

Calculations of the Moon's Thermal History At Different Concentrations of Radioactive Elements, Taking Into Account Differentiation on Melting

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Calculations of the thermal history of the moon were carried out by solving the thermal conductivity equation for the case in which the heat sources are the long-lived radioactive elements Th, U, and K⁴⁰. The concentrations of these elements were adjusted to give four variations of the heat flow: 1.35×10^{-8} and 0.91×10^{-8} cal cm⁻² s⁻¹ (I and I**), 0.61×10^{-8} (variant II, the terrestrial mixture of Lyubimova and Starkova), and 0.236×10^{-8} (variant III, the chondrite model of Urey and MacDonald). In the same calculations, we considered layering of the differentiated material with transport to the surface of the radioactive elements after the temperature of the layer rose to 200 K above the melting temperature, which is considered in five variants that differ in the amount of transported radioactive elements: 100 percent ($n = 1$), 80 percent ($n = 0.8$), 40 percent, 20 percent ($n = 0.6, 0.4, 0.2$). During fusion the heat capacity and heat conductivity were changed.

We considered two variants of an initially cold (273 K) and hot (900 K) Moon. Calculations show that the interior of the Moon was heated to melting during the first 0.7 to 2.3×10^9 years. The maximum fusion involved practically the entire Moon to a distance from 15 to 45 km beneath the surface, and started 3.5 to 4.0×10^9 years ago (I, I**), or 2.5 to 3.0×10^9 years ago (II, III) and continued for 1 to 2×10^9 years. Today the Moon is cooling. The current thickness of the solid crust is from 150 to 200 km and the heat flow exceeds the stationary value 1.5 fold. Apparently the most realistic variant is II (terrestrial mixture) for an initially hot Moon, and gives, regardless of the moderate concentration of radioactive elements, a heat flow of 0.9 to 0.95×10^{-8} cal cm⁻² s⁻¹, which agrees with the radioastronomical measurements of Troitsky and Krotikov and with the Apollo 15 data.

Papers by Urey, MacDonald, Lubimova, Levin, Mayeva, Fricker, Reynolds and Summers, Iriyama and Shimazu, Anderson and Phinney, Hanks and Anderson, MacConnel, Toksöz and Solomon, et al. (refs. 1-21) investigated the Moon's thermal history by solving the heat conductivity equation with given values for the parameters of lunar material and for the initial and boundary conditions, and with radioactive elements with the given concentrations as the heat sources. Our papers (refs. 21 and 22) are devoted to the same problem. Up to 1966-1967, homogeneous and layered lunar models were con-

sidered separately. In 1966-1967 we took into account in the calculations the differentiation of lunar material and convection of radioactive elements to the surface on melting. Working independently, P. Fricker, R. Reynolds, and A. Sommers conducted similar studies. The consideration of continuous differentiation in the calculation permits one to investigate the Moon's thermal history in more detail. In 1971 differentiation was also taken into account by Mayeva (ref. 13) and in 1973 by Toksöz and Solomon (ref. 21).

Thus, at the present time computer calculation schemes of lunar thermal history are

sufficiently fully developed and many new results have been obtained. However, interest in this problem has not yet decreased, but rather has increased. This is associated with the large uncertainty in the lunar parameters that enter into the heat conductivity equation. This applies also to the uncertainty in the values for density, heat capacity, and heat conductivity, and their dependence on the state of lunar material (for example, during melting). Also involved is uncertainty in the melting curve and the initial conditions (in particular, the initial temperature) and in the Moon's age. However, the determining factor in the Moon's thermal history is the accepted concentration of radioactive elements in the Moon and their redistribution with time in the lunar interior.

In the above papers, except for references 22 and 23, the concentration of radioactive elements is taken to be that of chondritic meteorites (for example, references 1-5, or of the Earth (refs. 7-13), or of a "terrestrial mixture," that lead to values of the heat flux through the lunar surface on the order of $(0.3 \text{ to } 0.6) \times 10^{-6} \text{ cal cm}^{-2} \text{ s}^{-1}$. At the same time radio astronomical investigations by V. S. Troitsky and V. D. Krotikov (refs. 24 and 25) give a flux value equal to 0.85 to $0.95 \times 10^{-6} \text{ cal cm}^{-2} \text{ s}^{-1}$ which was long considered to be rather doubtful but was confirmed by the recent analyses of the lunar regolith by Apollo 15 (ref. 26). As a result, it is necessary to calculate the Moon's thermal history for concentrations of the radioactive elements that may account for such a large heat flux.

The first attempt at this calculation was made in our papers in 1966-1967 (refs. 22 and 23) where we used four variants of the concentration of radioactive elements, two of which correspond to concentrations used by Levin and Mayeva (ref. 8) (variant "C" uses the mean terrestrial value of Urey and MacDonald). The other two use relatively large concentrations which give heat flux values close to the radio astronomical values. An exponential differentiation of radioactive elements was assumed to occur on melting. Since the large concentration of ra-

dioactive elements was close to the surface of the Moon (in 10-20 km they weakly influence the temperature of the main lunar mass, which quickly cooled). As a result, the thickness of the solid crust in these variants was equal to 600-700 km, i.e., larger than for the mean (Levin) and the low (Urey, MacDonald) concentrations where the thickness was 250 km and 400 km.

In our studies (refs. 21 and 22), we used the exponential model for transport of the radioactive elements to the surface on differentiation which corresponds in some degree to the so-called "sudden differentiation." This model permits one to determine the main physical peculiarities of the thermal history related to differentiation; yet it limits the number of variable parameters. In this respect, the layered differentiation proposed by Fricker et al. (ref. 14) appears to be closer to the real processes. Therefore, in the present paper we have used a layered differentiation of radioactive elements on melting with different portions of the elements (from 20 percent up to 100 percent) transported from layer to layer. The concentration variants of radioactive elements were the same as in our 1966-1967 papers (refs. 22 and 23).

It should be noted that we are not specialists in geophysics and have no right to discuss questions of the Moon's origin and its chemical composition. For this reason, for calculations we have taken parameters either from the expected values of the heat flux (at given concentrations of radioactive elements) or from papers by other authors. Thus, the initial temperatures (273 K and 900 K) were taken on the basis of references 14 and 16, and the heat capacity on the basis of the papers by Mayeva (refs. 11 and 12), where a sharp change in the heat capacity at the time of melting is considered. Remarks by Lubimova (ref. 6) are taken into account on the possibility of the flux increasing at moderate concentrations of radioactive elements by means of the contribution from the exciton component of the heat conductivity and from amplification of the efficiency of the radiational component.

$$C[T, r(T)] = \begin{cases} C_0 = 0.25 \frac{\text{cal}}{\text{g}^\circ \text{K}}, & \text{at } T \leq T_{\text{in.m.}} \text{ and } T \geq T_{\text{in.m.}} + \Delta T, \\ C_0 + \frac{4L}{(\Delta T)^2} (T - T_{\text{in.m.}}) & \text{at } T, T_{\text{in.m.}} < T < T_{\text{in.m.}} + \Delta T/2, \\ C_0 - \frac{4L}{(\Delta T)^2} (T - T_{\text{in.m.}}) + \frac{4L}{\Delta T} & \text{at } (T_{\text{in.m.}} + \frac{\Delta T}{2}) < T < T_{\text{in.m.}} + \Delta T \end{cases} \quad (1)$$

$$f(T) = A/T; A = 10.3 \times 10^7 \frac{\text{cal.}}{\text{cm year}}, \text{ at } T \leq T_{\text{in.m.}} \text{ and } T \geq T_{\text{in.m.}} + \Delta T;$$

$$f(T) = 0.04 \times 10^7 \frac{\text{cal}}{\text{cm year}} = \text{const, at } T_{\text{in.m.}} < T < (T_{\text{in.m.}} + \Delta T).$$

Consideration is given to the considerable idealization, primarily of the layering process, and therefore, the results obtained are correct only within the limits of our mathematical model.

Statement of the Problem

As is the custom, the Moon is assumed to be a sphere with the radius $r = 1735$ km, of homogeneous density $\rho = 3.34$ g/cm³, with heat capacity C and the heat conductivity K , defined according to Lubimova (ref. 6) (heat conductivity) and Mayeva (refs. 11 and 12) (heat capacity) as follows.

The heat capacity is shown in equation (1). $L = 100$ cal/g is the heat of fusion; $\Delta T = 200$ K;

$r =$ in cm, $T =$ in K.

$T_{\text{init. melt}} = 1373 + 500 (1 - r^2/r_0^2)$ is the beginning of melting of the silicate material (ref. 3).

Expression (1) considers the gradual absorption of the heat of fusion in the melting interval ΔT (the effective heat capacity in the interval ΔT first increases linearly and then decreases).

The heat conductivity is given by the expression:

$$K = f(T) + \frac{16n^2\delta T^3}{3\epsilon} e^{-\frac{E}{kT}} \quad (2)$$

In (2) the lattice (phonon), radiational (photon) and exciton components of the heat conductivity (ref. 6) are taken into account.

Phonon heat conductivity outside the melting interval varies in inverse proportion to the temperature; during melting it sharply increases (see ref. 27) and remains constant as shown in the equation above.

Photon and exciton components of the heat conductivity are defined by the well-known relations where $n^2 = 3$ is the refractive index, $\delta = 4.27 \times 10^{-5}$ cal/cm² grad⁴ year is the Stephan-Boltzmann constant, $\epsilon = 25$ cm⁻¹ is the absorption coefficient of the material, and $E = 5.17 \times 10^{-20}$ cal is the activation¹ energy of excitons.

For the assumption of a homogeneous distribution of heat sources and location of the initial coordinate in the center of the sphere, the heat conductivity equation has the form:

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(K r^2 \frac{\partial T}{\partial r} \right) + H, \quad (3)$$

where H is the heat due to the long-lived radioactive elements uranium, thorium, and potassium 40.

$$H = \sum_{j=1}^3 H_j; e^{-\lambda_j t} F(r, t) \rho \alpha_j, \quad (4)$$

where the function $F(r, t)$ defines the distribution of radioactive elements as a function of the radius at different times. Indexes $j = 1, 2, 3$ refer to uranium, thorium, and potassium.

¹The values are taken for pyrolite (a mixture of basalt and peridotite) lunar composition, which is similar to the Earth's mantle (see ref. 28).

Table 1.—*The U, Th, and K Concentrations in Several Variants of the Bulk Lunar Composition and the Stationary Heat Flow Values for These Variants*

Variants	Concentration of Radioactive Elements [g/g]			q_{stat} cal cm ⁻² s ⁻¹
	Uranium $H_1^{t_0}$	Thorium $H_2^{t_0} - 4H_1^{t_0}$	Potassium ⁴⁰ $H_3^{t_0}$	
Basalt 14% Peridotite 73% Iron 13% (K ⁴⁰ /U) = 1.6 } I	11.55×10^{-8}	46.7×10^{-8}	18.5×10^{-8}	1.35×10^{-6}
Basalt 10% (K ⁴⁰ /U) = 1.13 } I ⁺⁺	8.50×10^{-8}	34.0×10^{-8}	9.6×10^{-8}	0.91×10^{-6}
Basalt 5% Variant by Levin } II K ⁴⁰ /U = 1.6	5.20×10^{-8}	21.0×10^{-8}	8.4×10^{-8}	0.61×10^{-6}
Chondrite Model Variants by Urey and MacDonald } III	1.16×10^{-8}	4.67×10^{-8}	9.35×10^{-8}	0.236×10^{-6}

sium 40, respectively, $\lambda_1 = 1.54 \times 10^{-10}$ year⁻¹, $\lambda_2 = 5 \times 10^{-11}$ year⁻¹, $\lambda_3 = 5.7 \times 10^{-10}$ year⁻¹, the heat released by one gram of the radioactive element is $\alpha_1 = 0.805$ cal g⁻¹ year⁻¹, $\alpha_2 = 0.193$, $\alpha_3 = 0.224$ and values of H_i^0 , the concentration at the beginning are defined on the basis of the expected present concentration of $H_i^{t_0}$ according to the formula

$$H_i^0 = H_i^{t_0} e^{-\lambda_i t_0} \text{ where } t_0 = 4.7 \times 10^9 \text{ years}$$

is the age of the Moon. Let us consider four variants of the concentrations of radioactive elements given in table 1. The concentrations of radioactive elements were chosen on the basis of the stationary heat fluxes equal to 1.35 and 0.91 cal cm⁻² s⁻¹ for variants I and I⁺⁺ and correspond to the radio astronomical data by Krotikov and Troitsky (ref. 24) and to the Apollo 15 data (ref. 26) Stationary heat fluxes 0.61 and 0.236 cal cm⁻² s⁻¹ for variants II and III coincide

with one of the variants of Levin and Mayeva (ref.8) (II) and are close to concentrations taken by Urey and MacDonald (III). The ratio of thorium to uranium is taken equal to 4 (see ref. 8). The uranium concentration used in variants I, I⁺⁺, and II is based on the pyrolite lunar composition and the chondrite composition in variant III. The assumption of the pyrolite lunar composition is based on the similarity of the composition of the Moon to the Earth's mantle noted by Anderson (ref. 29) (for example, the mean atomic weight of the Earth's mantle is $\bar{M} = 22.4$, which refers to eruptive rocks and carbonaceous, ordinary, and enstatite chondrites and has the same mean atomic weight as lunar material—22.0).

The assumption of pyrolite lunar composition also is based on the data from Surveyor V and on the papers by McCrea (ref. 30) and Reynolds and Summers (ref. 15). From all these data it follows that the Moon

Rocks:	Granite	Basalt	Eclogite	Peridotite	Dunite	Chondrites
U x 10 ⁻⁸	400	80	4.3	0.6	0.1	1.1
K ⁴⁰ /U	1.05	1.13	1.44	1.2	1.2	9

consists of silicates (for example, basalt) similar to those in the Earth's mantle.¹ The above table gives uranium concentrations and the ratio of K⁴⁰ to uranium for different rocks.

From this table and the given stationary fluxes we chose the variants I, I⁺ and II with the content of basalt equal to 14 percent, 10 percent, and 5 percent, respectively; with peridotite equal to 73 percent, 77 percent, and 82 percent, respectively; and iron, 13 percent (ref. 15) with an impoverished content of radioactive elements (iron has U = 0.1 × 10⁻⁸ g/g, Th = 0.4 × 10⁻⁸, and K⁴⁰ = 0) and the ratio of K⁴⁰/U = 1.6, 1.13, and 1.6, respectively (see refs. 9 and 6). Variant III is the chondrite model (Urey and MacDonald). Note that variant II corresponds to variant "C" with the mean content of radioactive elements that of the Earth (see refs. 31 and 6¹).

As initial conditions we take two variants of the "cold" and the "hot" models for the formation of the Moon with initial temperatures of 273° K and 900° K. These are the same initial conditions taken by Urey, MacDonald, Iriyama, Shimazu, and Fricker² based on the different hypothesis of the Moon's origin and the time of its accumulation and initial heating, on which we will not dwell.

The boundary condition ($r = r_0$) is defined by the following relation

$$K \left(\frac{\partial T}{\partial r} \right)_{r=r_0} = \delta T^4 - B$$

¹ It does not necessarily follow that the hypothesis is true for formation of the Moon by fusion from the Earth, since even interstellar material contains grains of refractory silicates (see reference 30).

² Running ahead, we note that this variant especially gives the flux corresponding to Apollo 15 data and the radio astronomical data, i.e., evidently, the terrestrial composition of the Moon is rather probable.

³ Mayeva (ref. 13) used a parabolic temperature distribution with a value at the Moon's centre of 500° K.

where $B = 0.9 \times 10^{-2}$ cal cm⁻² s⁻¹ considers heating the Moon by solar radiation. On calculation this condition leads to practically the same results as does the more simple condition $T = 273^\circ \text{K} = \text{const}$.

THE MECHANISM OF DIFFERENTIATION

The mechanism of differentiation is defined by the function for the distribution of radioactive elements $F(r,t)$ which is given as follows. At first, we considered a homogeneous model for the distribution of radioactive elements, i.e., $F(r,t) = 1$ (analogous to refs. 22 and 23) for the first stage of the calculation. Then, after reaching at the moment t_1 , at the point r_1 , the temperature corresponding to the beginning of melting $T_{\text{init. melt}}$, the distribution of temperature obtained up to the time $t_2 = t_1 + \Delta t$ (where Δt is the time of melting (see below) is taken as the new initial distribution, and the distribution of radioactive elements is assumed to be layered; namely, radioactive elements from the layer $r_1 \pm \Delta r$ are transferred to the adjacent upper layer ($r_2 \pm \Delta r$) and the calculation is carried out with the depleted layer ($r_1 \pm \Delta r$). However, for the time Δt defined by the necessity of heating the layer by $\Delta T = 200^\circ \text{K}$, deeper layers have reached the melting temperature (since $T_{\text{init. melt}}$ increases with the depth, i.e., with the decrease of r). Radioactive elements from these layers go to the layer $r_1 \pm \Delta r$, i.e., their content in this layer is equalized and so on, until the lower layers no longer melt. Such layered differentiation (similar to that used by Fricker, Reynolds, and Summers) is defined by five variants that differ in the value n which is the fraction of radioactive elements removed from the layer. We accept $n = 1$ (complete removal), 0.8 (80 percent of the radioactive elements are removed from the layer), 0.6, 0.4, and 0.2. In this way,

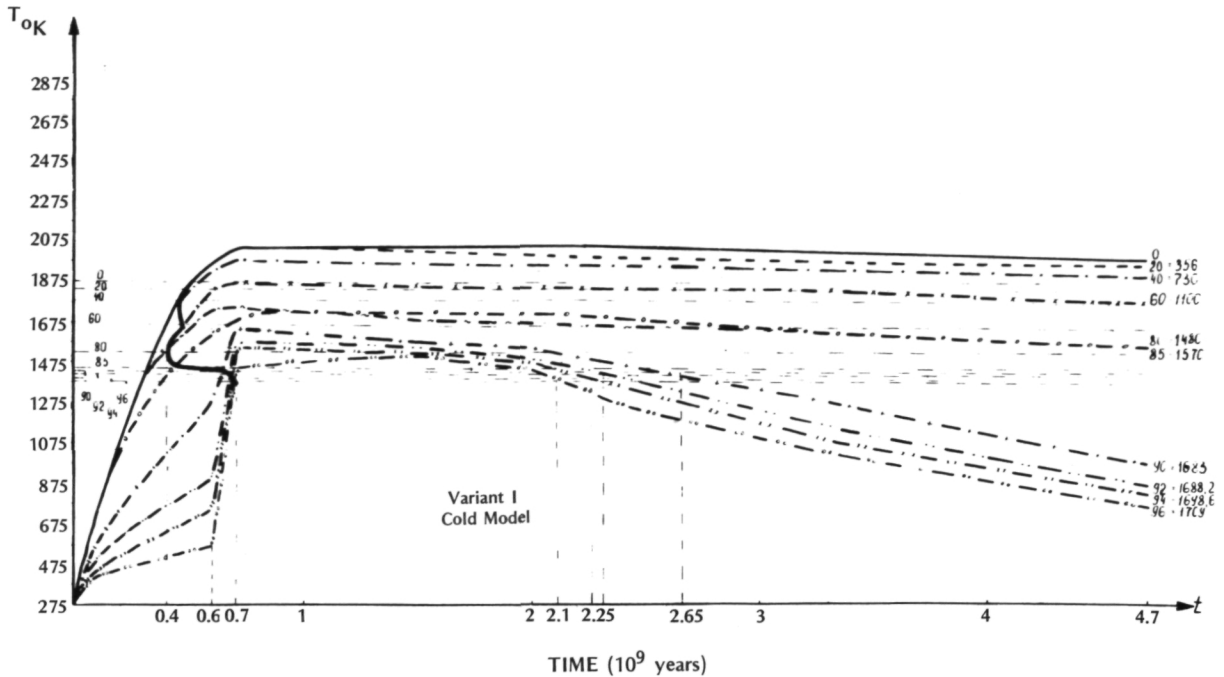


Figure 1.—The time dependence of temperature in different layers of the Moon for $n = 1$ (along the radius, starting from the center, 0, layer 20 = 356 km, 40, 60—96 = 1709 km). The melting temperature corresponding to each layer is shown (dashed lines), as is the time dependence of the start of melting (heavy solid line). The times of initial melting of the Moon, the end of melting of the outer layers, as well as the start of differentiation are shown on the abscissa.

after differentiation in each of the melted layers, there remains from 0 to 80 percent of the content of radioactive elements in the nondifferentiated material (note that in the latest paper by Mayeva (ref. 13) the residue was from 2 to 20 percent, i.e., $n \geq 0.8$).

The present paper does not consider the possibility of the melted material's penetrating into the external solid layer as was done in the paper by Mayeva (ref. 13), since the concentration of radioactive elements in the thin surficial layer leads, in reality, to more rapid cooling of the Moon and to the greater thickness of the hard crust, as obtained in the model of exponential differentiation considered in detail in references 22 and 23.

The Method of Calculation

For the numerical solution of the heat conductivity equation we use the method of line coordinates where the section $[0, r_0]$, (where r_0 is the radius of the Moon) is divided

into 100 layers and only the differentials in the *spatial* coordinate were replaced by difference relations ratio. Thus the solution of the boundary problem is reduced to a solution of the Cauchy problem for the system of ordinary differential equations. It should be noted that the approximation error is larger, the closer the layer is to the surface. That is why a non-uniform grid is used in the calculation: the layer thickness close to the surface (≈ 5 km) is several times smaller in comparison with the depth layer (≈ 18 km). The system obtained is solved by the approximation method, which provides an accuracy of the temperature calculation (at each step in time) of the order of 10^{-3} . All calculations are made by the computer BESM-6.

Results of Calculation

Results of the calculation are given in figures 1 through 12 and in tables 2 and 3.

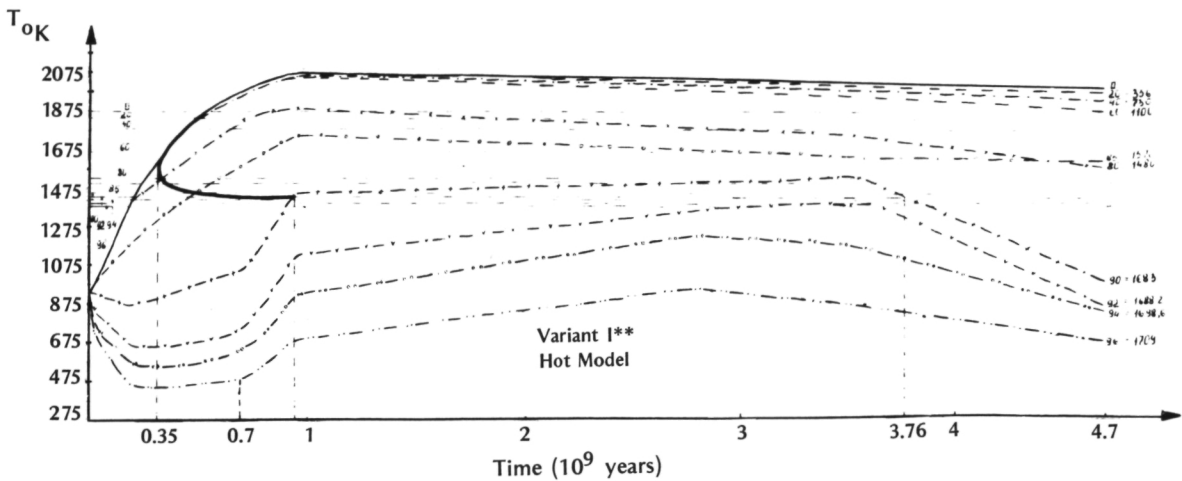
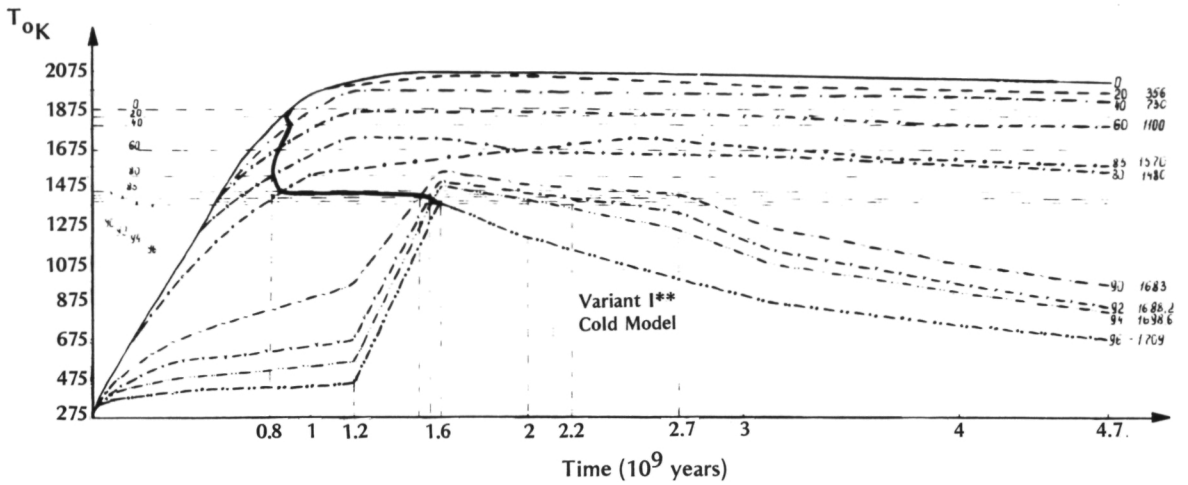


Figure 2.—The time dependence of temperature in different layers of the Moon.

THE PROCESS OF MELTING AND DIFFERENTIATION

Figures 1 through 4 show the time dependence of temperature in different layers of the Moon (along the radius beginning from the centre 0) for all variants at $n = 1$. Temperatures at the beginning of melting are plotted for each layer and the time dependence of the beginning of melting in different layers. From figures 1 through 4 it is seen that melting begins in layer 80¹ for all variants, about 1500 km from the center (i.e., at the depth ≈ 250 km under the surface)

during the period from 0.4 to 1.5 billion years from the beginning of lunar history. Rapidly (in 0.1 to 0.3 billion years) the region of melting propagates to the center and to the Moon's surface. In the layer where melting first begins, differentiation of the material begins after 0.2 to 0.5 billion years. The region of melting at the start of differentiation ($t_{\text{init. dif.}}$) reaches 1600 km; at the same time there is a sharp temperature increase in the layers close to the surface. As a result the temperature in these layers is close to or exceeds $T_{\text{init. melt.}}$. This is understandable since the melted radioactive elements are moved by convection to these layers from deeper layers. The deep layers (at a depth of more

¹ Altogether there are 100 layers.

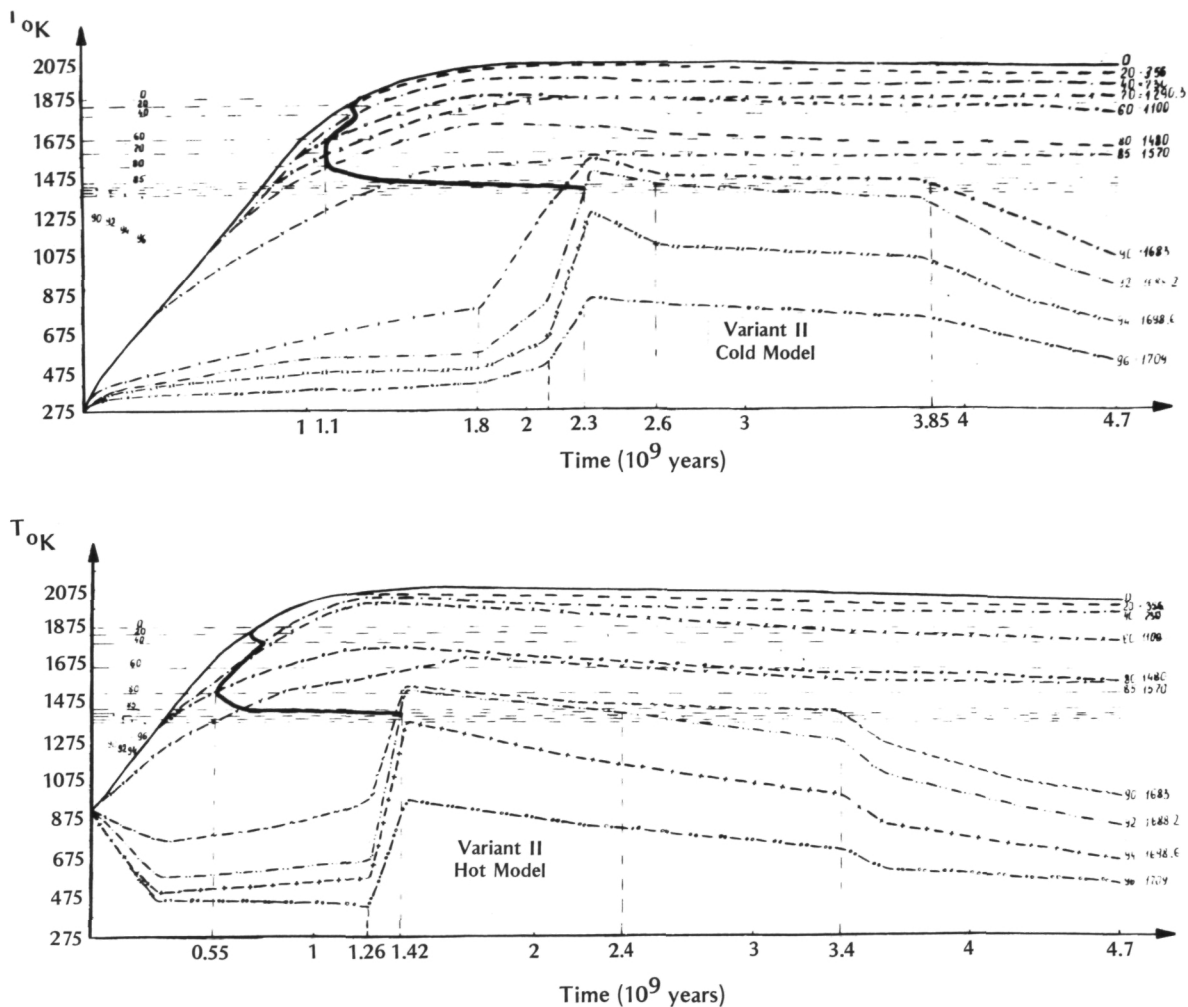


Figure 3.—The time dependence of temperature in different layers of the Moon.

than 500–600 km, i.e., $r = 1100$ – 1200 km) prior to differentiation have been heated above $T_{\text{init. melt.}}$ and are now slowly cooling due to the convection of radioactive elements to the upper layers². From figures 5 through 7 it is seen that in this way almost simultaneous heating of lunar material occurs up to depths of 200–250 km under the surface. Layers which are closer to the surface heat more slowly and the thickness of these layers increases with time. Numerical data are given in tables 2 and 3.

² Differentiation occurs in all variants except for III (cold model), where the energy of radioactive elements is not sufficient for the beginning of differentiation.

THE BEGINNING AND THE DURATION OF THE MAXIMUM MELTING OF THE INTERIOR

Figures 8 through 11 give the time dependence for the radius of melting. From these figures it is seen that in all variants the period of the maximum melting continues for 1 to 2 billion years (depending on the variant—see tables 2 and 3) and begins in the interval from 0.7 to 2.3 billion years from the beginning of lunar history. Naturally, for large concentrations and “hot” models the maximum melting begins earlier than for low concentrations and “cold” models. So for the

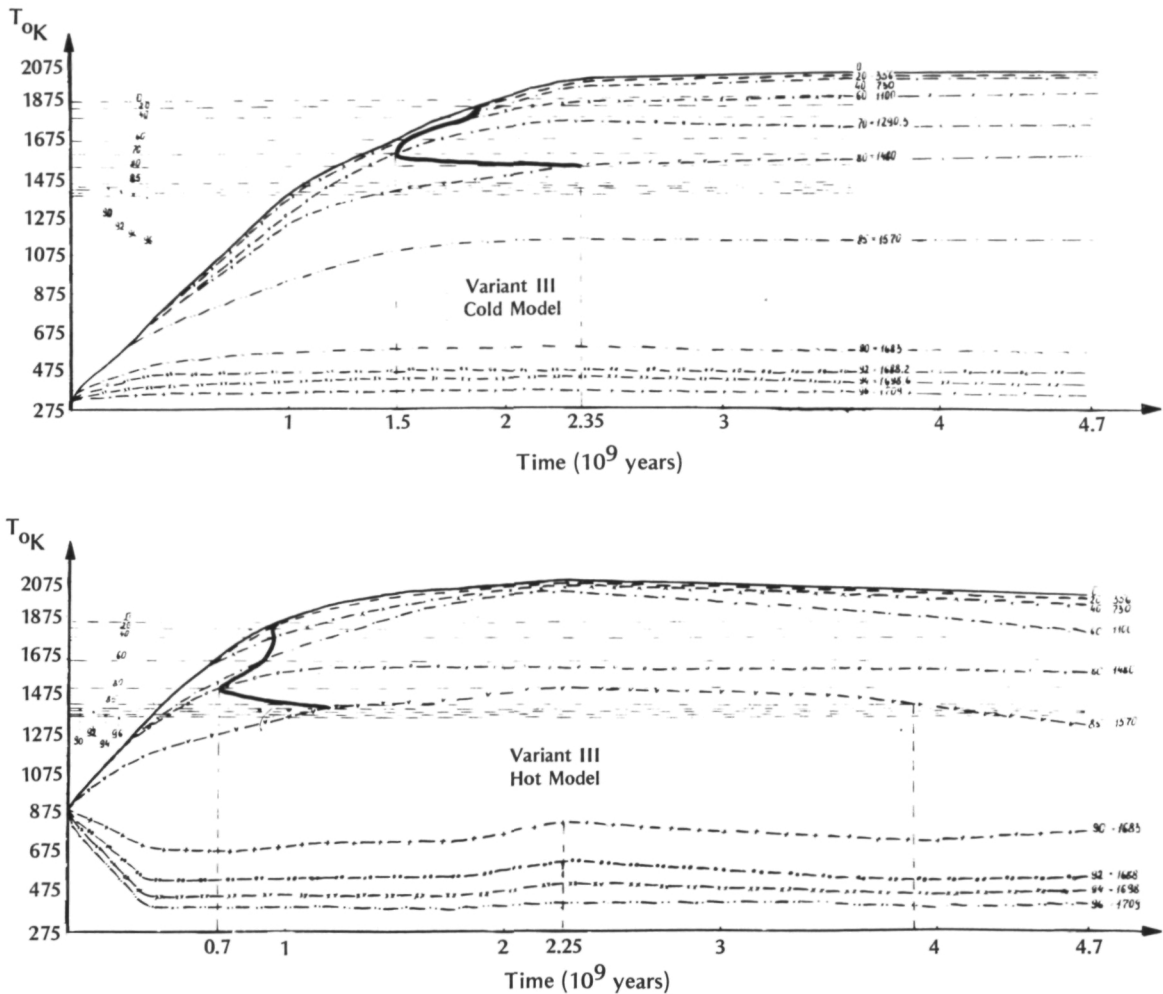


Figure 4.—The time dependence of temperature in different layers of the Moon.

variants I and I⁺⁺ the maximum melting begins approximately 3.5 to 4 billion years prior to the present time and continues for 1.5 to 1 billion years. In the case of low (variant III) and intermediate concentrations and large convection ($n \geq 0.8$) of radioactive elements (variant II) the maximum melting begins from 2.5 to 3 billion years prior to the present and continues for 1.5 to 2 billion years, i.e., it begins later and continues longer, as expected¹. A special case is variant II ("cold" model), which has a low degree of convection of radioactive elements

¹The smaller the concentration, the more quietly the processes occurred.

($n \leq 0.6$). In this case the period of maximum melting begins 2.5 billion years prior to the present and continues to the present time. Here a specific combination of conditions occurs. The concentration of radioactive elements is not so large and the process of differentiation is not so effective that a fast convection of radioactive elements to the surface occurs. Thus their influence on further history is small, but not sufficiently small for the natural cooling of the Moon.

Consequently, in all variants except for the above-mentioned II ($n \leq 0.6$) the Moon is presently cooling.

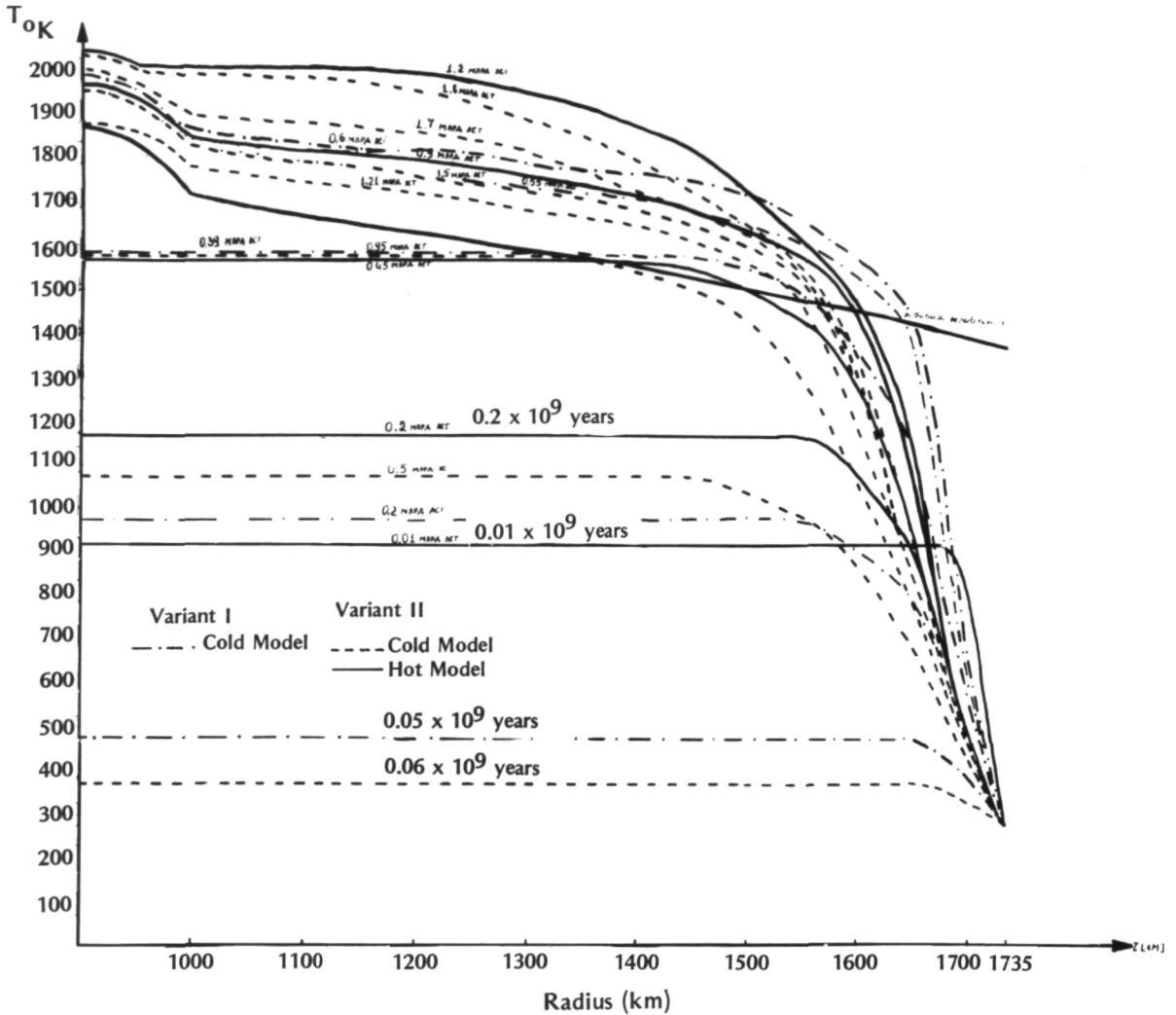


Figure 5.—The temporal variation of temperature in the lunar interior.

THE THICKNESS OF THE CRUST

As it is seen from figures 8 through 11 and tables 2 and 3, the thickness of the crust at the period of maximum melting ranges in variants I, I⁺⁺, II, and III from 15 to 20 km, from 25 to 30 km, from 35 to 45 km, and from 100 to 200 km, respectively; i.e., from 1 to 2.5 billion years ago the Moon was almost completely melted (in variant II with $n \leq 0.6$, the Moon even now should be melted up to the depth of about 45 km under the surface). Then cooling began and presently the crustal thickness in all variants is from 150

to 250 km (except for the above-mentioned "special case"). The same thing follows from figure 12, where the temperature distribution is given in the Moon for the present time.

THE HEAT FLUX THROUGH THE LUNAR SURFACE

Figure 12 gives the time dependence of the heat flux through the lunar surface. From these curves it is seen that at the period of maximum melting of the Moon the flux, as could be expected, is also maximum and ex-

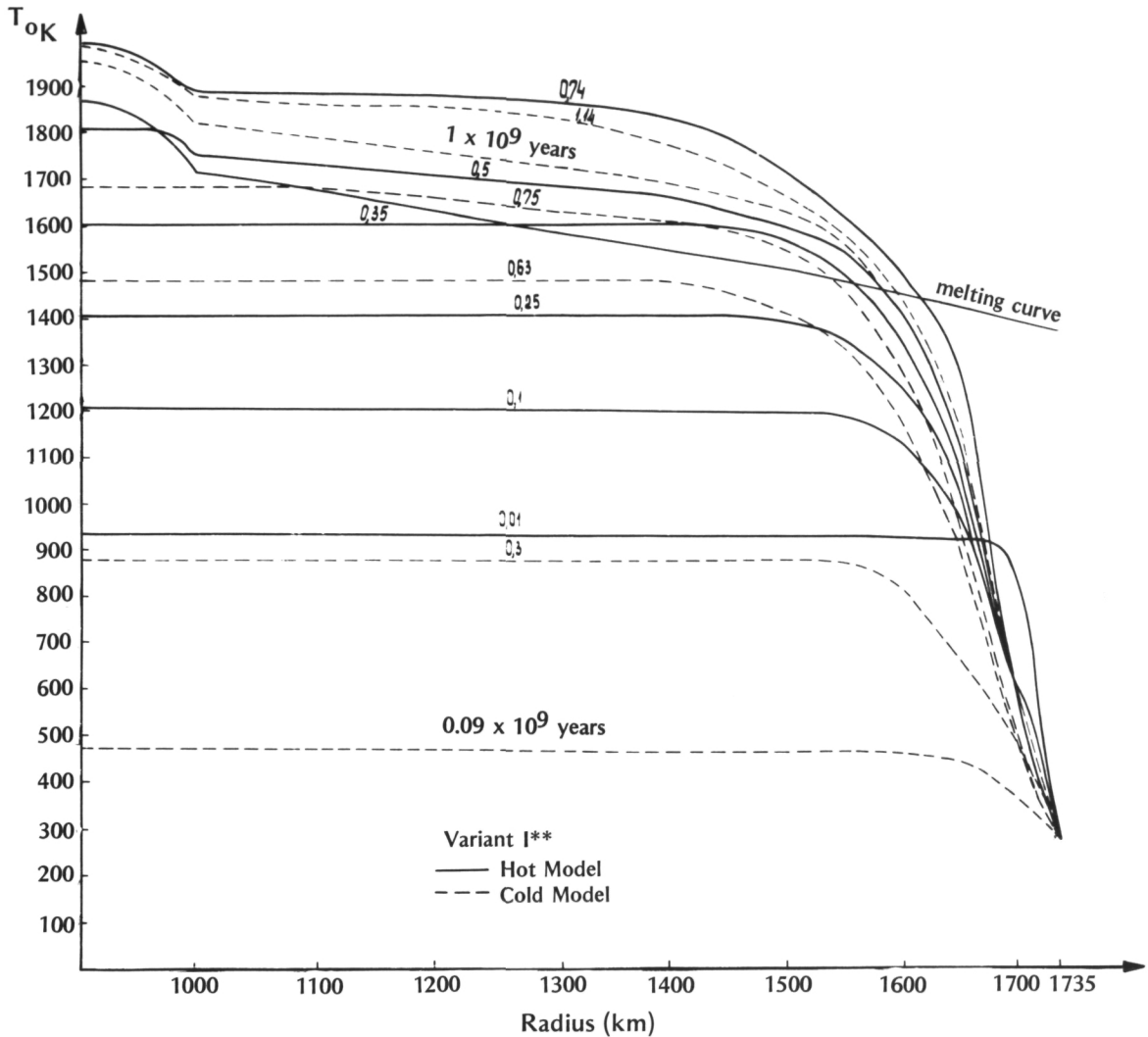


Figure 6.—The temporal variation of temperature in the lunar interior.

ceeds 2 to 3 times the stationary value for the given concentration of radioactive elements. At the present time for all variants (except for II with $n \leq 0.6$), the flux is decreasing and is approaching the stationary value $q_{stat.}$, yet even now the flux is nearly 1.5 times $q_{stat.}$ The flux value in variants I, I⁺, II ($n \geq 0.8$), and III is equal to 1.8×10^{-6} cal cm⁻² s⁻¹, 1.27×10^{-6} cal cm⁻² s⁻¹, and 0.9 to 0.95×10^{-6} cal cm⁻² s⁻¹, respectively. In variant III (“cold” and “hot” models) it is 0.28 and 0.55×10^{-6} cal cm⁻² s⁻¹ and variant II ($n \leq 0.6$) has a rather large flux equal to 1.6×10^{-6} cal cm⁻² s⁻¹, which is associated

with the continuation of melting in this variant up to the depth of 45 km.

Thus fluxes close to those measured by radio astronomical methods and obtained by Apollo 15 are realized in variants I⁺ and II ($n \geq 0.8$), i.e., for the terrestrial or “mantle” pyrolite compositions of lunar material.

Conclusion

Calculations are given for different concentrations of radioactive elements corresponding to a chondritic composition (III), to

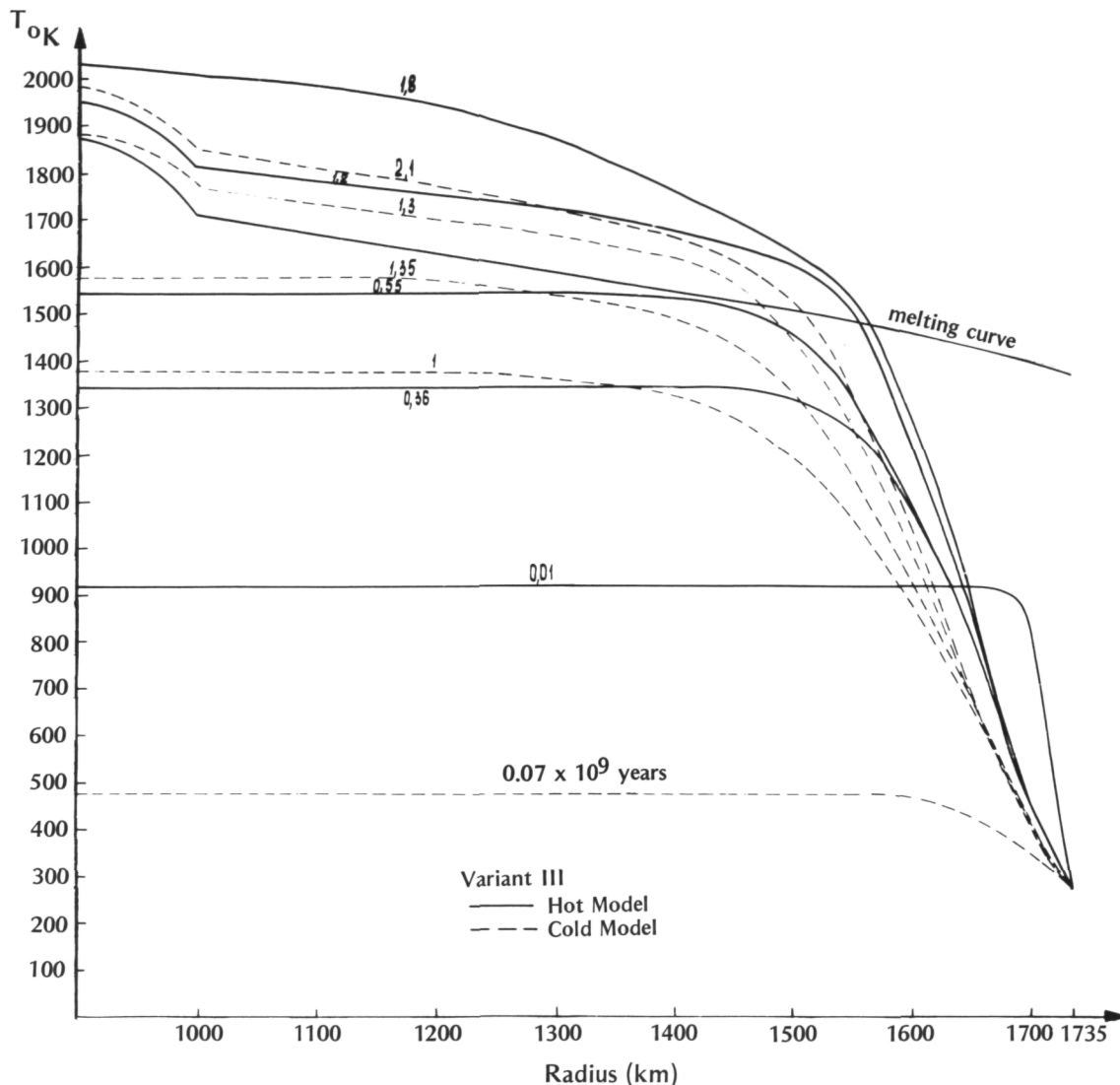


Figure 7.—The temporal variation of temperature in the lunar interior.

a terrestrial composition (II), and a terrestrial mantle-pyrolite composition (I and I⁺). Differentiation of material and the convection of radioactive elements to the surface due to melting are taken into account in the calculation by a scheme similar to that used by Fricker, Reynolds, and Summers. The calculations show that the Moon's interior has been heated to melting during the first 0.7 to 2.3 billion years after its formation. The maximum melting of the Moon covered

practically the entire Moon up to a depth of 15 to 45 km below its surface and began from 3.5 to 4 billion years ago, if one assumes a pyrolitic composition of the Moon; or 2.5 to 3 billion years ago, if one assumes a terrestrial or chondritic composition of the Moon. This maximum melting continued for 1 to 2 billion years and at present the Moon is cooling (true, there is an improbable variant of weak differentiation for the "terrestrial" composition of the Moon when melting is

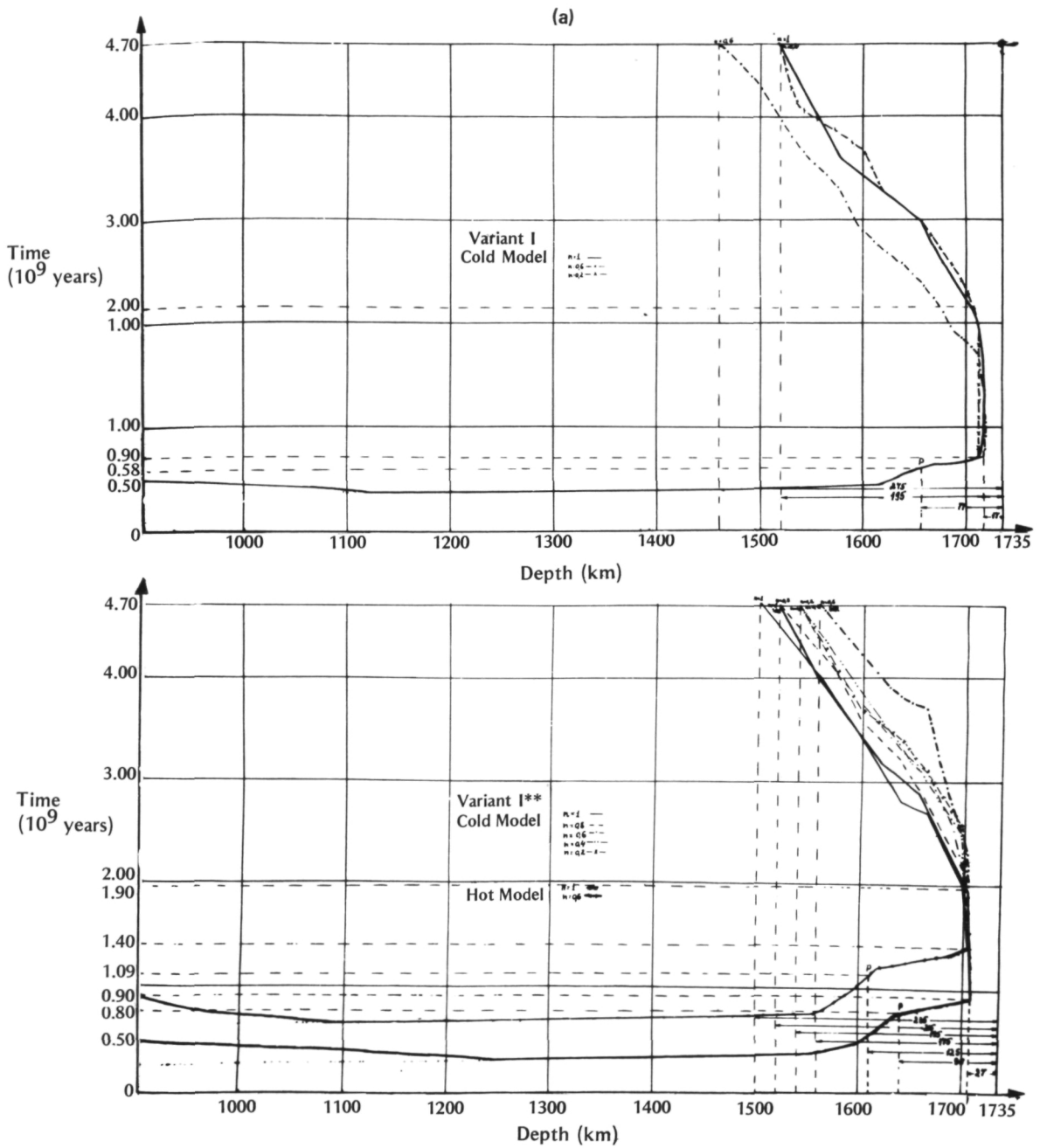


Figure 8.—The time dependence of the depth of melting for various values of n .

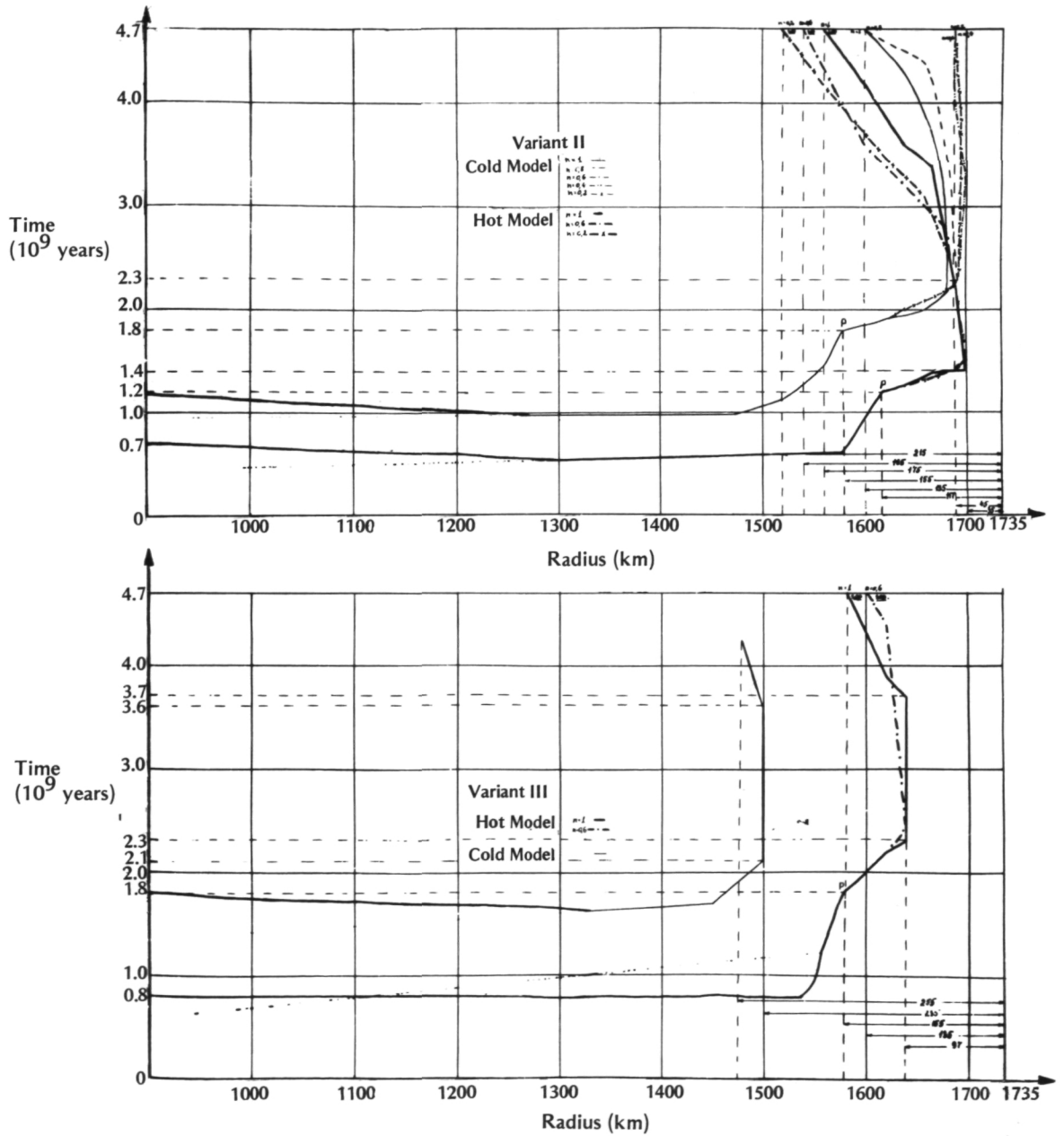


Figure 9.—The time dependence of the depth of melting for various values of n .

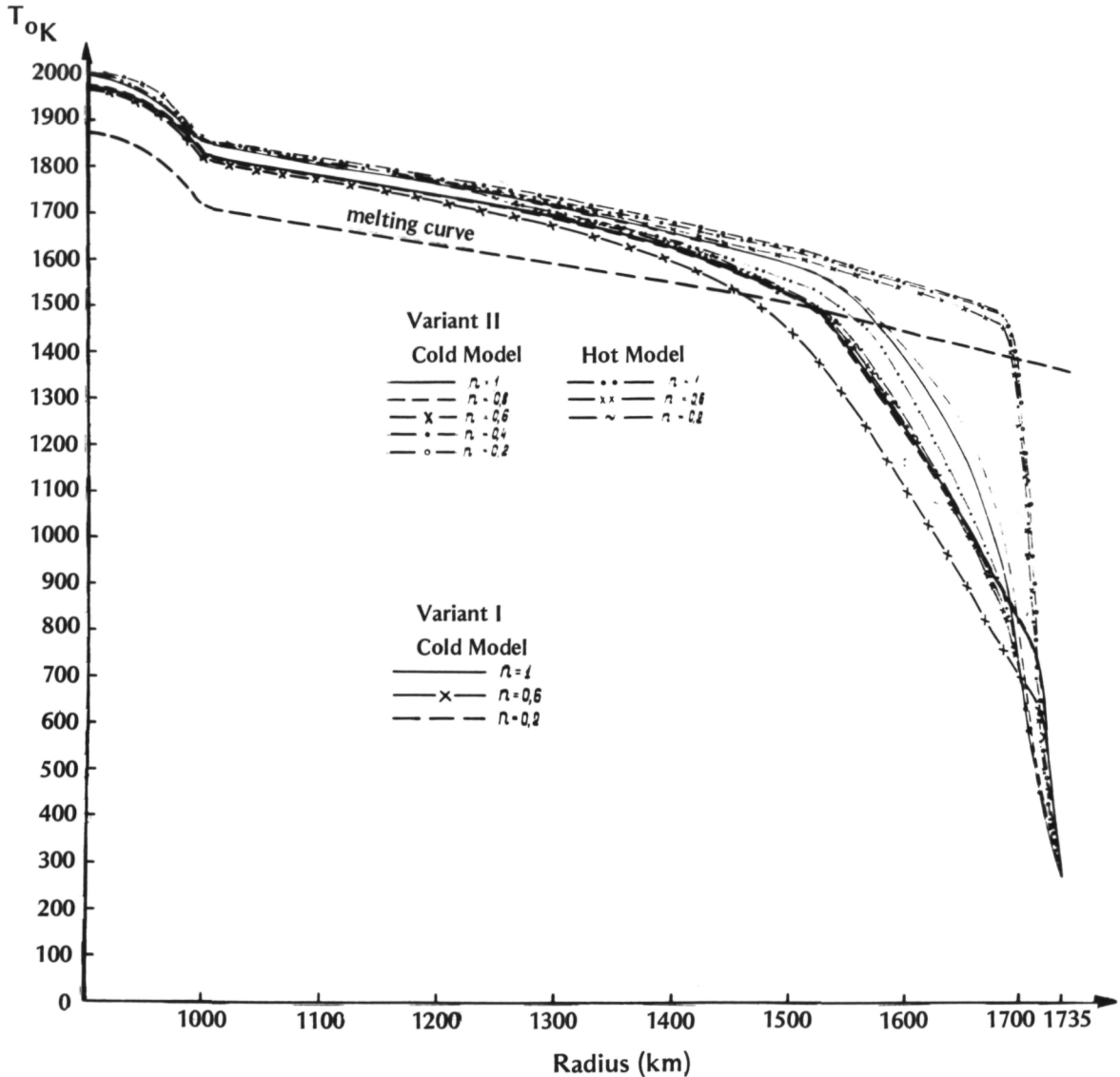


Figure 10.—The distribution of present temperatures for various values of n .

occurring even now). The present thickness of the crust is 150 to 250 km and the heat flux exceeds the approximately 1.5 times stationary value. The flux value for variants I, I⁺, II, and III is equal to 1.8, 1.27, 0.9 to 0.95, and 0.28 to $0.55 \times 10^{-6} \text{ cal cm}^{-2} \text{ s}^{-1}$, respectively.

From tables 2 and 3 it follows that in the most probable variants with the pyrolite-“mantle” (I⁺) and terrestrial (II) composition of the initially “hot” Moon, the

maximum melting of the Moon began 3.3 to 3.8 billion years ago, which corresponds to the age of mare basalts and mascons (3.16 to 3.71 billion years). These data testify to the volcanic activity that was completed approximately 2.7 to 3 billion years ago—evidence in agreement with the absence of lunar samples younger than 3 billion years (refs. 32, 33, and 34), when the activity stopped. Thus, limitations stated recently by Toksöz and Solomon (ref. 21) are satisfied, yet the thick-

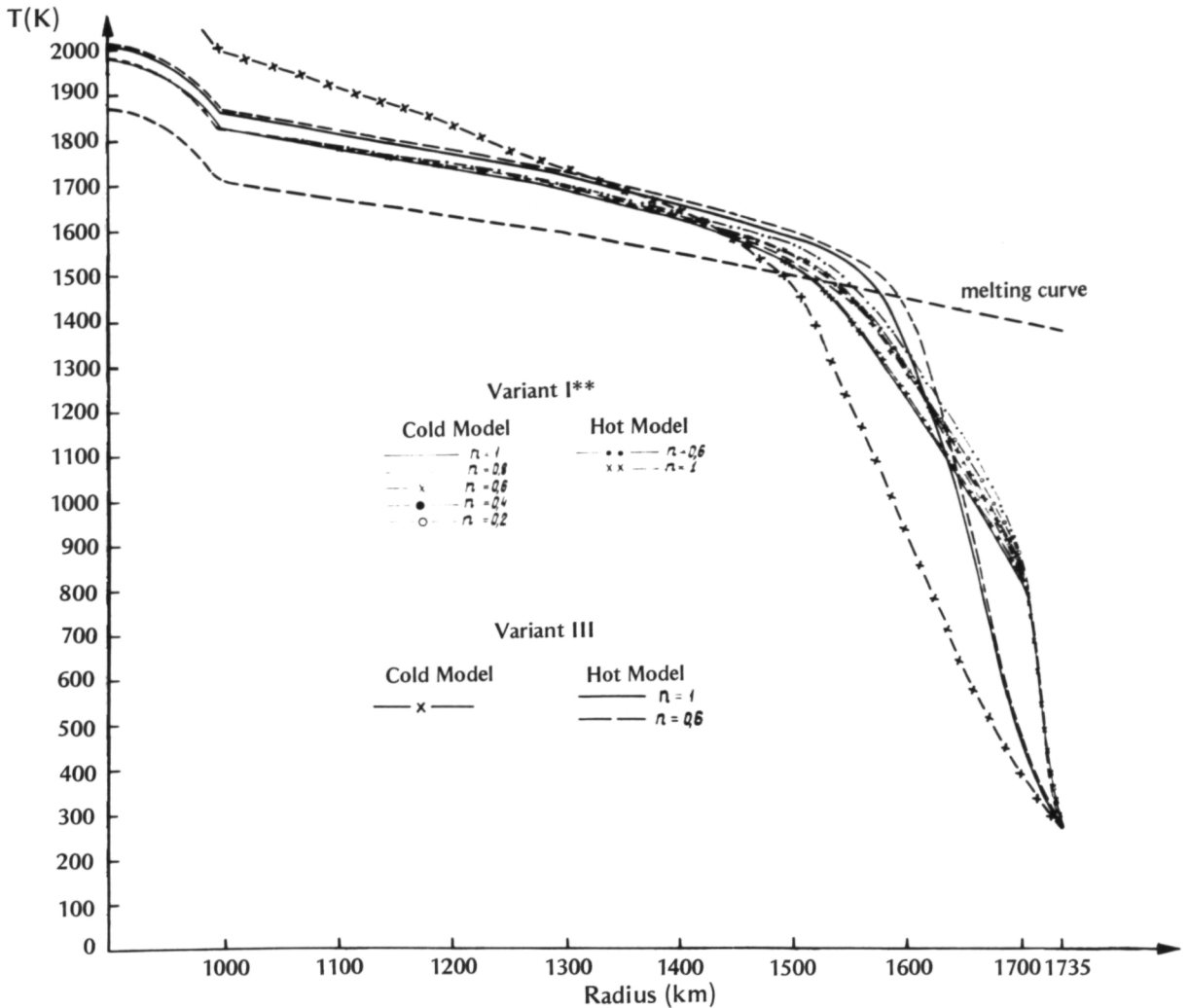


Figure 11.—The distribution of present temperatures in the Moon as a function of n .

ness of the crust obtained by our calculations is essentially small (ref. 21)—a crust 600 km thick.

It should be noted that the most realistic variant uses a "terrestrial" composition for the Moon (composition "C" according to Starkova), which gives, in spite of its moderate concentration of radioactive elements, a sufficiently large heat flux¹ that corresponds to the radio astronomical measurements and Apollo 15 data, i.e., to obtain the large observed flux it is not necessary to have high concentrations of radioactive elements.

¹This possibility was noted by Lubimova in reference 6.

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References

1. UREY, H. C., *Geochimica et Cosmochimica Acta*, Vol. I, 1951, p. 209.
2. UREY, H. C., *Proc. Natl. Acad. Sci. U.S.*, Vol. 41,

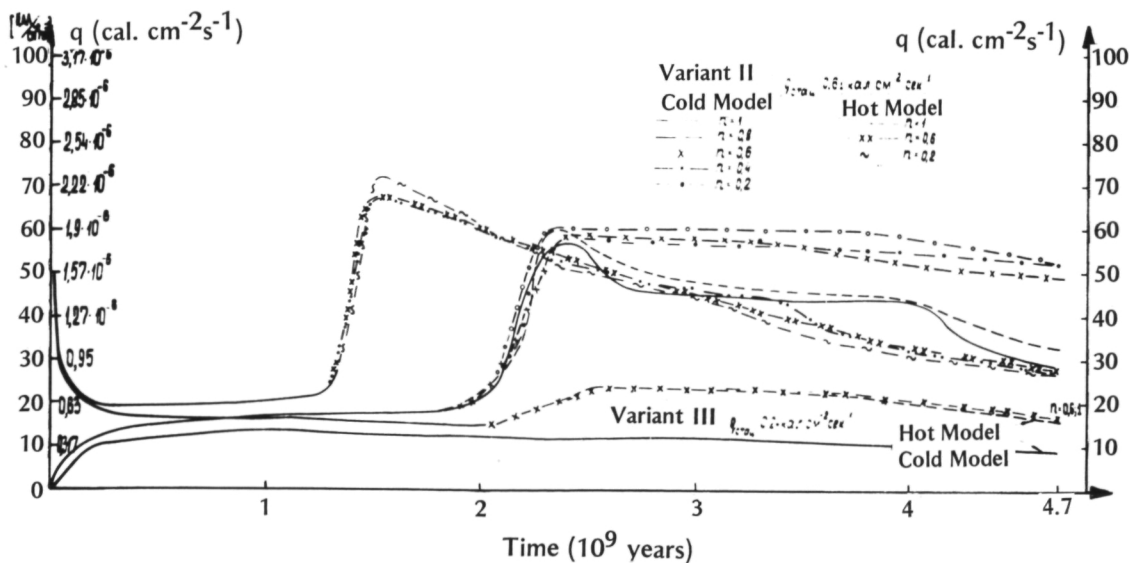
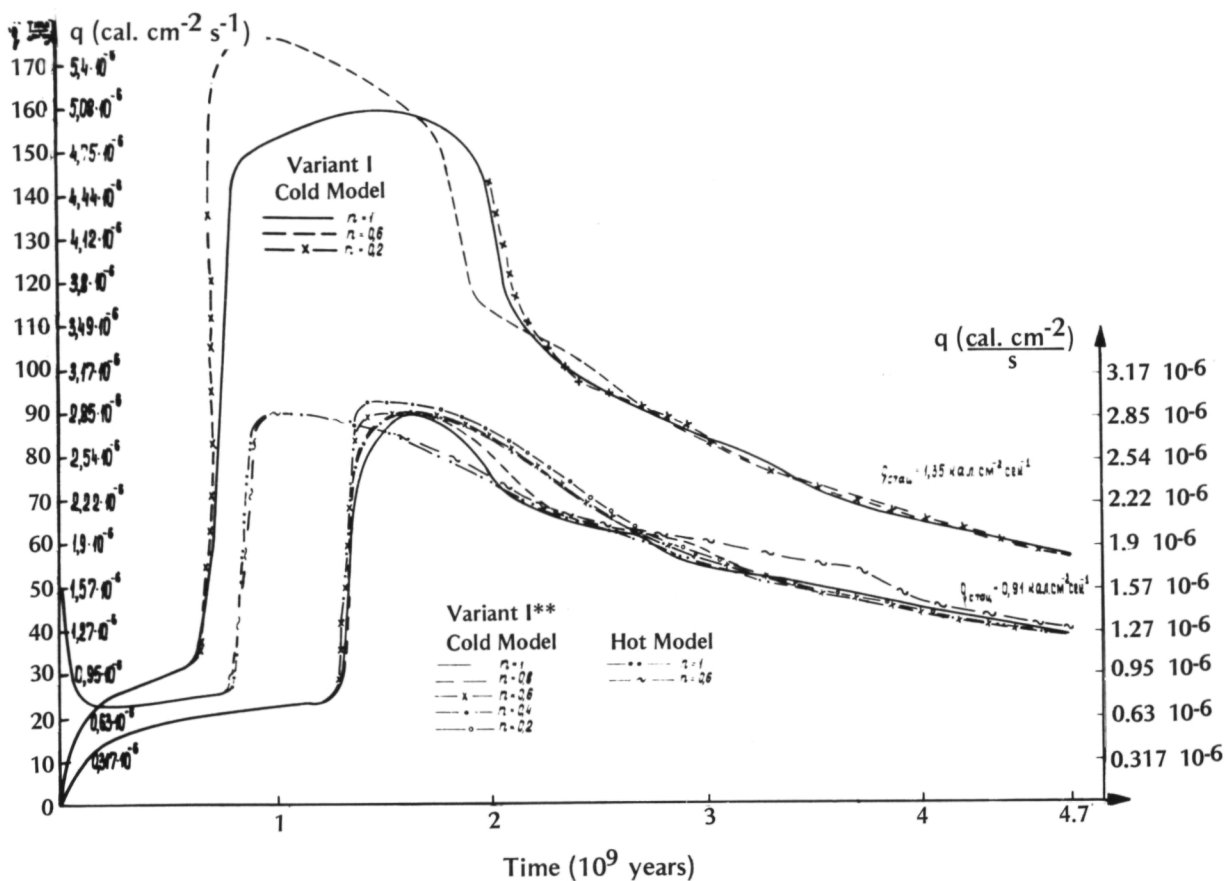


Figure 12.—The time dependence of heat flow through the lunar surface.

Table 2.—Some Thermal Parameters and Calculated Results for the Various Thermal Model Variants

Variant	n	Flux $q \cdot 10^{-9} \text{ cal cm}^{-2} \text{ s}^{-1}$			Time t Billion Years			Distance r km					
		q_{stat}	q_{max}	q_0	$\frac{t_{\text{init melt}}}{t_{\text{init diff}}}$	$t_{\text{max melting}}$	$t_{\text{max } q}$	$\frac{r_{\text{init mel diff}}}{r_{\text{mel init diff}}}$	$r_{\text{max melting}}$	solidification			
										r^{hard}	$r_{\text{h min}}$	r_{crust}	
I Cold Model	I 0.6 0.2	1.35	5 } 5.5	1.8	(0.4)	0.7-2.2	0.8-2	$\frac{1500}{1600}$	1720 1715	1540	15-20	195	
					0.6	0.7-1.8	0.7-1.8			1460		275	
						0.7-2.2	0.8-2			1540		195	
I ⁺⁺ Cold Model	I 0.8 0.6 0.4 0.2	0.91	2.85	1.27	(0.85)	1.4-2	1.4-2	$\frac{1500}{1610}$	1710 1705	1500	25-30	235	
					1.15							1520	215
												1540	195
												1540	195
I ⁺⁺ Hot Model	I 0.6	0.91	2.85	1.27	(0.35)	0.9-2	0.9-1.5	$\frac{1500}{1640}$	1710 1705	1520	25-30	215	
					0.8							1560	175
II Cold Model	I 0.8 0.6 0.4 0.2	0.61	1.85	} 0.95	1.2	2.3-3.5	2.3-2.6	$\frac{1500}{1580}$	1695 1690	1600	40-45	135	
						2.3-3.5	2.3-2.6			1600		135	
						2.3-4.7	2.3-4.7			1690		45	
						2.3-4.7	2.3-4.7			1690		45	
						2.3-4.7	2.3-4.7			1690		45	
II Hot Model	I 0.6 0.2	0.61	2.1	0.88	$\frac{0.55}{1.2}$	1.4-2.5	1.5-2	$\frac{1500}{1620}$	1700 1695	1560	35-40	175	
												1540	195
												1520	215
III Exponential Model		0.236	0.41	0.28	1.55	2.1-3.6		1300	1500	1480	235	255	
III Hot Model	I 0.6	0.236	0.73	0.55	(0.7) 1.8	2.3-3.7	2.5-3.7	$\frac{1500}{1580}$	1635	1580 1600	95-100	155 135	

Table 3.—*Calculated Results for Various Thermal Model Variants*

Variant	(cal cm ⁻² sec ⁻¹) 10 ⁻⁶			$t_{init\ dif}$ Billion Years	$t_{max\ mel\ flux}$ Billion years	$r_{melt\ init\ dif}^{(1)}$ (km)	$\Delta r_{crust\ min}$ (km)	Δr^0 crust (km)
	q_{stat}	q_{max}	q_0					
I	1.35	5.5	1.8	0.6 (0.4)	0.7-2	1660	15-20	200-250
I ⁺⁺	0.91	2.85	1.27	0.8 (0.5)	1 -2	1630	25-30	180-220
II	0.61	2	Cold $n \geq 0.8$ Hot	1.5 (0.9)	Cold $n \geq 0.8$ Hot	1600	35-45	Cold $n \geq 0.8$ 135
			0.9-0.95 Cold $n < 0.8$ 1.6		1.5-2+ 2.5-3.5 Cold $n < 0.8$ 2.3 + 4.7			Hot 200 Cold $n < 0.8$ 45
III	0.24	cold hot 0.4 - 0.7	cold hot 0.28 - 0.55	hot 1.8 (1.1)	2.3-3.7	hot 1600	cold hot 235 100	hot cold 250 150

Note: (1) $r_{init\ melt}$ and $r_{init\ dif} = 1500$ km.

- 1955, p. 127.
3. UREY, H. C., *Physics and Astronomy of the Moon*, 1962, p. 481.
 4. MACDONALD, G. J. F., *J. Geophys. Res.*, Vol. 64, 1959, p. 1967.
 5. MACDONALD, G. J. F., *Space Sci. Rev.*, Vol. 2, 1965, p. 473.
 6. LUBIMOVA, E. A., *Termica of the Earth and the Moon*, 1968.
 7. LEVIN, B. YU., AND E. A. LUBIMOVA, *Nature*, No. 10, 1955, p. 81.
 8. LEVIN, B. YU., AND S. V. MAYEVA, *DAN SSSR*, Vol. 133, 1960, p. 44.
 9. LEVIN, B. YU., *New About the Moon. AC SSSR*, 1963, p. 118.
 10. LEVIN, B. YU., *Vulcanism and the Death Construction of the Earth*, 1966.
 11. MAYEVA, S. V., *DAN SSSR*, Vol. 159, 1694, p. 2.
 12. MAYEVA, S. V., *Izv Commission on Physics of Planets*, No. 5, 1965.
 13. MAYEVA, S. V. *Physics of the Earth, Izv As SSSR*, No. 3, 1971, p. 3.
 14. FRICKER, P. E., R. T. REYNOLDS, AND A. L. SUMMERS, *J. Geophys. Res.*, Vol. 72, 1967, p. 2649.
 15. REYNOLDS, R. T., AND A. L. SUMMERS, *J. Geophys. Res.* Vol. 74, No. 10, 1969, p. 2494.
 16. IRIYAMA, J., AND I. SHIMAZU, *Icarus*, Vol. 6, 1967, p. 3.
 17. ANDERSON, D. L., AND R. A. PHINNEY, *Mantles of the Earth and Terrestrial Planets. Inter-science*, 1967, p. 113, and *Amer. Astron. Soc. Pub., Phys. Moon*, 1967, pp. 161-179.
 18. HANKS, T. S., AND D. L. ANDERSON, *Phys. Earth Planet. Interiors*, Vol. 2, 1969, p. 19, and *Phys. Earth Planet. Interiors*, Vol. 5, 1972, p. 409.
 19. ANDERSON, D. L., AND T. C. HANKS, *Science*, Vol. 3, 178, 1973, p. 1245.
 20. MACCONNEL, R. K., L. A. MACCLAINS, D. W. LEE, J. R. ARONSON, AND R. V. ALLEN, *Rev. Geophys.*, Vol. 2, 1967, p. 12.
 21. TOKSÖZ, M. N., AND S. C. SOLOMON, *The Moon*, Vol. 7, Nos. 3 and 4, 1973.
 22. ORNATSKAYA, O. I., AND YA. I. AL'BER, *Izv. V Radiofizika*, Vol. 9, No. 3, 1965.
 23. ORNATSKAYA, O. I., AND YA. I. AL'BER, *Astron. Zhurn.*, Vol. 44, No. 1, 1967, p. 158.
 24. KROTIKOV, V. D., AND V. S. TROITSKY, *UFN*, Vol. 31, 1962, p. 4.
 25. TROITSKY, V. S., *Izv. VUZ. Radiofizika*, Vol. 10, No. 8, 1967.
 26. LANGSETH, M. G., S. P. CLARK, J. L. CHUTE, S. J. KEIHM, AND A. E. WECHSLER, *The Moon*, Vol. 4, 1972, p. 390.
 27. TIKHONOV, A. N., E. A. LUMBIMOVA, AND VLASOV, *DAN SSSR*, Vol. 188, No. 2, 1969.
 28. RINGWOOD, A. E., *Advances in Earth Science*, 1966, pp. 237-356.
 29. ANDERSON, D. L., *Applied Optics*, Vol. 8, No. 7, 1969, p. 1271.
 30. MCCREA, W. B., *Nature*, Vol. 223, No. 5203, 1969, p. 1271.
 31. STARKOVA, A. G., *Meteoritics*, p. 13-19.
 32. PAPANASTASSIOU, D. A., AND G. J. WASSERBURG, *Earth Planet. Sci. Letters*, Vol. II, p. 37, and Vol. 12, p. 36, 1971.
 33. PAPANASTASSIOU, D. A., AND G. J. WASSERBURG, *Earth Planet. Sci. Letters*, Vol. 16, 1972, p. 289.
 34. WASSERBURG, G. J., AND D. A. PAPANASTASSIOU, *Earth Planet. Sci. Letters*, Vol. 13, 1971, p. 97.