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<u>LUNAR SURFACE CHARACTERISTICS</u>

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Bellcomm, Inc.
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By R.F. Fudali

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TABLE OF CONTENTS

Abstract

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An assessment of the lunar surface environment is herein presented. However, since there is little or no direct evidence bearing on certain aspects of the lunar environment, the estimates presented here should not be accepted uncritically and the generated environmental model must be regarded as provisional until more direct evidence becomes available.

Experimental evidence indicates that the lunar atmosphere may be considered essentially non-existent and that lunar surface temperatures vary from $390 \pm 20^{\circ}K$ to $110 \pm 25^{\circ}K$ for regions exposed to the sun during a lunation. Temperature variations are shown as a function of both phase angle and latitude. Large scale surface features are briefly described and small scale relief is inferred from the large scale features and a consideration of possible modes of origin. Continental areas show a high density of large scale features and must have exhibited substantial small scale roughness immediately after formation. Maria are monotonously smooth on a large scale and their initial small scale roughness was most probably not as great as that of continents. Both types of terrain are variable and have been modified to an unknown extent since formation by the effects of meteoroid bombardment. Post-marial craters are analogous to continental regions (with less subsequent modification). There is no definitive information on surface chemical composition. An estimate of the average radioactivity dose due to surface material (3 millirems/week) is much less than that considered hazardous. The surface is both a poor thermal and electrical conductor but the vertical extent of this insulating material is unknown. It probably consists of both dust and rock froth, with a thin, ubiquitous layer of whisker crystals and/or dust also a possibility. The dust layers should be no more than 1 to 6 inches thick in most places but may rarely accumulate to greater depths in restricted areas. Minimum bearing strengths for dust and rock froth are

20246

estimated to be 10 psi and 100 psi respectively. In marial regions, this heterogeneous surface should grade downward, in just a few feet, into rocks approaching normal terrestrial density and strength. The nature and distribution of hidden subsurface voids cannot be estimated. Maria seem to offer the least hazards for an initial lunar landing, but accessibility to other terrain types from a marial site is desirable for a maximum scientific return. Certain possible lunar surface hazards cannot be assessed without additional information. These are briefly discussed. Attention is drawn to the fact that little is known about lunar small scale topography, surface texture, and bearing strength, and numbers characterizing these aspects were mainly based on analogy with terrestrial features.

LUNAR SURFACE CHARACTERISTICS

1.0 INTRODUCTION

This report presents an interim model of the moon's surface environment, based on the experimental measurements, visual observations, and speculations reported in the literature on this subject. Unfortunately, both visual observations and experimental measurements are severely limited by the remote location of the moon and the intervention of the earth's atmosphere. Consequently, the bulk of the literature is speculative in nature and any model must be considered interim until more direct measurements of the lunar surface become available.

The present lunar surface model has been produced by summarizing the known definitive data and, further, by considering the controversial facts available solely in the light of Apollo requirements. The latter approach involved: (1) adopting a conservative model where uncertainties exist but the probable limits of variation are generally agreed upon; and (2) eliminating controversies which are essentially unimportant for an initial lunar landing. For example, instead of asking what the origin (or origins) of the lunar surface features are, one might reasonably ask what the differences in the lunar surface will be if formed by one or another process, with reference to Apollo requirements. This is a much more amenable task than the basic problem of origin, which is not going to be resolved without data collected on the lunar surface itself.

In the final analysis, many of the numbers assigned to lunar surface parameters are largely arbitrary. Barring unforeseen and/or highly improbable operative processes on the moon's surface, these numbers are believed to be reasonable for Apollo design purposes.

2.0 LUNAR ATMOSPHERE

The one aspect of the lunar environment which is almost universally agreed upon is that the lunar atmosphere, for most intents and purposes, is essentially non-existent (for a rare opposing viewpoint, see reference 1). Every experiment devised to date has failed to reveal any atmospheric density. The most recent experiments (2), radio-astronomical observations of the refraction of radio waves from cosmic radiation sources, indicate an upper limit for the lunar atmosphere of 10^{-13} terrestrial atmospheres (1.5×10^{-12} lbs./sq. in.).

The present state of the lunar surface may be attributed either directly or indirectly to the early loss and present lack of a lunar atmosphere. Specifically, the lack of terrestrial-type weathering and erosion processes has resulted in the preservation of very ancient surface features such that a more or less complete history of the moon (subsequent to its initial formation) is on record. On the other hand, lack of an atmospheric buffer has resulted in the modification of these surface features by primary micrometeorite and secondary flux impacts. Finally there is the possibility that solar and cosmic radiation, over long periods of time under high vacuum conditions, has produced surface material quite unlike anything found on earth.

3.0 LUNAR SURFACE TEMPERATURES

Detailed and precise temperature measurements are lacking for most of the lunar surface. Aside from measurements made during lunar eclipses, most of the temperature measurements are of points on the lunar equator, especially at phase angles corresponding to lunar noon (subsolar point) and lunar midnight. Probably the most widely quoted temperatures in the literature are 374 degrees K (3) for lunar noon and 120 degrees K (4) for lunar midnight. Sinton (5) has re-measured these temperatures and quotes values of 389 degrees K and 122 degrees K, respectively.

However, knowing the solar constant G, the moon's distance from the sun r, the moon's rotational period P, and the albedo of the moon's surface A, one can calculate the equatorial variation in surface temperature with phase angle by assuming a reasonable value for the thermal inertia $(K\rho c)^{1/2}$ where K is the thermal conductivity, ρ is the density and c is the specific heat of the lunar surface material (5). The calculation depends upon only one temperature measurement. In the case of the curve reproduced in Fig. 1, the solar constant G was assumed to be that which would give a maximum (subsolar) temperature of 389 degrees K (experimentally determined). Indeed, one can estimate curves for various latitudes based solely on the equatorial curve, for the only difference will be that the incident solar radiation will be reduced by an approximate factor of $\cos\theta$, where θ is the latitude. Consequently the temperature at any latitude will merely differ from the equatorial temperature at the same phase angle by a factor of $(\cos\theta)^{1/4}$. Such a series of plots is shown in Fig. 2, based on the equatorial curve of Fig. 1.

How good these temperature curves are depends upon: (1) the accuracy of the experimental temperature or temperatures upon which they are based; (2) the magnitude of the error introduced by the assumptions which must be made in deriving the curves from the experimental temperatures; and (3) the magnitude of the deviations caused by lunar surface variations, which cannot be taken into account on these plots.

A consideration of the experimental errors, theoretical assumptions, and variations caused by surface inhomogeneities, as discussed in the literature (3-10), forces one to conclude that reported temperatures have a probable associated error of ±20 degrees C and the calculated temperature curves have a likely error of no less than ±25 degrees C over the most accurate portions of the curves. These errors are likely to be somewhat greater between lunar sunset and lunar sunrise.

4.0 LARGE-SCALE SURFACE FEATURES

Utilizing well-known geologic principles, it is possible to construct a threefold division of the lunar surface based on the relative times of formation of the surface materials (11). It is most convenient to consider the nature of the large-scale lunar surface features in terms of these three systems.

The characteristics of the material comprising these three systems are tabulated below, in order of decreasing age.

4.1 Pre-marial material - the lighter-colored, elevated, rough-appearing, so-called continents, which exhibit the following major features:

(a) A multitude of crowded and overlapping, circular and sub-circular craters ranging in size from 180 miles in diameter to below the limit of optical resolution. There is a rough inverse relationship between crater size and depth (depth/diameter = 0.02 to 0.03 for 100 Km diameter; = 0.1 for 10 Km diameter - ref. 12), and between depth and apparent age for craters of the same size. The crater floors are generally considerably depressed below the ground level outside the rims. Slopes of inner rims may attain 35-40 degrees; the outer rims average just a few degrees. Some craters exhibit central peaks or rubble heaps. A few of the smaller craters are aligned in chains, but the vast majority of all-size craters exhibit a random distribution.

(b) Mountains - rubble areas with peak heights up to 20,000 feet consisting of "more or less rounded structures heaped together" (13).

(c) Linear features - numerous valleys, ridges, rills (floored cracks), and faults which are often associated in a well-defined network of intersecting families. Faults are particularly numerous and appear to exhibit only vertical displacement, with the sole exception of the probable strike-slip fault dissecting the crater Gassendi B. Concentric escarpments are also found near the perimeter of certain maria.

The pre-marial materials are, in places, covered by both marial material and post-marial craters.

4.2 Marial material - The dark, depressed, apparently smooth "lunar seas" which are superimposed on the older, pre-marial surface and exhibit the following characteristics:

(a) Large areas which are featureless down to the limit of optical resolution and almost flat (max. slopes of 2-3 degrees).

(b) Low domes and anticlines with very gentle slopes (2-4 degrees).

(c) Shallow depressions with very gentle slopes (2-4 degrees).

(d) Rare crater chains similar to those found in continental regions, but composed of smaller sized craters.

(e) Linear features - short, narrow valleys, rills, and faults are present, but much less abundant than in pre-marial material.

(f) Random craters ranging from 40-50 miles in diameter to below the limit of optical resolution are present, but again, much less numerous than in pre-marial material. These craters are mainly post-marial in age.

4.3 Post-marial material - The youngest craters, ranging in size from 40-50 miles in diameter to below the limit of optical resolution, which are superimposed on both of the older systems. These craters have sharp, little-eroded rims and many exhibit the well-known phenomena of radial rays, which are interpreted as very thin ejecta deposits from the craters, still visible because of their relatively young age.

From consideration of the above facts, one may conclude:

(a) The pre-marial history of the moon resulted in an extremely rough, heavily fractured surface, certainly on a large scale and most probably on a small scale as well;

(b) The marial material has subsequently covered much of this rough pre-marial surface and is very much smoother on a large scale;

(c) The post-marial processes have been much less intense or have been operating for a much shorter time period than pre-marial processes, leaving the maria almost unchanged since their formation, at least on a large scale.

5.0 SMALL SCALE SURFACE ROUGHNESS

The small scale roughness of the moon's surface ($<$ 500 feet), being unobservable with earth-based optical instruments, must be inferred from indirect evidence.

The presently prevalent interpretation of radar reflectivity data is that only a relatively small percentage of the lunar surface behaves as a rough scatterer to radar wavelength radiation and that the average (rms) lunar slope is only a few degrees (14, 15, 16, 17). There is, however, still considerable doubt connected with the interpretation of radar returns, primarily because of the necessary simplifications and assumptions which must be made and the almost complete lack of any empirical substantiation. Furthermore, it is not as yet clear what the prevalent interpretation means in terms of possibly hazardous terrain (18). It would appear then, to be unwise to base any estimate of lunar small-scale roughness solely on radar data at this time.

The only other indirect evidence available is a consideration of the processes of formation and subsequent modification of the lunar surface.

The processes which shaped the original lunar surface are still a matter of heated debate. The only two theories which merit serious consideration are meteoric impact origin (with modification for maria formation) and volcanic origin. With one notable exception (19), the proponents of both theories of origin agree that the maria are covered by extrusive igneous rocks. The theory that the maria are covered with loose dust to a depth of several hundred feet, with the total layer of dust obtaining a thickness of one-half mile or more, does not explain a number of observational facts and is considered highly improbable (20-23).

For purposes of determining small scale surface roughness, it is not necessary to choose between the two theories. To be consistent with observed large-scale surface features, both predict that the continental areas and the post-marial craters were quite rough on a small scale immediately after formation (blocks or flow structures up to 3 feet in height covering much of the surface, numerous larger blocks or lava flow structures up to 15-20 feet in height, local slopes up to 40 degrees). Depending upon the assumptions made as to composition, both theories predict the maria may have been reasonably smooth (that is, passable for an ordinary wheeled vehicle without special design characteristics) if formed mainly from pahoehoe-type lava

(11, 24) or welded tuffs (25) or rough (on a small scale) if formed mainly from aa-type lava flows (11, 24), the most probable surface being heterogeneous and varying between these extremes. Thus initial small scale roughness, except very locally, would probably not be as hazardous as that associated with continental regions (slopes more gentle, cracks and faults much less numerous, larger blocky material not as prevalent).

Since formation, the continents and maria have been subject to large-scale meteoric bombardment or volcanic activity (post-marial craters), small scale meteoric bombardment and/or volcanic activity (producing features in the size range 3-500 feet) and micrometeorite bombardment. The first two processes tend to increase small-scale roughness. The third process tends to decrease it. The net effect is not known.

It is concluded that the small scale roughness model of the maria for Apollo purposes should be one exhibiting considerable small scale relief - rubbly material with blocks and flow structures up to 3 feet in height not uncommon, larger blocks and flow structures up to 20 feet in height found locally, small craters ranging from fractions of an inch up to several hundred feet in diameter numerous (but most are on the lower end of the size scale, larger ones quite scarce), gentle slopes, except for inner rims of craters, some small scale fissures and faults.

It is not impossible that, except for small craters, the maria are almost smooth, in whole or in part, but lacking any proof of such a possibility it would be foolhardy to design for such conditions.

6.0 NATURE OF THE SURFACE MATERIAL

6.1 Chemical Composition

There is no direct observational evidence bearing on the chemical composition of the moon's surface, and the indirect evidence simply leads to widely divergent personal opinions, producing estimates ranging from chondritic to granitic compositions. After extensive consideration of the evidence to date, Urey (22) succinctly summarizes the situation by stating (p. 511): "We may conclude that we have no definitive evidence in regard to the chemical composition of the surface materials of the moon."

6.2 Radioactivity

The radiation produced by the lunar surface results from a combination of three factors: (1) cosmic and solar radiation-induced neutron back-scattering from the surface material; (2) the decay of short-lived, unstable isotopes produced by the same cosmic and solar radiation; and (3) the decay of the radioactive species originally present in the surface material. Only the radiation due to neutron back-scattering and gamma emission is significant since most of the alpha and beta radiation is absorbed before it reaches the surface.

It has been estimated that back-scattering produces a flux of 0.02 neutrons $cm^{-2}sec^{-1}$ and that the radiation due to induced radioactive species (for an average solar flux, i.e. excluding solar flares) approximates 0.6 gammas $cm^{-2}sec^{-1}$ (31). This corresponds to a total dose rate of 0.5 millirems/week - two to three orders of magnitude less than that due to the primary cosmic and solar radiation. The natural radioactivity is almost entirely due to the decay of the radioactive isotopes of potassium, uranium, and thorium. Assuming an average chondritic meteorite abundance for these isotopes, the gamma radiation has been estimated (26) as approximately 0.02 gammas $cm^{-2}sec^{-1}$. This may be too low if the moon's surface has concentrated these isotopes in the same way that the earth's crust has. In this event, the dose rate would be in the range 0.3 to 2 millirems/ week (31). If local "hot spots" multiplied this factor by as much as 1000, it would still be 2 orders of magnitude less than a hazardous dose.

6.3 Texture and Structure of the Lunar Surface Material

To be consistent with thermal conductivity and optical wavelength reflectivity data, the lunar surface must be composed of low density, porous material which is extremely rough on a microscale (millimeters to microns).

This material need not be more than an inch or so thick but it must be almost ubiquitous on the lunar surface.

Possible textures which fit the observational data are:

(a) Whisker layer - the solar and cosmic proton flux may cause the growth of fine whisker crystals on the surface material by sputtering, producing a delicate mat of very fine, elongated crystal hairs. Such a process would be self-stopping after an insignificant thickness had developed, unless new source material was continuously supplied.

(b) Rock froth - the degassing of the upper part of a molten extrusive rock may produce a layer one to several feet thick of porous rock froth. The number and size of the vesicules depends upon the amount of contained volatiles and is apt to be highly variable.

(c) Dust - the erosion of topographic highs by micrometeoritic and secondary particulate bombardment leads to accumulation of the eroded dust-sized particles in the topographic lows. This process tends to smooth out the macro-relief, lowering and rounding the highs and filling in the lows. This dust layer should be no more than 1 to 6 inches thick in most places but locally may accumulate to several tens of feet.

There is no good reason for believing the lunar surface material is homogeneous. It most probably consists of both dust and rock froth; a thin whisker layer or a thicker layer of mixed dust and whiskers are lesser possibilities. Continental areas are difficult to predict, but underlying the surface material in marial regions, at a depth of no more than a few feet in most places, the rocks most probably approach normal terrestrial density and structural strength.

6.4 Bearing Strength

The bearing strength of a whisker mat is likely to be negligible, but if such a surface exists, it is much too thin to be considered hazardous.

Terrestrial rock froths range in bearing strength from 200 psi to 12,000 psi (24). Lunar rock froths may or may not be comparable. Factors to consider are the reduced lunar gravity, lack of an atmosphere and the amount of total volatiles the lunar magmas contained. A precise analysis is not possible but it does seem highly unlikely that the bearing strength of any lunar rock froth is less than 100 psi.

The bearing strength of a dust layer is a continuously varying parameter, since the application of a load to such a layer causes compacting and interlocking of the underlying individual particles. Thus the bearing strength increases rapidly with the depth of penetration of a blunt surface. For example, the load necessary to penetrate to depths of 1 inch and 5 inches, respectively, increases from 4 to 25 psi, for a layer of finely-ground pumice under standard temperature and pressure conditions (29).

The variation in bearing strength of a lunar dust layer depends upon the initial degree of compaction attained. Except for the first inch or so of such a layer, which may be kept loose by impact churning, the remainder most probably attains a more compact packing than laboratory-simulated layers, due to the "shakedown" effect of seismic pulses over very long periods of time. A reasonable figure for negligible penetration (1-2 inches) of such a lunar dust layer is 10 psi; i.e. a load of 10 psi will penetrate to a maximum depth of 1-2 inches.

It has been suggested that such a dust layer would be fused to a greater or lesser extent by micrometeorite and/or cosmic ray bombardment (27) or by partial sintering of individual particles in the near vacuum environment (29). The first process would result in increased bearing strengths. The second process could either increase or decrease the bearing strength, depending upon the degree of compaction attained and the strength of the intergranular bonds.

The foregoing discussion of bearing strength assumes a uniform distribution of solid material with depth. If there are near-surface voids, such as large gas vesicles which did not quite breach the surface of a lava flow or crevices which are bridged by thin layers of sintered dust, then all bets are off. The load-carrying capacity of a roof or bridge, whatever the intrinsic bearing strength of the material, is also dependent upon other factors, such as the size and shape of the void, the thickness of the roof or bridge and its geometric configuration.

6.5 Thermal Conductivity

Lunar surface temperature measurements made during the course of lunations and eclipses have established that the thermal inertia $(K\rho c)^{1/2}$ of the moon's surface is of the order 0.001 to 0.002 cal/cm^{2}sec$^{1/2}$degree C, where K is the thermal conductivity, ρ the density and c the specific heat of the surface material (5). None of the three quantities are accurately known by themselves. Further, both K and c and thus also $(K\rho c)^{1/2}$ decrease with decreasing temperature. The amount of variation is uncertain but is presumed to be small. The least uncertainties are involved in the quantities ρ and c and by assuming reasonable values for these parameters, the thermal conductivity K may be approximated. The preferred values are:

$(K\rho c)^{1/2}$ 001-0.002
ρ ....0.6 to 1.5 gm/cm^3
c ....0.2 cal/gm degree
K ....3×10^{-5} to 3×10^{-6} cal/cm^2...$\frac{\text{sec degree}}{\text{cm}}$

The above approximation assumes a homogeneous surface. If the surface is in fact heterogeneous, the range in thermal conductivity will probably lie at least partially outside the estimated range.

Attempts have been made to fit the available infrared data more closely by assuming a 2-layer surface, each layer having different values of K, ρ, and c. If the upper layer is taken to be very thin ($<$1 cm), one can juggle these values to give satisfactory agreement with the infrared data. At this time, the quality of the available data is believed to be insufficient to warrant the added complexity of a 2-layer model (5).

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6.6 Electrical Conductivity

Evans (16), in discussing the work of Senior and Siegel, quotes a value of 3.4×10^{-4} mhos/meter (3.4×10^{-5}emu) for the electrical conductivity of the lunar surface material. This figure is subject to an error of unknown magnitude because of the assumptions, both theoretical and experimental, which were necessary for the calculation. The measured electrical conductivity for terrestrial materials, such as dry sandy soil, is 2×10^{-14} emu (28). This tends to corroborate the calculated lunar conductivity since one would expect the lunar surface conductivity to be somewhat lower than this figure.

7.0 LUNAR LANDING SITE

The available evidence indicates that an Apollo landing and subsequent exploration on marial material is apt to be less hazardous than on continental material. Specifically: large scale slopes should be only 2-4 degrees, except very locally; craters are substantially less abundant and the small scale surface roughness, especially that caused by faults and fissures, should be considerably less hazardous than on continental areas, with the possibility that the terrain encountered will actually be much smoother than postulated; finally, if isolated, thick dust deposits should prove hazardous, the frequency of their occurrence in marial regions should be much smaller than in continental areas, since the relief is, in general, not nearly so great.

For a maximum scientific return, the marial landing site should be within exploration range of a continental area and/or a post-marial crater.

Finally, the landing site should be close enough to the terminator for shadows to be conspicuous, for purposes of video and photographic enhancement, while still allowing sufficient light for optimum functioning during the entire stay period.

8.0 LUNAR SURFACE CHARACTERISTICS - SUMMARY

8.1 Lunar Atmosphere - $< 1.5 \times 10^{-12}$ lbs/sq. in.

8.2 Temperature of Surface Material - Ranges from 390 ±20 to 110 ±25 degrees K for areas that are exposed to the sun at some time during a lunation. Permanently shaded areas will be colder than the lowest figure quoted. The variation with longitude and latitude (with a probable error of ± 25 degrees) is shown in Fig. 2.

8.3 Large-Scale Surface Features - see text.

8.4 Small-Scale Surface Features

Continents - Blocks and/or flow structures up to three feet in height covering much of the surface, many small craters ranging from a fraction of an inch to several hundred feet in diameter, numerous small faults and fissures, numerous larger blocks or lava flow structures up to 15-20 feet in height, local slopes up to 40 degrees not uncommon. Modified to an uncertain extent by rounding of projections and accumulations of dust in topographic lows.

Maria - Rubbly material with blocks and flow structures up to three feet in height not uncommon; larger blocks and flow structures up to 20 feet in height locally, small craters ranging from fractions of an inch to several hundred feet in diameter numerous (but most are on the lower end of the size scale, larger ones quite scarce), gentle slopes except for inner rims of rare craters, some small scale fissures and faults. Modified to an uncertain extent by rounding of projections and accumulations of dust in topographic lows.

8.5 Chemical Composition - No definitive information

8.6 Radioactivity - Average dose due to surface radioactivity is 3 millirems/week. This is 5 orders of magnitude less than that considered hazardous over long periods of time.

8.7 Texture and Structure - A heterogeneous surface composed of pockets of dust filling the depressions between topographic highs of rock froth. The dust layer should be no more than 1 to 6 inches thick in most areas of accumulation, but rare, very local depositions up to tens of feet are not impossible. It is also possible that even the topographic highs are covered by a very thin dust and/or whisker layer. The marial surface materials are underlain in most places at a depth of no more than 1 to 5 feet by competent rock of normal terrestrial density and structural strength.

8.8 Bearing Strength

Dust - Disregarding the top inch or so, which may or may not be loosely packed, a load of 10 psi will produce a maximum penetration of 1-2 inches. There will be some variation in this figure from area to area.

Rock Froth - 100 psi minimum and highly variable from one area to another.

Underlying Rock - 25,000 psi minimum

8.9 Thermal Conductivity - 3×10^{-5} to 3×10^{-6} $\mathrm{cal/cm^2 sec} \frac{\mathrm{degree}}{\mathrm{cm}}$ for an assumed homogeneous surface material. The underlying solid rock should approximate terrestrial igneous rocks, which have thermal conductivities on the order of 4×10^{-3} $\mathrm{cal/cm^2}$ $\mathrm{sec} \frac{\mathrm{degree}}{\mathrm{cm}}$.

8.10 Electrical Conductivity - 3.4×10^{-4} mhos/meter for an assumed homogeneous surface material.

9.0 DISCUSSION

There are processes which may be operative on the lunar surface which have not been discussed in the proposed surface model. The reason for this apparent neglect is that not only is it difficult to estimate their effects but their very existence is questionable. If they do exist, and their magnitudes are not negligible, they could constitute a distinct danger for a lunar expedition. These phenomena are listed and briefly discussed below.

Chemical Activity: The lunar surface materials have been subject to irradiation over a wide energy spectrum for a very long period of time in a high vacuum. This could result in material having a chemically "clean" surface with many unsatisfied surface bonds. Such a material would be highly unstable in an atmospheric environment and might react violently with a rocket exhaust or any other foreign gases with which it came in contact. The extent of the hazard depends entirely upon how much energy is released and how it is dissipated. Thus, instead of a violent reaction, released energy could simply serve to heat the surface material a few degrees.

Dust Behavior: The behavior of an agitated dust layer, possibly electrically charged and/or chemically "clean" on the lunar surface is not known. Neither the movement of the dust particles under tractive or exhaust impulses nor their adhesiveness to surfaces can be predicted. These properties could be important to a landing spacecraft, a roving vehicle, or an astronaut on foot.

Impact-Produced Ejecta: The impact of meteoroids on the lunar surface results in the ejection of secondary particles which then become available for further erosion of the surface, and the possible frosting of polished optical surfaces and penetration of space suits. These secondaries may be more hazardous than the primary particles because: (1) The mass of ejected material may be 10^3 to 10^4 times greater than the incident mass; and (2) Many of the lower velocity particles may not have proportionately diminished penetrating power as compared with the primary, whose higher velocity causes an explosion upon impact. The magnitude of the hazard due to secondary ejecta depends upon the primary meteoroid flux, which is not well known. If this primary flux is very small, the effect of the secondaries will be negligible for Apollo stay times even if the mass ejected is a factor of 10^4 greater than the primary mass. Furthermore, estimates of ejected mass are based on experiments in which the impacting body encounters a dense, smooth surface (30). In fact, the lunar surface layer may be highly porous and may exhibit a surface configuration which is complex on a larger scale than the size of the impacting particles (dominantly micrometeorites). Under these circumstances the amount of ejected material could be considerably smaller than that observed in laboratory experiments to date.

Next, it should be emphasized that included among those aspects of the lunar surface environment about which there is little information are the most important surface characteristics from a manned landing viewpoint. These are the nature of the surface material with respect to structure, texture, and bearing strength, and the nature of the small scale surface relief.

The most hazardous surface material would be a thick, extremely porous layer having a very low structural strength. An extrusive lunar rock froth might have these characteristics, although it is difficult to conceive of conditions on the moon affecting the vesiculation of a lava in a manner so radically different from what we observe with terrestrial flows. Another possibility is a dust layer which does not compact because the individual particles stick together on contact, building up a very open texture.

There is, however, no good reason to expect dust layers more than a few inches thick in marial regions. The known facts about the lunar surface are equally well explained by a surface of dense, hard rock covered by an inch or less of dust and/or whisker crystals.

In the final analysis the bearing strength figures which were assigned to the probable surface materials are thought to represent the minimum strengths which there is a reasonable probability of encountering. Further, the lowest bearing strength quoted (10 psi for dust) is considered close enough to any conceivable minimum to necessitate only minor changes in Apollo design characteristics should lower strengths be subsequently observed.

These bearing strength figures do not apply to the load carrying capacity of roofed or bridged voids, which may constitute collapse hazards. It has been assumed that such voids can be detected and either avoided or crossed with special equipment.

Estimates of the moon's small scale surface relief range from very rough (for a detailed rough model description see the discussion in this report on continental areas) to very smooth (most slopes very gentle but occasionally reaching an upper limit of 10-15°. Few, if any, pits and protuberances greater than 4 inches in depth and height, crevice density assumed low enough so that individual crevices may be avoided by maneuvering). On the basis of available evidence, neither extreme can be precluded. However, both are considered unreasonable for Apollo purposes.

If extreme small scale roughness occurs in marial regions, it is almost certainly not continuous and information from unmanned probes should permit avoidance of these areas. Thus, such a model is unrealistic since designing Apollo for extreme small scale roughness is expensive in terms of time, weight, and money. On the other hand, an unmanned probe must be able to land and function in such areas, for it cannot pick its landing spot to reduce small scale hazards.

The nature of the processes operating to reduce the moon's surface to a Daytona Beach could affect a large portion of the total surface area. But in the absence of concrete evidence, this model must be ignored, because it is too optimistic. It would be embarrassing if a "smooth moon design" encountered a rough surface.

On the basis of the above analysis it can be seen that the intermediate model described in the body of this report for marial regions is the preferred model.

Finally, attention is again drawn to the fact that the moon's crust is undoubtedly heterogeneous, varying both laterally and with depth. This variation has been referred to in numerous places throughout the report, but has been pointedly ignored in the assignment of numbers to <u>some</u> surface characteristics. The sole justification for this inconsistency is the complete lack of data concerning the distribution, characteristics and effects of this heterogeneity with respect to these surface parameters.

In past working statements, it has been assumed that the lunar surface could be described in terms of three continuous, superimposed layers, each having certain constant characteristics. It is hoped that the present report helps to dispel this misconception.

10.0 REFERENCES CITED

1. Firsoff, V. A., Strange World of the Moon, Science Editions Inc., New York, 1962.

2. Elsmore, B., Radio observations of the lunar atmosphere, Philos. Magazine, Vol. 2, No. 20, p. 1040, 1957.

3. Pettit, E., Radiation measurements on the eclipsed moon, Astrophysical Journal, Vol. 91, pp. 408-420, 1940.

4. Pettit, E. & S. B. Nicholson, Lunar radiation and temperatures, Astrophysical Journal, Vol. 71, pp. 102-135, 1930.

5. Sinton, W. M., Temperatures on the lunar surface, Physics & Astronomy of the Moon, pp. 407-428, Academic Press New York, 1962.

6. Gilvarry, J. J., The nature of the lunar maria, Astrophysical Journal, Vol. 127, p. 751, 1958.

7. Garstang, R. H., The surface temperature of the moon, Journal Brit. Astron. Assoc., Vol. 68, pp. 155-165, 1958.

8. Pettit, E., Lunar radiation as related to phase, Astrophysical Journal, Vol. 81, p. 17, 1935.

9. Conel, J. E., R. C. Speed, R. J. P. Lyon & E. A. Burns, A proposal for temperature and compositional mapping of the lunar surface from surveyor orbiter by infra-red spectrometry. Proposal submitted to Office of Grants and Research, Code SC (Surveyor Orbiter) NASA Headquarters from JPL and SRI, 1962.

10. Geoffrion, A., M. Korner & W. M. Sinton, Lowell Obs. Bull. No. 5, 1960.

11. Hackman, R. J., Engineer special study of the surface of the moon, Dept. of the Interior, U.S.G.S., 1961.

12. Fielder, G., Structure of the Moon's Surface, Pergamon Press, New York, 1961.

13. Whitaker, E., Lunar topography, preprint of paper delivered at the Lunar Flight Symposium, Denver, Colorado, Dec. 29, 1961.

14. Daniels, F. B., Radar determination of the root mean square slope of the lunar surface, Jour. Geophys. Res. Vol. 68, No. 2, pp. 449-453, 1963.

15. Daniels, F. B., Radar determination of lunar slopes; correction for the diffuse component, Jour. Geophys. Res. Vol. 68, No. 9, pp. 2864-2865, 1963.

16. Evans, J. V., Radio echo studies of the moon, Physics and Astronomy of the Moon, pp. 429-478, Academic Press New York, 1962.

17. Pettengill, G. H. and J. C. Henry, Radar measurements of the lunar surface, The Moon, pp. 519-525, Academic Press, New York, 1962.

18. Thompson, W. B. Lunar Radar Studies, Bellcomm, Inc. Technical Report, June 30, 1963.

19. Gold, T., The lunar surface, Monthly Notices Royal Astron. Soc., Vol. 115, No. 6, p. 585, 1955.

20. Kuiper, G. P., The moon, Jour. Geophys. Res., Vol. 64, No. 11, pp. 1713-1719, 1959.

21. Whipple, F. L , On the lunar dust layer, Vistas in Astronautics, Vol. II, Pergamon Press, New York, 1959.

22. Urey, H. C., Origin and history of the moon, Physics and Astronomy of the Moon, pp. 481-523, Academic Press, New York, 1962.

23. Singer, S. F. & E. H. Walker, Electrostatic dust transport on the lunar surface, Icarus, Vol. 1, No. 2, p. 112, 1962.

24. Green, J., The Geology of the Lunar Base, Space Sciences Laboratory, North American Aviation Inc. Publication SID 61-358, 1962.

25. O'Keefe, J. A. and W. S. Cameron, Evidence from the moon's surface features for the production of lunar granites, Icarus, Vol. 1, No. 3, pp. 271, 1962.

26. Anonymous, Tentative Model for the Lunar Environment, Internal JPL Document, Re-order No. 61-263, 1961.

27. Sharonov, V. V. The nature of the lunar surface, The Moon, A Russian View, pp. 338-368, University of Chicago Press, 1962.

28. Reference Data for Radio Engineers, 4th edition, International Telephone and Telegraph Corporation, New York.

29. Halejian, J. D., Laboratory investigation of "moon-soils" IAS Paper No. 62-123, 1962.

30. Gault, D. E., E. M. Shoemaker and H. J. Moore, Spray ejected from the lunar surface by meteoroid impact, NASA Technical Note D- (Preliminary Data).

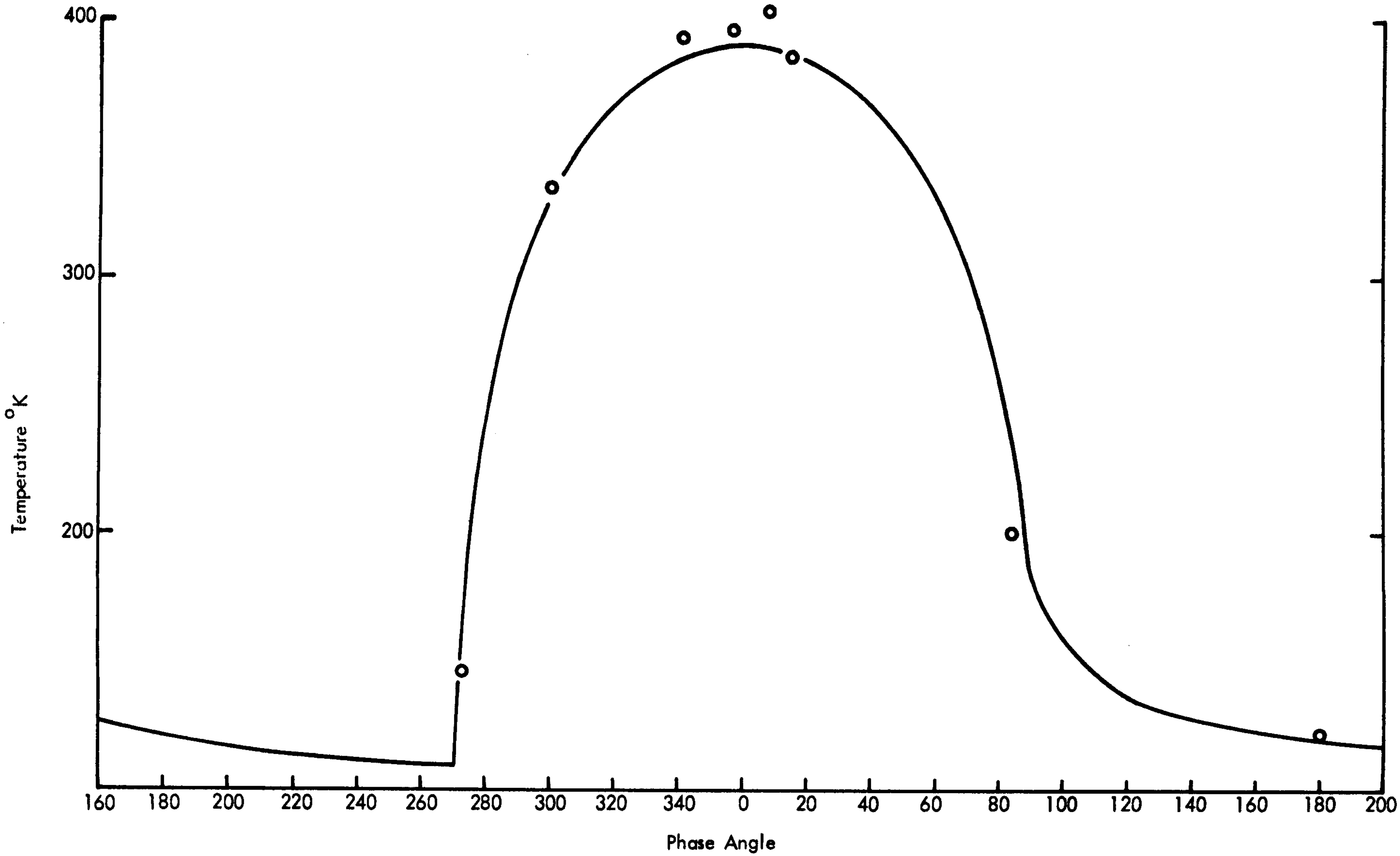
31. Barton, J A., An estimate of the nuclear radiation at the lunar surface, Advances in the Astronautical Sciences, Vol. 6, pp. 794-804, The Macmillan Company, New York, 1961.

APPENDIX

Figure 1. Theoretical curve with $(K\rho c)^{1/2} = 0.0023$ showing the variation of lunar surface equatorial temperatures with phase angle. The circles represent surface temperature measurements made throughout a lunation. After Sinton (5).

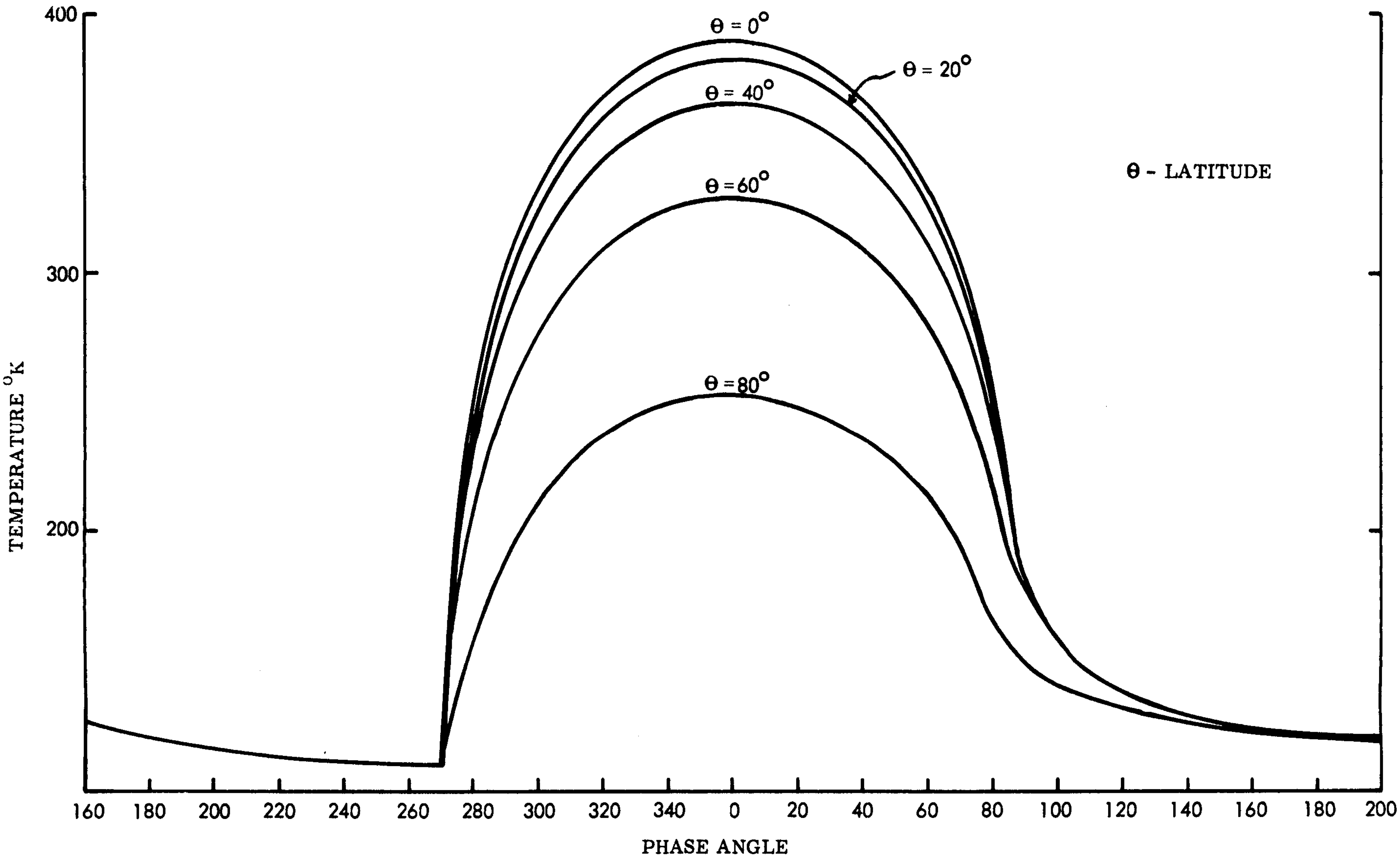
Figure 2. Theoretical curves showing the variation of surface temperatures with latitude and phase angle. The curves are based on the equatorial curve of Sinton shown in Figure 1.

FIGURE 1



Temperature °K
400
300
200
160
180
200
220
240
260
280
300
320
340
0
20
40
60
80
100
120
140
160
180
200
Phase Angle

FIGURE 2



400
300
200
TEMPERATURE °K
θ = 0°
θ = 20°
θ = 40°
θ = 60°
θ = 80°
θ - LATITUDE
160 180 200 220 240 260 280 300 320 340 0 20 40 60 80 100 120 140 160 180 200
PHASE ANGLE