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THERMAL CHARACTERISTICS OF THE LUNAR SURFACE LAYER†

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Abstract—The thermophysical properties of the fines from the Apollo 12 landing site have been determined as a function of their relevant parameters. These properties include the thermal conductivity, thermal diffusivity, directional reflectance and emittance. The density used was the same as that observed from the returned core-tube samples and so should be close to the true density of the surface layer at the Apollo 12 site. The measured properties are used to calculate the diurnal temperature variation of the moon's surface as well as for several depths below the surface. The maximum surface of 389°K is obtained at lunar noon while the minimum temperature of 86·1°K is obtained at sunrise. It is shown that the most significant effects on temperature, as compared with previous calculations, are caused by using the directional reflectance which controls the amount of solar energy absorption during the day in place of a constant hemispherical reflectance. The results are compared with previous analyses and remote measurements.

NOMENCLATURE

- t, time;
- P, lunation period;
- x, depth below surface;
- T, temperature;
- c, specific heat;
- k, thermal conductivity;
- S, solar constant;
- T_0, surface temperature;
- r, directional reflectance.

Greek symbols

- ρ, density;
- Λ, lunar latitude;
- β, lunar longitude;
- ξ, dimensionless depth $x/(4\pi\alpha^* P)^{1/2}$;
- τ, dimensionless time t/P;
- ε, emittance;
- σ, Stefan–Boltzmann constant;
- α, thermal diffusivity, $k/\rho c$;
- α^* thermal diffusivity evaluated at the average temperature far below the lunar surface;
- γ, thermal parameter $(k\rho c)^{-1/2}$.

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1. INTRODUCTION

THE PROPER design and operation of systems or structures which may be constructed for or on the lunar surface depend to a large degree on a complete knowledge of the thermal transport properties of the material in the lunar surface layer. Accurate data on the local thermal environment are also needed particularly on the moon where there are wide extremes of temperature. However, up to now there have not been any direct measurements of the temperature field in the surface nor have there been any reports until recently of the actual properties of the lunar media.

There have been a number of soft landings on the moon in the past several years including five unmanned Surveyor flights and three manned Apollo flights by the United States and several unmanned Lunar flights by the Soviet Union. None of these missions included provision for measurement of lunar surface temperatures or heat fluxes. Ironically, the only flight which included such experiments was the Apollo 13 flight which was aborted before a landing could take place. The only actual measurements of temperature have been remote measurements from earth in which infrared or microwave radiation emitted by the dark moon, either at lunar nighttime or during an eclipse, is analyzed to yield an apparent radiation temperature, e.g. [1–5].

There have been numerous attempts in the past to calculate lunar temperatures using assumed values of the thermophysical properties of the lunar surface layer as well as attempts to infer these temperatures from spacecraft heat balances. These are summarized in Cremers *et al.* [6]. While these analyses lead to lunar temperatures which are in the proper range, they do not yield proper temporal variation because they do not retain the proper time and temperature dependence of the thermophysical properties. The only attempts to use the actual properties of the lunar surface layer in temperature calculations were done for the Apollo 11 and 12 sites by Cremers *et al.* [6, 7]. In those papers the temperature dependent thermal conductivity and diffusivity were measured for the respective lunar samples and used along with a constant value of reflectance and emittance to calculate surface layer temperatures. It is shown in the present paper that the assumption of constant radiative properties leads to a considerable discrepancy in predicted temperatures.

The successful landings on the moon of the Apollo flights along with the return of samples of the surface material have permitted the measurements of the thermophysical properties necessary for heat transfer calculations. These explorations have also proven what was previously hypothesized, that the lunar surface is covered to a depth of several meters or more, at least in the mare regions, with a layer of fine particulate soil or fines as it has been called. There is a hard substratum below these fines and there are many rocks and sometimes boulders scattered about as well. However, these occur randomly and may be considered perturbations in the porous powdery surface layer.

The particulate nature of the lunar surface complicates the problem as compared to the case of a solid surface. Considerations of energy transfer in an evacuated porous medium show that there will not only be conduction through the particles and their contact areas but also radiation which is scattered in the voids and also absorbed and reemitted by the particle surfaces.

The purpose of this paper is to present measured data on the thermophysical properties of the Apollo 12 fines sample. These are presented as a function of the relevant parameters that are important for the calculation of the temperature field in the surface layer at the Apollo 12 landing site. These properties are then introduced into the one-dimensional transient energy equation which is solved for the temperature as a function of depth and time during a lunar day. The results are compared with calculations for the Apollo 11 site which, however, are not as valid since the surface radiation properties were held for that analysis.

2. ANALYTICAL CONSIDERATIONS

2.1 *Energy equation*

The Apollo 12 Lunar Excursion Module landed in the Ocean of Storms at 3·2° south latitude and 23·4° west longitude [8]. The surface here is relatively flat and smooth but there is a cluster of craters ranging in diameter from 50 to 400 m in the neighborhood. These could possibly be associated with thermal anomalies, although none have yet been detected in this region. Consequently, one would not expect to find horizontal variations in temperature at this site.

Photographs of the Apollo 12 landing area [8] show that there are few rocks or boulders present. The regolith or surface layer is made up of particles which vary in size from the occasional centimeter sized rock on down to the submicron range. An analysis of the particle size distribution by Gold and co-workers [9] showed that the Apollo 12 sample is somewhat coarser than is the Apollo 11 sample. However, the sample contains particles with effective diameters down to below 0·1 μm which is the limit of measurement. It is apparent that the surface layer is primarily particulate in nature and that the particles are present in a random distribution of sizes. The heat transfer problem is then one involving an evacuated porous matrix.

The thermal energy transport problem for a porous evacuated medium is one involving both conduction and radiation heat transfer. These can be combined so that the total heat flux may be considered as an entity. Fourier's heat conduction law can then be used to describe the heat flux as long as it is recognized that the thermal conductivity so defined is an effective one rather than a basic property of the porous medium itself. Elementary theory [10–12] shows that the effective conductivity of such a medium is given by a constant plus a term proportional to the temperature cubed. Studies on lunar fines [6, 13] as well as on powdered terrestrial basalt [14], which is similar to the lunar fines, show that this temperature dependence describes the data quite well. These studies by Cremers [13] showed that below environmental pressures of about 10^{-3} torr, there is no effect of gaseous conduction or convection in the voids.

These considerations make it possible to establish a rather straightforward model for energy transfer in the lunar surface layer. Because of the excellent insulating qualities of evacuated rock powders, the depth to which there will be significant daily temperature variation is on the order of a meter whereas the moon's diameter is on the order of 3×10^6 m. Therefore, the heat flow can be considered as one dimensional in a cartesian coordinate system. The energy equation is then expressed as

$$\rho c(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right). \tag{1}$$

In equation (1) it is assumed that the specific heat is an explicit function of temperature as has been demonstrated for the Apollo 11 fines [15] and that the density is a constant with depth. The latter assumption is borne out by observations made by the Apollo 12 astronauts [8].

It is convenient to express equation (1) in terms of dimensionless variables. Because the problem is periodic, it is convenient to make the time dimensionless with the period of lunation P which is $2{\cdot}55143 \times 10^6$ seconds so that $\tau = t/P$. The length variable x is made dimensionless with the wavelength of the first fundamental wave of the constant property solution of equation (1). That is, $\xi = x/(4\pi\alpha^* P)^{\frac{1}{2}}$. Here α^* is the thermal diffusivity evaluated at the average lunar temperature, that is, the temperature far below the moon's surface. The dimensionless equation can then be expanded and written as

$$\frac{\partial T}{\partial \tau} = \frac{\alpha}{4\pi\alpha^*}\left[\frac{1}{k}\frac{dk}{dT}\left(\frac{\partial T}{\partial \xi}\right)^2 + \frac{\partial^2 T}{\partial \xi^2}\right] \tag{2}$$

where k and α are both functions of temperature.

2.2 *Boundary and temporal conditions*

There are several schools of thought regarding the thermal status of the moon in geological time. These can be grouped, for our purposes, into "cold" moon and "hot" moon theories. If the moon is "hot" then it is slowly cooling as is the earth and the maximum expected time average heat flux at the surface is only about 7×10^{-8} W/m^2 [16]. If it is cold, then it has long ago reached some time averaged steady state and is at some constant average temperature. In either case, then, it is obvious that the net flux from the surface over one solar day is negligible and so the spatial condition far below the surface where the periodic fluctuations are damped out is that the heat flux is zero. That is, for large values of ξ, $\partial T/\partial \xi = 0$.

The condition at the surface is expressed by a heat balance between the incoming solar radiation and the energy which is emitted to space plus that which is conducted into the surface layer. As the sun's angle with respect to the normal varies during the day the fraction of incoming radiation which is absorbed also changes. These conditions are written as

$$\xi = 0, I(\tau) = \varepsilon\sigma T_0^4 - k(T)\frac{\partial T}{\partial \xi}. \tag{3}$$

The insolation term $I(\tau)$ is

$$I(\tau) = S[1 - r(\tau)] \cos A \cos [\beta + 2\pi\tau] \quad (4)$$

during the half period of daytime and

$$I(\tau) = 0 \quad (5)$$

during the half period of nighttime. In equation (3), ε is the total hemispherical emittance which is a functional of temperature and in equation (4), $r(\tau)$ is the directional reflectance which will vary with the sun's angle of incidence and so it can be expressed as a function of the time variable τ. A is the latitude and β is longitude of the lunar site in question. S is the solar constant.

3. THERMOPHYSICAL PROPERTIES

The properties needed for solution of equation (2) subject to the above conditions have been measured in our laboratory. The samples used for the tests were Apollo 12 samples number 12001 and 12070 as cataloged by the Lunar Receiving Laboratory of the National Aeronautics and Space Administration, Houston, Texas. The density used was 1970 kg/m^3 which is the density obtained from analysis of the upper half of the core tube sample [8] and so should be close to the true surface-layer density at the Apollo 12 site. Only about 10 g of sample was made available for analysis and there is no record of how far below the surface it came from or how representative of the overall regolith it is.

3.1 *Thermal conductivity and diffusivity*

The thermal conductivity of sample 12001 for a density of 1970 kg/m^3 was measured over a temperature range of 104–425°K which corresponds approximately to the range of temperatures experienced on the moon. The method used was the line heat-source technique. The method and apparatus used are described in a previous paper [17]. In brief, this approach utilizes about 6 g of lunar material. The sample, with a fine wire imbedded in it, is allowed to come to an equilibrium temperature. Then the wire is heated slightly by a constant current and for a limited period of time the heat transfer from the wire to the medium is a good approximation to heat transfer from an infinitely long heat-source in a medium of infinite extent. The equation describing the time–temperature history of such a model can be solved for the thermal conductivity once the actual time-temperature history of the sample is known.

The data are shown in Fig. 1 along with a cubic least-squares curve fitted to the data in accordance with elementary theory as mentioned

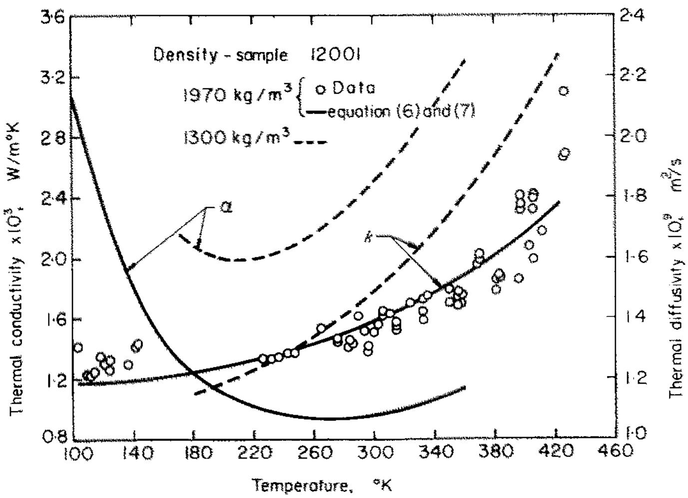

FIG. 1. Thermal conductivity and diffusivity of lunar fines.

previously. The curve is given by

$$k = 0{\cdot}115 \times 10^{-2} + 0{\cdot}159 \times 10^{-10}\, T^3 . \quad (6)$$

The units of k here are W/m°K. Other data for the same sample at a density of 1300 kg/m^3 are given in an earlier paper [18] and fitted curves are shown for comparison.

It has not yet been possible to measure the thermal diffusivity of the small evacuated samples with a sufficient degree of accuracy and reproducibility. Consequently, this property is calculated as $\alpha = k/\rho c$ for use in the present analysis. Therefore knowledge of the temperature dependent specific heat is also required.

There have not yet been any published measurements of the specific heat of the Apollo 12 fines. However, there are some data available for the Apollo 11 samples [15] and it is expected that for the Apollo 12 fines the specific heat will be much the same because of the chemical and mineralogical similarity of the samples [19]. The data in [15] were used on a point by point basis with the conductivity from the least squares curve in Fig. 1. A fourth degree polynomial was then fitted to the resultant diffusivities. As the specific heat was given in [15] only up to a temperature of 360°K, the curve was extrapolated to cover the full range of lunar temperatures. The diffusivity is also shown in Fig. 1 and it is given by

$$\alpha = 0{\cdot}586 \times 10^{-8} - 0{\cdot}610 \times 10^{-10}T + 0{\cdot}293 \times 10^{-12}T^2 - 0{\cdot}635 \times 10^{-15}T^3 \times 0{\cdot}531 \times 10^{-18}T^4 . \quad (7)$$

The units of α in equation (7) are m^2/s.

3.2 *Radiation properties*

It has been mentioned that the sample used for analysis was of undetermined origin in reference to the surface. That is, the sample was scooped up, placed in a bag and the sample used for the present analysis was taken from the bag. Consequently, there is no possibility of making surface property measurements on the actual lunar surface material. This is unfortunate because it has been noted [8] that there are distinct changes in sample coloring with depth. However, one might expect that these effects are most pronounced considered as functions of wavelength. The properties used in the present analysis are integrated over wavelength and so the uncertainties caused by sample mixing should not be severe and should give an average representation of the upper soil.

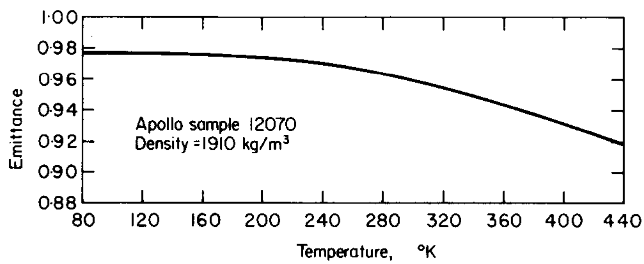

FIG. 2. Hemispherical emittance of lunar fines.

The total hemispherical emittance was calculated from measured spectral emittance values [20] and was found to vary with temperature. These results are presented in Fig. 2.

The directional reflectance of lunar fines in the visible region of the spectrum was obtained using the center-mounted sample integrating sphere reflectometer [33]. The reflectance is a function of wavelength and of the angle of incidence of the incoming radiation and the spectral reflectance of the Apollo 12 fines for an angle of incidence of 10° is shown in Fig. 3. The curve is a smooth fit through points recorded at 0·02 μm intervals. The total directional reflectance is obtained by multiplying the spectral reflectance on a point by point basis with the

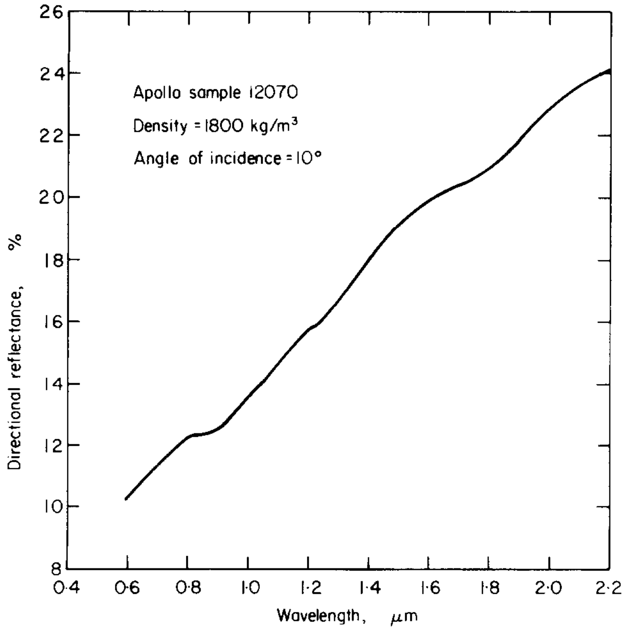

FIG. 3. Directional reflectance of lunar fines.

solar spectrum [21] integrating and dividing by the total solar input. Results for other angles of incidence show similar characteristics to those of Fig. 3. The angular distribution of the total solar directional reflectance is presented in Table 1. For the temperature calculations it was assumed that the reflectance went to unity at 90° as it does for all dielectrics.

Table 1. Solar reflectance of Apollo sample 12070

Angle of illumination (degrees)	Directional reflectance
10	0·120
20	0·126
30	0·131
45	0·138

The density used for the determination of the reflectance was 1800 kg/m^3 and for the emittance, 1910 kg/m^3, which is somewhat less than that used in the analysis (1970.kg/m^3). It was not possible to achieve densities greater than this without disturbing the surface of the sample in the holder. This should be of no consequence, however, because as shown by Birkebak *et al.* [22] there is no noticeable effect of density on the radiation properties above densities of 1600 kg/m^3.

4. RESULTS

Equation (2) was solved on the IBM 360–65 digital computer using a modified Runge–Kutta scheme. The results for the lunar surface and several depths below the surface are given in Fig. 4. The maximum temperature which occurs at lunar noon is 389°K and the minimum temperature which occurs at lunar sunrise is 86·1°K.

The only previously published analysis of lunar surface temperatures using actual properties of the lunar surface material did not take into account the directional characteristics of the reflectance. This is significant because if a constant reflectance is assumed, the surface immediately begins absorbing a given fraction

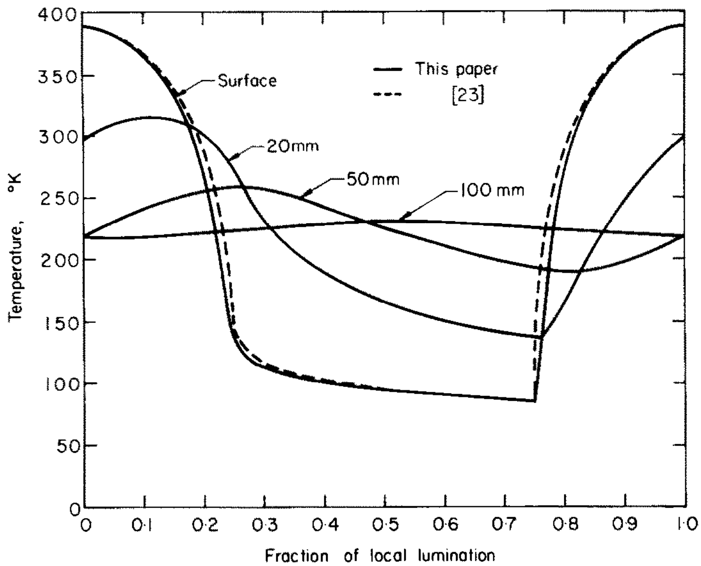

FIG. 4. Temperature variation of lunar surface layer during a lunation.

of radiation at sunrise and continues absorbing this fraction until sunset. In the real case, however, at grazing angles the reflectance is near unity and so there is no absorption. Inclusion of the directional dependence of the reflectance has the important effect of moderating changes between night and day temperatures in periods near sunset and sunrise. A comparison between temperatures from the present study and the results of an analysis in which the reflectance and emittance are held constant at mean values [23] is given in Table 2 and by the dashed line in Fig. 4. Note that at noon there is practically no difference because the sun is directly overhead and the normal reflectance was that used in the constant surface property analysis. The only difference then in the two calculations is in the emittance. The really significant differences in the two models are just before sunset and just after sunrise. The maximum differences occur at $\tau = 0{\cdot}24$ where the temperature is lower by 43·7°K in the variable property case and at $\tau = 0{\cdot}76$ when the temperature is lower by 64·1 K in the variable property case.

Table 2. Comparison of temperatures for case of variable surface properties with that of constant surface properties

τ	Temperatures (K) Variable $r(\tau)$, $\varepsilon(T)$	Temperatures (K) Constant r, ε [23]
0 (noon)	389·3	389·4
0·24	161·2	204·9
0·25 (sunset)	134·4	147·5
0·50 (midnight)	94·7	96·8
0·75 (sunrise)	86·1	87·8
0·76	125·4	189·5

The temperatures at the Apollo 12 site are compared with those calculated for the Apollo 11 site in Table 3. It should be reemphasized that there were no total directional reflectances or temperature dependent emittances available when the latter calculations were made and so constant radiative properties were assumed. The generally lower temperatures in the Apollo 12 case are due primarily to the lesser amount of energy calculated to be absorbed during the day. This difference is caused by taking the directional dependence of reflectance into account. The most significant differences occur again just before sunset and just after sunrise when the

Table 3. Comparison of measured and calculated lunar surface temperatures

Source	Noon (K)	Sunset (K)	Midnight (K)	Sunrise (K)
Apollo 11 [6]	395	152	101	92·9
Apollo 12 (this study)	389	134	95	86·1
Wesselink [24]	370	144	98	90
Jaeger [25]	368	178	97	89
Linsky [26]			98	89
Pettit and Nicholson [27]	374		120	
Sinton [28]	389	181	122	109
Saari [29]			104	
Low [30]				
Ingrao *et al.* [31]	393			
Stimpson and Lucas [32]	386–390	140–200	100–112	

constant surface property model deviates the most from the actual situation. The differences in conductivity and diffusivity become most apparent beneath the surface. The amplitude of the diurnal variation at depths of 20 and 50 mm is on the order of 20°K greater in the Apollo 11 case.

It is of historical interest to compare the present results with some prior calculations of lunar temperatures which were based on assumed properties. This is also done in Table 3. These calculations were usually made in terms of the thermal parameter defined as $\gamma = (k\rho c)^{-1/2}$. For the present study the value of γ based on the reference properties is $\gamma = 1025$. For comparison, temperatures calculated by Wesselink [24] ($\gamma = 119$), Jaeger [25] ($\gamma = 1000$), and Linsky [26] ($\gamma = 1000$) are shown. Wesselink and Jaeger assumed constant properties throughout and the numbers taken from Linsky were calculated for an assumed medium with temperature dependent specific heat and thermal conductivity.

Also shown in Table 3 are the results of remote measurements of lunar surface temperatures. These include measurements of infrared or microwave radiation during lunar nighttimes or during eclipses, from which temperatures are inferred, by Pettit and Nicholson [27], Sinton [28], Saari [29], Low [30], Ingrao *et al.*, [31], and Stimpson and Lucas [32]. In the latter paper several separate determinations are made of each temperature and the results are presented here as a range. Considering the assumptions

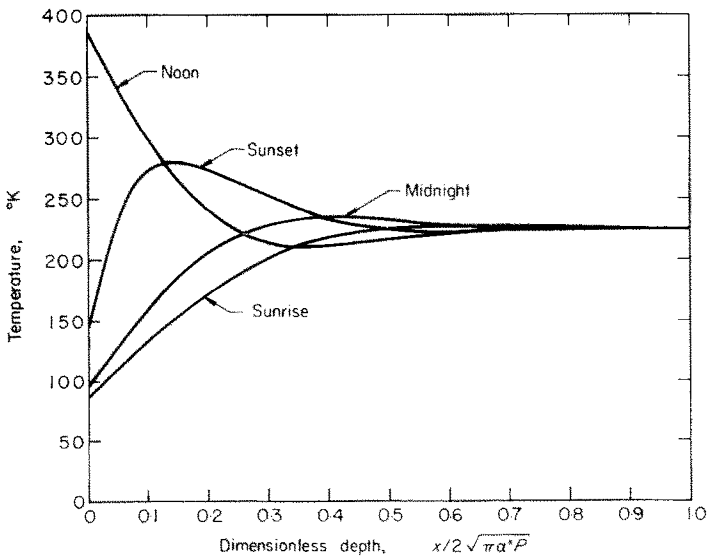

FIG. 5. Temperature variation with depth in surface layer.

required to deduce temperatures from the data and the wide area from which the measured radiation originates, the agreement is quite good.

Figure 5 shows the variation of temperature with depth for several times during the lunar day. It is seen that the temperature wave damps out rapidly with distance because of the excellent insulating characteristics of the lunar surface material. In both the Apollo 11 and 12 cases, the daily variation in temperature drops to about one degree at about $\xi = 0{\cdot}85$ which corresponds to a depth of $x = 0{\cdot}172$ mm. The steady temperature of the moon below this depth is 225°K. The reference diffusivity evaluated at this temperature is $\alpha^* = 0{\cdot}110 \times 10^{-8}$ m^2/s and the reference conductivity $k^* = 0{\cdot}135 \times 10^{-2}$W/m°K.

5. CONCLUSIONS

The thermophysical properties of the lunar fines returned from the Apollo 12 site have been determined as a function of the relevant parameters for conditions as they exist at the landing site. Utilization of these variable transport properties in the solution of the differential energy equation for the case of a lunation should give an accurate description of the daily temperature variation on the surface of the moon, or at least on the mare regions where the surface material, or regolith, is definitely powdered (rather than solid) rock. Comparison of these results with those of earlier studies shows that the various assumptions made previously (properties constant with temperature or direction) had significant effects on the predicted temperature at sunset and sunrise but the differences on the predicted peak, minimum and average temperatures were only a few degrees.

The temperature distribution presented in this report should be close to the true surface temperatures at the Apollo 12 site unless there are significant variations of density or composition within the first meter of depth. The results should apply to other mare regions on the lunar equator as well because it was found that the materials returned from the Apollo 11 and 12 flights did not differ significantly in properties that might effect heat transfer. Only when projecting the results to uplands regions should there be any difficulty. Here the larger number of rocks with their higher conductivities (by about a factor of 100) would make the present analysis less applicable.

In closing it should be mentioned that the radiative properties used in this paper are for a randomly procured sample. That is, there is no way that a true surface can be obtained and analyzed. The samples are scooped up by the astronauts and placed in bags where they become mixed. The core tube sample is sufficiently disturbed that the true surface is destroyed. This is unfortunate because studies on powdered terrestrial basalts which are similar chemically and mineralogically to the lunar fines show bleaching effects upon exposure to proton beams similar to the solar wind. However, these are spectral effects and one might find that the total reflectance, integrated over all wavelengths, would not be strongly affected.

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CARACTÉRISTIQUES THERMIQUES DE LA COUCHE SUPERFICIELLE LUNAIRE

Résumé—Les propriétés thermophysiques des poussières provenant du site d'alunissage d'Apollo 12 ont été déterminées pour dégager les paramètres utilisables. Ces propriétés comprennent la conductivité thermique, la diffusivité thermique, la réflectance et l'émittance directionnelles. La densité utilisée était la même que celle observée avec les échantillons prélevés et proche ainsi de la vraie densité de la couche superficielle du site Apollo 12. Les propriétés mesurées sont utilisées afin de calculer la variation de température diurne de la surface lunaire aussi bien qu'au-dessous de cette surface. La température superficielle maximale de 398°K est obtenue au midi lunaire tandis que la température minimale de 86.1°K est obtenue au lever du soleil. On montre que les effets les plus significatifs sur la température quand ils sont comparés avec les calculs antérieurs sont dus à l'utilisation de la réflectance directionnelle qui contrôle l'intensité de l'absorption d'énergie solaire durant le jour plutôt qu'à une réflectance hémisphérique constante. Les résultats sont comparés aux analyses et mesures précédentes.

THERMISCHE EIGENSCHAFTEN DER OBERFLÄCHENSCHICHT DES MONDES.

Zusammenfassung—Die thermophysikalischen Zustandsgrössen der Oberflächenschicht am Landeplatz von Apollo 12 sind als eine Funktion ihrer relevanten Parameter berechnet worden. Diese Zustandsgrössen sind die Wärmeleitfähigkeit, die Temperaturleitfähigkeit, die direkte Reflexionszahl und die Emissionszahl. Die dabei benützte Dichte war jene, die bei der zurückgebrachten Probe der Oberflächenschicht festgestellt wurde. Sie müsste möglichst nahe an den Wert der tatsächlichen Dichte der Oberflächenschicht am Landeplatz von Apollo 12 herankommen. Die gemessenen Zustandsgrössen wurden zur Berechnung der täglichen Temperaturschwankungen auf der Mondoberfläche, sowie der in verschiedenen Tiefen unterhalb der Oberfläche, verwendet. Die maximale Oberflächentemperatur von 389 K erhielt man am Mondmittag und die minimale Temperatur von 86,1 K bei Sonnenaufgang. Es wird gezeigt, dass die meisten charakteristischen Effekte des Temperaturverlaufs, verglichen mit früheren Berechnungen, durch die direkte Reflexion verursacht werden, die für den Betrag der solaren Energieabsorption während eines Tages an Orten konstanter hemisphärischer Reflexion ausschlaggebend ist. Die Ergebnisse wurden mit früheren Berechnungen und Fern-Messungen verglichen.

ТЕПЛОФИЗИЧЕСКИЕ ХАРАКТЕРИСТИКИ СЛОЯ ЛУННОЙ ПОВЕРХНОСТИ

Аннотация—В работе определялись теплофизиуеские характеристики (теплопроводность, температуропроводность, направленная отражательная способность и излучательная способность) сыпучего грунта, взятого на месте посадки Аполлона 12, в зависимости от соответствующих параметров. Использовались те же значения плотности грунта, что и у образцов, взятых ранее с помощью автоматически доставленных капсул, которая должна быть близкой к истинному значению плотности слоя поверхности в месте посадки Аполлона 12. Измеренные характеристики использовались для расчёта суточного изменения температуры поверхности Луны, а также темперытуры на некоторой глубине от поверхности.

Найдено, что максимальная температура поверхности в лунный полдень равна 389°К, а минимальная температура при восходе солнца равна 86°К. Показано, что температура изменяется наиболее значительно, если вместо ранее используемой в расчетах постоянной полусферической отражательной способности использовать направленную отражательную способность, определяющую количество поглащаемой в течение для солнецной энергии. Результаты сравниваются с предыдущими анализами и дистанционными измерениями.