty.

The lunar-traverse task was then attempted with the test subjects using the state-of-the-art space suit pressurized with water to 3.7 psig and the backpack, as shown in figure 7. The test subjects were ballasted to achieve a negative buoyancy of 1/6 g.

Surprisingly, when the astronauts tried to walk on the bottom of the bay in the pressurized space suit, they fell over to the side. Neither test subject was able to maintain his balance and walk purposefully in this fully suited 1/6 g condition. The problem appeared to be a strong tendency of the subjects to overcontrol when they were shifting weight from one leg to the other in order to take the next step. Hampered by the resistance of the pressurized space-suit joints, the test subjects were unable to maintain the fine positional control and muscular coordination necessary to walk purposefully under these conditions, particularly upgrade. The difficulty in rising in a pressurized space suit after a fall presented another problem area.

It was found that the use of a walking staff provided the test subjects with a mobility aid which did make it possible for them to traverse the lunar course and return. The average time to traverse the course, climb and descend the ladder, and return to the starting point was 4 minutes and 45 seconds. Thus the average velocity was approximately 0.6 ft/sec, or 1/3 mph.

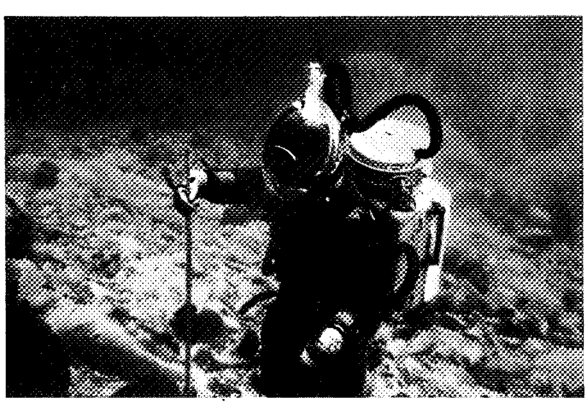


FIGURE 7.—Simulated lunar traverse.

Both test subjects found walking somewhat hampered by the reduced downward visibility in the space suit. It was difficult for a subject to look down at his own feet and see the next place where a foot would be planted. This resulted in some stumbling over small objects which would normally be avoided.

The reduced-gravity simulation resulted in a marked decrease of pressure between the test subject's boots and the ground surface. This was expected, and it had the expected result of reducing the traction by reducing friction between the boot and the ground. Similar experience was had during 1/6 g Keplerian flights. At 1/6 g, the lower limit for surface traction for walking is approached. This may be compared to the feeling one gets when he tries to walk on ice. The test subjects did notice this effect during the lunar-traverse simulation. The selected traverse path included a long slope of approximately 10° which they covered; however, a 2-foot-high boulder was an object to be avoided rather than surmounted.

One of the significant factors noted during the simulation was the tendency of the test subject to overshoot his target if he tried to hurry. This is not surprising if one considers that the test subject's apparent mass, caused by his backpack, his space suit, the pressurization water in his space suit, and the ballast, is much higher than that he is used to normally and his traction is much less than normal. Consequently, when he does get up to reasonable speed, he finds it difficult to stop again.

Although both test subjects were in excellent physical condition, they both found the lunar-traverse task to be very tiring. Of course, this physical tiring was partially due to the exertions in donning the equipment, checking it out, and getting ready to perform the task.

CONCLUDING REMARKS

The lunar-traverse task was performed to investigate the underwater simulation techniques for astronaut mobility under lunar gravity conditions. It proved to be a useful tool in highlighting potential trouble areas when an astronaut first tries to walk on the Moon. It has aided in the understanding of his physical problems in a way that can seldom be achieved analytically. The results achieved clearly indicate that the astronaut may have to do some relearning before he can walk on the Moon with any ease. The test subjects in our simulation task considered the walking staff to be a mandatory mobility aid. Subjective comparison to 1/6 g Keplerian flights was stated to be excellent.

EDWIN G. VAIL
United Aircraft Corp.
Windsor Locks, Conn.

Man as a Resource on the Moon

INTRODUCTION

All of the objectives for the maximum utilization of extraterrestrial resources will depend upon the performance capability of man under the environmental conditions on the lunar surface. Any discussion of man as a resource must of necessity consider what he will be required to do. In this paper man is viewed as the primary integrator performing those functions for which there is no substitute. These integrator functions fall under the interpretation, judgment, and decisionmaking requ'red to keep a closed loop between man and equipment.

This paper is predicated upon the assumption that the initial Apollo missions have completed the preliminary exploration and geological survey of parts of the lunar surface and have identified a good site for a permanent base installation for exploiting extraterrestrial resources. The timespan for the activities described may begin in 1975 to 1978 and extend over a period of 10 years. This hypothetical base will be used to describe the role of man as a resource and to highlight his areas of activity.

Acknowledgment is made to the members of the Working Group on Extraterrestrial Resources who contributed technical papers to the *Proceedings of the Fourth Annual Meeting,* which provided much useful information for defining the role of man on the Moon, and to the Goddard Space Flight Center for copies of Orbiter photographs of the lunar surface and for advanced data of lunar soil analysis from Surveyor VI.

PROGRAM AREAS OF INTEREST

In considering the resourcefulness of man in the exploitation of lunar resources, 15 major program areas of interest can be identified where man's performance capability can be clearly defined on the basis of known Earth technology (table 1). Each of these areas can be identified with an anticipated work level. Metabolic work levels may be considered to be as follows: light work represents 800 to 1000 Btu/hr; moderate work, 1000 to 1800 Btu/hr; and heavy work, 1800 Btu/hr or more. Many subdivisions of the tasks and each respective task performance capability can be predicted. A complete description can be obtained by detailed functional task analysis. A description of the scope of these areas of interest will assist in obtaining a perspective of the extent of man as a resource and his performance capability for various tasks.

TABLE 1.—*Program Areas of Interest*

Area	Work level
Exploring	Light-moderate
Surveying	Light-moderate
Experimenting	Light-moderate
Mining	Moderate-heavy
Tunneling	Moderate-heavy
Processing	Light-moderate
Excavating	Moderate-heavy
Building	Moderate-heavy
Farming	Light-moderate
Unloading	Moderate-heavy
Hauling	Light-moderate
Launching	Light-moderate
Physical conditioning	Moderate
Playing	Light-moderate
Maintaining	Light-moderate

Exploring

The area of exploring is considered to be a continuous activity, because man has never stopped exploring Earth. He will continue to search for additional lunar resources that will be essential in making a fixed lunar base as self-sufficient as science and technology can make it. It is assumed that most of the exploring will be conducted from a rover-type vehicle with a self-contained life-support system. Sorties will be conducted from this vehicle by space-suited men. The overall work level for these activities will be light to moderate. The highest level of activity will occur while they are climbing crater walls and lunar mountains.

Surveying

Surveying is an activity essential to the site layout and construction. It will also be required in support of lunar mapping activities. This task area will probably require the full time of at least two or three men. Some surveying will probably occur concurrently with exploring activities of other lunar areas. The work level will be light to moderate.

Experimenting

Experimenting is another activity that will occur as long as man is on the Moon. It will extend across all scientific areas as man seeks further knowledge and solves problems of living, working, and operating equipment in the lunar environment. All scientific knowledge that will be obtained about the Moon is considered essential to successful exploration of other planets in the solar system. Work level in performing experiments outside life-support shelters will not exceed light to moderate metabolic activity.

Mining

Once proper mineral resources are located, man's performance in initial mining operations may require moderate to heavy work levels. It may be possible, however, by proper man-equipment design, with automation and remote control of various types of mining equipment, to reduce the work level from heavy work to light or moderate. It is estimated that approximately 50 percent of man's time will be spent in life-support cabs, while the rest of the time will be involved in surface tasks such as loading a drill hole for blasting; adjusting, servicing, and maintaining mining equipment; and recovering drill cores for analysis. Logging may be a standard activity of all drilling operations in support of geophysical studies of the lunar crust.

Tunneling

Tunneling was considered a potential part of three base activities. It may be necessary in mining operations in order to exploit a particular vein of high-grade minerals. Tunneling into a crater wall may be required to provide protection for cryogenic storage tanks. Lastly, tunneling into a crater wall may be a more economical means of constructing well-protected life-support shelters. As is true for mining operations, the work level for initial tunneling operations may be moderate to heavy. Again this will depend to a large degree upon the equipment design.

Processing

The processing of ore and its reduction to usable products encompass a large number of subtasks that will require man to operate in the external lunar environment. Many of the activities can be identified as being at the location of surface mining equipment, rock crushers, and the ore-conveying systems where service and maintenance activities will be required to maintain a steady flow of ore into the processing facility. Once the ore has been graded, the extraction process may take place in a semivacuum by use of a large solar furnace or in a special pressurized building or fractionating unit.

Excavating

Various types of excavating activities are considered fundamental to all lunar building construction. Many concepts have been proposed such as surface shelters, buried structures, and structures installed in tunnels made in crater walls. In this analysis it is assumed that many permanent structures will require excavation in order to obtain a firm foundation for buildings. The type of excavating considered requires vehicles related to present bulldozers and earthmovers. In some instances, surface mining equipment might be used to prepare construction sites. Another type of required excavation is ditching, which will be primarily for the purpose of burying power cables running from remotely located powerplants. Man will perform these tasks in much the same manner as he does on Earth. The work level will range from light activity while driving to moderate activity while performing equipment maintenance.

Building

Initial building construction was considered to be primarily an assembly task. Prefabrication of various types of buildings on Earth is considered the most feasible means of establishing the initial base capability. Erection of these structures was considered on a modular concept. In all probability the base layout will evolve from scale models on Earth with each step well planned in advance. Eventually, the base should reach a capability of manufacturing additional buildings from lunar materials as well as interplanetary exploration vehicles and other supporting equipment. The work level will be moderate to heavy when muscular effect is required in alinement and joining tasks.

Farming

As the capabilities of the lunar base are extended, farming will become an essential activity. A farm and food-processing facility will probably begin in a module separate from the main life-support shelter. It will initially provide staple vegetables to supplement the basic food supplies. As the base grows in size, the farming facility will gradually grow until it reaches the level of a balanced closed ecology. At this point, selected animals will be raised within the complex for dietary protein. The work level will range from light to moderate. No lunar-surface activities are visualized for this area except for external building maintenance.

Unloading

This activity is associated with unloading logistic supply vehicles. The operation may initially consist of placing an unloading ramp in position and pulling the supply modules from the vehicle. Eventually the launch site will have mobile service towers that will reduce the turnaround time for supply vehicles considerably. The workload for man can range from light to heavy and will depend upon the type of support vehicle equipment and its multipurpose capability.

Hauling

Numerous hauling activities will move throughout the entire base from the launch complex. Several types of personnel and equipment carriers will be required. Movement of ore from mining sites to processing facilities will depend upon the multiplicity of mining operations. Hauling and erecting numerous communication antennas around the crater rim will be required to provide maximum coverage for exploration and landing and launch control. Specialized experimental instrumentation will probably be placed at preselected sites for geophysical studies on a continuing basis.

Launching

The launching of logistic vehicles and eventually manned interplanetary exploration vehicles will certainly be one of the major facility requirements for a permanent lunar base. Up to the time that the service towers and landing pads are constructed, the major launch operation is viewed as primarily a refueling activity. Later capability will include maintenance and checkout of entire vehicles much as is accomplished at Cape Kennedy today. When the full capability of the launch complex is attained, interplanetary vehicles will be assembled and launched to explore the solar system further.

Physical Conditioning

Long periods of living in a 1/6 g environment represent an unknown in human physiological adaptation. The greatest physiological area of concern is centered around the body muscle and cardiovascular system. Maintenance of body muscle tone by a prescribed series of physical exercises will probably be necessary at least three times a week for all lunar-base personnel.

Playing

Various types of light recreation should be provided as a means of relaxation. All work and no play will eventually make sluggish men. As we learn more about the prolonged effects of lunar gravity, a recreational program will evolve that will provide body conditioning as well as relaxation. Games and competitive sports may evolve that are peculiar to the 1/6 lunar gravity.

Maintenance

Maintaining and repairing equipment is considered to be the second largest area of activity in the entire lunar-base operation. The base complex is visualized as growing via the "bootstrapping" technique beginning with the initial landing of equipment. It will be absolutely essential, in the interests of self-sufficiency and minimum logistical support, for the lunar-base personnel to develop the capability for maintainability. Initially, equipment may have to be serviced and maintained in a vacuum by space-suited mechanics. It may be good design philosophy to consider replacement of major modular components; the modular units could be replaced and taken into a small pressurized shelter for maintenance and repair. Maintenance of full-size vehicles inside a pressurized facility will be an early objective in construction the base complex. The organization of a fabrication facility should consider the requirements of repairing existing equipment as well as the manufacture of replacement parts and new equipment assemblies. Maintenance logs and component failure identification for all lunar equipment items throughout the program for lunar exploitation will be essential in planning for maximum self-sufficiency. Space-suit workload will be moderate and maintenance workload in the shelter will be light to moderate.

OPERATIONAL LUNAR BASE

Concept

A concept for a fully operational lunar base is shown in figure 1. The site chosen for this base is representative of numerous lunar craters observed on Orbiter photographs. The crater as shown is approximately 20 miles across and about 2500 feet deep. The minerals in this area are located in accessible surface deposits along the walls of the crater. This mining site contains minerals with abundant quantities of oxygen, magnesium, aluminum, silicane, and iron. Previous core analyses have indicated that the mineral deposits extend to 50 meters or more into the crater wall. It is economical to consider extensive exploitation of these lunar resources by use of surface mining techniques. A study of this facility will indicate the following types of installations and equipment erected by man:

(1) Living shelters
(2) Powerplants
(3) Landing pads
(4) Equipment sheds
(5) Launch control center
(6) Surface vehicles and support equipment
(7) Mining equipment
(8) Cryogenic storage tanks
(9) Processing plant
(10) Communication and radar antennas
(11) Launch towers and equipment
(12) Farming shelter and equipment
(13) Telescopes
(14) Maintenance shop
(15) Fabrication plant
(16) Recreation area
(17) Research laboratory
(18) Sewage and waste disposal plant

Note that the units are modularized, for growth and flexibility. As a result of integrated functional planning, a stepwise programed increase in lunar-base capability can occur. In figure 2, the site is shown during the initial stages of construction.

General Construction Tasks

Site Preparation

After the landing of the first logistic vehicles, civil engineers will begin the specific activities in preparation of the site:

(1) *Surveying.*—The entire crater will be surveyed and the location of each permanent facility marked out.

(2) *Mapping.*—Concurrent with the survey-

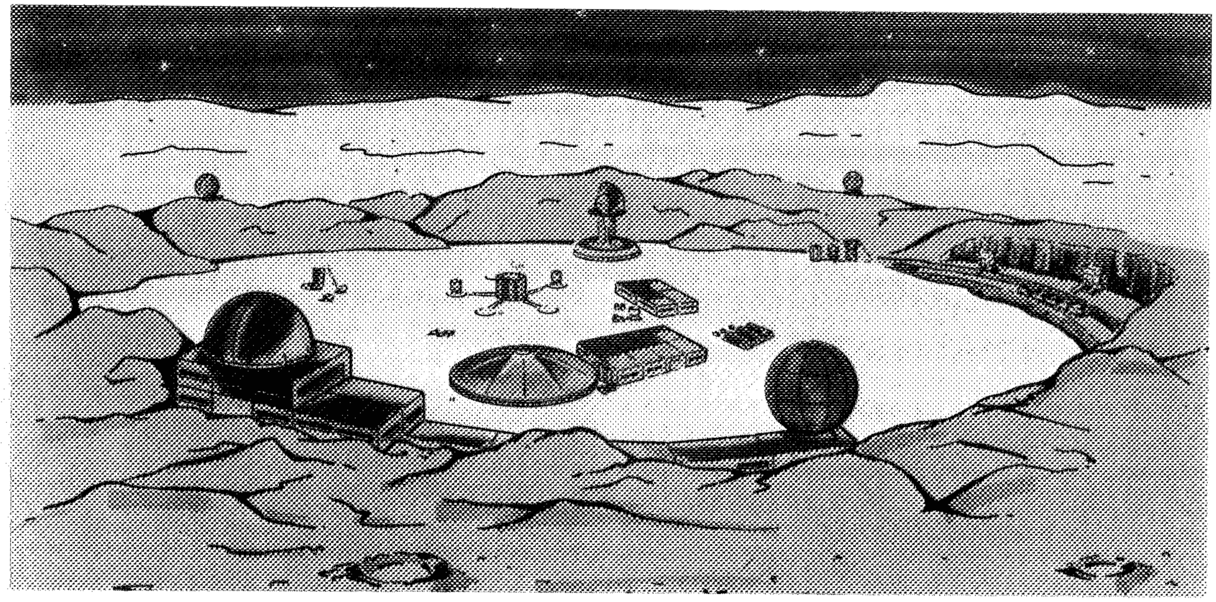


FIGURE 1.—Concept of fully operational lunar base.

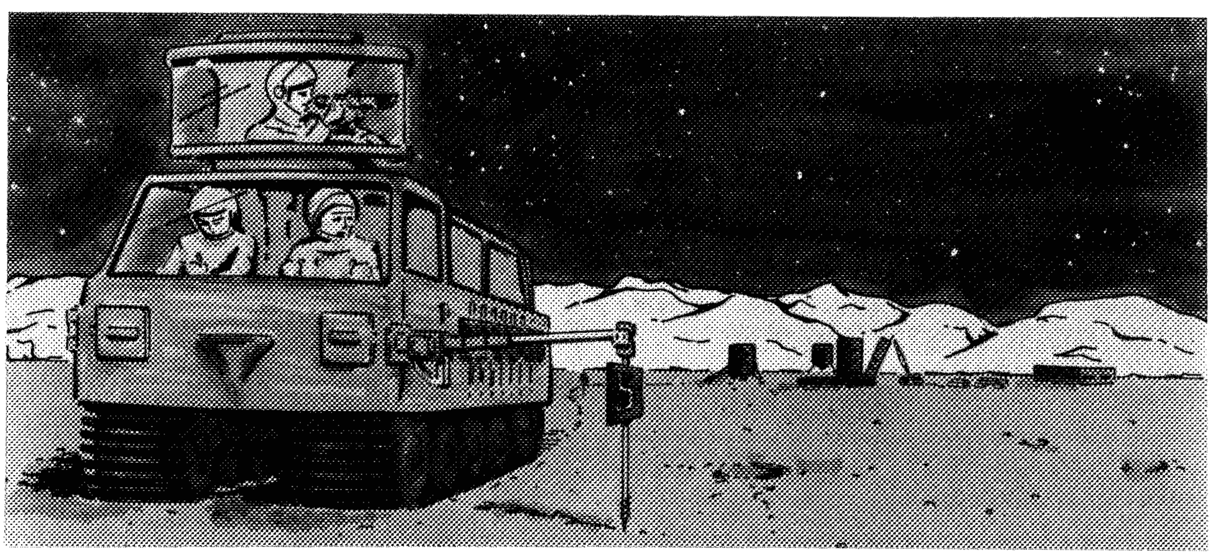


FIGURE 2.—Concept of lunar base site during initial stages of construction (exploring and surveying).

ing activity, maps will be prepared to facilitate building construction. These maps will include pertinent data describing terrain composition and geological structure for the site of each major facility.

(3) *Excavating and/or tunneling.*—Some excavating may be required to provide a level site for each building; this will depend upon the nature and depth of lunar soil. Excavating or tunneling may be required for protection of cryogenic storage tanks because the frequency of meteor fall on the lunar surface is unknown.

(4) *Hauling.*—The movement of equipment of all types from logistic vehicles to all parts

of the lunar base is considered to be a continuous activity. Multipurpose vehicles will be required so that maximum flexibility can be obtained.

(5) *Drilling and blasting.*—Although these activities are primarily associated with mining operations, some drilling and blasting may be required in the preparation of building foundations and access roads.

Assembly and Erection of Building Forms

In the foreground of figure 3, two space-suited workmen are shown fastening an anchor cable on the research laboratory located on the crater rim. In the background various assembly activities can be seen. In the foreground on the crater floor can be seen the primary life-support shelter. This unit has been assembled from eight prefabricated units. The adjacent farming dome is provided with shutters to control solar energy for optimal photosynthesis. The cryogenic tanks of life-support gases are being buried by the bulldozer to the right of the main building. In the center of the crater is located the beginning construction of the launch and landing complex. One supply vehicle is seen being unloaded while another is landing. A third pad is unoccupied. A centrally located service tower is being assembled in the launch complex. Note the vehicles with telescoping erection devices supporting major structure during joining and mating activities. To the right are located three maintenance sheds. These have been erected from nine prefabricated unit modules. Specific task areas for building construction will include:

(1) Hauling
(2) Lifting or erecting
(3) Bolting and joining
(4) Welding
(5) Cutting
(6) Plastic spraying

Plastic spraying to achieve pressurized joint integrity is considered a feasible lightweight technique for sealing these pressurized units once physical joining is completed. The plastics industry has the capability of developing a technique for spraying plastics in a vacuum.

Powerplant Assembly

The power supply for this lunar base is visualized as coming from three possible sources: solar, nuclear, and geothermal. The initial powerplant will probably be a nuclear unit or units. As the base capability grows, these will be augmented by batteries of solar cells to generate power during the lunar day. It may be necessary to locate a nuclear power plant adjacent to each major facility. In any event, all power cables will be laid in underground ditches for maximum protection. This will require that at least one of the multipurpose vehicles have a unit attachment, much like a ditcher for laying drain tile, that will dig ditches 3 to 4 feet deep.

Exploitation of lunar geothermal power based upon the increasing evidence for volcanic activity on the Moon provides a fertile area in which man can exercise his resourcefulness in the hostile lunar environment. It will be assumed for this discussion that a geothermal deposit has been identified and will be exploited. This was accomplished during the initial surveying and mapping for the base complex and is the result of geophysical analysis of the lunar-surface strata within the crater. The first plans call for drilling and capping a test well in order to determine the content of the geothermal fluid and to establish the "in-the-well" pressure. This phase of the operation is viewed as a two-man job. Once this task is accomplished, the operating pressure of the geothermal fluid will be utilized as a power source to drill a larger and deeper well. It is assumed that processing equipment will be provided to recover all essential minerals and gases from the geothermal fluid. At this point in the exploitation of lunar geothermal power, the operational feasibility should be established. Further expansion will depend upon lunar-base demands and the nature of the geothermal fluid.

Service Area and Support Equipment

The equipment and maintenance area for the lunar base is shown on the right in figure 3. The small units are among the first permanent

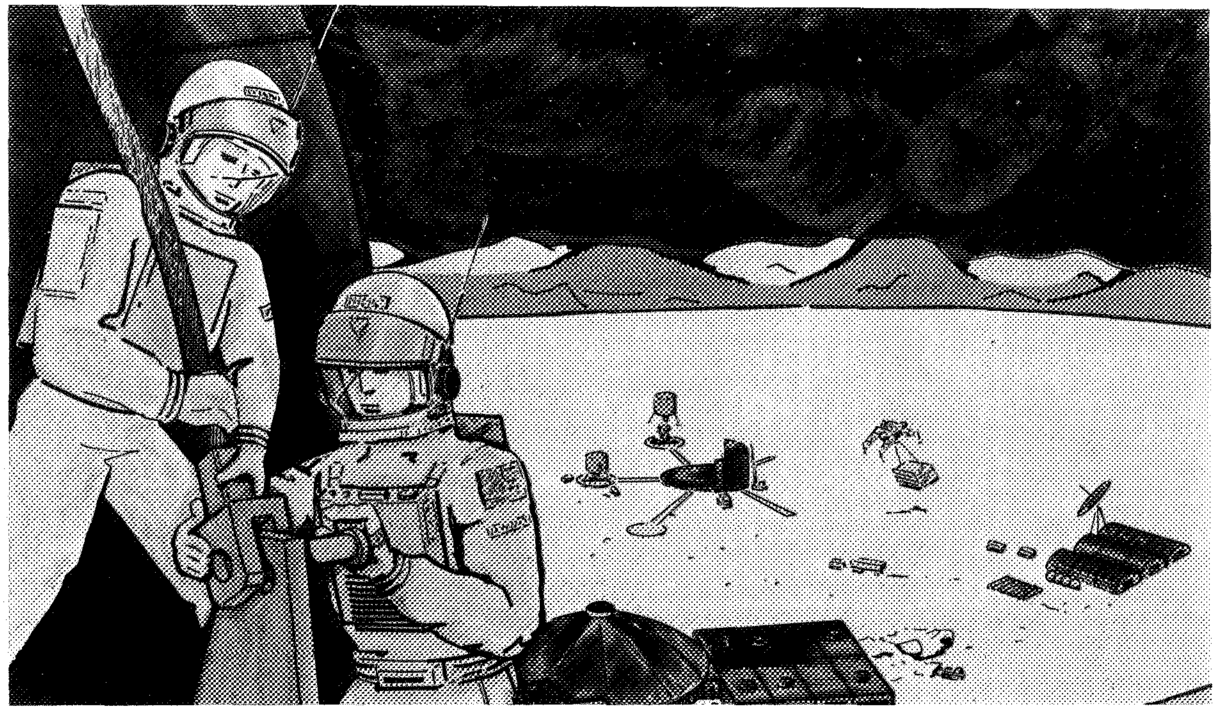


FIGURE 3.—Concept of lunar base site during construction.

facilities established. Initially, only two units comprised a small workshop where equipment components were maintained and repaired, while the other served as a life-support shelter until the main shelter was completed. Gradually, the facility grew to nine prefabricated modular units. The workshop would then provide service and maintenance for all heavy work equipment such as bulldozers, drills, cranes, trucks, rovers, and service and maintenance space suits. This facility may contain a small concrete-processing plant. The power supply for the lunar vehicles will be provided by fuel cells. The water produced by these fuel cells would be removed from storage tanks on each vehicle and stored in the service area for use by the base complex.

Life-Support Station

The main life-support station will contain the following activity areas:

(1) *Emergency safety areas.*—Such areas will be provided to isolate modules in the event one is penetrated by a meteor.

(2) Living quarters will combine the recreation area, sleeping area, rest area, and food preparation and dining areas. It is possible that each major facility will also contain a smaller life-support station for use of each respective work crew.

(3) Adjacent to the living quarters will be a hospital and dispensary.

(4) Communications will be a very important function for work integration throughout the lunar base. It is visualized that the main life-support station will contain a central work site control center. Eventually this will become the base operating control center.

MINING AND PROCESSING OPERATIONS ON THE MOON

Exploitation of lunar mineral resources will be in progress concurrently with the activities which have just been described. Figure 4 shows a concept for open-pit mining of minerals located on the crater rim. The mining vehicles shown are multipurpose units containing life-support cabs. The vehicles perform the inte-

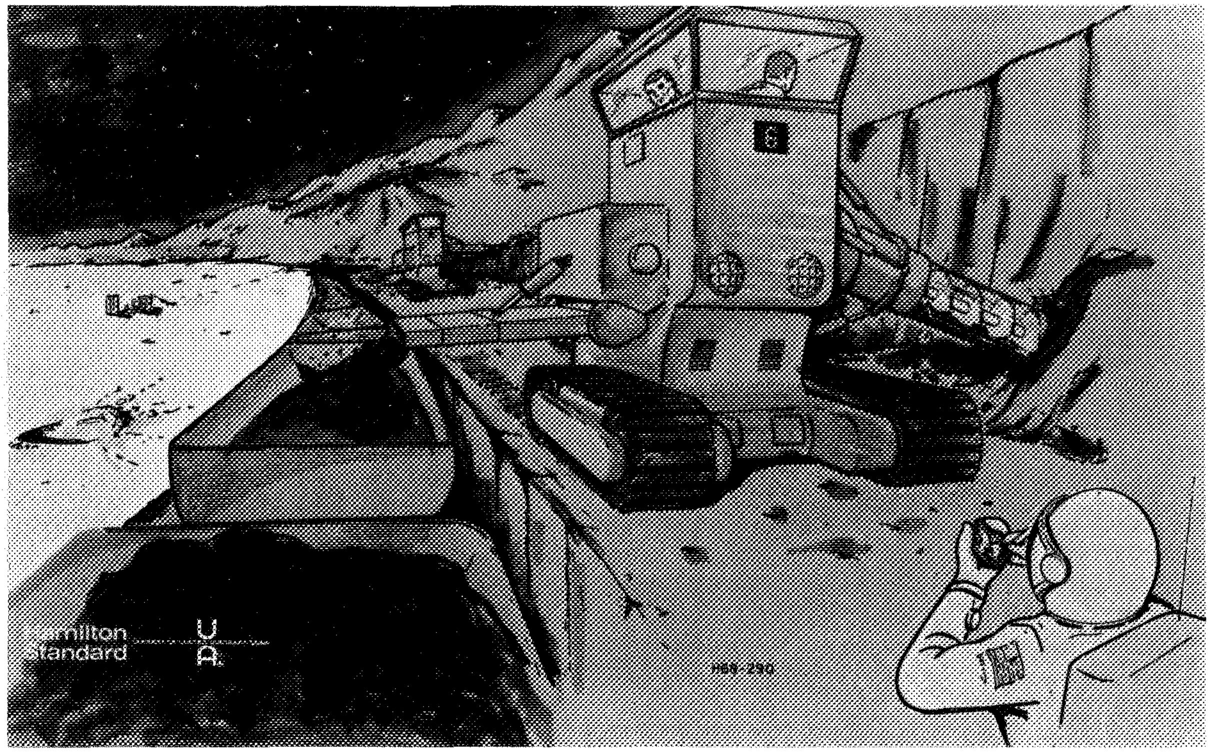


FIGURE 4.—Concept of open-pit mining for minerals located on crater rim.

grated functions of drilling and loosening the ore, grading and conveying it into a crusher, and then loading the ore into a transport carrier. The ore-processing facility can be seen on the left side of figure 4. Other mining-site tasks not shown in the figure that may be required are outlined as follows:

(1) Drill rigs:
  (*a*) Setup and assembly
  (*b*) Drill monitoring
  (*c*) Geological survey
  (*d*) Drill core recovery
  (*e*) Logging and data recovery
  (*f*) Blast preparation
  (*g*) Blasting

(2) Additional mining support or excavating equipment:
  (*a*) Bulldozers
  (*b*) Scoop shovels or diggers
  (*c*) Earthmovers
  (*d*) Conveyor belts and/or buckets
  (*e*) Rock crushers
  (*f*) Mineral hoppers
  (*g*) Trucks and trailers

From time to time, ore samples for mineral assay will be collected at the mining site to assure that mining operations are concentrated on the highest grade ore deposits. A space-suited geologist is shown in the right corner of the figure performing this task.

After the ore has been mined, it is transported to the processing and extraction facility. Figure 5 shows a processing and extraction facility primarily concerned with the recovery of oxygen and hydrogen for use as rocket engine fuel and life support. Other types of extraction processes will be required to reduce ore to basic minerals such as iron, aluminum, and magnesium. Extraction of gases from minerals was considered to be a process similar to that used by the oil industry to fractionate petroleum. The gas mixture is collected in the storage tanks, which may be either fixed or mobile. The space-suited workmen seen in the fore-

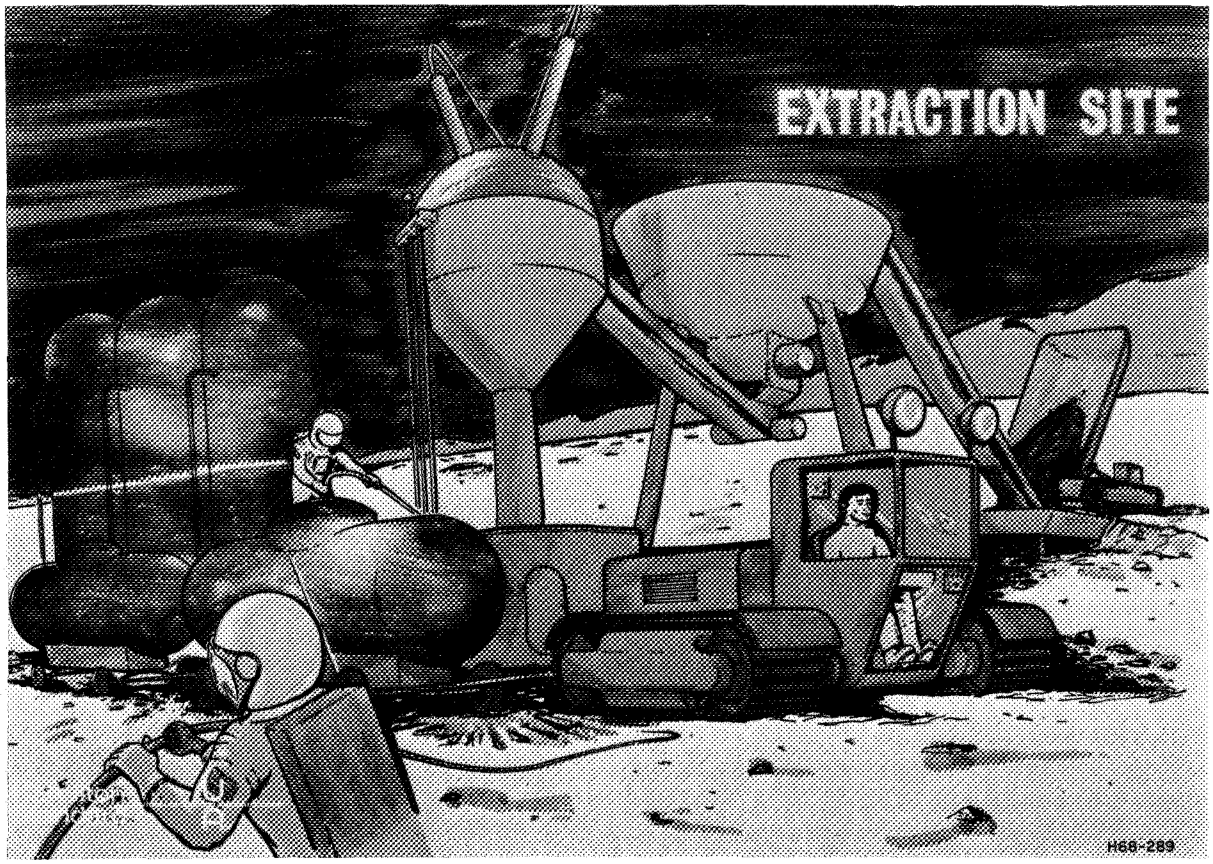


FIGURE 5.—Concept of extraction site.

ground may be completing the connections of a high-pressure gasline leading to a cryogenic facility where the gas is liquefied and stored in underground storage tanks. The portable tanks seen may be used for the purpose of collecting precipitates and sublimates, which will be reduced by other extraction processes to useful minerals. An operation of this type will require three to four men.

When the mining and mineral extraction capabilities reach a level where pure metals are available, then a fabrication facility for the manufacture of all types of equipment will be required. Such a facility is shown in figure 6. The activity emphasized in this figure is the fabrication and assembly of rocket vehicles for further scientific exploration of the solar system. In addition to this important activity, the fabrication facility will be capable of manufacturing new pressurized shelters as well as replacement components for base equipment. In many respects, the manufacturing facility might be considered as a supermodel shop, because many new equipment items could be one-of-a-kind special-purpose units. This is the last step in maximizing the self-sufficiency of the lunar base complex.

CONCLUDING REMARKS

In conducting the analysis of all activities that man will perform on the Moon, no task could be found that could not be performed by the proper man-equipment relationships. This can be assured by extensive planning and sound engineering design of equipment. As a sum-

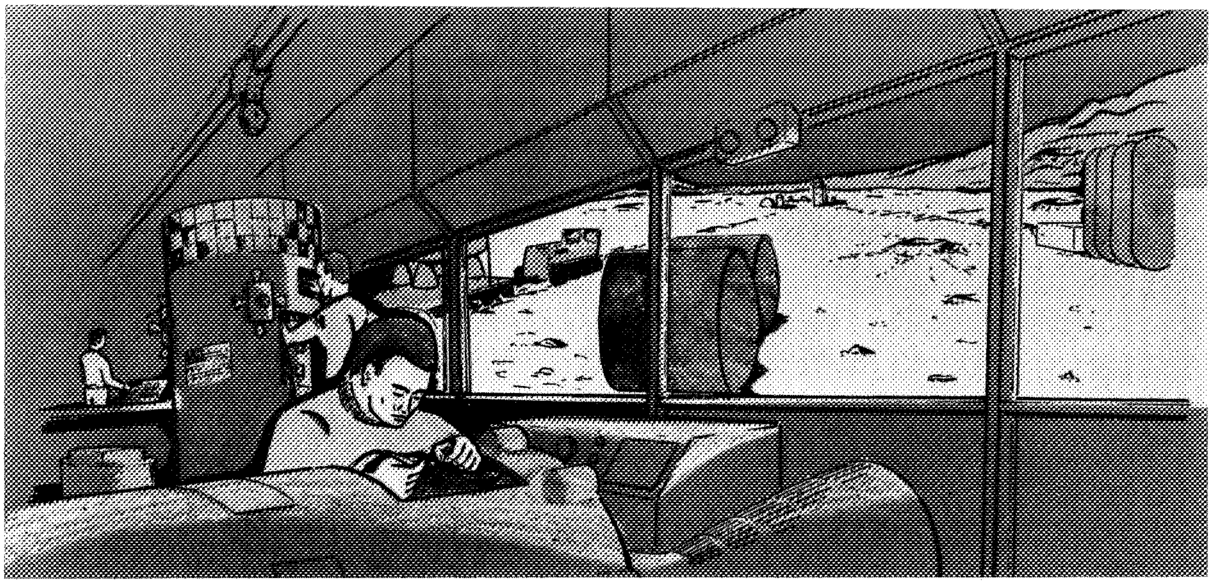


FIGURE 6.—Concept of fabrication plant.

mary of man-equipment requirements, six major areas concerned with the safety of man in the lunar environment are:

(1) Space suits
(2) Life support
(3) Tools, vehicles, and support equipment
(4) Radiation warning system
(5) Integrated communications:
  (*a*) Work frequencies
  (*b*) Emergency frequencies
(6) Performance capability

In the next 20 years, space suits will evolve into well-engineered functional units with integrated life-support systems having a minimum of 8 hours' capability. Man will readily adapt to the working environment using this equipment.

Tools, vehicles, and support equipment will be initially designed to maximize their utility on the lunar surface. Yet, knowing man, he will find means of using them effectively for purposes for which they were not intended, so that he can accomplish maximum mission effectiveness. Man's inherent ability to improvise spot solutions for the unexpected is man's greatest attribute.

The lunar research laboratory shown on the crater rim in figure 1 in conjunction with Earth-based observatories will have the primary responsibility of operating and maintaining a radiation warning system. This warning system will be keyed into the integrated communications network. Through assigned emergency frequencies, all base personnel will be informed of anticipated increases in radiation levels that may require temporary cessation of external base operations.

An integrated communications network is considered essential to safe lunar-surface operations. In addition to emergencies mentioned above, all major work parties should be monitored in the base central control. As man extends exploration activities over the lunar surface, communication with these exploring parties may be maintained first via Earth relay and later by lunar-orbiting communication satellites. It is visualized that man will service and maintain these satellites by service vehicles launched from and returned to the lunar-base complex.

What is meant by performance capability? This is a term that means different things to each scientific discipline. When applied to man, it means the capability of accomplishing the general performance functions of walking, running, jumping, climbing, standing, driving,

TABLE 2.—*Space-Suit Performance Capability*

Joint system	Movement if nude, deg	Range of movement, deg		Max torque, ft-lb	
		Present	Future	Present	Future
Shoulder	180	165	180	20	5
Elbow	140	140	140	5	2
Wrist	135	135	135	.75	.75
Waist-hip	120	110	120	40	20
Knee	135	130	135	10	5
Ankle	35	20	35	2	1

Task	Unsuited cost, Btu/hr	Suited metabolic cost, Btu/hr	
		Present	Future
Standing	440	500	450
Walking slow	900	1200	1000
Walking fast	1100	1600	1200
Assembling	680	1600	900

and flying, and the specific performance functions of—

Reaching	Pulling
Grasping	Pushing
Holding	Turning
Transferring	Inspecting
Opening	Probing
Connecting	Squeezing
Locking	Sighting
Stowing	

in any combination. When man is considered as a resource in the accomplishment of a mission, all his tasks and equipment relationships can be detailed in a functional task analysis. These data are then useful in establishing man-equipment requirements for use as design criteria. Depending upon the detail required, each task can be reduced to a range of motion for each one of man's joints. Such data can then be applied in space-suit design, in work-space layout, and providing accessibility for equipment repair and maintenance. We have obtained such data for a man-space-suit system by establishing an overall performance level for the use of the equipment design.

Many of the tasks that have been discussed will require extravehicular performance by man. Table 2 summarizes the present space-suit performance capability for both range of motion and metabolic cost of suited performance. These data lend credibility to the estimates outlined for man as a resource on the Moon. On the basis of improvements in pressurized performance achieved in the last 2 years, it is predicted that the nude range of motion for all suit joints with fairly low force levels and metabolic cost will be accomplished in the next 5 years.

U.S. GOVERNMENT PRINTING OFFICE: 1969—O-324-954