HIGH-ENERGY NUCLEON TISSUE DOSES

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1. INTRODUCTION

Along with the growth of energy and intensity of accelerated particles the relative rise of high-energy radiation component behind the shield should be expected. It is also caused by the necessity to include different technological canals into the shield.

At present there is practically no data about the dose characteristics of nucleons with the energies above 3 Gev which determine admissible fluxes of nucleons in this energy range. It makes the protection calculations for accelerators and spaceships difficult.

Existent calculations are mainly based on the Monte-Carlo technique and are carried out for nucleons with energies up to 2-3 Gev[1,2). Extension of such a method to a region of higher energies faces considerable difficulties due to the lack of information about the differential characteristics of nucleon-nuclear interaction with biological tissue elements and also due to essential growth of the computor time needed for calculation.

Mention should be made of the fact that the dose is a mean characteristic of radiation effect to the substance and therefore taking into account many details of interaction (the Monte-Carlo technique) is not always justified. Solving this problem it is possible to use average characteristics of nuclear interactions. Such an approach considerably reduces the calculation volume and is justified by the fact that the existing nuclear interaction theories and experiments give the most accurate data about the averaged characteristics in particular.

We suggested such a method when we calculated the doses from nucleons with energies up to 2 Gev3). The extension of this method for higher energies is the purpose of the present report.

2. CALCULATION METHOD

The absorbed dose and dose equivalent were calculated for nucleons that are normally incident on one surface of a slab 30 cm thick and infinite in lateral extent. The tissue composition corresponded to the formula $H_{140}C_{21}N_3O_{57}$. The tissue density was equal to 1 g/cm^3.

The solution of that kind of a problem is based as a rule on using the nuclear cascade process equation or on the Monte-Carlo technique.

The solution of the kinetic equation naturally reduces the calculation volume as compared to the Monte-Carlo technique. However to obtain the solution of this equation is very difficult even using the computer. That is why some simplifying assumptions that allow to obtain the results with the necessary accuracy have been adopted.

In the present report as a result of the kinetic equation solution the distribution function of cascade particles with the energies up to 0.4 Gev has been obtained. The assumptions at which this function was obtained will be described later.

The method suggested in Ref. 3 and based as it was mentioned above on the mean characteristics of nuclear interaction has been used for the transformation from the obtained distribution function to the dose distribution.

2.1. Solution of nuclear cascade process equation

There exists inelastic interactions, elastic scattering, ionization and so on in the phantom when nucleons pass through the matter.

In a general case particles passing through the matter are described by the system of integro-differential equations which are analogical to the known kinetic equation or to the transport equation.

To facilitate this system solution, as it was mentioned above, some simplifications are necessary. Experimental and theoretical data show that nucleons emitted in the cascade process have the same direction as the nucleon which initiated the cascade (straight-ahead approximation). This fact allows to transform the problem to one dimension. The validity of the straight-ahead approximation has been considered at 400 Mev by Alsmiller et al4) by calculating the depth dose distribution in a slab of tissue placed behind an aluminium shield. The approximation was found to be good. It is expected that this approximation would be even better at higher energies.

Besides that the following assumptions have been made while solving the equation:

1. The cross section was assumed to be constant for both nucleons and mesons.
2. The stopping power of particles is constant with the depth of phantom.
3. The changing of cascade particles energy at elastic scattering was neglected.
4. The neutral pions decay into two photons practically immediately and do not participate in the cascade.
5. The difference between positive and negative particles was neglected.
6. The charged pions assumed to be stable.

On these assumptions the system of nuclear cascade process equations will be written in the following way:

$$\frac{d}{dx} n_i(E,x) + \Sigma_i n_i(E,x) = \sum_K \int_E^{E_0} \frac{d\Sigma_{iK}(E',E)}{dE} n_K(E',x)\, dE$$

where $n_i(E,X)$ - distribution function of particles of type i with energy E at depth X;

Σ_i - microscopic cross section for particles of type i

$\frac{d\Sigma_{ik}(E',E)}{dE}$ - differential cross section for particles of type i with energy E which is emitted during the nuclear interaction of the particles of type k with energy E'.

The differential cross sections described by Thrilling formulas[5)] have been used in solving the equation system. The Thrilling formulas describe the energy distribution of secondary nucleons and pions with energy $0.4 \text{Gev} < E_N < E_{max}$. and $0.06 \text{Gev} < E_\pi < E_{max}$. when the cascade is initiated by nucleons. There are no formulas analogical to the Thrilling formula for primary pions. So we assumed the identical energy distribution of secondary particles for both primary nucleons and primary pions.

As for the problem considered the relation $d/\lambda_i = 3/8$ (d - phantom thick, $\lambda_i = \frac{1}{\Sigma_i}$) is small enough, we used it as a parameter for the expansion of equation solution in a series. The equation was solved by the step-by-step method. The first three terms were used in calculation. The error in this case is not more than one per cent. So the application of the Thrilling formula for differential cross sections allowed to obtain the distribution function of cascade particles with the energy above 0.4 Gev from nuclear cascade process equation.

2.2. Calculations of absorbed and equivalent dose distribution

The transformation from the obtained distribution function of cascade particles to the dose distribution was made in the following way. It is convenient to express the total dose as a sum of three components:

$$D(x) = D_1(x) + D_2(x) + D_3(x)$$

where $D_1(x)$ - dose corresponding to the energy deposited in the tissue as a result of the cascade particles ionization above 0.4 Gev; $D_2(x)$ - dose corresponding to the energy deposited in the tissue as a result of ionization and nuclear interaction of cascade particles up to 0.4 Gev; $D_3(x)$ - dose corresponding to the energy deposited in the tissue as a result of ionization of the particles formed in the evaporating stage of nuclear reaction caused by the cascade particles with the energy above 0.4 Gev.

The first component in the sum was calculated according to the expression:

$$D_1(x)=\sum_{i=p,\pi}\int_{0,4Gev}^{E_0} n_i(E,x)\,\frac{dE}{dx}\,dE$$

using the ionization losses determined by the Bethe-Bloch formula. Apart from ionization in this energy region there exists radiation which increases more rapidly than ionization for protons with the energy 30 Gev. The contribution to the dose of radiation losses of energy can be calculated quite accurately but it is negligible and it has not been considered in the work.

The consideration of the influence of δ-electrons has been made by the method described in Ref.6. It shows that this influence reduces D_1 by 20 per cent on the surface and by 10 per cent at the depth of 5 cm. Taking into consideration comparatively small contribution of D_1 to the total dose distribution this effect can be neglected. The quality factor was assumed to be equal to one.

While calculating D_2 it was taken into account that D_2 is mainly determined by the average number of cascade nucleons with the energy up to 0.4 Gev. The form of the energy distribution of these particles is not very important. Besides that the experimental fact thet the number of the cascade nucleons with the energies up to 0.4 Gev and their average energy in the region from several Gev to 10^3 Gev has been used. On this basis the spectrum of nucleons with the energy up to 0.4 Gev given in Ref.8 has been used in the calculations.

The nucleon spectrum with energies up to 0.4 Gev has been normalized by the average number of nucleon which was considered to be equal to the difference between the total number of nucleons given by Barashenkov9) and the number of nucleons with energies above 0.4 Gev given by Malhotra10) when the energy of the incident particles is up to 5 Gev. At higher energies tha average number of nucleons with energies up to 0.4 Gev was assumed to be constant and equal to this number at 5 Gev. Energy spectrum of pions has been determined by the Thrilling formula. Therefore the second component in the sum was calculated according to the formula:

$$D_2(x)=\sum_i\sum_K\int_{0,4Gev}^{E_0}dE\int_0^x dx'\int_0^{0,4Gev}\frac{d\Sigma_{iK}(E,E')}{dE'}n_i(E,x')D_K(x-x',E')dE'$$

where E - energy of the cascade particles with the energy above 0.4 Gev;

$D_k(X,E')$ - dose distribution from the particles of type k;

$\frac{d\Sigma_{ik}(E,E')}{dE}$ - energy spectrum of the particles with the energy up to 0.4 Gev; emitted at interactions of incident particles with the energy E.

The absorbed dose and dose equivalent data for nucleons up to 0.4 Gev have been taken from Ref.11, 12. The calculations of the dose distribution in the case of the average angle of the secondary particles with the energy up to 0.4 Gev equal to 30 and 60 degrees have been made for the determination of the secondary particles angle distribution influence. It was found that at the angle 60 degrees the total dose increases by 15 per cent together with the more rapid increase of the dose within the first cm of the slab.

In the calculation of D_3 the basic characteristic of the nuclear interaction evaporating stage - the average exitation energy has been used. The characteristic is practically constant with the energy. A considerable rise of the exitation energy with the energy of incident particles noted in some works is in disagreement with the experimental data[13)] concerning the constancy of the number of black prongs and the average energy of the evaporating particles and obtained in studies of the nuclear interactions in emulsions. In accordance with the stated above the average excitation energy is assumed to be equal to 30 Mev when nucleons are incident and 50 Mev when pions are incident and constant with incident energy[8,9,11,14)].

Calculating the quality factor for the radiation of the evaporating stage of nuclear interaction the independence of the radiation composition from the incident energy has been used. The quality factor was calculated using the composition and quality spectrum of the evaporating particles given in the experimental works[15,16] where the protons interactions with C^{12} at the energy 660 Mev were considered. As there are particles mainly with a short path emitted in the evaporating stage the deposited energy was assumed to be absorbed locally.

$$D_3(x)=\sum_i\int_{0,4Gev}^{E_0} n_i(E,x)\Sigma_i\varepsilon_i\,dE$$

where ε_i - average excitation energy of residual nucleus formed at the interaction of the type i cascade particles with energy above 0.4 Gev with a tissue nucleus,

As it was pointed above, π^0-mesons were assumed to be decayed into two photons and therefore their contribution to the dose was calculated with the use of photons dose distribution obtained in Ref.17 and their distribution function obtained in the kinetic equation of this work.

The contribution to the dose from the recoil nuclei formed during the elastic scattering which usually was neglected increases with the incident particles energy. As the recoil nuclei have a short path their energy can be considered to be absorbed locally and their contribution to the dose will be determined by the average energy of the recoil nuclei and by the cascade particles distribution function.

The average energy of the recoil nuclei was calculated from the angle dostribution of the elastic-scattered particles[18] making use of the known relativistic correlations between the angle and the energy. The quality factor for the nuclei C,N,O was assumed to be equal to 20 and for H - 1,5 on the basis of its dependence upon the stopping power.

3. RESULTS

The calculations on the basis of the suggested method were performed for the nucleons at each of the incident energies 0.4;0.6;1;2;3;5;10;20;30 Gev and some of the absorbed and equivalent dose distributions obtained are presented in Fig. 1-5.

From the calculation results it follows that the absorbed and equivalent doses increase with depth within the slab both for protons and neutrons of the energies considered reaching the maximum values at the back of the slab.

The most rapid dose buildup is observed near the surface of the slab within the first 5-10cm. At larger depth the dose buildup decreases. It can be explained by the saturation of the particles number which has the path equal approximately to 5-10cm.

The maximum and mean doses rise with the energy but this growth is not so large as it was expected. When the energy increases from 3 to 30 Gev the absorbed and equivalent doses increase approximately 1.8 times for protons and 1.9 times for neutrons.

The quality factor was calculated as a relation of maximum equivalen dose to the maximum absoebed dose.In the range of the nucleon energies from 3 to 30Gev it is particularly constant and equal to 2 for neutrons and 1.9 for protons.

4. COMPARISON WITH OTHER RESULTS

There are no theoretical and experimental works dealing with the determination of the dose distribution from nucleons with the energy above 3Gev.So we can compare the results obtained in this work with those obtained by the Monte-Carlo technique2) only for nucleons with energies up to 3 Gev.

It is interesting to compare our results obtained by means of a simplified method with those obtained by Alsmiller2) in detail calculations. This comparison presented in Fig.6 indicates satisfactory agreement. Some disagreement seems to be explained by the fact that the cascade nucleons angle distribution is not taken into account in this work.

The comparison with the experimental data made by Phillips19) for protons with the energy 2.9 Gev indicates higher dose near the back of the slab obtained in our work than the experimental doses. This disagreement is common for the majority of the comparisons between the calculation results and the experimental data1). It may be the result of some idealization in the calculations which were made for a strictly parallel beam and an infinite slab tissue phantom and also the result of non-identity of geometries in the experiments and the calculations.

At the conclusion the necessity of the experimental works and calculations for obtaining dose distribution due to the high-energy particles should be noted. Special attention should be paid to the determination of the equivalent dose distribution and to the distribution quality factor. Besides that the calculations for finite and geterogenious phantoms are of great interest.

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CAPTIONS FOR FIGURES

Fig. 1. Absorbed dose (D) and dose equivalent (DE) due to protons (p) and neutrons (n) with the energy 3 Gev.

Fig. 2. Absorbed dose (D) and dose equivalent (DE) due to protons (p) and neutrons (n) with the energy 5 Gev.

Fig. 3. Absorbed dose (D) and dose equivalent (DE) due to protons (p) and neutrons (n) with the energy 10Gev.

Fig. 4. Absorbed dose (D) and dose equivalent (DE) due to protons (p) and neutrons (n) with the energy 20Gev.

Fig. 5. Absorbed dose (D) and dose equivalent (DE) due to protons (p) and neutrons (n) with the energy 30Gev.

Fig. 6. Comparison of the depth dose distribution for 3-Gev protons calculated by Alsmiller Ref.2 and the data obtained in this work.

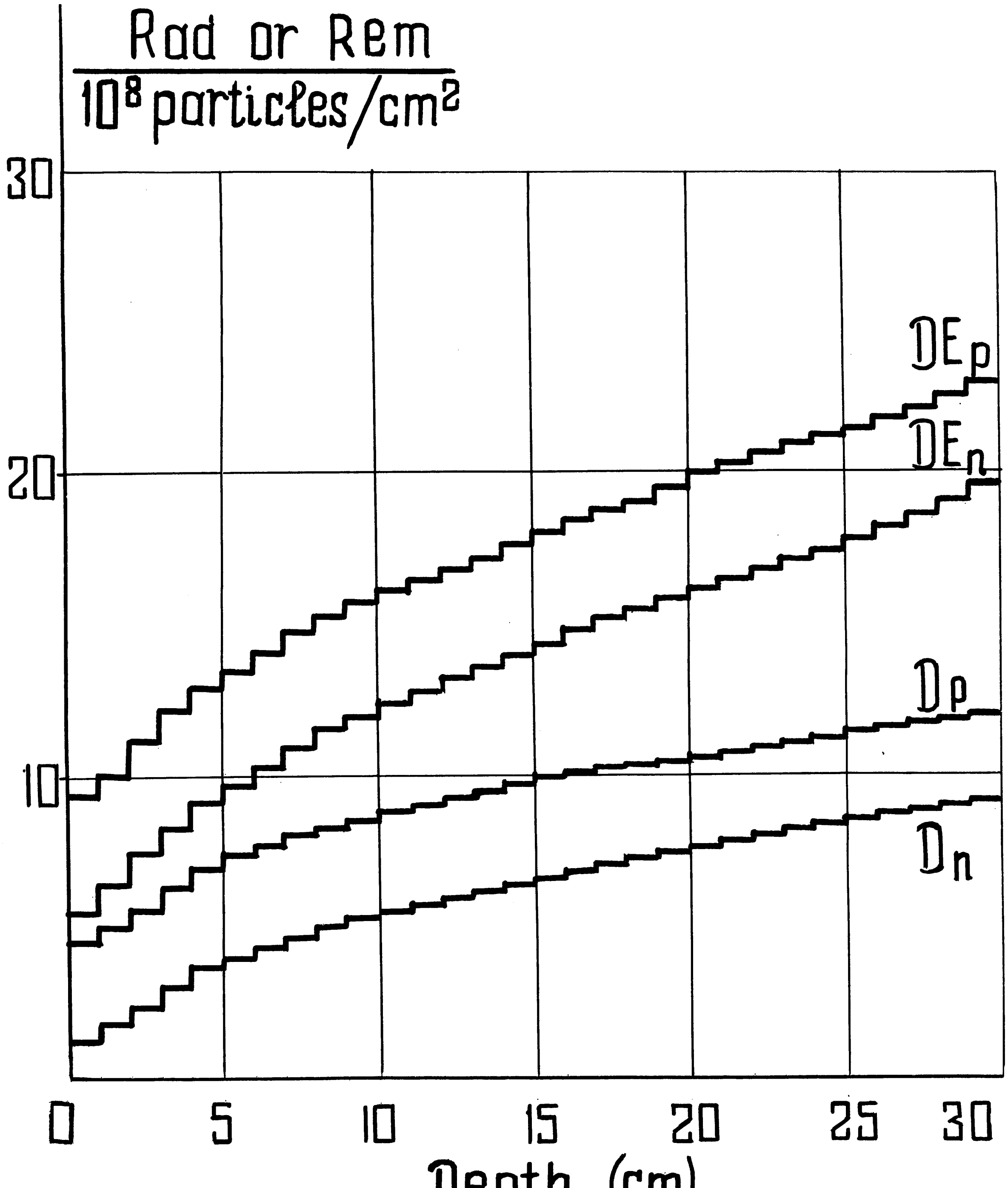
Rad or Rem
10⁸ particles/cm²
30
20
10
0
5
10
15
20
25
30
Depth (cm)
DEp
DEn
Dp
Dn

Fig. 1

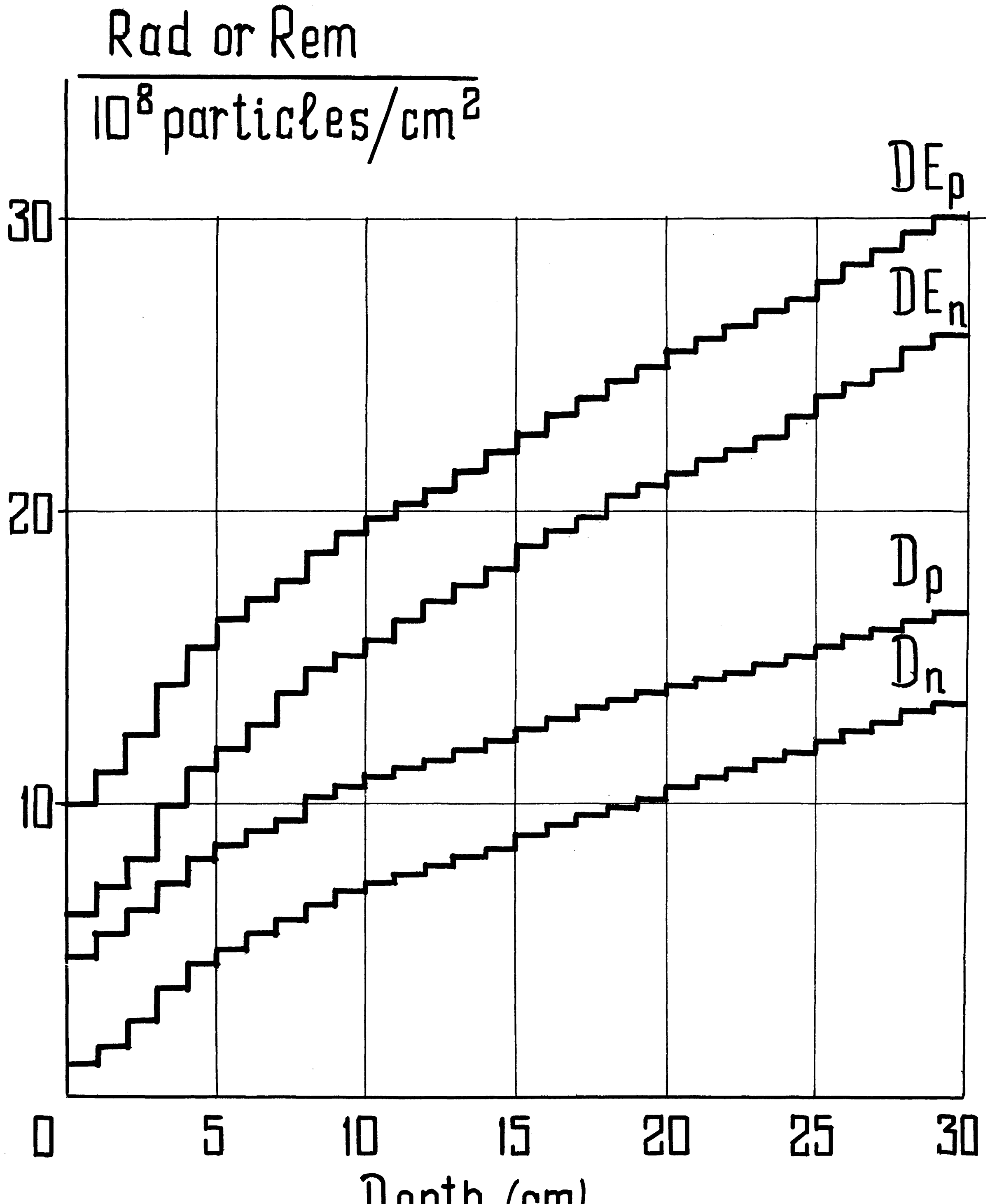
Rad or Rem
10^8 particles/cm^2
30
20
10
0
5
10
15
20
25
30
Depth (cm)
DEp
DEn
Dp
Dn

Fig.2

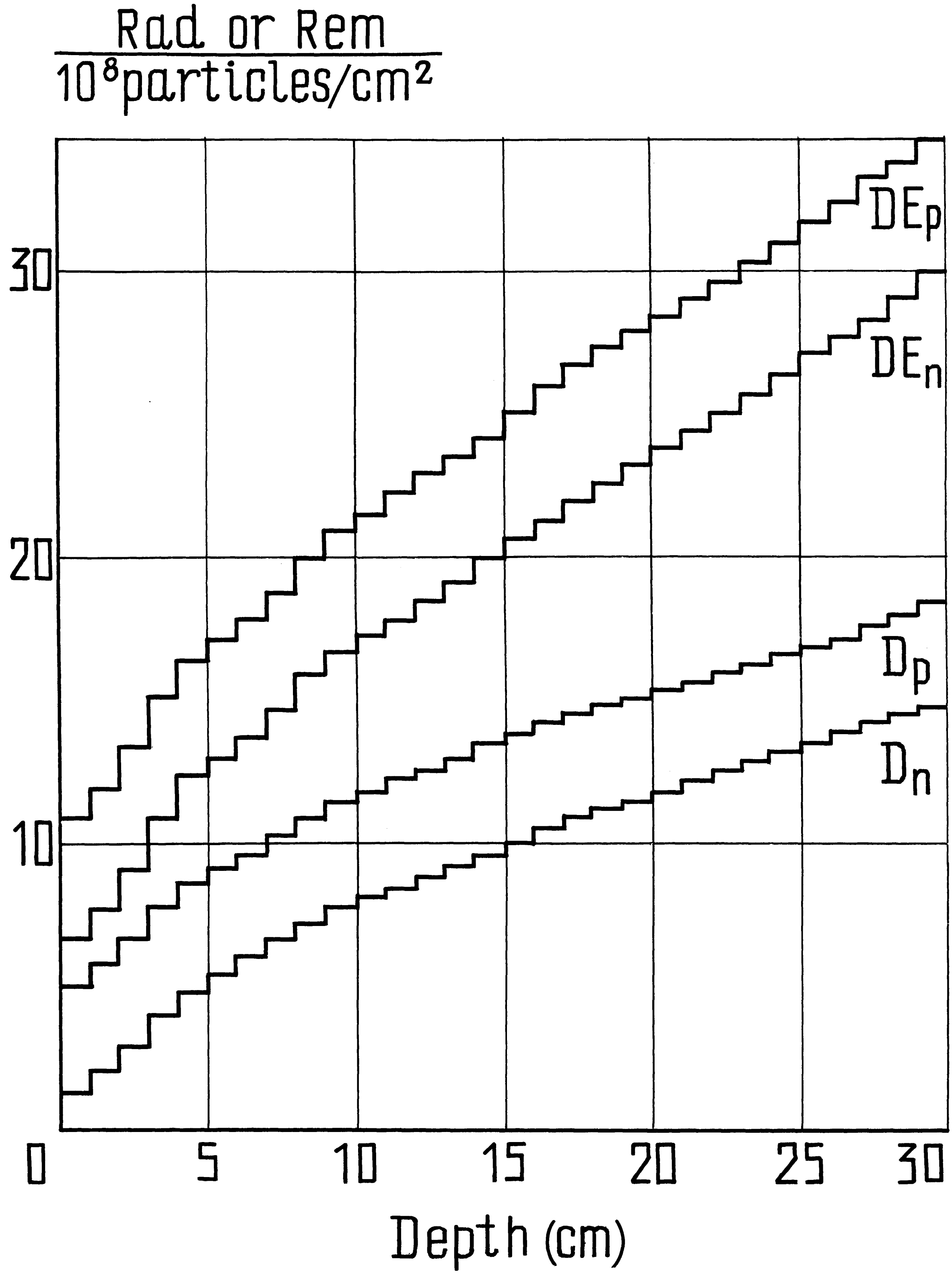
Rad or Rem
10⁸particles/cm²
30
20
10
0
5
10
15
20
25
30
DEp
DEn
Dp
Dn
Depth (cm)

Fig.3

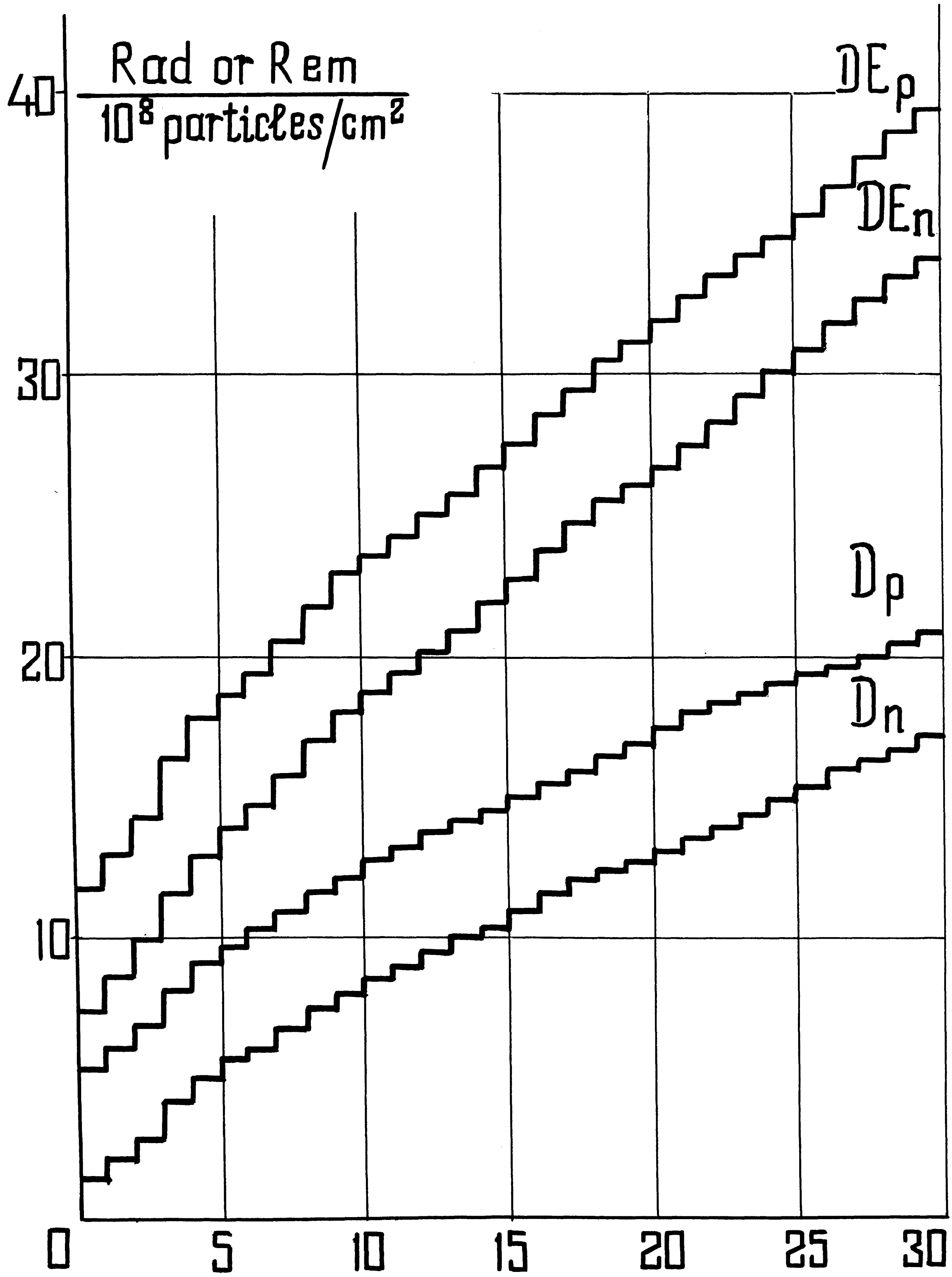
Rad or Rem
10^8 particles/cm^2
40
30
20
10
0
5
10
15
20
25
30
DEp
DEn
Dp
Dn
Depth (cm)

Fig.4

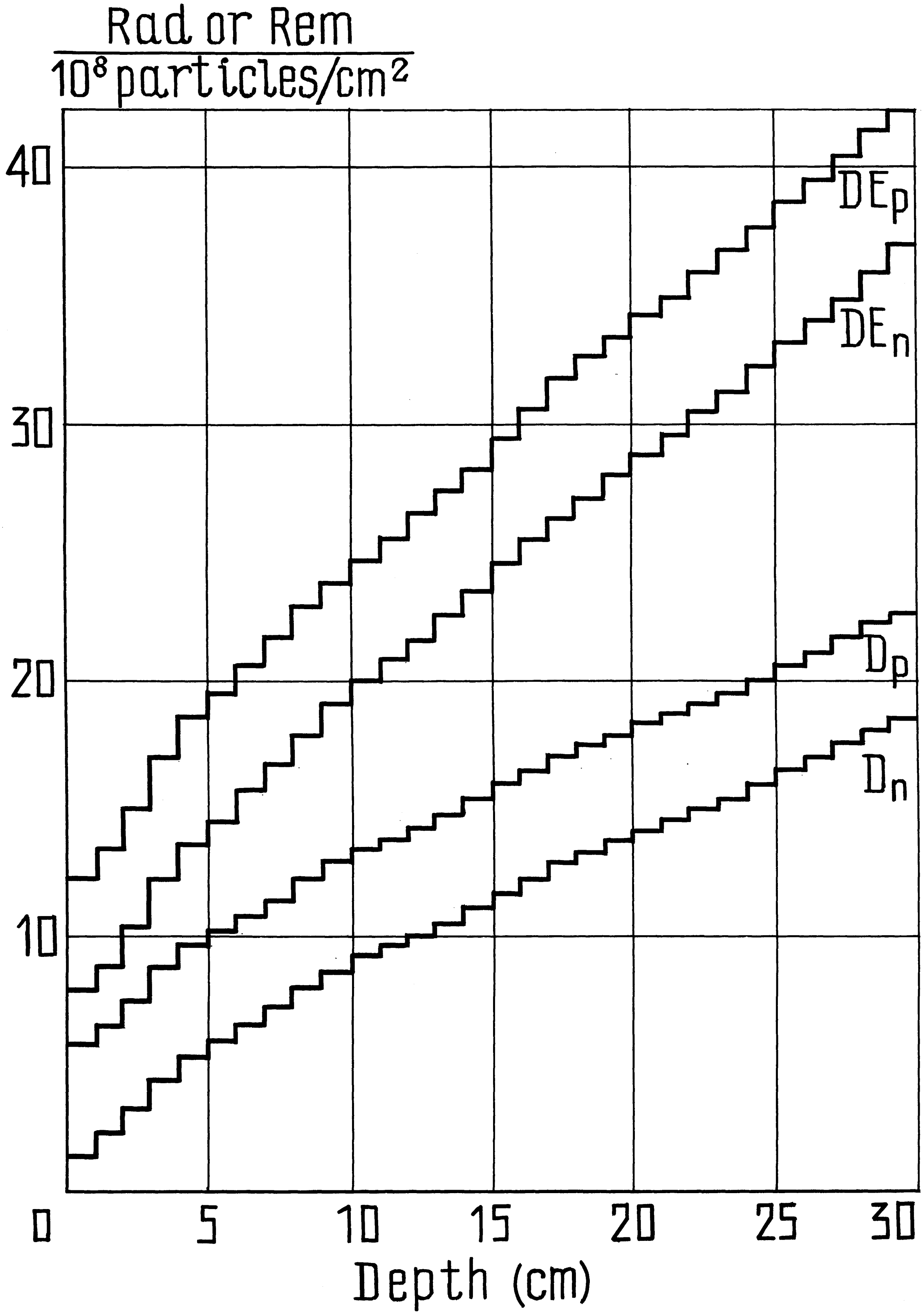
Rad or Rem
10⁸ particles/cm²
40
30
20
10
0
5
10
15
20
25
30
Depth (cm)
DEp
DEn
Dp
Dn

Fig.5

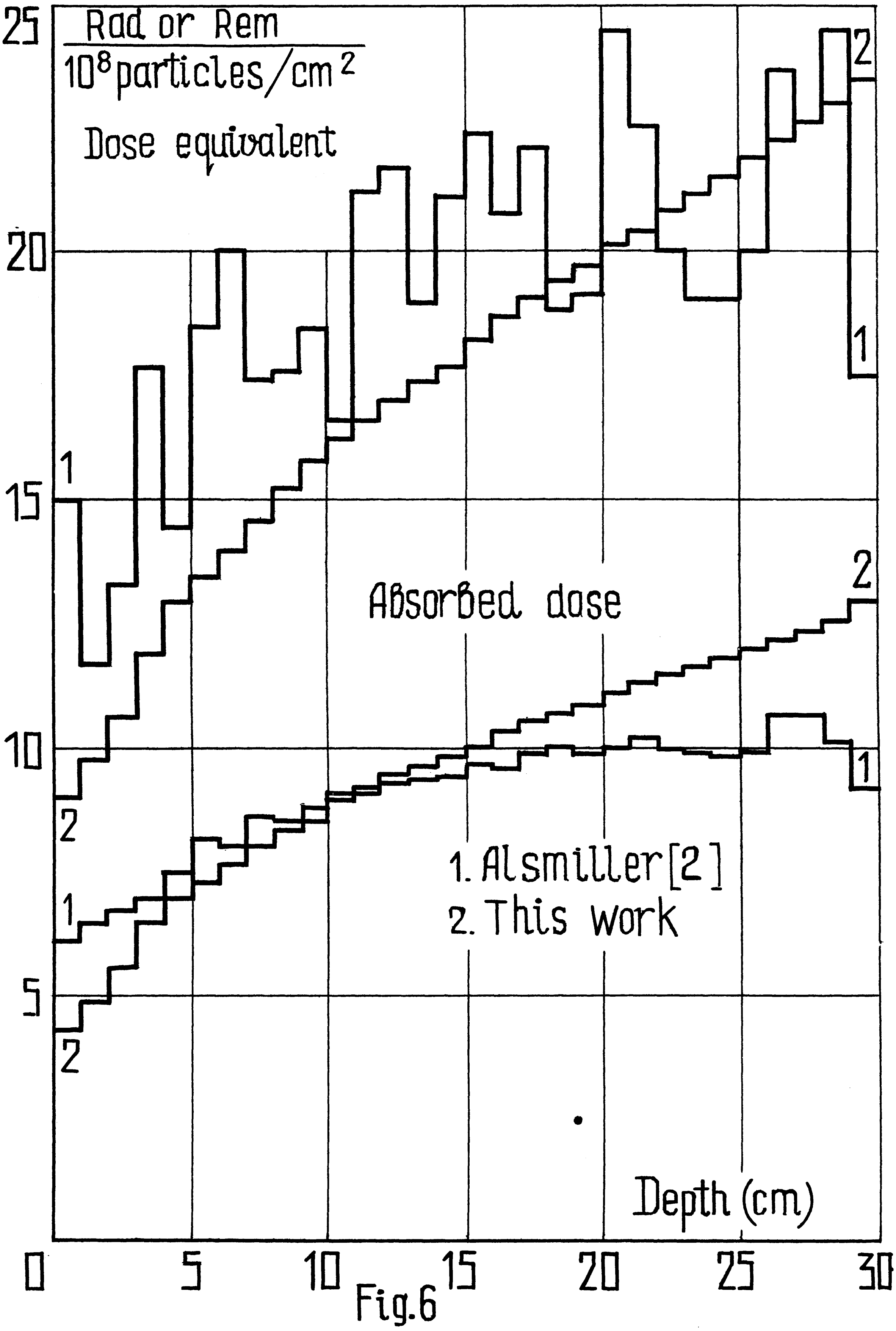
Rad or Rem
10⁸particles/cm²
Dose equivalent
Absorbed dose
1. Alsmiller[2]
2. This Work
Depth (cm)
25
20
15
10
5
0
5
10
15
20
25
30
1
2
1
2
1
2
1
2

Fig.6