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Estimation of the Dose from Accidental Irradiation by a Large Amount of High-Energy Particles

by

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Operation of present-day high-energy proton accelerators gives rise to radiation consisting mainly of protons and neutrons, which in the vicinity of accelerators may reach several hundreds of rad/sec. The existing systems of radiation protection and monitoring reduce to a minimum the possibility of accidental irradiation of staff with large doses, although they do not completely exclude it. Under these circumstances it is important for dosimeter monitoring services to have available a method for determining high doses due to accidental radiation at accelerators. The application of the existing methods of monitoring accidental doses in reactors can only partly solve the problem posed, as the spectrum of neutrons and protons from accelerators is essentially different from that of fission neutrons, since it includes high-energy particles.

In this paper an experimental method is suggested for estimating the accidental high-energy neutron and proton radiation dose. The method consists of measuring the induced radioactivity of a human body irradiated by high-energy particles. As is known, such a method of determining the extent of radiation effect is not new. This report proposes no more than a simplified version of the usual method, which can be easily used for the staff of high-energy proton accelerators.

1. QUANTITATIVE CHARACTERISTICS OF THE METHOD

When human tissue is irradiated by neutrons and protons, radioactive isotopes are formed, the specific radioactivity of one of which, q_i, can be determined by means of the following well-known relation :

$$q_i = J\ \sigma_{i,j} n_j [1 - e^{-\lambda_i t}] e^{-\lambda_i \tau} . \qquad (1)$$

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Here J is the particle flux density, for instance of protons;

$\sigma_{i,j}$ is the production cross-section of the i^{th} isotope in the interaction between protons and nuclei of the j^{th} element;

n_j is the number of nuclei of the j^{th} element in unit volume;

λ_j is the decay constant of the i^{th} isotope;

t is the exposure time;

τ is the time after exposure.

For determining the activity of the i^{th} isotope by means of any sensitive radiometer, the following relation can be used:

$$q_i = \frac{N_i}{\epsilon_i} ,$$

where N_i is the radiometer reading, and ϵ_i the coefficient taking into account the geometry of the measurement, the efficiency of recording the radiation, etc. The following expression is also obviously correct:

$$N_i = J\, \epsilon_i \sigma_{i,j} n_j [1 - e^{-\lambda_i t}] e^{-\lambda_i \tau} . \qquad (2)$$

The reading of the instrument resulting from the radioactivity of all the isotopes produced in the tissue is defined by the following relation:

$$N = J \sum_i \sum_j \epsilon_i \sigma_{i,j} n_j [1 - e^{-\lambda_i t}] e^{-\lambda_i \tau} . \qquad (3)$$

Out of the large quantity of radioactive isotopes produced in human tissue by exposure to high-energy particles, only those produced in considerable quantity by a reasonable period of accidental exposure are of practical importance ($t < 1$ hour). Among these are the radioactive isotopes of ^{15}O, ^{13}N and ^{11}C produced mainly from ^{16}O and ^{12}C nuclei. The production cross-section of ^{15}O, ^{13}N and ^{11}C isotopes is known for a wide range of proton energies[1]. Therefore, in order to determine the dependence of the radiometer reading on the flux density or on the proton dose it is sufficient to determine the ϵ_i coefficients.

2. CALIBRATION OF RADIOMETER

As an instrument for recording induced radioactivity in tissue we chose a standard radiometer for measuring levels of gamma-beta-alpha radiation of the "Tiss" type, which is widely used in the USSR. The measurements were made with a gamma-beta radiation detector consisting of a set of Geiger counters with steel walls 0.5 - 0.55 kg/m^2 thick. The determination of the ϵ_i coefficients -- the calibration of the radiometer -- was carried out by measuring the radioactivity of water exposed to a known 660 MeV proton flux from the synchro-cyclotron This substitution of water for tissue appears to be justified, since when water is irradiated it is mainly the same radioactive isotopes that are produced as when tissue is irradiated, and water is a sufficiently tissue-equivalent medium. For the calibration of the radiometer and the subsequent measurements, the constancy of the efficiency of recording beta-gamma radiation was checked with a reference specimen of ^{204}Tm. The beta-particle recording efficiency of the thulium was 10% when the area of the radiometer counter was equal to that of the surface to which the ^{204}Tm was applied. Under these conditions, the ϵ_i coefficients determined for radioactive isotopes of ^{15}O, ^{14}N and ^{11}C were found to be 5×10^{-6}, 0.9×10^{-8}, and 1.9×10^{-6} pulse $\times$ m^3/proton. These data make it possible to determine the sensitivity of the method for the radiometer used, which under favourable conditions (measurements being made a few minutes after irradiation in the presence of the natural background only) is a few hundred millirad.

3. DOSE ESTIMATION FROM RADIOMETER READINGS

The values calculated by means of formula (3) for the dependence of the instrument readings on the dose absorbed in tissue (J,t,k) are shown in Fig. 1. The calculation was made for 660 MeV protons, for which the absorbed dose for one proton "K" equals 5.3×10^{-8} rad/proton [2,3]. When the proton energy decreases, the increase in the coefficient "K" is to a large extent counterbalanced by an increase in the production cross-section of radioactive isotopes, as shown by calculations based on experimental data[1,3]. On the other hand, when the proton energy rises above 660 MeV, the fall in the absorbed dose for one proton is offset by a reduction in the cross-section $\sigma_{i,j}$. All this makes it possible to use the data in Fig. 1, with an accuracy of up to a factor of 1.5, in order to determine the dose absorbed in tissue for a wide range of proton energies from 100 MeV to tens of GeV. The use of the data in Fig. 1 for estimating the dose from high-energy neutrons in tissue involves greater uncertainty than is the case for protons, because of the absence of reliable information concerning the values $\sigma_{i,j}$ and "K". The estimates of the absorbed dose made in the paper[2] and the data on the cross-section of the reaction $^{12}C(n,2n)^{11}C$ [3] allow only approximate determination of the ratio between the dose absorbed when tissue is exposed to high-energy protons and the dose absorbed from neutrons for the same induced activity in the tissue (i.e. for identical readings on the radiometer). This ratio is 2:3 for particle energies of a few hundred MeV and over.

It should be noted that the uncertainty in estimating the dose by the method concerned also depends essentially on the reliability of the time of the accidental radiation t, and the length of time between the end of the irradiation and the moment when the measurements are made, τ. This length of time τ can as a rule be determined, whereas the time t cannot always be established. Fortunately, for small intervals of time t, which are more probable in practice, great uncertainty regarding the time t (for instance, by a factor of 10) gives rise to an uncertainty of only 15% regarding the absorbed dose.

4. TESTING OF THE METHOD ON IRRADIATED DOGS

In order to test the practical usefulness of the method, control measurements were made of the absorbed dose received by two dogs in a 120 MeV proton beam. The irradiation technique and the characteristics of the radiation field are described in a paper[3]. Each dog was irradiated twice: left side and right side separately, with a small interval between the exposures. The proton beam, and consequently the absorbed dose, were checked by means of carbon detectors and luminescent indicators[3]. The dose received by the dog at each exposure was 125 rad. The dependence of the radiometer readings on the time elapsing after irradiation τ, calculated by means of Eq. (3) for this case, is shown by the continuous curves in Fig. 2. The upper curve corresponds to a dose of 250 rad, and the lower to 125 rad. In this way the curves form a corridor of uncertainty, due to the two exposures to radiation and the comparatively low energy of the protons. Figure 2 also shows the experimental points obtained for one of the dogs. The fact that the experimental points are outside the uncertainty corridor for low values of τ is apparently due to the exaggerated value of the coefficient for the radioactive isotope of ^{15}O, determined during the calibration measurements with radioactive water.

The results of the measurements and calculations presented show that the proposed method of dose estimation can be recommended for practical purposes.

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2) G.A. Avrunina in the book "Data on the biological action of high-energy protons", edited by A.A. Letavet and E.B. Kurlandskaya. AMN USSR, Moscow (1962), pp. 10-29.

3) V.P. Afanas'ev et al. Establishment and study of dose fields for the irradiation of experimental animals with high-energy protons. In Proc.Conf. on Biological Effects of Irradiation by Neutrons and Protons, IAEA, Vienna (1964), pp. 71-90.

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Figure captions

Fig. 1 : Nomograms for determining the proton dose absorbed from the radioactivity induced in biological tissue:
t - exposure time, τ - time between the end of exposure and the moment when measurements are made.
Left-hand side : Radiometer reading pulse/min.
Bottom : Dose, rad.

Fig. 2 : Radioactivity induced in the body of a dog at different periods after irradiation with protons.
Radiation dose : 250 rad.
Ɨ - experimental points ——— - calculated curves.
Left-hand side : Radiometer reading, pulse/min.
Bottom : Time after irradiation, min.

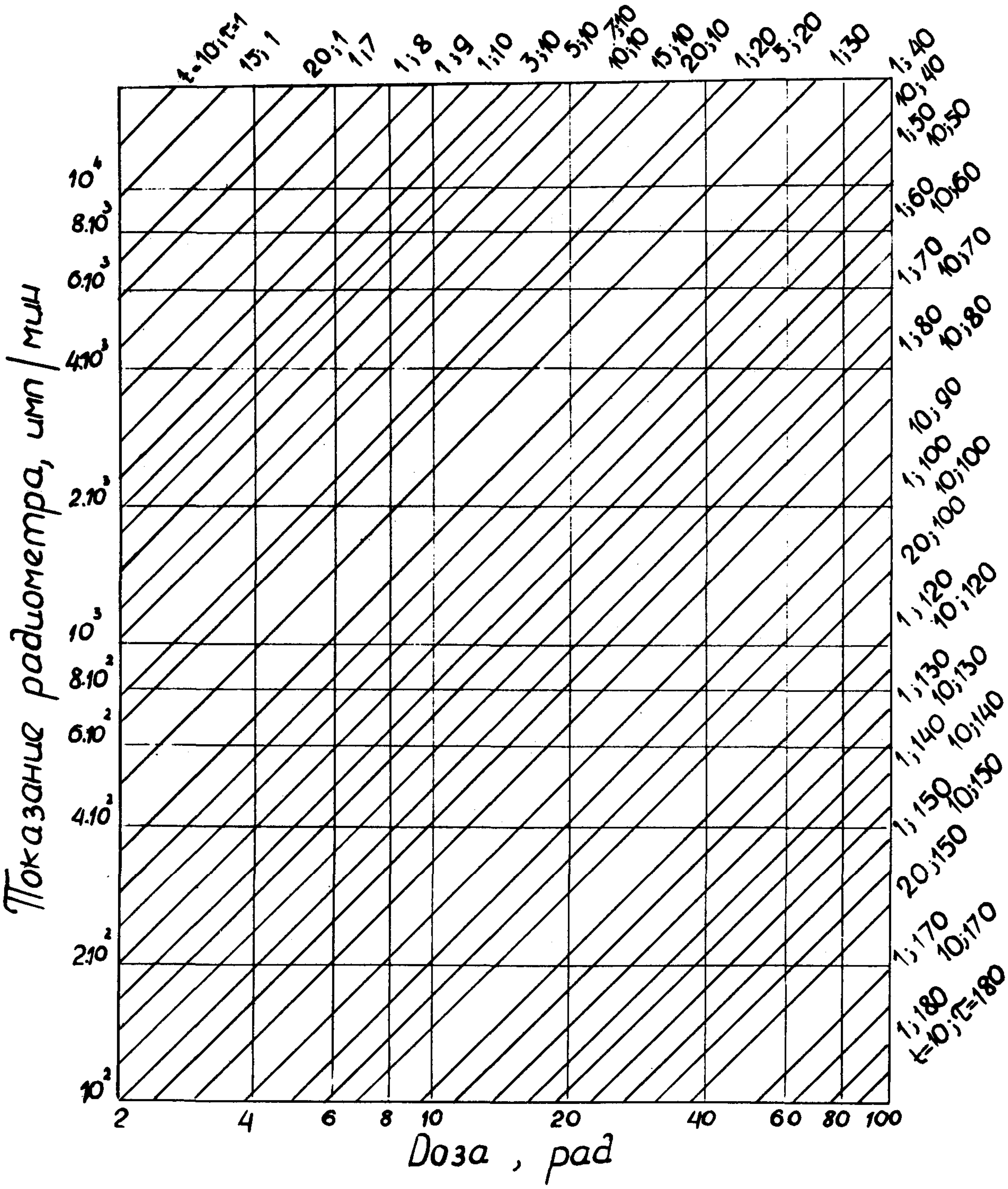

Рис. 1. Номограммы для определения поглощенной дозы протонов по наведенной ими радиоактивности в биологической ткани:
t – время облучения, τ – время от конца облучения до момента измерения.

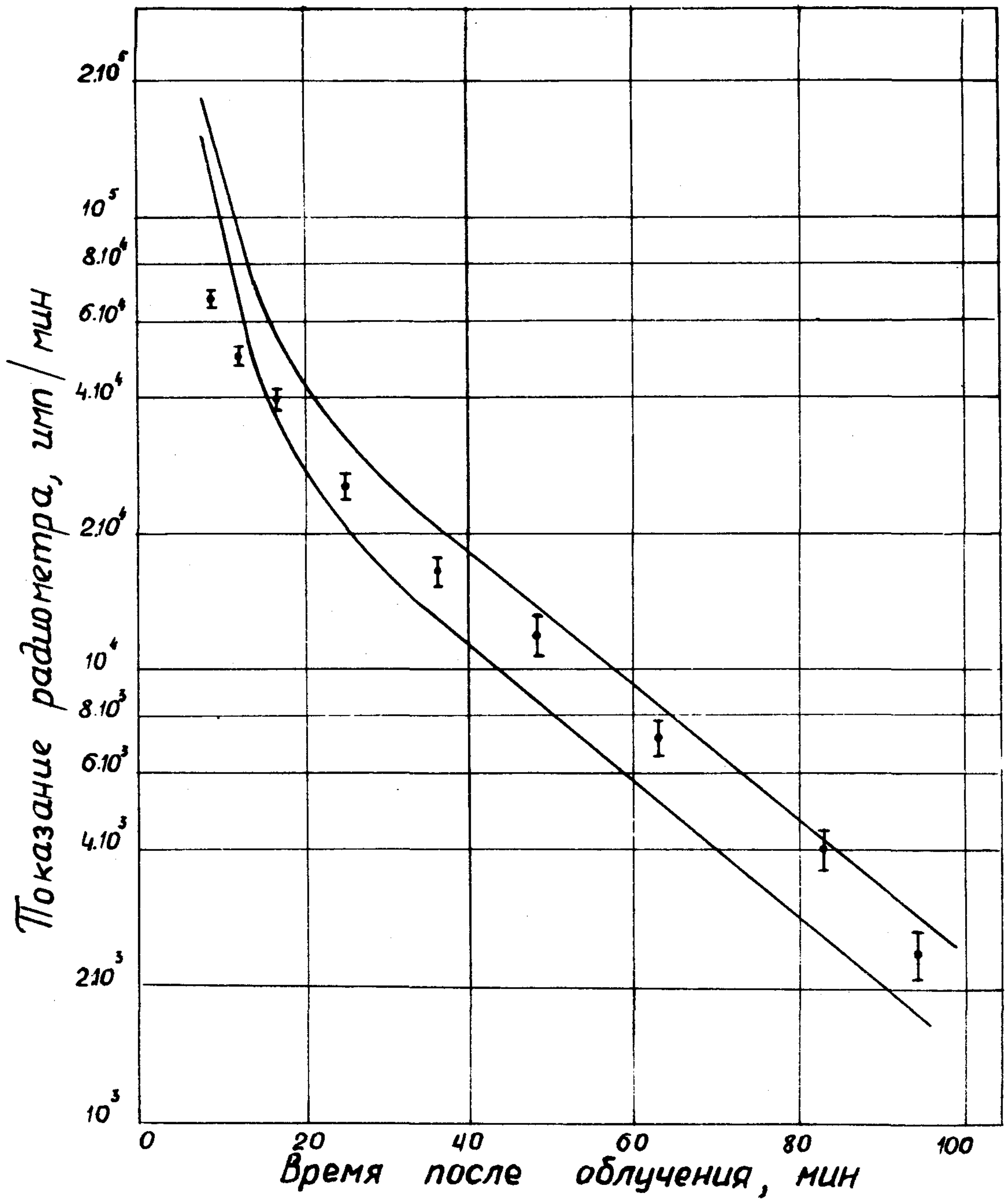

Рис. 2. Наведенная радиоактивность в теле собаки в различные моменты времени после облучения протонами. Доза облучения 250 рад:
– экспериментальные точки, ——— – расчетные кривые.