# ON THE HEAT FLOW OF A GRAVITATIONALLY-DIFFERENTIATED MOON OF FISSION ORIGIN

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**Abstract.** It is shown that the mean value for the heat flow of a gravitationally-differentiated Moon of fission origin is about 13 erg cm$^{-2}$ s$^{-1}$ and that the heat flow varies regionally from about 3 erg cm$^{-2}$ s$^{-1}$ to more than 45 erg cm$^{-2}$ s$^{-1}$. These regional variations in the heat flow are caused by a non-uniform distribution of K, U and Th in the KREEP zone at the crust-upper mantle boundary and the redistribution of crustal materials and K, U and Th rich KREEP materials by basin-forming impacts. The scale of these regional variations is hundreds of km. The models presented are in accord with the Apollo 15 and 17 heat flow measurements.

In earlier papers it has been shown that the basic composition, petrology and structure of a gravitationally-differentiated Moon of fission origin match those now known for the Moon (Binder, 1974a, b, 1975a, b). The results presented in these papers are largely based on the compositional and petrological data derived from the samples returned by the various Apollo and Luna missions. While the models developed are in accord with these data, the selenophysical data obtained as a result of the Apollo program provide additional important constraints on the lunar models. The purpose of this paper is to present an analysis of the expected heat flow and its variations over the lunar surface for a Moon of fission origin and to compare these values with those obtained by the Apollo 15 and 17 heat flow experiments (Langseth *et al.*, 1972, 1973).

According to the fission hypothesis in general and to the models and discussions given by Binder (1974b, 1975b, hereafter referred to as papers I and II), the bulk composition of the proto-Earth's mantle and the Moon are, to a first order, the same and, hence, the concentration of the heat producing elements per unit mass in both bodies is the same. As is briefly discussed by Langseth *et al.* (1973), it is generally assumed that the Earth and Moon are in steady state; thus the present heat flow of both bodies is due only to heat produced by the radioactive decay of K, U and Th. Hence, to a first order, the ratio of the heat flow of the Moon to that of the Earth is simply the ratio of their masses divided by the ratio of their surface areas – i.e.,

$$\frac{F_{\mathrm{M}}}{F_{\mathrm{E}}} = \frac{M_{\mathrm{M}} R_{\mathrm{E}}^2}{M_{\mathrm{E}} R_{\mathrm{M}}^2}, \tag{1}$$

where $F_{\mathrm{M}}$ and $F_{\mathrm{E}}$ are the heat flow of the Moon and Earth; $M_{\mathrm{M}}$ and $M_{\mathrm{E}}$ are the masses of the Moon and Earth; and $R_{\mathrm{M}}$ and $R_{\mathrm{E}}$ are the radii of the Moon and Earth, respectively.

However, K, U and Th are lithophile elements and should not be found in signif-

icant amounts in the Earth's iron core. Thus, heat is being produced in the Earth, effectively, only in the crust and mantle, i.e. in only 70% of the mass of the Earth. Thus $M_E$ in Equation (1) must be multiplied by 0.7 in order to account for the Earth's core. Since the mass of the suspected lunar core is $\lesssim 1\%$ of the Moon's mass (Nakamura et al., 1974), no correction is necessary to $M_M$.

In addition, as reviewed and discussed in papers I and II, the Moon has lost the major part of its volatile metals and according to the analysis presented in paper II, the Moon now has only $20 \pm 10\%$ of its original K. From the data given in Table I, it is

TABLE I

Heat Generated in the Earth by the radioactive disintegration of K, U and Th

| Isotope | Heat[a] produced (erg gm s$^{-1}$) | Mixing[a, b] ratio | Percent of heat produced in the Earth |
|---------|-----------|----------|-------------|
| $U^{238}$ | 0.95 | 0.9928 | 41.7 |
| $U^{235}$ | 5.78 | 0.0071 | 1.8 |
| $Th^{232}$ | 0.27 | 3.5 | 41.8 |
| $K^{40}$ | 0.30 | 1.1 | 14.6 |

[a] Jacobs et al. (1959).
[b] Isotope/Uranium.

found that $K^{40}$ produces 15% of the heat of the Earth. If the Moon has retained 20% of its original K, the heat produced per unit mass in the Moon is 0.88 that produced per unit mass in the Earth's mantle and crust. Thus in order to account for volatilization losses of K by the Moon, the right side of Equation (1) must multiplied by 0.88.

Based on these two corrections, the mean heat flow for a Moon of fission origin is

$$F_M = \frac{0.88 F_E M_M R_E^2}{0.7 M_E R_M^2}. \tag{2}$$

After Langseth et al. (1973) the mean heat flow for the Earth is 63 erg cm$^{-2}$ s$^{-1}$; thus from Equation (2) the average heat flow for a Moon of fission origin is about 13.2 erg cm$^{-2}$ s$^{-1}$.

In paper II, a simple model for the distribution of K, U and Th in a pyrolite norm model is developed using a distribution coefficient of 0.1 derived from data given by Rice and Bowie (1971) for the Apollo 11 rocks. Based on a fit of the data for the K, U and Th contents of the lunar rocks to the model curves, a heat flow of 21 erg cm$^{-2}$ s$^{-1}$ is derived for this simple model. This value is 60% higher than the value derived above for a Moon of fission origin. However, as is discussed in the sequel, a second-order analysis of the distribution of K, U and Th in a gravitationally-differentiated Moon indicates that the petrological models presented in papers I and II have heat flow values which are in agreement with the value of about 13 erg cm$^{-2}$ s$^{-1}$ derived above.

First, in Section 3 of paper II, it is assumed that the three major phases of a pyrolite Moon (olivine, pyroxene and anorthite) all have distribution coefficients (K) of 0.1 for K, U and Th. However, comparisons of the concentrations of these elements in terrestrial minerals indicate that, while this approximation is valid for pyroxene and anorthite, it is not valid for olivine (Wedepohl, 1969, 1970). The concentration of these elements in olivine is about an order of magnitude or more lower than in pyroxene and anorthite. Thus the distribution coefficient for K, U and Th for olivine must be ≲0.01. Model calculations made with K=0.01 for olivine indicate that the concentration of K, U and Th in the dunite lower mantle of such a model is ∼1% of that of the total Moon and, as such, can be ignored (i.e., it can be assumed that K, U and Th are completely excluded from the lower mantle).

Second, the first-order model developed in Section 3 of paper II is based on a simple norm model for the Moon whose basic composition is that of pyrolite III, i.e. the proposed composition of the terrestrial mantle (Ringwood, 1966). However, as is discussed in Section 2 of paper II, model Moons based on the composition of pyrolite I (Green and Ringwood, 1967), another suggested model for the composition of the terrestrial mantle, are also in accord with the lunar data. From Table IV of paper II, the dunite lower mantles of pyrolite III and I norm models contain about 55% and 65% of the mass, respectively. As is discussed in the previous paragraph, the dunite lower mantle of a pyrolite Moon is essentially devoid of K, U and Th. Thus the concentrations of these elements in the pyroxene upper mantle, which is the source area of the mare basalt magmas (e.g., Ringwood and Essene, 1970; Green and Ringwood, 1972; papers I and II), and the anorthosite crust are strongly dependent on the size of the lower mantle. Now, the models are constrained to match the data on the concentrations of K, U and Th in the lunar rocks and to yield a heat flow of about 13 erg cm$^{-2}$ s$^{-1}$. Since the former are related to the concentrations of K, U and Th in upper mantle and crust and the latter is directly related to the total concentration of these elements in the model, the size of the lower mantle is an important parameter in the models.

Third, for the simple model developed in paper II, it is assumed that the crust formed by the cumulation of pure anorthite and that the distribution of K, U and Th in the crust follows directly from the distribution law, see Figure 5 of paper II. However, as is discussed in Section 5 of paper II, the primitive suite of upland rocks was formed by the cumulation of plagioclase, pyroxene and olivine and the trapping of small amounts of peritectic melt by the crystals. As is discussed in detail elsewhere (Binder, in preparation), the trapping of peritectic melt by the cumulating crystals increased the concentration of K, U and Th in the final rock since the concentration of these elements in the melt was, according to Equations (1) and (2) in paper II, 10 times that in the anorthite crystals. In contrast, the cumulation of olivine and pyroxene with the anorthite decreased the concentration of K, U and Th in the final rock since the olivines are essentially devoid of K, U and Th and the pyroxenes have a mean concentration of these elements which is lower than that in the anorthite according to the model developed in paper II. As is discussed in Section 5 of paper II, the earliest upland rocks

were formed predominantly from anorthite crystals and a small amount of peritectic melt and the later rocks were formed predominantly by the cumulation of anorthite, pyroxene and olivine crystals. Based on these results, an analysis of the data presented in Figures 5, 13, 14, 15b and 15c of paper II indicates that the concentrations of K, U and Th in the early- and later formed rocks are nearly a factor of 2 greater than – and over a factor of 2 lower than is indicated for the crustal rocks by the simple model developed in paper II.

On the basis of these three considerations, the simple model for the distribution of K, U and Th in a differentiated pyrolite Moon has been slightly revised. The results derived for models with dunite lower mantles containing 55, 60 and 65% of the lunar mass are given in Table II and Figure 1 gives the distribution of K, U and Th in the

TABLE II

Properties of simple models for the distribution of K, U and Th in a differentiated pyrolite Moon

| Mass of lower mantle (%) | Mean concentration of | | | Mean heat flow (erg cm$^{-2}$ s$^{-1}$) | Range of[a] heat flow (erg cm$^{-2}$ s$^{-1}$) |
| | K (ppm) | U (ppm) | Th (ppm) | | |
| --- | --- | --- | --- | --- | --- |
| 55 | 106 | 0.036 | 0.130 | 14.4 | 12.8–16.1 |
| 60 | 99 | 0.034 | 0.121 | 13.4 | 11.9–15.0 |
| 65 | 86 | 0.029 | 0.105 | 11.6 | 10.3–13.1 |

[a] The upper and lower limits are based on models in which the KREEP zone was formed from the last 0.625% and 0.3125% of the lunar mass respectively and the lunar rock data are fit on the partial melt curves so that the Apollo 11 low K basalt magma was formed by 3% and 1% partial melting, respectively.

model Moon with a lower mantle containing 60% of the mass of the Moon. As in paper II, the lunar rock data taken from Tables VIIa, b of paper II are fit on the curves such that the upland rock with the lowest concentration of K, U and Th falls on the lower part of the crustal distribution curve at the same time the Apollo 11 basalts fall on the mare basalt curves at points which correspond to 1–3% partial melting (e.g., Ringwood and Essene, 1970).

From Table II it is clear that, based on these simple models, the expected heat flow for a Moon of fission origin can easily be matched by the gravitationally differentiated pyrolite models and, at the same time, the observed range of the concentrations of K, U and Th in the lunar rocks can be accounted for. It is noted, however, that the mean concentration of K, U and Th in the lunar upland rocks is considerably higher than the mean concentration of these elements in the crust of the model(s), see Figure 1. As is briefly discussed in Sections 5 and 8 of paper I and in detail elsewhere (Binder, in preparation), the K, U and Th rich KREEP materials of the KREEP zone apparently have been incorporated into the crust via metamorphic and volcanic processes during the first $5-6 \times 10^8$ yr after the primitive crust formed. Thus, the distributions of K, U and Th in the various models shown in Figures 5, 6 and 10 of
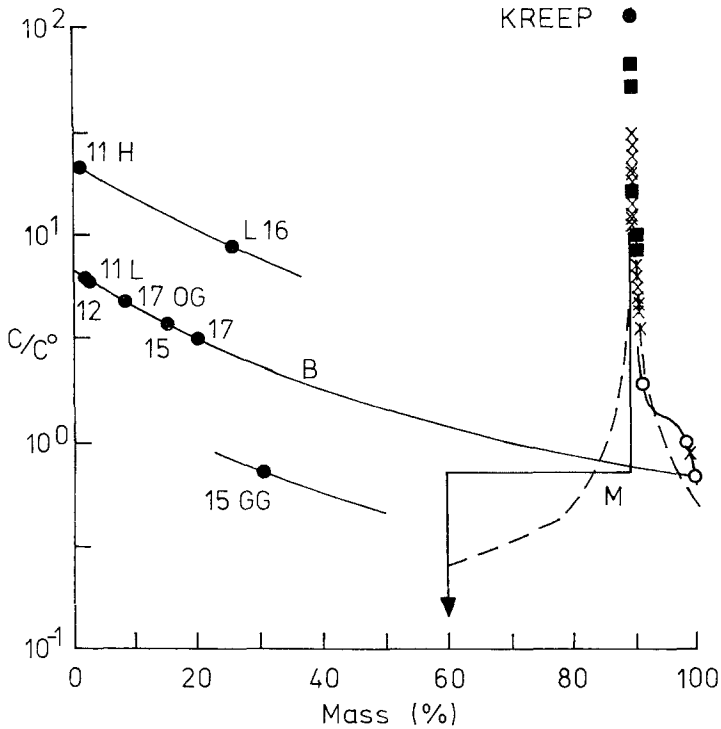
Fig. 1. Predicted concentration ($C$) of K, U and Th in a simple pyrolite norm model moon. The dunite lower mantle in this model contains 60% of the mass of the Moon and lies between 0% and 60% mass in the figure; the pyroxene upper mantle contains 30% of the mass and lies between 60% and 90% mass in the figure and the anorthositic crust contains 10% of the mass and lies between 90% and 100% mass in the figure. Curve $M$ gives the K, U and Th concentration in the whole Moon. The dashed branches of curve $M$ give the distributions of these elements in the upper mantle and crust if the upper mantle were not nearly homogeneous and if the crust were formed from pure anorthite. The solid branches of curve $M$ show the distributions of these elements according to the models developed in papers I and II and in the present paper. Curve $B$ gives the concentrations of K, U and Th in partial melts derived from the upper mantle. The short segments of curves above and below $B$ give the concentrations of K, U and Th in partial melts of the upper mantle in areas where the concentrations of these elements are a factor of $\pm\sqrt{10}$ of that of the average upper mantle. The KREEP point gives the concentration of K, U and Th in a KREEP layer 3.75 km in thickness at the interface of the upper mantle and crust. The lunar rock data, taken from Tables VIIa and b of paper II, are fit on the curves such that the Apollo 11 low K basalt magma was derived by 3% partial melting of the upper mantle. The various mare basalts and the green (GG) and orange (OG) glasses are indicated by filled circles accompanied by identification numbers and, in some cases, a letter. The highland rocks are indicated as following: anorthosites by open circles, breccias by $x$'s and crystalline rocks by filled squares. The $x$ axis gives the mass of the Moon crystallized for curve $M$ and the mass of the upper mantle which partially melted for curve(s) $B$.

paper II and Figure 1 of this paper represent the initial distribution of these elements in the crust of the Moon and not their present distribution. This is also true for the upper mantle under the maria since, from Equations (1) and (4) of paper II, the partial melting (on the average $\sim 10\%$) which produced the mare basalt magmas (e.g., Ringwood and Essene, 1970; Green and Ringwood, 1972; paper I and II) has removed

about 65% of the K, U and Th originally found in the periodite upper mantle. How-
ever, both of these processes (i.e., partial melting of the upper mantle and the meta-
morphism of the primitive crust via KREEP fluids) would have effected the distribu-
tion of K, U and Th mainly in the vertical column, not horizontally. Thus the basic
models presented in Table I and in Figure 1 can be used as a basis for discussing the
variations of the heat flow over the lunar surface without leading to incorrect con-
clusions.

According to the models calculated, the percent of the total heat produced in the
various zones in a pyrolite Moon are quite insensitive to the model parameters and
are as follows: the dunite lower mantle $\sim 0\%$; the peridotite upper mantle $\sim 21\%$;
the KREEP zone $\sim 60\%$; the anorthositic crust $\sim 19\%$. Thus, for a mean heat flow of
13.2 erg cm$^{-2}$ s$^{-1}$ as calculated above, the upper mantle, KREEP zone and the crust
contribute $\sim 2.8$, $\sim 7.9$ and $\sim 2.5$ erg cm$^{-2}$ s$^{-1}$ respectively to the total heat flow.

From the above, it is apparent that the KREEP zone is the most important con-
tributor to the heat flow. According to the models developed in paper II and in this
paper, the KREEP zone is at most a few km thick. However, it is most unreasonable
to assume that such a thin layer would be uniform on the Moon-wide scale. According
to the sequence developed in papers I and II, the mixture of crystals and melt, from
which the upper mantle and the crust developed, was in convective motion in the
region now occupied by the upper mantle until the time when the solidification of the
last few tenths of a percent of the Moon produced the KREEP zone at the crust-
upper mantle boundary. Thus, the KREEP, U and Th rich residual fluids were prob-
ably concentrated in the KREEP zone in areas where ascending and descending cur-
rents of the convection cells occurred. Also, the bottom of the crust was most probably
irregular due to isostatic adjustments of the crust as a result of cratering and tectonic
processes which were active prior to the formation of the KREEP zone. It is likely
that the KREEP rich fluids were concentrated in the highs (i.e., where the crust was
thin) and deficient in the lows (i.e., where the crust was thick) of the crust-upper
mantle interface. Since the average thickness of the crust is $\sim 65$ km; and since the
last part of the upper mantle which was in convective motion (see paper II) was
several tens of km thick, the horizontal scale of the irregularities in the thickness of
the KREEP zone, due to the above mentioned effects, must be a few hundreds of km
and greater. It is estimated that the thickness of the KREEP zone must vary from
essentially 0 to, conservatively, 3 times its average thickness. Based on the heat pro-
duction values given in the last paragraph, the heat produced by the undisturbed
crust and upper mantle are, together, 5.3 erg cm$^{-2}$ s$^{-1}$ and the heat flow produced
by the non-uniform KREEP zone varies from 0 to more than 24 erg cm$^{-2}$ s$^{-1}$. Thus,
the non-uniform distribution of the KREEP zone must lead to values of the heat flow
from about 5 to more than 30 erg cm$^{-2}$ s$^{-1}$ on a scale of hundreds of km and greater.

In addition to the heat flow variations caused by the initial irregularities in the
distribution of the KREEP zone, basin forming impacts must have also led to heat
flow variations. First, any impact which produced a transient crater (Dence et al., 1974)
deep enough to reach well into the upper mantle (craters or basins larger than about

300 km) would have removed the KREEP zone and the crust from the area within the crater. The initial basin must be filled with a plug of upper mantle peridotite (Wise and Yates, 1970) which is capped by 20–25 km of mare basalts (see paper I) derived by partial melting of the upper mantle (e.g., Ringwood and Green, 1972; papers I and II) below the basin. As discussed earlier, the net balance of the concentration of K, U and Th in a vertical column is uneffected by partial melting and the migration of the resulting magmas to the surface; thus, the heat flow in large basins is essentially equivalent to the heat produced in the pristine upper mantle, i.e. $\sim 2.8$ erg cm$^{-2}$ s$^{-1}$.

Second, the ejecta thrown out by the impact will cause an enhancement of the heat flow due to the local thickening of the crust and the deposition of K, U and Th rich materials, which were excavated from the KREEP zone as part of the ejecta. Rough estimates of the enhancement of the heat flow around a large basin based on the data given by Stöffler et al. (1974) indicate that a 20–30% increase at the true rim of the basin is to be expected. The magnitude of this effect decreases rapidly to 3–4% at 1 radius from the basin rim. However, in areas such as the Apollo 15 and 17 landing sites, where several basin ejecta blankets overlap (e.g., see Figure 3 of Taylor et al., 1974), the cumulative effects of the K, U and Th enrichment in the upper layers of the crust and the thickening of the crust by the deposition of ejecta can lead to an increase in the local heat flow of roughly 50%. Depending on the local thickness of the KREEP zone, the effects of basin ejecta deposition can result in regional variations in the heat flow from about 8 erg cm$^{-2}$ s$^{-1}$ to more than 45 erg cm$^{-2}$ s$^{-1}$ at the rim of the basin.

It is also noted here that the accumulation of K, U and Th (derived from the KREEP zone) in the upper layers of the crust in areas where several ejecta blankets overlap might explain the asymmetric distribution of these elements in the surface layer of the Moon as found by Metzger et al. (1973, also see the frontispiece of Vol. 1 of the *Proceedings of the Fourth Lunar Science Conference*). This would be the case if (1) the basin impacts (principally the Imbrium basin impact) on the front side of the Moon, where the crust is relatively thin (see papers I and II), were able to excavate large amounts of K, U and Th rich materials from the KREEP zone and spread it around the front side of the Moon and (2) if these processes were not as effective on the back side of the Moon since the crust there is significantly thicker than on the front side.

Alternatively, the data of Metzger et al. (1973) might indicate that, originally, the KREEP zone on the front side of the Moon was several times thicker than on the back side. Such a large scale asymmetry in the distribution of U, Th and KREEP could have occurred if the asymmetry in the thickness of the crust pre-dated the formation of the KREEP zone. As is discussed above, it is expected that, on the regional scale, the U, Th and KREEP residual fluids would have been concentrated in areas where the crust was thin and deficient in areas where the crust was thick. If this also holds on the Moon-wide scale, then the KREEP zone would be much thicker under the thin front side crust and much thinner under the thicker back side crust. If so,

then the early metamorphism of the crust by the K, U and Th rich fluids from the KREEP zone would have produced the asymmetric distribution of K, U and Th in the crust of the Moon as indicated by the data of Metzger *et al.* (1973). It also follows that the heat flow on the front side of the Moon would be, on the average, considerably higher than on the back side. If this is correct, then the regional variations in the heat flow discussed above would be superimposed on this hemispherical variation in the heat flow. However, at the present, the available data are too limited to allow one to determine which of these two explanations of the Metzger *et al.* (1973) data is more likely. As such, the former will be adopted in this paper.

Figure 2, which is based on the above discussions, depicts schematically the regional variations in the structure of the crust and the KREEP zone and the associated variations in the heat flow.

At the present, there are only two meaningful heat flow measurements made on the Moon – i.e., the Apollo 15 and 17 heat flow measurements (Langseth *et al.*, 1972, 1973). Unfortunately, both of these measurements were made at the edges of maria which, from the discussions given above, are expected to have atypically high heat flow. As discussed by Langseth *et al.* (1973), the heat flow at Rima Hadley is $31 \pm 6$ erg cm$^{-2}$ s$^{-1}$ and that at Taurus-Littrow is $28 \pm 6$ erg cm$^{-2}$ s$^{-1}$. However, Langseth *et al.* (1973) indicate that the Taurus-Littrow measurement must be corrected
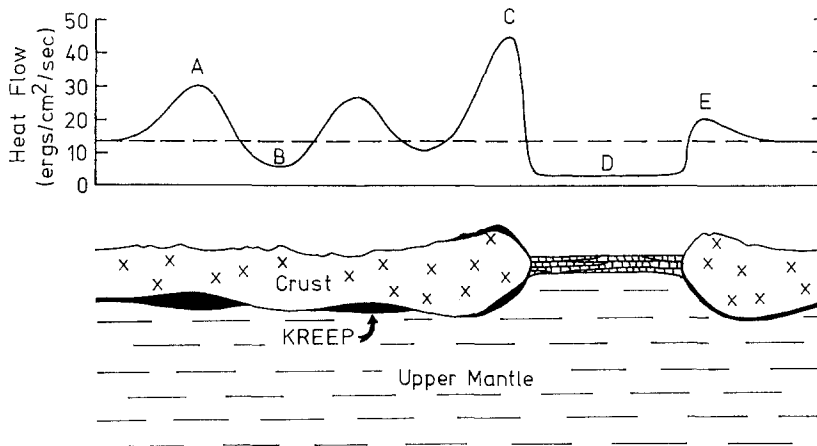


Fig. 2. Schematic cross-section of the lunar crust, the KREEP zone and the upper mantle and the regional variations in the heat flow associated with non-uniformities in the distribution of KREEP (black) and mare basins. The dashed line in the upper part of the figure gives the predicted, mean value for the lunar heat flow, i.e. 13 erg cm$^{-2}$ s$^{-1}$. The maximum of 30 erg cm$^{-2}$ s$^{-1}$ at $A$ is caused by a conservatively estimated maximum concentration of K, U and Th rich KREEP of a factor of 3 above the mean value. The minimum of 5 erg cm$^{-2}$ s$^{-1}$ at $B$ is due to the complete lack of the KREEP zone at the crust-upper mantle boundary. The maximum of 45 erg cm$^{-2}$ s$^{-1}$ at $C$ is due to a factor of 3 concentration of KREEP in the KREEP zone and the thickening of the crust and the accumulation of KREEP in mare basin ejecta. The minimum of 3 erg cm$^{-2}$ s$^{-1}$ at $D$ is due to the removal of the crust and the KREEP zone by basin forming impacts. The maximum of 20 erg cm$^{-2}$ s$^{-1}$ at $E$ is due to the thickening of the crust and the accumulation of KREEP in mare basin ejecta in an area with the mean concentration of KREEP in the KREEP zone.

for topographic effects and that the correction is $-15$ to $-25\%$. Thus, the heat flow at Taurus-Littrow is apparently $22 \pm 5$ erg cm$^{-2}$ s$^{-1}$. If we assume that the undisturbed heat flow at these two sites is equal to the mean lunar value of 13.2 erg cm$^{-2}$ s$^{-1}$ and that the effects of basin ejecta overlap have increased the heat flow by 50% as estimated above for these two sites, then these sites are expected to have a heat flow of about 20 erg cm$^{-2}$ s$^{-1}$. This value is essentially the same as the Taurus-Littrow measurement and only 20% below the lower limit of 25 erg cm$^{-2}$ s$^{-1}$ for the Rima Hadley measurement. Alternatively, the values of 22 and 31 erg cm$^{-2}$ s$^{-1}$ found for these two sites and even the upper limit of 37 erg cm$^{-2}$ s$^{-1}$ for the Rima Hadley site are lower than the conservatively estimated upper limit of 45 erg cm$^{-2}$ s$^{-1}$ for the heat flow at a basin rim. Thus, the available data do not contradict the differentiated pyrolite Moon models of fission origin developed in papers I and II.

In conclusion, it is noted that while the computed value of 13 ergs cm$^{-2}$ s$^{-1}$ for the lunar heat flow is diagnostic for a Moon of fission origin, the analysis of the regional and possible hemispherical variations in the heat flow applies to any model of the Moon in which large scale gravitational differentiation has played an important role in the development of the crust and mantle of the Moon.

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