# Lunar Surface Temperatures at Tranquillity Base

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**The diurnal temperatures in the lunar soil in the vicinity of Tranquillity Base are calculated from the one dimensional energy equation. The thermophysical properties used in the calculation are the experimentally determined ones which, in general, are temperature dependent. The temperature distributions are calculated over one lunation period for the surface and also several depths below the surface. Comparisons are made with temperatures determined by early investigators using assumed property values and also with values obtained by remote measurement.**

## Introduction

A NUMBER of investigators[1–5] have calculated lunar surface temperatures at the lunar equator using constant thermophysical properties obtained for an assumed medium. Others have suggested certain models for the temperature variation of the thermal conductivity and specific heat without making calculations of the actual temperature distribution. The most advanced work to date has been done using measured values of the thermophysical properties of an assumed medium.[6–9,11,12] The merit of these lies more in what they inferred about the moon than in temperatures themselves. The temperature distributions were compared with those obtained from Earth based microwave and infrared measurements. Excellent working models for the lunar surface layer were constructed from which thermal and mechanical calculations could be carried out.

Many previous papers[10,13–15] have reported direct, although remote, measurements from which the lunar surface temperature distribution was calculated. Photometric scans of the lunar disk during eclipses or lunar nighttimes were made through several infrared and microwave windows in the atmospheric absorption spectrum. All lunar radiation in the absence of sunlight is emitted radiation and so the temperature can be evaluated using the Planck distribution law. These measurements yield spatially integrated values of the lunar emission over areas on the order of 20–50 km in diameter. This can cause some difficulty in interpretation because of the existence of thermal anomalies on the moon caused either by density variations of the surface layer or significant local heat-flow from the lunar interior. The existence of these anomalies is well known and the effect of their presence is apparent on the emission scans made of the lunar surface.[14–16]

The only localized experimental determinations of the temperature of the lunar surface have been obtained through an ingenious application of the heat balance to spacecraft components.[17–21] The temperatures of two component panels of the Surveyor I, III, V, VI, and VII landing vehicles were obtained from data telemetered from the vehicles. These temperatures were then used in a heat balance involving conduction through components and radiation exchange between the panels and the lunar surface as well as with other components of the spacecraft. An error analysis on the calculations[21] showed that the nighttime temperatures were accurate to within 8°K while the daytime temperatures were good to within 12 to 40°K, depending on sun angle. The longest time period covered was about two thirds of a lunar day. This was done on the Surveyor V mission.

The Apollo 13 flight was the first mission to the moon which carried a probe for direct measurement of the temperature in the lunar surface layer.[22] The flight was aborted on the way to the moon because of a system malfunction and consequent failure.

The foregoing can be summarized as follows: there have been predictions of the lunar temperatures based on assumed models; there have been temperatures determined for the moon from remote measurements of the emitted radiation from large areas; and there have been lunar temperatures inferred from other temperature measurements over part of the lunar day. It is the object of this paper to present the results of calculations made of lunar temperatures at a particular point on the moon using the properties of the actual lunar soil as measured in the laboratory.

## Heat-Transfer Model

### Energy Equation

The Apollo 11 lunar module landed in the southwestern part of Mare Tranquillitatis at 0.67°N and 23.49°E (Ref. 23). The surface here is gently undulating and free of large gravity anomalies and craters and so the region should be free of thermal anomalies. These are suspected to be related to horizontal variations in surface or subsurface layer densities. The surface layer, or regolith, at Tranquillity Base is a layer of fragmental debris that ranges in thickness from about 3 to 6 m (Ref. 24). The particles are reported to have a mean grain size of 60 $\mu$m with 2% of the particles having a grain diameter less than 8 $\mu$m (Ref. 25). A separate sizing study[26] reports that the great majority of the particles are less than 10 $\mu$m in diameter, with many having diameters less than 1 $\mu$m. It is not clear whether the discrepancy is due to variations between the samples which were studied or to differences in the sizing techniques which were used. It is apparent, however, that the lunar surface layer is composed of a finely powdered material.

Energy transfer in a particulate medium in vacuum is by both thermal conduction and radiation. The conduction through the solid material depends on the contact between the particles while the radiation occurs primarily in the voids. There may be some small amount of transmission through the solid basaltic and glassy particles but one would expect the primary radiant transfer mechanisms to be scattering and also absorption and subsequent emission.

The complete problem of simultaneous radiation and conduction in the absence of convection is a difficult one to solve, and many approaches have been attempted, particularly in the study of glassy solids and radiating-absorbing gases.[27] The problems with particulate media are more severe and the

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Index categories: Liquid and Solid Thermophysical Properties; Thermal Surface Properties; Thermal Modeling and Experimental Thermal Simulation.

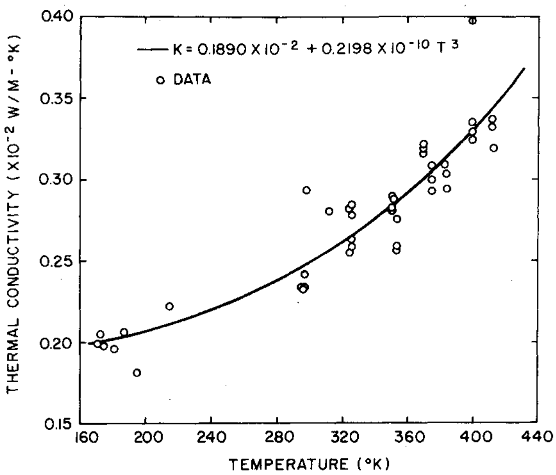


**Fig. 1 Thermal conductivity of lunar fines.**

assumption is usually made that the radiative effects can be explained in terms of a temperature gradient, similar to the Fourier conduction law, only with a coefficient which depends on the cube of the local temperature.[9,11,28,29] Experiments with finely powdered rock and also with glass beads have shown this approximation to be a good one.[9,30–32]

The assumption that both conductive and radiative heat fluxes in the particulate medium are functions of the temperature gradient allows one to write the heat flux density according to Fourier's law. The heat flux $q_x$ in the $x$ direction is given by

$$q_x \doteq -k(T)\partial T/\partial x \tag{1}$$

where the thermal conductivity $k(T)$ is only an effective one including radiative effects rather than a coefficient expressing a basic transport property of the medium. $T$ is the local temperature. The conductivity is given by the sum of a conductive term, assumed constant, and a radiative term assumed to be a function of temperature. That is

$$k(T) = k_c + k_r(T) \tag{2}$$

Any effects of interparticle contact resistance are assumed to be included in the conductive term $k_c$.

The energy equation can be expressed as

$$\partial/\partial x[k(T)\partial T/\partial x] = \rho c(T)\partial T/\partial T \tag{3}$$

The condition imposed on Eq. (3) at the lunar surface expresses a balance between the incoming radiation and the conduction plus emitted radiation. This can be written as

$$I(t) = \epsilon\sigma T_0^4 - k(T)(\partial T/\partial x)_{x=0} \tag{4}$$

Here $I(t)$ is the insolation and is given by

$$I(t) = S(1 - A)\cos\alpha\cos(\beta + 2\pi t/P) \tag{5}$$

during the half period of the daytime and by

$$I(t) = 0 \tag{6}$$

during the half period of the nighttime. $\epsilon$ is the hemispherical emittance, $\sigma$ is the Stefan-Boltzmann constant and $T_0$ is the instantaneous surface temperature. In Eq. (5), $S$ is the solar constant, $A$ is the hemispherical albedo, $\alpha$ is the lunar latitude, $\beta$ is the longitude, $t$ is the time, and $P$ is the lunation period.

The assumption is made, in solving Eq. (3) subject to Eq. (4), that the net heat flux from the moon during a lunation period is zero. This assumption is typical and is based on the fact that the maximum expected heat flux is only about $7 \times 10^{-8}$ w/m² (Ref. 22).

## Thermophysical Properties

### Thermal Conductivity

The thermal conductivity to be used in Eq. (3) is that measured for sample 10084,68,2 as cataloged by the Lunar Receiving Laboratory at the NASA Manned Spacecraft Center, Houston. It is assumed that the sample is representative of the lunar surface layer in the region around the Apollo 11 landing site. The material, being finely divided, is somewhat compressible in bulk. Consequently, the density is a parameter in measurement of the conductivity. The density used for this study was 1640 kg/m³ which is the average value for the two core tube samples taken by the astronauts.[33] This value for the density should be close to the actual value for the undisturbed lunar surface layer.

The thermal conductivity was measured over a range of temperatures from about 160°K to 400°K and the measurement technique is described elsewhere.[34] Measurements at lower temperatures are still in progress. The measurements were made on a limited amount of sample, occupying only about $5 \times 10^{-6}$ m³. The severe constraints placed on the experiment by the lack of generous amount of sample led to a data scatter of about ±7%. Some data at the density of 1640 kg/m³ are given in a previous paper.[34] Additional data have since been taken and, in total, the conductivity over the above temperature range is well approximated by a cubic least-squares fit given by

$$k = (0.189 \times 10^{-2} + 0.220 \times 10^{-10}\, T^3) w/m-°K \tag{7}$$

The data and the fitted curve are shown in Fig. 1. Note that the retention of all the data points has shifted the curve upwards at high temperatures over the position it might have if there were less scatter.

### Specific Heat

The specific heat used with Eq. (3) is taken from the work of Robie et al.[35] They measured this property for the same sample, 10084, as ours but for a different split (number not given). The temperature range was from 90 to 350°K. Over this range the specific heat increased by about a factor of three from a minimum of 0.0615 cal/g-°K. This is considerably lower than the values predicted for pre-Apollo 11 models.[8]

The thermal diffusivity can be calculated for the range of lunar temperatures by extrapolating the curve of the temperature dependent conductivity to 90°K and then evaluating $\alpha = k/\rho c$ on a point by point basis from Robie's data. As the latter were not reported for sufficiently high temperatures, the resulting diffusivity data were then fitted with a fourth degree polynomial and this was extrapolated to higher temperatures.

**Table 1 Comparison of temperatures for variable properties ($V$) with those for constant properties ($C$)**

| $\xi$ | 0.0 | | 0.1 | | 0.2 | | 0.3 | | 0.4 | | 0.5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Properties | $V$ | $C$ | $V$ | $C$ | $V$ | $C$ | $V$ | $C$ | $V$ | $C$ | $V$ | $C$ |
| $\tau = 0.0$ | 395 | 395 | 309 | 300 | 247 | 239 | 220 | 215 | 216 | 212 | 220 | 216 |
| 0.25 | 152 | 153 | 285 | 280 | 281 | 274 | 257 | 250 | 237 | 233 | 227 | 224 |
| 0.50 | 101 | 104 | 170 | 167 | 215 | 210 | 235 | 230 | 239 | 234 | 235 | 231 |
| 0.75 | 93 | 95 | 141 | 140 | 180 | 177 | 207 | 203 | 222 | 218 | 228 | 224 |

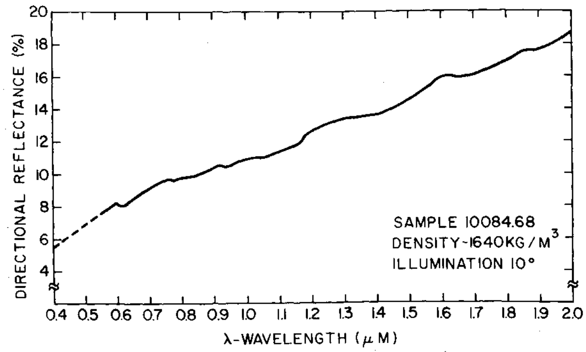


**Fig. 2 Lunation temperatures.**

### Albedo

The albedo used in Eq. (5) is that obtained for sample 10084,68. The measurements of the directional reflectance from which the albedo was obtained were made for the sample exposed to both atmospheric pressure and pressures below $10^{-6}$ torr. No significant differences were noted between these sets of test results and therefore, for ease of measurement, most runs were made under atmospheric conditions. The measurement technique as well as the reflectance of sample 10084,68 at a lower density is presented elsewhere.[36]

The directional reflectance of the lunar fines measured for an angle of viewing of 10° is presented in Fig. 2. The curve is a smooth fit through data points taken at 0.02 $\mu$m. The albedo, calculated using the standard solar spectrum[37] along with the present measurements and others,[38] is 0.10 ± 0.01. Results for other angles of viewing[36] show similar behavior characteristic of a dielectric surface. The albedo as a function of illumination angle also shows these general characteristics.

### Total Normal Emittance

The total normal emittance of the lunar fines was obtained over a temperature range of 270°K to 370°K. The apparatus used to obtain these results is similar to a basic instrument described previously.[39] This was modified to be used with lunar fines and a complete description of the modified apparatus is found elsewhere.[40] The results of these measurements gave an emittance of 0.90 ± 0.02.

### Results and Discussion

The energy equation, Eq. (3), was solved in terms of dimensionless independent variables (see Appendix). The time was made dimensionless by the period $P$ of the lunar diurnal-cycle. The distance from the surface was made dimensionless with the wavelength of the first fundamental wave of the constant property solution. These are given by

$$\tau = t/P, \ \xi = x/2(\pi\alpha^* P)^{1/2}$$

where $\alpha^*$ is the diffusivity evaluated at the average lunar temperature, that is, the temperature far beneath the lunar surface. In terms of the scaling parameters, then, $x = 0.262$ m and $t = 2.55143 \times 10^6 \ \tau$ sec. Equation (3) was valued numerically on the IBM 360-65 computer. The left-hand side was cast in finite difference form and the time derivative solved for explicitly. The system of equations which resulted was solved using a Runge-Kutta integration scheme. The diurnal temperature variation at the surface and also several depths below the surface is given in Fig. 3. It is seen that the surface temperature at Tranquillity Base varies between a maximum of 395.3°K at noon to a minimum of 92.9°K at sunrise. Some surface temperatures for the constant property case are also shown in Fig. 3. The worst deviation from the measured variable property case occurs where the temperature is changing most rapidly with time, that is, in the lunar afternoon and again in the morning.

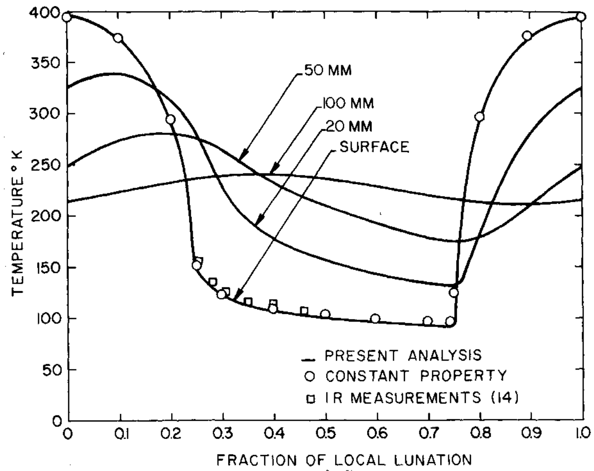


**Fig. 3 Thermal diffusivity of lunar fines.**

The accuracy attained by carrying out the calculations assuming constant values of the thermal conductivity and diffusivity is not particularly good except perhaps at the surface. However, one should anticipate this judgment when faced with such severe variations of the thermophysical properties with temperature as are evident in Figs. 1 and 4. Some actual values illustrating the difference between the real property results and those obtained for a constant property assumption are given in Table 1. Here the temperatures for the real problem are compared with the temperatures for the assumed constant property case. The properties for the latter are given by

$$\bar{k} = \frac{1}{T_{\max} - T_{\min}} \int_{T_{\min}}^{T_{\max}} k(T)dT \tag{8a}$$

and

$$\bar{\alpha} = \frac{1}{T_{\max} - T_{\min}} \int_{T_{\min}}^{T_{\max}} \alpha(T)dT \tag{8b}$$

The maximum and minimum temperatures are taken from variable property solutions. $k(T)$ is given by Eq. (7) and $\alpha(T)$ is given by a fourth degree polynomial fitted to the data shown in Fig. 4. The calculations yield $\bar{k} = 0.234 \times 10^{-2}$ w/m-°K and $\bar{\alpha} = 0.229 \times 10^{-8}$m²/sec.

A constant property analysis as done in the classical sense[1,2] reveals the so-called thermal parameter $\gamma = (k\rho c)^{-1/2}$ to be of importance. In terms of the conductivity and diffusivity this may be written $\gamma = \alpha^{1/2}/k$. If an average value of the thermal parameter is calculated using average values of the constituent properties just given, there results

$$\bar{\gamma} = 0.0204 \text{ m}^2 - {}^\circ\text{K/w-sec}^{1/2}$$

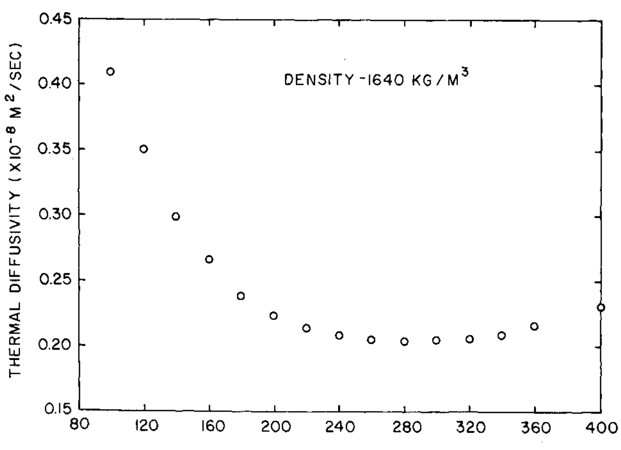


**Fig. 4 Reflectance of lunar fines.**

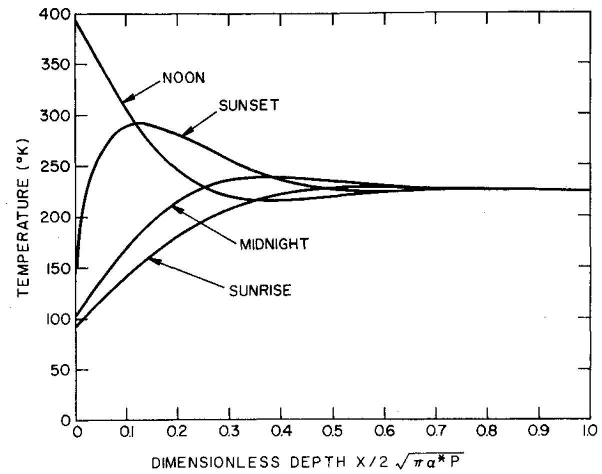


**Fig. 5 Temperature in surface layer.**

or

$$\bar{\gamma} = 856 \text{ cm}^2 - {}^\circ\text{K-sec}^{1/2}/\text{cal}$$

Several previous authors have predicted a value for the thermal parameter near this value.[14,21]

There have been a number of experiments reported in the literature in which the lunar brightness-temperature is determined from infrared or microwave-radiation measurements. The actual temperature can then be estimated by assuming a value for the monochromatic emittance of the lunar surface at the wavelength in question. A number of these temperatures are compared with the results of the present analysis in Table 2. Numerous scans of the dark lunar disc made at 20 $\mu$ indicated that the nighttime temperature of the moon varied between 70°K and 150°K depending on location.[15] This wide variation was explained as being caused by thermal anomalies on the lunar surface. These probably occur because of variations in the surface layer density caused either by inhomogenieties in the moon itself or by buried meteorites.

It is difficult to assess the information in Table 2. Perhaps the most gratifying aspect of the table is the general agreement on the noon temperature while the most disquieting aspect is the lack of agreement on the midnight temperature. However, there is a possibility of significantly varying nighttime surface temperatures because the problem is conduction dominated. These are caused by the varying surface-layer properties from one site to another (thermal anomalies). So, not too much should be made of these differences because they may represent real variations in the lunar surface temperature. These variations are not so noticeable at noon when the problem is radiation dominated.

The temperatures in the lunar surface layer are given as a function of depth for several times during the lunation period in Fig. 5 and some values are also given in Table 1. It may be seen that the diurnal temperature variation is damped out to be less than 1% of the average temperature at about $\xi = 0.75$ or $x = 0.196$ m. This explains the success of many of the early models wherein a depth of powdered material much less than that extant was postulated. It makes little difference if the lunar surface layer is 4 to 0.04 m thick.

It is apparent that the daytime surface temperatures are dependent on the radiation properties for such an excellent insulating material. Table 3 gives the temperatures calculated with various combinations of the expected extreme values for our radiation experiment. This gives some indication of the accuracy of the results as they depend on the emittance and albedo. It is interesting to note that there is very little effect from using extreme values of the radiation properties. This was predicted by Jaeger.[3]

**Table 2 Comparison of calculated temperatures with remotely measured values**

| Noon | Midnight | Source |
|---|---|---|
| 395 | 101 | Calculated, variable prop. |
| 395 | 104 | Calculated, constant prop. |
| 389 | 122 | Sinton[4] |
| 391 | 120 | Pettit, Nicholson[13] |
| 395 | | Ingrao et al.[41] |
| | 90 | Low[15] |
| 391 | 112 | Stimpson, Lucas[21] |
| | 104 | Saari[42] |

## Appendix

The energy equation in dimensionless time and space coordinates is expressed as

$$\partial T/\partial t = (\alpha/4\pi\alpha^*)[(1/k)(dk/dT)(\partial T/\partial \xi)^2 + \partial^2 T/\partial \xi^2]$$

Conductivity $k$ is represented by $A + BT^3$ and the diffusivity $\alpha$ is represented by a fourth degree least squares polynomial which gives an excellent fit through the values shown in Fig. 4.

The partial differential equation is approximated by expressing time partial derivatives by ordinary derivatives and spatial partial derivatives by finite differences. The resulting system of ordinary differential equations is solved by a fourth order Runge-Kutta integration scheme.[43] The integration scheme used for this paper is a library subroutine.[44]

Spatial nodes are given by

$$\xi = (j + \tfrac{1}{2})\Delta\xi \qquad j = 1, 2, \ldots n$$

At interior nodes the energy equation is expressed as

$$\frac{dT_j}{d\tau} = \frac{\alpha(T_j)}{4\pi\alpha^*}\left[\frac{1}{k}\frac{dk}{dT}\left(\frac{T_{j+1} - T_{j-1}}{2\Delta\xi}\right)^2 + \frac{T_{j+1} - 2T_j + T_{j-1}}{\Delta\xi^2}\right]$$

$$j = 2, 3, \ldots n - 1$$

The surface temperature $T_0$ is found by iteratively solving Eq. (4) expressed in finite-difference form. That is

$$\epsilon\sigma T_0^4 = I(\tau) + k[(9T_1 - T_2 - 8T_0)/3\Delta\xi]$$

An energy balance on the first interior node is expressed as

$$\frac{dT_1}{d\tau} = \frac{P\alpha(T_1)}{2\Delta\xi(\pi\alpha P)^{1/2*}}\left(\frac{I(\tau) - \epsilon\sigma T_0^4}{k} + \frac{T_2 - T_1}{2\Delta\xi(\pi\alpha)^{1/2*}P}\right)$$

The temperature at the deepest interior node is represented as

$$\frac{dT_n}{d\tau} = \frac{\alpha(T_n)}{4\pi\alpha^*}\left[\frac{1}{k}\frac{dk}{dT}\left(\frac{T_n - T_{n-1}}{\Delta\xi}\right)^2 + \frac{T_n + T_{n-2} - 2T_{n-1}}{\Delta\xi^2}\right]$$

Solution of this system is started with an assumed initial temperature distribution. Computations proceed until the temperature distribution becomes periodic in time. Because of the nonlinearities introduced by thermally dependent transport properties the stability of this method is not known. Solutions are therefore checked for stability by variation of step size and the number of nodal points. Computation by this method is slow but not excessively so and has the attractive features of flexibility and ease of programing.

**Table 3 Surface temperatures for the average and extreme values of the radiation properties**

| | | | | | |
|---|---|---|---|---|---|
| $\epsilon$ | 0.90 | 0.88 | 0.88 | 0.92 | 0.92 |
| A | 0.10 | 0.11 | 0.09 | 0.11 | 0.09 |
| $\tau = 0.00$ | 395 | 396 | 399 | 392 | 394 |
| 0.25 | 152 | 153 | 153 | 150 | 151 |
| 0.50 | 101 | 102 | 102 | 100 | 101 |
| 0.75 | 93 | 93 | 93 | 92 | 92 |

## References


[1] Wesselink, A. J., "Heat Conductivity and Nature of the Lunar Surface Material," *Bulletin of the Astronomical Institute of the Netherlands*, Vol. X, April 1948, pp. 351–363.

[2] Jaeger, J. C., "Conduction of Heat in a Solid with Periodic Boundary Conditions, with an Application to the Surface Temperature of the Moon," *Proceedings of the Cambridge Philosophical Society*, Vol. 49, April 1953, pp. 355–359.

[3] Jaeger, J. C., "The Surface Temperature of the Moon," *Australian Journal of Physics*, Vol. A6, March 1953, pp. 10–21.

[4] Sinton, W. M., "Temperatures on the Lunar Surface," Chap. 11, *Physics and Astronomy of the Moon*, edited by Z. Kopal, Academic Press, New York, 1962, pp. 407–428.

[5] Muncey, R. W., "Calculations of Lunar Temperatures," *Nature*, Vol. 181, May 1958, pp. 1458–1459.

[6] Reichman, J., "Dependence of the Surface Temperature of the Moon on Particle Size and Porosity," AIAA Paper 68-746, Los Angeles, Calif., 1968.

[7] Halajian, J. D. and Reichman, J., "Correlation of Mechanical and Thermal Properties of the Lunar Surface," *Icarus*, Vol. 10, Oct. 1969, pp. 179–196.

[8] Winter, D. F. and Saari, J. M., "A Particulate Thermophysical Model of the Lunar Soil," *The Astrophysical Journal*, Vol. 156, June 1969, pp. 1135–1151.

[9] Watson, K, *I*. The Thermal Conductivity Measurements of Selected Silicate Powders in Vacuum from 150°–350°K; II. An Interpretation of the Moon's Eclipse and Lunation Cooling as Observed through the Earth's Atmosphere from 8–14 Microns, Ph.D. thesis, 1964, California Inst. of Technology, Pasadena, Calif.

[10] Earl of Rosse, "On the Radiation of Heat from the Moon," *Proceedings of the Royal Society (London)*, Vol. 17, March 1869, pp. 436–443.

[11] Linsky, J. L., "Models of the Lunar Surface Including Temperature-Dependent Thermal Properties," *Icarus*, Vol. 5, Nov. 1966, pp 606–634.

[12] Ulrichs, J. and Campbell, M. J., "Radiative Heat Transfer in Lunar and Mercurian Surface," *Icarus*, Vol. 11, Sept. 1969, pp. 180–188.

[13] Pettit, E. and Nicholson, S. B., "Lunar Radiation and Temperature," *The Astrophysical Journal*, Vol. 71, Jan. 1930, pp. 102–135.

[14] Murray, B. C. and Wildey, R. L., "Surface Temperature Variations During the Lunar Nighttime," *The Astrophysical Journal*, Vol. 139, Feb. 1964, pp. 734–750.

[15] Low, F. J., "Lunar Nighttime Temperatures Measured at 20 Microns," *Astrophysical Journal*, Vol. 192, Feb. 1965, pp. 806–808.

[16] Shorthill, R. W. and Saari, J. M., "Non-uniform Cooling of the Eclipsed Moon: a Listing of Thirty Prominent Anomalies," *Science*, Vol. 150, Oct. 1965, pp. 210–212.

[17] Lucas, J. W., Conel, J. E., and Hagemeyer, W. A., "Lunar Surface Thermal Characteristics from Surveyor I," *Journal of Geophysical Research*, Vol. 72, Jan. 1967, pp. 779–789.

[18] Vitkus, G., Lucas, J. W., and Saari, J. M., "Lunar Surface Thermal Characteristics during Eclipse from Surveyors III, V and after Sunset from Surveyor V," AIAA Paper 68-747, Los Angeles, Calif., 1968.

[19] Vitkus, G., Garipay, R. R., Hagemeyer, W. A., Lucas, J. W., and Saari, J. M., "Lunar Surface Temperatures and Thermal Characteristics," *Surveyor VI A Preliminary Report*, NASA SP-166, 1968, pp. 97–106.

[20] Vitkus, G., Garipay, R. R., Hagemeyer, W. A., Lucas, J. W., Jones, B. P., and Saari, J. M., "Lunar Surface Temperatures and Thermal Characteristics," *Surveyor VII A Preliminary Report*, NASA SP-173, 1968, pp. 163–180.

[21] Stimpson, L. D. and Lucas, J. W., "Revised Lunar Surface Thermal Characteristics Obtained from the Surveyor V Spacecraft," AIAA Paper 69-594, San Francisco, Calif., 1969.

[22] Langseth, M. G., Jr., Wechsler, A. E., Drake, E. M., Simmons, G., Clark, S. P., Jr., and Chute, J. Jr., "Apollo 13 Lunar Heat Flow Experiment," *Science*, Vol. 168, April 1970, pp. 211–217.

[23] Schmitt, H. H., Lofgren, G., Swann, G. A., and Simmons, G., "The Apollo 11 Samples: Introduction," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 1, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 348–361.

[24] Shoemaker, E. M., Hait, M. H., Swann, G. A., Schleicher, D. L., Dahlem, D. H., Schaber, G. G., and Sutton, R. L., "Lunar Regolith at Tranquillity Base," *Science*, Vol. 167, Jan. 1970, pp. 452–455.

[25] Duke, M. B., Woo, C. C., Sellers, G. A., Bird, M. L., and Finkelvan, R. D., "Genesis of Lunar Soil at Tranquillity Base," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 1, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 348–361.

[26] Gold, T., Campbell, M. J., and O'Leary, B. T., "Optical and High-Frequency Electrical Properties of the Lunar Sample," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 3, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 2149, 2154.

[27] Sparrow, E. M. and Cess, R. D., *Radiation Heat Transfer*, Brooks/Cole, Belmont, Calif., 1966, pp. 249, 265.

[28] Clegg, P. E., Bastin, J. A., and Gear, A. E., "Heat Transfer in Lunar Rock," *Monthly Notices of the Royal Astronomical Society*, Vol. 133, Jan. 1966, pp. 63–66.

[29] Wildey, R. L., "On the Treatment of Radiative Transfer in the Lunar Diurnal Heat Flow," *Journal of Geophysical Research*, Vol. 72, Sept. 1967, pp. 4765–4767.

[30] Merrill, R. B., "Thermal Conduction through an Evacuated Idealized Powder over the Temperature Range of 100° to 500°K," TND-5063, 1969, NASA.

[31] Wechsler, A. E. and Simon, I., "Thermal Conductivity and Dielectric Constant of Silicate Materials," CR NAS8-20076, 1966, A. D. Little, Cambridge, Mass.

[32] Fountain, J. A. and West, E. A., "Thermal Conductivity of Particulate Basalt as a Function of Density in Simulated Lunar and Martian Environments," *Journal of Geophysical Research*, July 1970, pp. 4063–4069.

[33] Fryxell, R., Anderson, D., Carrier, D., Greenwood, W. G., and Heiken, G. H., "Apollo 11 Drive-Tube Core Samples: An Initial Physical Analysis of Lunar Surface Sediment," *Science*, Vol. 167, Jan. 1970, pp. 734–737.

[34] Cremers, C. J., "Thermal Conductivity of Lunar Fines from Apollo 11," *Proceedings of the Fifth Symposium on Thermophysical Properties*, American Society of Mechanical Engineers, New York, 1970, pp. 391–395.

[35] Robie, R. A., Hemingway, B. S., and Wilson, W. H., "Specific Heats of Lunar Surface Material from 90° to 350°K," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 3, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 2361–2367.

[36] Birkebak, R. C., Cremers, C. J., and Dawson, J. P., "Directional Spectral and Total Reflectance of Lunar Material," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 3, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 1993–2000.

[37] Johnson, F. S., "The Solar Constant," *Journal of Meteorology*, Vol. 11, Dec. 1959, pp. 431–439.

[38] Adams, J. B. and McCord, T. B., "Remote Sensing of Lunar Surface Mineralogy: Implications from Visible and Near-Infrared Reflectivity of Apollo 11 Samples," *Proceedings of the Apollo 11 Lunar Science Conference*, Vol. 3, edited by A. A. Levinson, Pergamon Press, New York, 1970, pp. 1937–1945.

[39] Birkebak, R. C., Hartnett, J. P., and Eckert, E. R. G., "Measurement of Radiation Properties of Solid Materials," *Progress in International Research on Thermodynamics and Transport Properties*, edited by J. Masi and D. Tsai, Academic Press, New York, 1962, pp. 563–574.

[40] "Thermophysical Properties Measurements of Lunar Soils," TR-2, 1971, High Temperature and Thermal Radiation Lab., Univ. of Kentucky, Lexington, Ky.

[41] Ingrao, H. C., Young, A. T., and Linsky, J. L., "A Critical Analysis of Lunar Temperature Measurements in the Infrared," *The Nature of the Lunar Surface*, edited by W. N. Hess, D. H. Menzel, and J. A. O'Keefe, Johns Hopkins Press, Baltimore, 1966, pp. 185–211.

[42] Saari, J. M., "The Surface Temperature of the Antisolar Point of the Moon," *Icarus*, Vol. 3, July 1964, pp. 161–163.

[43] Fehlberg, I., "Low-Order Classical Runge-Kutta Formulas with Stepsize Control and their Application to some Heat Transfer Problems," TR-315, 1969, NASA.

[44] System/360 Scientific Subroutine Package (360A-CM-03X) Version III, Programmer's Manual, 4th ed., 1968, IBM Technical Publication Dept., White Plains, N. Y., pp. 333–336.