Calculation of the Ionization due to Radioactive Substances in the Ground

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Abstract

In earlier calculations it seems not to have been considered that the penetrating γ radiation from the ground can, independent of the density and composition of the ground, be expressed by the simple formula $I = C \times S$, where S is the proportion of radioactive element in g/g and C is a constant. Formulas for the ionization in the case when the ground is covered with an absorber of greater density than air, or when the radiation travels through air for long distances, are derived. The ionization from various minerals is calculated and is found to agree in magnitude with measured values. Curves, showing the decrease in the ionization as a function of the depth of snow cover, are given for three different values of snow density. The decrease in the dose rate with the altitude above the earth's surface is shown graphically.

Introduction

Natural ionization over the earth's surface is caused mainly by radioactive radiation coming from the ground and by cosmic radiation. The latter radiations result in a nearly constant ionization, if variations during short intervals and changes with the altitude are not taken into account. In contrast, radiation from the ground varies widely with local conditions.

In this communication formulas for the ionization due to radioactive minerals have been derived, and the absorption caused by snow and air has been taken into account. All the previous calculations, which were made 30—40 years ago, were characterized by the fact that one (or in some cases 2—3) (KOHLRAUSCH 1917) absorption coefficient was used to describe the total radiation from a decay series. A few years ago these older formulas were used by V. F. HESS (1947) and recently, formulas for the natural background radiation based on the same simplifications have appeared in the literature (PEIRSON and FRANKLIN 1951).

Radiations

Gamma radiation: Only the γ radiation from the U-Ra- and Th-series and from K^{40} gives a measurable contribution to the natural ionization, and this contribution is due to a comparatively small number of the γ energies. Table I gives the energy levels whose rhm/curie[1] values are greater than 0.001 and the corresponding absorption coefficients for snow and air.

Column 3 shows the number of quanta emitted per primary disintegration for each of the energy values. This number is found from the decay scheme of the nuklides. For MsTh 2 this scheme is not known in detail. But about 90 % of the radiation, measured photographically (BLACK 1924) is due to the three lowest energies. If we take an average of these as the radiation energy of MsTh 2, the error in the final value will be negligible since the radiation dose from MsTh 2 amounts

[1] rhm is the radiation in r units per hour at 1 m distance, r being the international dose-unit measured by ionization in air.

Table I

Element	$h\nu$ MeV	n quanta per prim. disintegr.	$h\nu nf$ MeV	σ_i snow $\varrho = 0.10$	σ_i snow $\varrho = 0.25$	σ_i snow $\varrho = 0.40$	σ_{il} air
Ra	0.184	0.012	0.0005	$1.246 \cdot 10^{-2}$	$3.113 \cdot 10^{-2}$	$4.989 \cdot 10^{-2}$	$16.12 \cdot 10^{-5}$
RaB	0.241	0.115	0.0066	1.150	2.873	4.603	14.88
	0.294	0.258	0.0205	1.078	2.692	4.314	13.94
	0.350	0.450	0.0457	1.008	2.519	4.037	13.04
RaC	0.607	0.658	0.1454	0.801	2.000	3.205	10.36
	0.765	0.065	0.0199	0.722	1.805	2.892	9.346
	0.933	0.067	0.0270	0.659	1.647	2.639	8.528
	1.120	0.206	0.1061	0.599	1.496	2.398	7.749
	1 238	0.063	0.0373	0.563	1.406	2.253	7.282
	1.379	0.064	0.0433	0.527	1.316	2.109	6.815
	1.761	0.258	0.2362	0.439	1.098	1.759	5.682
	2.198	0.074	0.0887	0.376	0.940	1.506	4.868
MsTh 2	0.090	1.00	0.0113	1.514	3.783	6.061	19.59
ThB	0.1151	0.03	0.0005	1.451	3.625	5.808	18.76
	0.2381	0.91	0.0516	1.156	2.888	4.627	14.95
	0.3001	0.03	0.0024	1.069	2.670	4.278	13.82
ThC″	0.2518	0.02	0.0005	1.129	2.820	4.519	14.60
	0.2767	0.10	0.0025	1.096	2.737	4.386	14.17
	0.5110	0.17	0.0103	0.861	2.151	3.446	11.14
	0.5832	0.60	0.0441	0.816	2.038	3.266	10.55
	2.624	0.92	0.4782	0.328	0.820	1.313	4.244
	3.240	0.08	0.0540	0.271	0.677	1.085	3.505
K^{40}	1.54	0.04	0.0310	0.488	1.218	1.952	6.308

to about 5 % of the total dose from the thorium series, which means approximately 1 % of the total natural radiation on the earth's surface from the most common minerals (see below).

Several schemes for the disintegration of K^{40} have recently been proposed (SPIERS 1950, MATTAUCH and FLAMMERSFELD 1949, GRÁF 1951). Since none of these seem to have any marked superiority over the others, the calculations have been made for three different alternatives.

Actinium gives no measurable radiation because of its very small occurrence and the low gamma energies. C^{14}, and probably Rb^{87}, are beta emitters.

Beta radiation: The β radiation is absorbed by the air already at a few meters above the earth's surface. The ionization due to β radiation is usually small because only those particles emitted from a thin layer near the surface actually escape into the atmosphere. Even with very thin-walled measuring chambers the ionization due to β rays from the earth's surface will be very small and will not be considered here.

"*Bremsstrahlung*": However, β radiation gives a secondary effect, the "Bremsstrahlung", which must be taken in account. The approximate formula

$$\frac{(dE/dx)_{\text{"Bremsstrahlung"}}}{(dE/dx)_{\text{ionization}}} = \frac{E \cdot Z}{820}$$

shows that for K^{40} in the most common igneous rocks, for which the average of the atomic number is about 12, approximately 10 % of the energy of the β radiation is transformed into the "Bremsstrahlung". Its total absorption coefficient is somewhat higher than that of the γ radiation. The "Bremsstrahlung" dose from K^{40} on the earth's surface may be about 10 % of the γ dose from the same isotope.

A rough estimate of the contribution of the "Bremsstrahlung" to the ionization due to radium and thorium in the ground shows this to be 1 % or less of the total ionization from these elements.

The absorption coefficient

The total absorption coefficient μ is given by $\mu = \tau + \sigma + \pi$, where τ is the absorption coefficient due to the photo effect, σ to Compton scattering and absorption and π to pair production. The energies recorded in table I vary between 90 and 3,240 keV. Between 200 and 2,000 keV, energy absorption due to photo effect and pair production is negligible compared with that due to the Compton effect for the absorbers considered below.

The photo effect is of secondary importance compared with the Compton effect even at energy levels as low as 90 keV (MsTh 2) in the absorbers considered. Since the radiation from MsTh 2 contributes only about 1 % of the total absorbed energy it is not necessary to take the photo effect into account.

Pair production, which occurs for energies greater than 1.02 MeV, is measurable only for the two highest γ energies of 2.624 and 3.240 MeV respectively from ThC″. For these energies π is 4 % and 7.4 % respectively of σ. Taking these corrections into consideration a value for the dose rate is obtained that is about 99.7 % of that without correction. Consequently, the pair production can also be neglected.

The Compton absorption coefficient can be calculated by the use of KLEIN-NISHINA's (1929) formulas. The total Compton coefficient per electron, ${}_e\sigma$, and the Compton absorption coefficient per electron, ${}_e\sigma_a$, are given as functions of the energy in MeV in fig. 1.

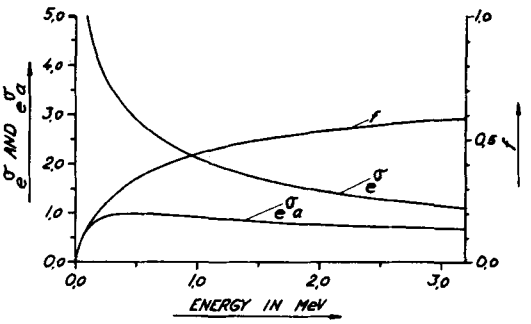

Fig. 1. The total Compton coefficient per electron, ${}_e\sigma$, the Compton absorption coefficient, ${}_e\sigma_a$, and their quotient ${}_e\sigma_a/{}_e\sigma$ are given as functions of the energy in MeV.

The third curve of fig. 1 shows the dependance of $\left(\frac{{}_e\sigma_a}{{}_e\sigma}\right)_i = f_i$ on the energy. To find the absorption coefficient we have to multiply the Klein-Nishina coefficient with the number of electrons per cc. We arrive at

$$\sigma = L\varrho\,{}_e\sigma \sum_i p_i \frac{Z_i}{W_i} \text{ and } \sigma_a = L\varrho\,{}_e\sigma_a \sum_i p_i \frac{Z_i}{W_i}$$

where L is Avogadro's number ($6.023 \cdot 10^{23}$)
ϱ the density
Z_i the atomic number of the element with index i, contained in the absorber
W_i the atomic weight of the same element
p_i the part by weight of the absorber that consists of the element with the atomic number Z_i

Scattered radiation

The lack of information on the scattered radiation makes calculations of this kind approximate. This problem has been dealt with in a theoretical way by several authors (HIRSCHFELDER et al. 1948, LEWIS 1950, MEREDITH 1951), with different limiting assumptions. Using values published by HIRSCHFELDER, MAGEE and HULL (1948) for the part of the total intensity which is due to unscattered radiation, a rough estimate of the contribution of the scattered radiation has been made in the following way. Let us imagine a series of planes in the ground parallel to the earth's surface separated by a distance of one cm. The ionization due to the radiation from a layer bounded by two of these planes can be expressed in per cent of the total primary radiation. From the values given by Hirschfelder et al. we find what part this is of the total radiation from the layer in question. Dividing by this number we get the total radiation from the layer. By adding the radiation from the different layers an approximate integration is made. The total radiation determined in this way will be expressed in per cent of the primary radiation. These calculations have been made for 1 MeV and for 3 MeV. In the first instance the total radiation was found to be 118 % of the primary one and in the latter 116 %.

For this estimate the following simplifications have been made. Hirschfelder's formulas are valid only for a homogeneous bundle. As will be seen below, the natural radiation from the ground in special cases behaves like a homogeneous bundle, for if the absorption caused by the air is neglected, the dose is not dependent on the distance from the earth's surface. This simplification makes the values too small. However, no account is taken of the fact that the scattered radiation is softer than the unscattered one, and this will make the correction too high. Since, as was said above, the effect of the scattered radiation is almost the same, expressed in per cent, for radiation of the energies one and three MeV, and because the energies of greatest importance in the practical case are of a magnitude between these limits, we see that we can take the correction factor to be 1.2 and that we can be almost sure that this figure should not be 1.1 or 1.3.

A correction of 20 % for the scattered radiation is therefore added to all values obtained. The calculated radiation for potassium is corrected by an additional 5 or 10 % to account for the "Bremsstrahlung".

Theoretical calculations

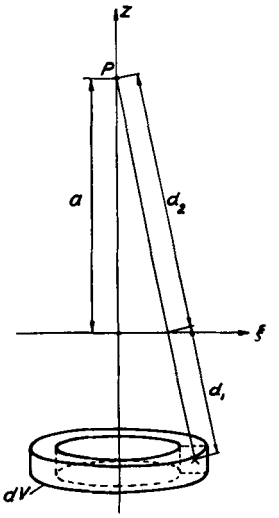

Fig. 2.

The ionization contribution in point P (fig. 2 above) from the ring-shaped volume element dV and of energy E_i is

$$dI_i = \frac{1}{4\pi r^2} \cdot \frac{E_i n_i \sigma_{ial}}{6.77 \cdot 10^4} \cdot c\,dV \cdot \cdot 3.7 \cdot 10^{10} \cdot e^{-(\sigma_{ig} d_1 + \sigma_{il} d_2)}$$

roentgen/sec.

I_i = dose rate due to quanta of energy E_i
r = distance in cm
E_i = quantum energy in MeV
n_i = number of quanta of energy E_i per primary disintegration
σ_{ial} = absorption part of the Compton coefficient for the air and energy E_i
σ_{il} = total Compton coefficient for the air and for energy E_i
σ_{ig} = total Compton coefficient for the ground and energy E_i
c = number of curies of radioactive element per cc

Here $3.7 \cdot 10^{10} \cdot c$ is the number of disintegrations/cc sec. Let us assume that the ground contains S g radioactive element per g. The amount of the nuklide per cc is $S\varrho_g$, where ϱ_g is the density of the ground. The number of atoms of the nuklide per cc is $S\varrho_g L/W$ where W is the atomic weight and L Avogadro's number. The number of disintegrations per second will be

$$\lambda \cdot \frac{S\varrho_g L}{W} = \frac{0.693}{T_{sec}} \cdot \frac{S\varrho_g L}{W} = 3.7 \cdot 10^{10} \cdot c$$

Inserting this expression for c, adding over all energies and multiplying by $2.08 \cdot 10^9$, we find the ionization in ion pairs/cc sec.:

$$dI = 3.24 \cdot 10^{19} \cdot \frac{S\varrho_g}{T_{years} W} \cdot \frac{1}{r^2} \cdot \cdot \sum_i E_i n_i \sigma_{ial} \cdot e^{-(\sigma_{ig} d_1 + \sigma_{il} d_2)} \cdot dV$$

ion pairs/cc sec.

Here is

$$dV = 2\pi \xi\, d\xi\, dz, \quad d_1 = \frac{-z}{a-z} \cdot r \text{ and}$$

$$d_2 = \frac{a}{a-z} \cdot r$$

The radiation over an infinite plane is expressed by the following, if we take into account the

radiation coming from layers down to a depth of A cm under the earth's surface.

$$I = 2.03 \cdot 10^{20} \frac{S\varrho_g}{T_{\text{years}} W} \cdot$$

$$\cdot \sum_i E_i n_i \sigma_{ial} \int_{-A}^{0} dz \int_{0}^{\infty} \frac{e^{-(a\sigma_{il} - z\sigma_{ig}) \cdot \frac{r}{a-z}}}{(a-z)^2 + \xi^2} d\xi$$

If we take r as the independent variable and take $\frac{a\sigma_{il} - z\sigma_{ig}}{a-z} \cdot r = \gamma$, the expression becomes

$$I = 2.03 \cdot 10^{20} \cdot \frac{S\varrho_g}{T_{\text{years}} W} \cdot$$

$$\cdot \sum_i E_i n_i \sigma_{ial} \int_{-A}^{0} dz \int_{a\sigma_{il} - z\sigma_{ig}}^{\infty} \frac{e^{-\gamma}}{\gamma} d\gamma =$$

$$= -2.03 \cdot 10^{20} \cdot \frac{S\varrho_g}{T_{\text{years}} W} \sum_i E_i n_i \sigma_{ial} \cdot$$

$$\cdot \int_0^A \boldsymbol{Ei}\left[-\sigma_{ig}\left(t + \frac{\sigma_{il}}{\sigma_{ig}} \cdot a\right)\right] dt$$

where $\boldsymbol{Ei}$ denotes the exponential-integral.

For this is valid

$$\int_{x+b}^{\infty} \frac{e^{-mt}}{t} dt = e^{-mb} \int_{x}^{\infty} \frac{e^{-mt}}{b+t} dt =$$

$$= -\boldsymbol{Ei}[-m(x+b)]$$

Thus

$$\int_0^{\gamma} \boldsymbol{Ei}[-m(b+t)]\, dt = -e^{-mb} \int_0^{\gamma} \phi(x)\, dx$$

where $\phi(x) = \int_x^{\infty} \frac{e^{-mt}}{b+t} dt$

By partial integration we find

$$\int_0^{\gamma} \boldsymbol{Ei}[-m(b+t)]\, dt = -e^{-mb}[x \cdot \phi(x)]_0^{\gamma} +$$

$$+ e^{-mb} \int_0^{\gamma} x \cdot \frac{d\phi(x)}{dx} dx = (\gamma + b) \cdot$$

$$\cdot \boldsymbol{Ei}[-m(\gamma+b)] - b \cdot \boldsymbol{Ei}(-mb) -$$

$$- e^{-mb} \cdot \frac{1 - e^{-m\gamma}}{m}$$

As γ approaches infinity this becomes

$$\int_0^{\infty} \boldsymbol{Ei}[-m(b+t)]\, dt = -b \cdot \boldsymbol{Ei}(-mb) - \frac{e^{-mb}}{m}$$

or in the practical case

$$I = 2.03 \cdot 10^{20} \cdot \frac{S\varrho_g}{T_{\text{years}} W} \cdot \sum_i E_i n_i \cdot$$

$$\cdot \frac{\sigma_{ial}}{\sigma_{ig}} [a\sigma_{il} \boldsymbol{Ei}(-a\sigma_{il}) + e^{-a\sigma_{il}}]$$

If the absorption caused by the air is neglected, which is permissible if the distance from the earth's surface does not exceed a few meters, we get

$$I = 2.03 \cdot 10^{20} \cdot \frac{S\varrho_g}{T_{\text{years}} W} \cdot \sum_i E_i n_i \cdot \frac{\sigma_{ial}}{\sigma_{ig}}$$

ion pairs/cc sec.

We see from this that the dose rate is independent of the distance from the earth's surface, taking into consideration the limitations imposed by the absorption due to air.

If we introduce the expressions for σ_{ig} and σ_{ial} from page 56 this becomes

$$I = 2.03 \cdot 10^{20} \cdot \frac{S\varrho_l}{T_{\text{years}} W} \cdot$$

$$\cdot \frac{\sum_j p_{jl} \cdot \frac{Z_{jl}}{W_{jl}}}{\sum_\nu p_{\nu g} \cdot \frac{Z_{\nu g}}{W_{\nu g}}} \cdot \sum_i E_i n_i f_i$$

where $f_i = \left(\frac{e\sigma_a}{e\sigma}\right)_i$ of the energy in question (see fig. 1) and ϱ_l is the density of the air. For the elements contained in air and most common minerals, $\Sigma p \cdot \frac{Z}{W}$ has a value near to 0.500. For the minerals for which calculations have been made the value is between the limits 0.497 and 0.500. Therefore the formula can be written

$$I = 2.63 \cdot 10^{17} \cdot \frac{S}{T_{\text{years}} W} \cdot \sum_i E_i n_i f_i$$

ion pairs/cc sec.

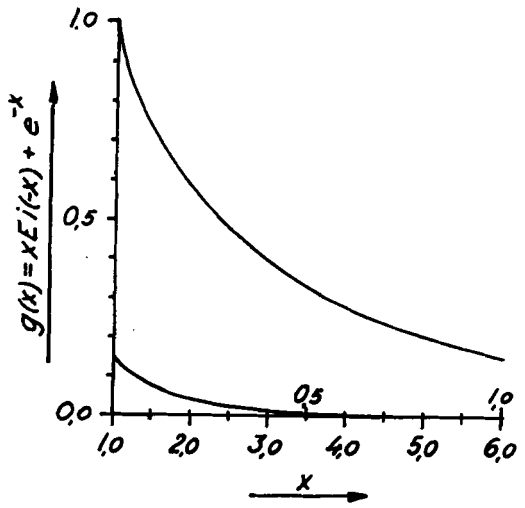

Fig. 3. The upper curve refers to the upper scale on the abscissa and the lower curve to the lower one.

$\sum_i E_i n_i f_i$ is a constant. Thus the radiation from a decay series can, near the earth's surface, be expressed by $I = \text{const.} \cdot S$

It is apparent that the only variable is the proportion of the radioactive element expressed in g/g. We need know neither the density of the ground nor its composition (and so the absorption coefficients) to be able to calculate the ionization on the surface.

If, however, the absorption caused by the air cannot be neglected or if the earth's surface is covered with an absorber of greater density, for example snow, the formula must be written

$$I = 2.63 \cdot 10^{17} \cdot \frac{S}{T_{\text{years}} W} \cdot \sum_i E_i n_i f_i g_i$$

where

$$g_i = a\sigma_i \, \boldsymbol{Ei}(-a\sigma_i) + e^{-a\sigma_i}$$

or if we write $a\sigma_i = x$; $g_i = x \cdot \boldsymbol{Ei}(-x) + e^{-x}$ where σ_i is the total Compton coefficient of the absorber. $g(x)$ is seen in fig. 3. The upper curve refers to the upper scale on the abscissa and the lower curve to the lower one.

If we take into account the absorption caused both by the snow and the air g_i has the form

$$g_i = [b\sigma_i + (a - b)\sigma_{il}] \cdot \boldsymbol{Ei}[-b\sigma_i - (a - b)\sigma_{il}] + e^{-b\sigma_i - (a-b)\sigma_{il}}$$

(where b is the depth of the snow cover and a is the distance from the earth's surface to the measuring point) or by writing $b\sigma_i + (a - b)\sigma_{il} = x$

$$g_i = x \cdot \boldsymbol{Ei}(-x) + e^{-x}$$

This function is also valid if the air absorption it neglected, and we see that $g(x_1) \cdot g(x_2) = g(x_1 + x_2)$.

Practical calculations

Because the statements as to the half-life and decay scheme of K^{40} differ so widely, dose rate calculations for the potassium radiation have been made for three alternatives.

The expressions for the dose rates due to the different decay series are:

$$I_{Ra} = 0.565 \cdot 10^{12} \cdot S_{Ra}$$
$$I_{Th} = 0.534 \cdot 10^{5} \cdot S_{Th}$$
a. $I_K = 44.1 \cdot S_{K^{39}}$
b. $I_K = 27.3 \cdot S_{K^{39}}$
c. $I_K = 50.7 \cdot S_{K^{39}}$

The alternatives a, b and c refer to the following constants:

a. $T_{\frac{1}{2}} = 0.55 \cdot 10^9$ years; $\% \gamma = 4$[1]
b. $T_{\frac{1}{2}} = 1.11 \cdot 10^9$ years; $\% \gamma = 5$[2]
c. $T_{\frac{1}{2}} = 1.33 \cdot 10^9$ years; $\% \gamma = 11$[3]

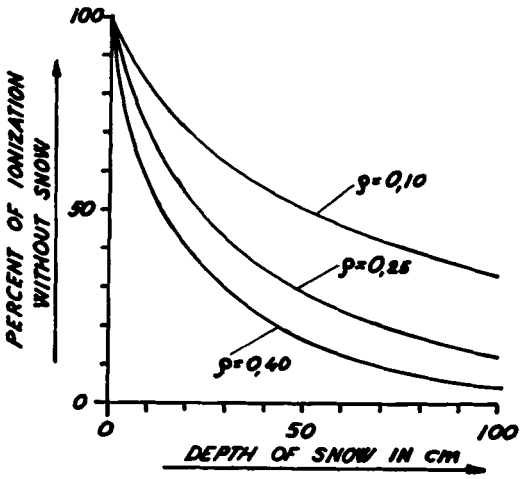

Fig. 4. The decrease in the ionization with the depth of the snow cover is given for three different densities of the snow.

[1] SPIERS (1950). [2] MATTAUCH and FLAMMERSFELD (1949). [3] GRÁF (1951).

The potassium radiation is corrected by 10 % for the "Bremsstrahlung" in the alternatives a and b and by 5 % in the alternative c. It is assumed that 0.0119 % of all potassium is K^{40} (NIER 1950).

The proportions of radium, thorium and potassium (observe that it is the usual potassium isotope) in some common minerals are collected in table II.

On the basis of these proportions the values of ionization over different minerals in table III have been calculated.

Fig. 4 shows the decrease in the ionization as a function of the depth of the snow cover, for three different values of the density of the snow.

It is to be observed that the curves show only the decrease in the radiation from the ground. The almost constant contribution of the cosmic radiation makes the observed variations less. The earth's surface is assumed to be composed of igneous rocks having an average composition. The form of the curves in the case when the ground has another composition are very similar to that of fig. 4.

The decrease in the radiation with the altitude above the earth's surface is given in fig. 5. (The earth's surface is assumed to be composed of igneous rocks.) The lower curve shows the decrease in the primary radiation. The upper one gives an upper limit for the radiation, taking into account only the absorption part of the Compton coefficient of air in the exponential factor. This means that it has been assumed that all scattered radiation is directed forward and is of the same wavelength as the unscattered radiation.

All values required for the calculations are given in table I. SPIERS' values for the constants of K^{40} are used in the calculation of the values on which the curves of figs 4 and 5 are based.

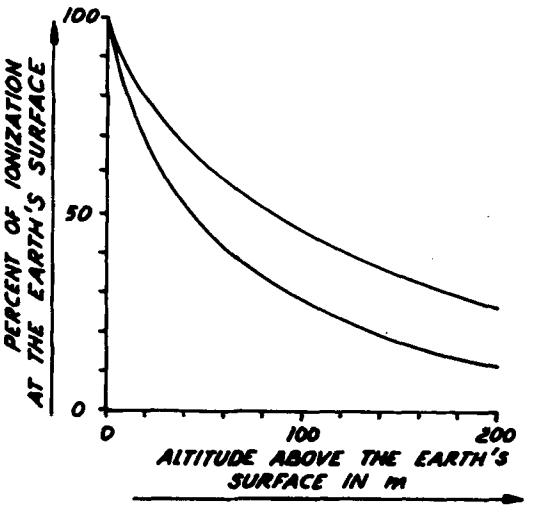

Fig. 5. The lower curve shows the decrease in the primary radiation with the altitude above the earth's surface. The upper curve gives an upper limit for the radiation.

Discussion

The errors depending on the uncertainty of the constants used are only 2 to 3 % for Ra and Th, whereas they are 40—50 % for K^{40}. This is evident from the expressions for the three alternatives for the potassium radiation.

If we assume that one of the three statements as to the constants of K^{40} is correct, we can say that the error of that value of the total dose rate which is obtained by use of the corresponding expression for the radiation from K^{40}, after correction for scattering and "Bremsstrahlung", is 15 % or less. This is the case if, as we can assume, the error of the correction factor for the scattered radiation is less than 10 %, the error of the primary dose is 2—3 % and if that of the correction factor for the "Bremsstrahlung" from potassium results in an error of 1—2 % in the final value. To this are to be added the errors caused by the uncertainty of the proportions of radioactive elements given in table II.

In a recent paper some measurements have been published (SIEVERT and HULTQVIST 1952) showing a variation in the radiation over different rocks from 5.5 to 10.5 ion pairs/cc sec., and these values are situated between the limits which are to be expected from table III.

Table II

Mineral	(g Ra^{226} per g) · 10^{12}	(g Th^{232} per g) · 10^{6}	(g K^{39} per g) · 10^{2}
Igneous rocks:			
Average[1]	1.3	12	2.6
Acidic rocks: > 65 % SiO_2			
Granites, average[2]	3.1	20	3.4
Quincy granite[3]	1.0	9	3.9
Younger granites in Finland (max. values)[2]	6.5	59	5.1
Granodiorit[2]	2.7	18	2.5
Medium rocks 65—55 % SiO_2			
Diorit[2]	1.4	6	1.7
Basic rocks < 55 % SiO_2			
Gabbro[2]	0.83	5.1	0.7
Ultrabasic rocks			
Peridodit[2]	0.52	3.3	0.8
Sedementary rocks:			
Clay	1.5[4]	11[4]	2—3[5]
Sandstone	1.4[4]	5[4]	1.1[5]
Limestone	0.9[4]	< 1[4]	0.3[5]

[1] RANKAMA and SAHAMA 1950. [2] HOLMES 1930. [3] HESS 1947. [4] HOLMES 1915. [5] MACHATSCHKI 1948.

Table III

Calculated values of the dose rate over various minerals

The dose rate is expressed in ion pairs/cc sec. For each mineral the values corrected for scattered radiation and "Bremsstrahlung" are given by the numerals in bold face. The cosmic radiation is not included.

Mineral	Ionization due to content of					Total ionization		
	Ra	Th	K^1	K^2	K^3	1	2	3
Igneous rocks:								
Average	0.7	0.6	1.1	0.7	1.3	2.5 **3.1**	2.1 **2.6**	2.6 **3.2**
Acidic rocks: > 65 % SiO_2								
Granites, average	1.8	1.1	1.5	0.9	1.7	4.4 **5.4**	3.9 **4.8**	4.7 **5.7**
Quincy granite	0.6	0.5	1.7	1.0	2.0	2.8 **3.5**	2.2 **2.7**	3.1 **3.8**
Younger granites in Finland (max. values)	3.7	3.2	2.2	1.4	2.6	9.2 **11.2**	8.4 **10.2**	9.5 **11.5**
Granodorit	1.5	1.0	1.1	0.7	1.3	3.7 **4.5**	3.3 **4.0**	3.9 **4.8**
Medium rocks 65—55 % SiO_2								
Diorit	0.8	0.32	0.7	0.46	0.9	1.9 **2.4**	1.6 **1.9**	2.0 **2.4**
Basic rocks < 55 % SiO_2								
Gabbro	0.5	0.27	0.31	0.19	0.35	1.1 **1.3**	1.0 **1.2**	1.1 **1.3**
Ultrabasic rocks								
Peridodit	0.30	0.18	0.35	0.22	0.41	0.8 **1.0**	0.7 **0.8**	0.9 **1.1**
Sedementary rocks:								
Sandstone	0.8	0.30	0.49	0.30	0.6	1.6 **1.9**	1.4 **1.7**	1.7 **2.1**
Limestone	0.5	0.05	0.13	0.08	0.15	0.7 **0.8**	0.6 **0.7**	0.8 **1.0**
Clay	0.9	0.7	1.1	0.7	1.3	2.7 **3.3**	2.2 **2.7**	2.8 **3.4**

[1] SPIERS 1950. [2] MATTAUCH and FLAMMERSFELD 1949. [3] GRÄF 1951.

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