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Moderated rem Meters in Pulsed Neutron Fields

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Abstract: The diffusion time of neutrons in the moderators of four well known instruments measuring neutron equivalent doses was determined. From these data the counting losses are calculated. Diagrams are shown from which the correction factors can be deduced for a given accelerator neutron field.

1. Introduction

The most common method of measuring neutron equivalent doses is by slowing down the neutrons in a moderator and counting them by means of a detector sensitive to thermal neutrons. This technique has the advantage that the response of such an instrument as a function of neutron energy can be varied within wide limits by the shape and composition of the moderator. The detector for thermal neutrons may be a counting device (e.g. BF_3 counter, ^{6}LiI scintillator) or an integrating solid-state detector (e.g. activation probe, ^{6}LiF dosemeter). In this way both the dose rate as well as the dose integrated over a long time can be measured.

Spherical moderators of polyethylene with different diameters are used for the measurement of the flux density or the fluence, or in neutron spectroscopy. They may also be used for neutron dosimetry in a certain energy interval depending on the diameter of the sphere (see, e.g., ref. 1). A rough measurement of the equivalent dose of neutrons from 0.1 to 10 MeV is possible by a spherical moderator of 30 cm diameter. This device is in operation at various accelerator facilities for the survey of the site dose. A larger moderator of 45 cm diameter allows dosimetry of neutrons between 3 and 100 MeV (ref. 2).

In portable neutron rem meters, moderators designed by Anderson and Brown (ref. 3) and Leake (ref. 4) are used. An absorber placed within the moderator removes the oversensitivity in the keV-region. With these commercially available instruments the neutron dose can be determined from thermal energies up to 10 MeV within a factor of two. This precision is sufficient for practical use and certainly not worse than the concept of expressing the interaction of neutrons with the human body by one single parameter, the dose equivalent.

Moderated neutron counters may also be used in pulsed radiation fields of small duty cycle encountered around accelerators. Although the dose during an accelerator pulse will be very high for a given averaged dose rate, the counting losses will be small because the neutrons are "stored" as thermal neutrons in the moderator and can reach the detector hundreds of microseconds later. Leake (ref. 5) and Jenkins (quoted in ref. 1) referred to this point.

This time delay was measured by us for four commonly used neutron dosemeters. From the results we calculated the counting losses. For a given averaged dose rate the correction factors can be deduced from the enclosed diagrams if the length and the repetition rate of the accelerator pulses are known.

2. Measurements

The time distribution of the pulses was determined experimentally for the following instruments:

polyethylene sphere (30 cm diameter) with a ^{6}LiI scintillator,

polyethylene sphere (45 cm diameter) with a spherical ^{3}He counting tube,

portable instrument after Anderson und Brown with a BF$_3$ counting tube (AB counter),

portable instrument after Leake with a spherical ^{3}He counting tube (Leake counter).

The time delay does not result from the slowing down of the neutrons to thermal energies but from the diffusion of the thermal neutrons in the moderator. Therefore the delay is practically independent of the neutron spectra encountered around accelerators. We measured the time delay by using giant-resonance neutrons produced by 300 MeV-positrons impinging on a copper target of 3 cm length. As the beam was of very low intensity ($1 \cdot 10^{10}$ e$^+$/s), the instruments could be positioned at a distance of 1 m from the target. The width of the beam pulses was 0.2 μs, the repetition rate was 50 s^{-1}. The time intervals between beam pulse and neutron pulses were measured with a multichannel analyzer (multichannel scaling mode). The width of one channel was 10 μs. The results are shown in fig. 1.

We studied the beginning of the curves by additional delays of 1 μs each. In this way we could convince ourselves that the counting rate resulting from incomplete discrimination of the photon pulses is only measured within the first microsecond, and that it does not disturb the rest of the curve; this effect is not shown in fig. 2. In order to reduce the γ-component the instruments had to be surrounded by 10 cm of lead which also has no effect on the shape of the curves. Neither were the curves disturbed by dead-time effects because only about 3 pulses were counted per beam pulse. With a time width of 10 μs the rise of the curves in fig. 1 could not be observed in our measurements because 1 MeV-neutrons are slowed down to 1 eV within 1 μs (at this energy the reaction cross sections are already high), and the thermal energy within 5 μs. At the end the curves bend over into a very slowly decreasing background resulting from the diffusion of thermal neutrons in the walls. This effect is not indicated in fig. 1. Clear separation from the background was confirmed by varying the distance to the walls and by measurements without moderators.

The delay time of the thermal neutrons obviously depends on the volume of the moderator. The moderators of the AB counters and of the Leake counter are subdivided by perforated boron containing plastics and by a layer of cadmium, respectively; the resulting inner moderator is small and gives a higher response probability than the outer one. This construction explains the change in the slope of the two curves in fig. 1. The correlation between the volume of the detector and the delay time is shown in fig. 2. Here the curves of fig. 1 were approximated by one or two exponential functions, and the delay time was defined as the 10-percent value of the exponential curve.

3. Results

From fig. 1 we can deduce the correcting factor for the counting losses at a given mean dose rate in any pulsed neutron field. We divide the abscissa into i channels of width T, T being the dead time of the instrument. At first we assume that the width of the accelerator pulse is smaller than T. In addition, the distance between two successive accelerator pulses shall be larger than $i \cdot T$; this is the case at any accelerator. Then from fig. 1 we obtain for each channel the probability W_i that a pulse is counted within this channel; $\sum W_i = 1$.

The true dose (given in rem) per accelerator pulse is called D_p. The true number of instrument pulses per accelerator pulse is D_p/c where c is the calibration constant of the instrument expressed in rem/pulse. Then the number of pulses expected on the average in channel i is

$$m_i = W_i \cdot D_p/c.$$

The distribution of pulses in channel i is assumed to be a Poisson distribution

$$P\,(m_i,\ x) = \frac{m_i^{\,x}}{x\,!}\ e^{-m_i},$$

where x is the observed number of pulses. Since in a channel with a width equal to the dead time of the instrument only one pulse can be recorded, the counting-loss factor is

$$C = \frac{\text{number of counted pulses}}{\text{true number of pulses}} = \frac{\sum\left(1-\exp\left(-W_i\ D_p/c\right)\right)}{D_p/c}.$$

In the case of accelerator pulses of widths larger than T we assume that the width can be expressed as a multiple of T. Then the actual W_i can be calculated by a superposition of the W_i from fig. 1.

The relevant data of the four instruments are summarized in tab. 1. As usual the calibration constants refer to Am-Be-neutrons, as their spectrum is similar to that of giant-resonance neutrons at electron accelerators and of evaporation neutrons at proton accelerators. The choice of the dead time is somewhat arbitrary. We assumed that the two spheres are used for site monitoring; the commonly used electronics might have a dead time of 2 µs. (The time constant of a LiI scintillator is 1.2 µs.) Portable instruments usually show a longer dead time, which is also dependent on the actual rate meter circuit.

For a given instrument the correction factors depend only on D_p and L_p. They are indicated in the right hand part of fig. 3 and in fig. 4 to 6.

For a pulse length L_p and for a given factor C the dose per pulse D_p is roughly inversely proportional to the dead time T. This dependence allows an estimate of C for dead time constants different from those given in tab. 1 .

The true mean dose rate of a neutron field depends on D_p and on the repetition rate f of the accelerator pulses. Fig. 3 shows how the correction factor can be determined. The indicated example: For a true mean dose rate of 100 mrem/h, a pulse length of 1 ms and a repetition rate of 1 s^{-1}, the correction factor for a 30 cm-sphere is 80%. For the other instruments the right hand part of fig. 3 is to be substituted by fig. 4, 5, or 6.

A rough estimate of the correction factor for an instrument with a completely different moderator can be obtained in the following way: The delay of the neutrons in the moderator is estimated from fig. 2, from this the W_i are determined and then the calculation can be performed in the same way.

Literature

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3. I. O. Anderson and J. Braun, in: Neutron Dosimetry, Vol. 2, p. 87 (IAEA, Wien 1963); Nukleonik 6 (1964) 237
4. J. W. Leake, Nucl. Instr. Meth. 45 (1966) 151; 63 (1968) 329
5. J. W. Leake, Kerntechnik 9 (1967) 451;
   Report Authority Health and Safety Branch, Harwell, AHSB (RP) R 91(1969)

Tab. 1

Instrument	Manufacturer	calibration constant c rem/pulse	dead time μs
30 cm-sphere		$8.5 \cdot 10^{-8}$	2
AB counter	Aktiebolaget Atomenergi, Studsvik, Sweden	$8.2 \cdot 10^{-8}$	4
Leak counter	Nuclear Enterprized, Edinburgh U. K.	$8.4 \cdot 10^{-8}$	7
45 cm-sphere		$1.0 \cdot 10^{-7}$	2

Figure captions

Fig. 1 Time distribution of pulses from four moderated neutron rem meters after a very short (< 1 μs) accelerator pulse. In the measurement the width of the time channels was 10 μs. The statistical errors can be neglected.

Fig. 2 Dependence of the delay time (taken as the 10% value from fig. 1) on the volume of the moderator.

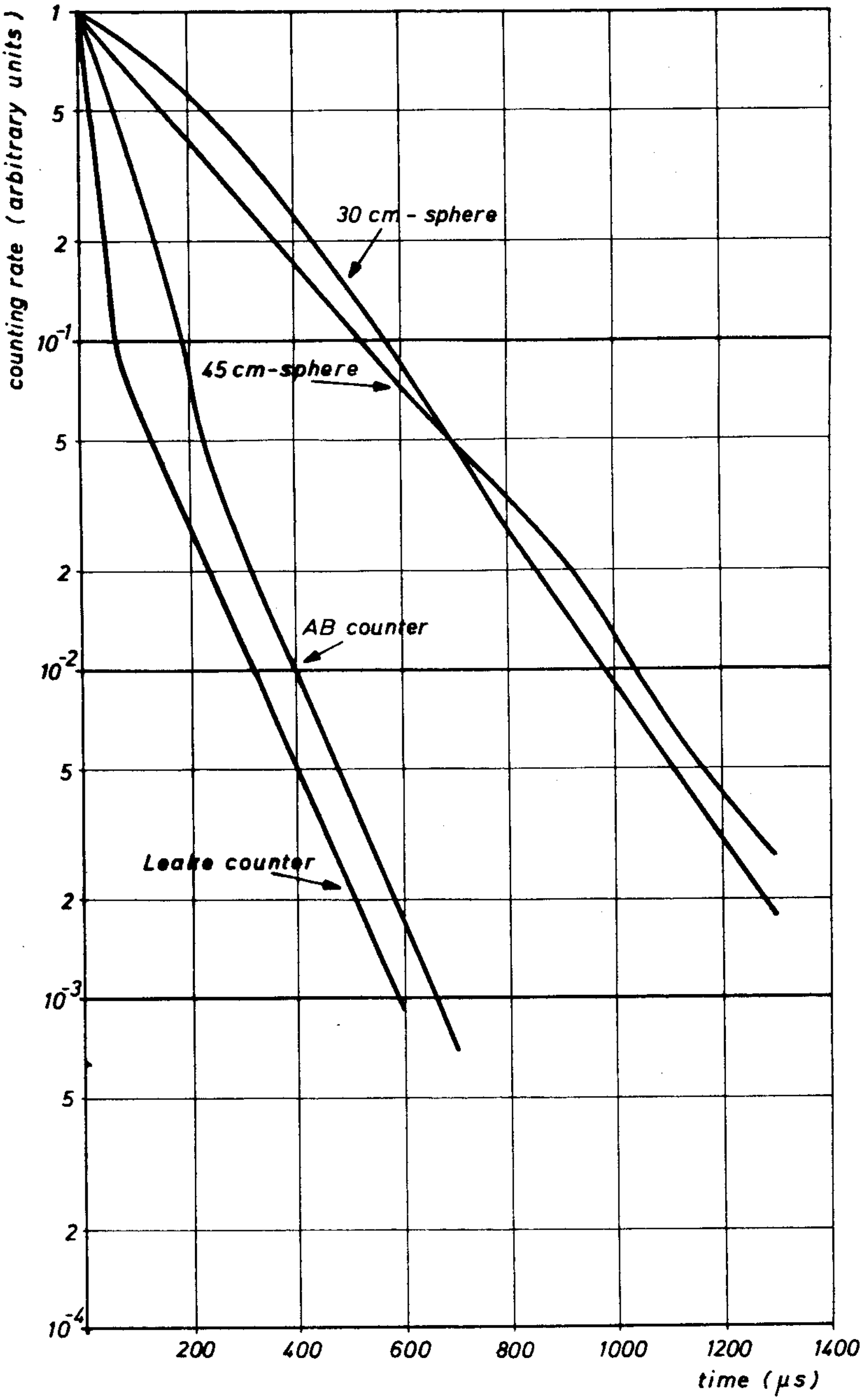
Fig. 3 Diagram for determining the correction factor C for a rem meter with a 30 cm-moderator. $\bar{D}$ is the true mean equivalent dose rate, D_p the dose per accelerator pulse, L_p and f the length and repetition rate of the accelerator pulses.

Fig. 4 The right hand part of fig. 3 for the AB counter.

Fig. 5 The right hand part of fig. 3 for the Leake counter.

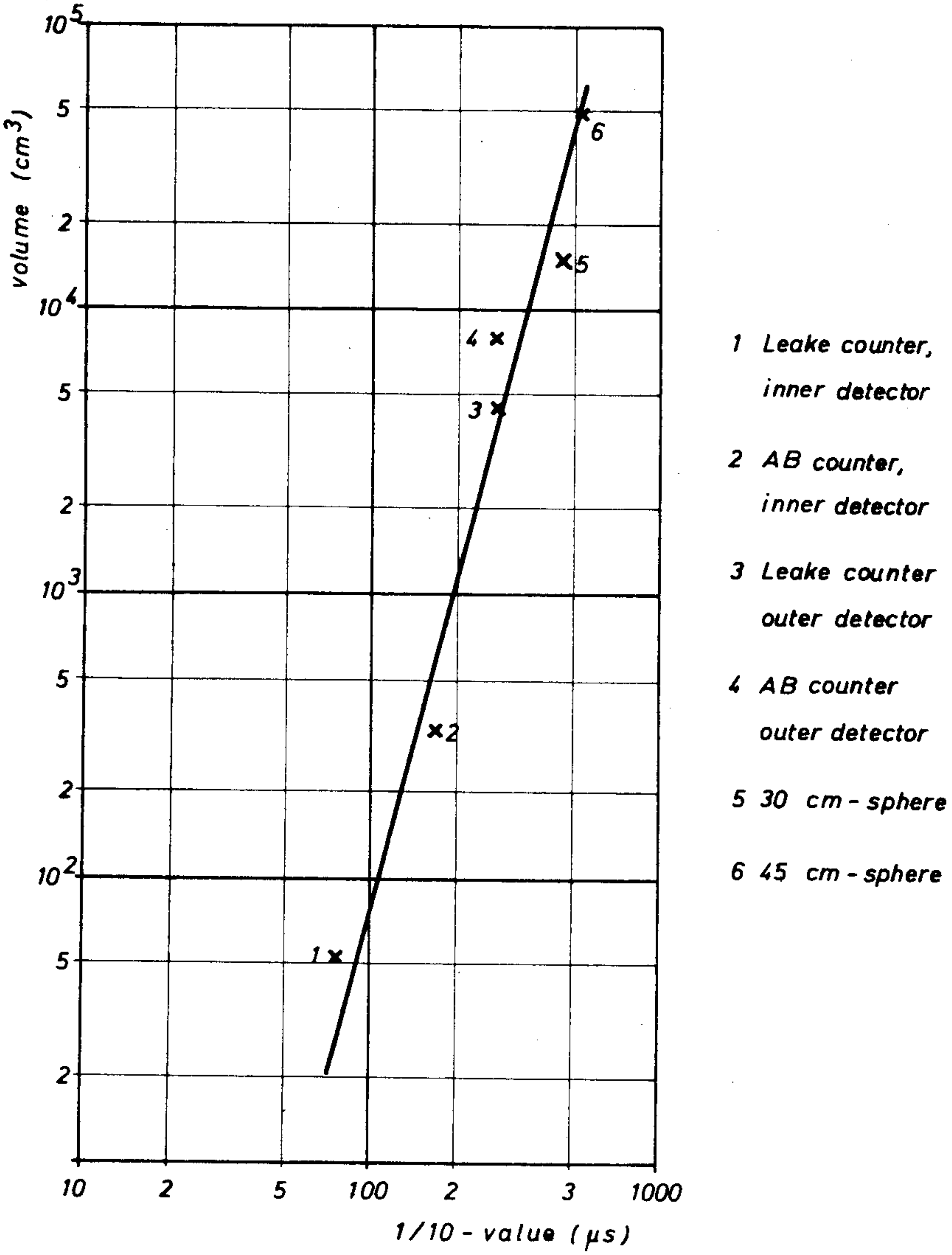
Fig. 6 The right hand part of fig. 3 for a rem meter with a 45 cm-moderator.

Fig. 1



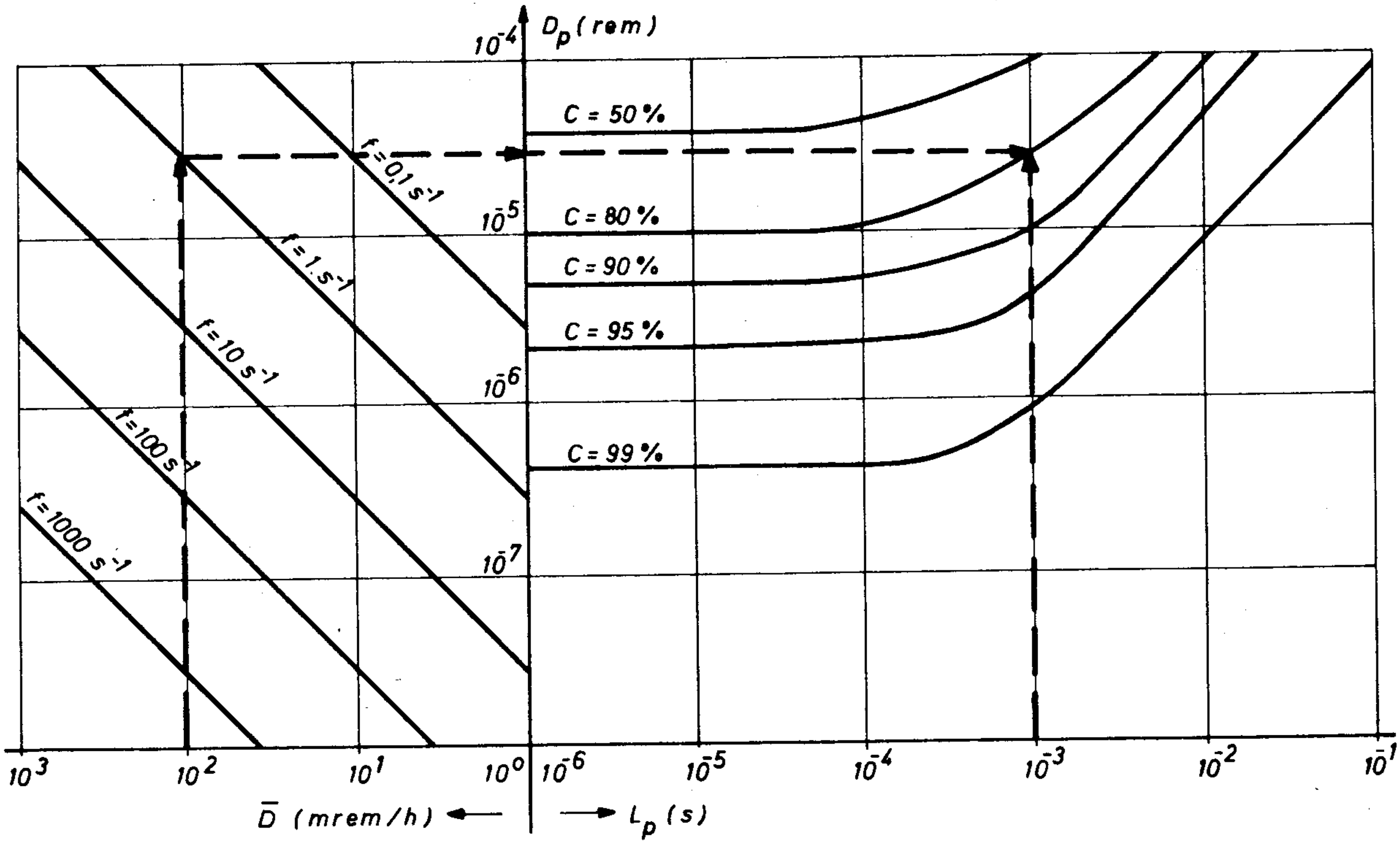
counting rate (arbitrary units)
1
5
2
10^{-1}
5
2
10^{-2}
5
2
10^{-3}
5
2
10^{-4}
200
400
600
800
1000
1200
1400
time (μs)
30 cm - sphere
45 cm-sphere
AB counter
Leake counter

Fig. 2



volume (cm³)
10⁵
5
2
10⁴
5
2
10³
5
2
10²
5
2
10
2
5
100
2
3
1000
1/10 - value (μs)
1
2
3
4
5
6
1 Leake counter, inner detector
2 AB counter, inner detector
3 Leake counter outer detector
4 AB counter outer detector
5 30 cm - sphere
6 45 cm - sphere

Fig. 3



D_p (rem)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
C = 50 %
C = 80 %
C = 90 %
C = 95 %
C = 99 %
f = 0,1 s^{-1}
f = 1 s^{-1}
f = 10 s^{-1}
f = 100 s^{-1}
f = 1000 s^{-1}
10^3
10^2
10^1
10^0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\bar{D}$ (mrem/h) ⟵
⟶ L_p (s)

Fig. 4

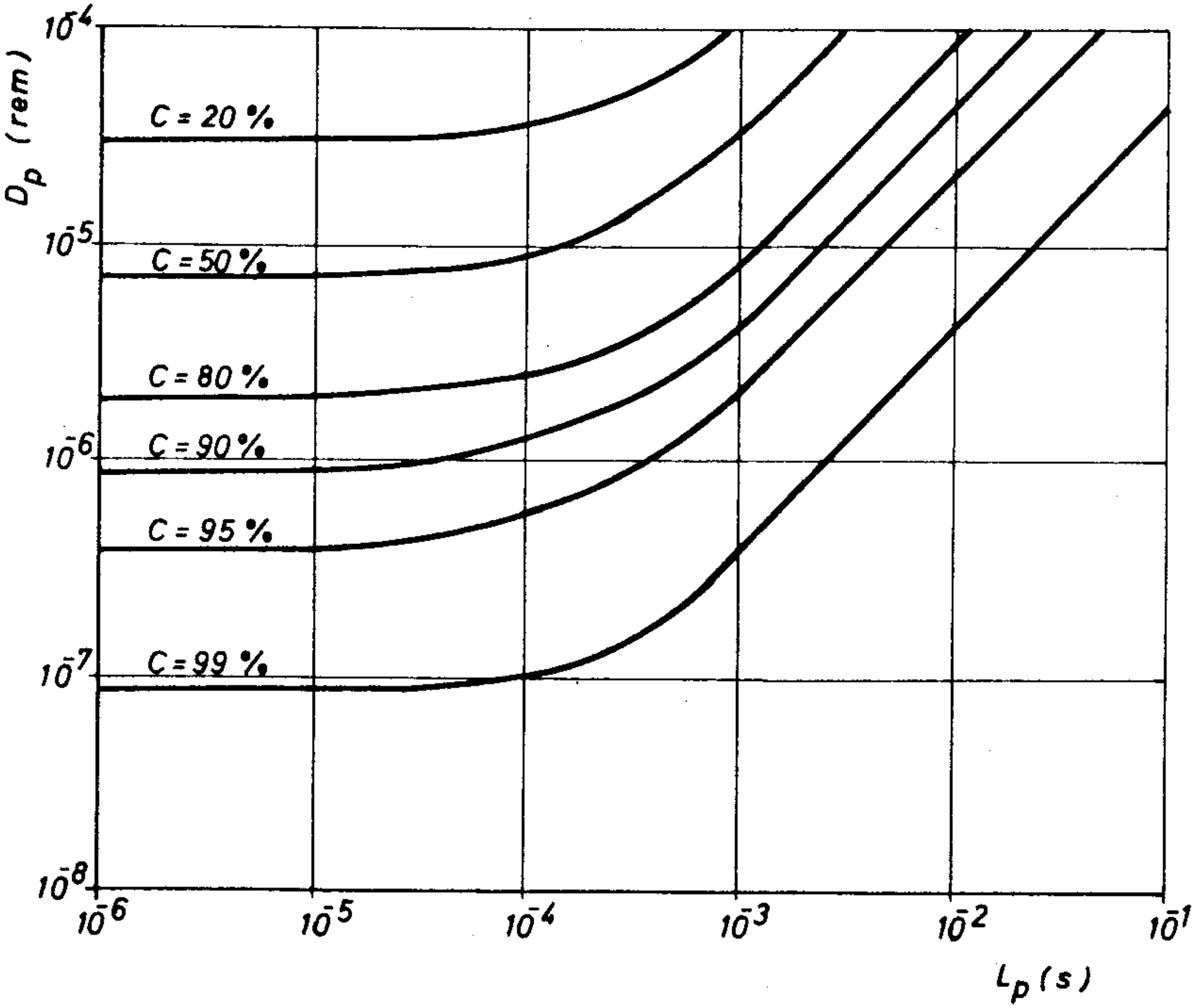

D_p (rem)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
C = 20 %
C = 50 %
C = 80 %
C = 90 %
C = 95 %
C = 99 %
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
L_p (s)

Fig. 5

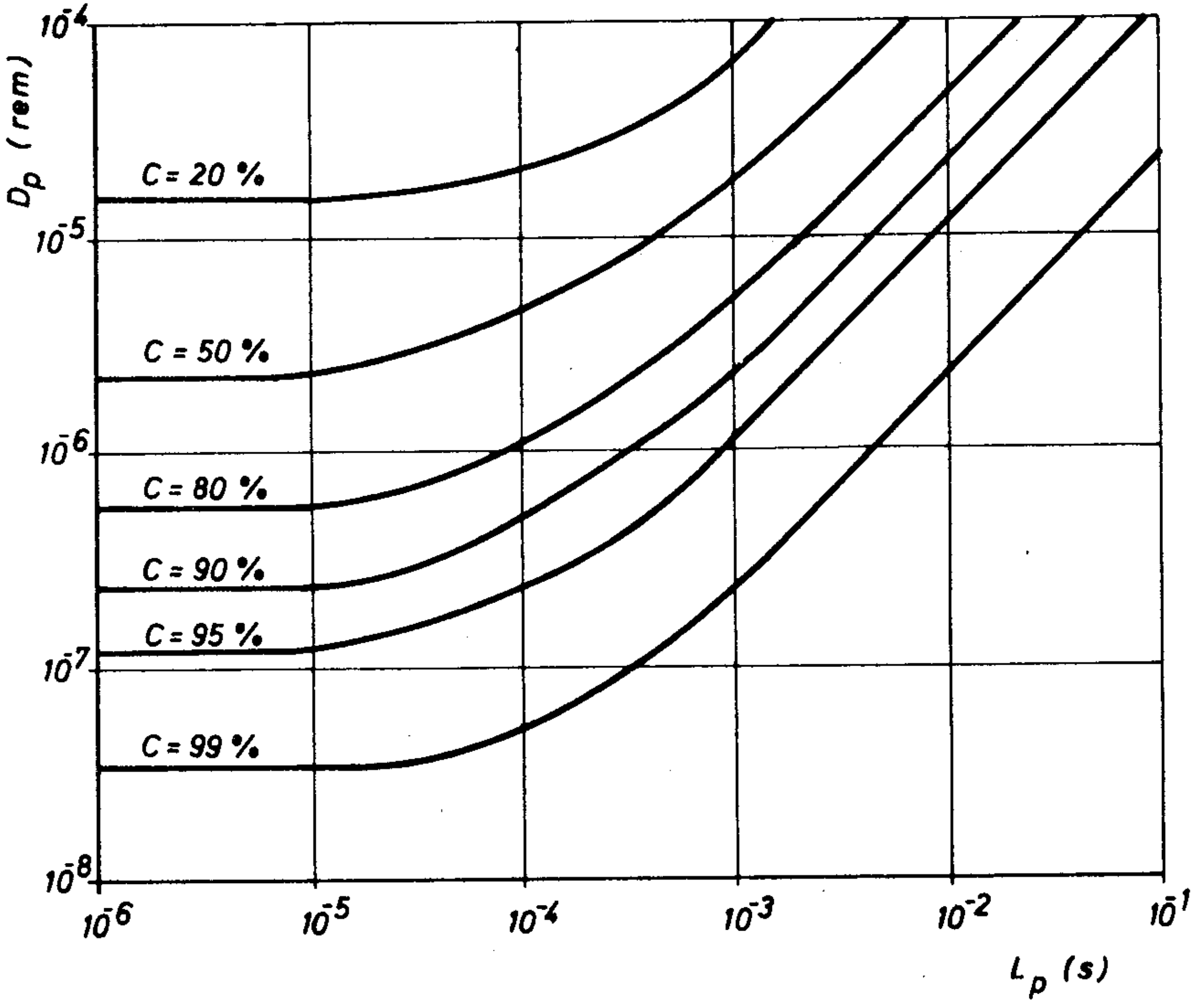
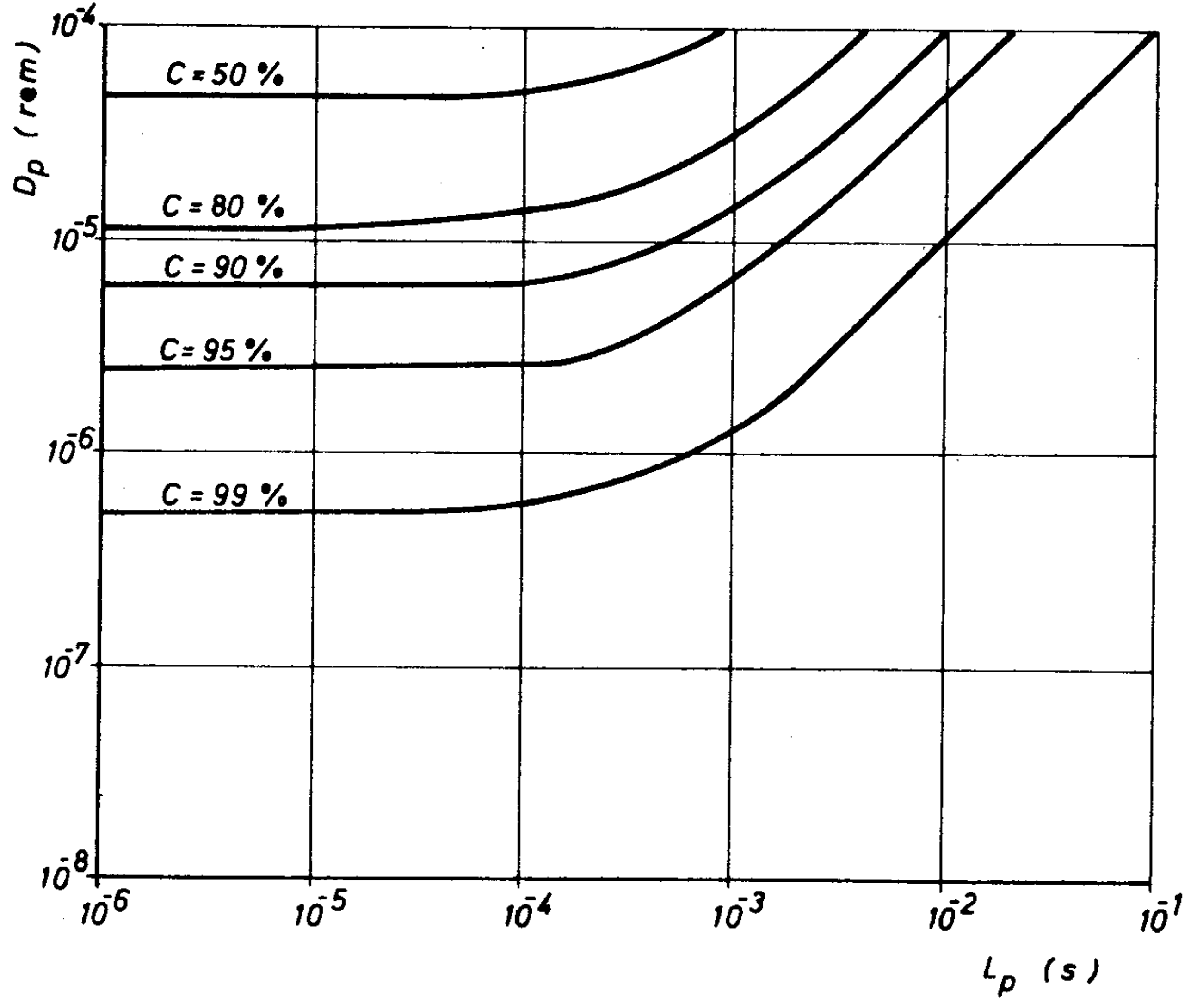

D_p (rem)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
C = 20 %
C = 50 %
C = 80 %
C = 90 %
C = 95 %
C = 99 %
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
L_p (s)

Fig. 6


D_p (rem)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
C = 50 %
C = 80 %
C = 90 %
C = 95 %
C = 99 %
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
L_p (s)