Polish Journal of Occupational Medicine and Environmental Health, Vol. 5, No 1, 77–86, 1992

# TRANSFORMATION OF FIELD MONITORING RESULTS INTO MINERS' ANNUAL EXPOSURES TO RADON PROGENY

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**Key words: Radon daughter products, Miners, Field monitoring, Annual exposures**

**Abstract.** This paper presents the theory of estimating miners' radiation hazard, using the values of radon daughters' concentration in the work-environment. All measurement results can be obtained with any technique beginning with instant measurement and ending with long-term dosimetry. The measurements carried out in metal ore mines show that the seasonal changes in radon daughters' concentration have their main influence in the estimation of the miners' hazard.
The estimation of the hazard which was obtained from equations, was compared with the results given from the computer simulation.

## INTRODUCTION

Due to the presence of radon and its progeny in uderground mines' atmosphere there is a necessity for environmental monitoring of the radiation hazard as well as estimating individual and group exposures. Both activities are carried out using different measuring techniques (from grab air sampling to long-term measurements) (3, 7, 8). In general, the reported differences in results are the consequence of different integration time-intervals of the used devices. Still more problems arise in exposure evaluations, when only incomplete information about the changes in radon daughter concentration at the workplace is available (4).

This paper discusses a theory of the transformation of the distribution of radon daughter concentration into the distribution of miners' annual exposure.

## THEORETICAL MODEL OF THE DISTRIBUTION'S TRANSFORMATION

It is extremely difficult to determine the physical parameters of an underground mine owing to its intricate internal structure and the mileage of the underground tunnels. This requires modeling of all the values dependent upon the ventilation, including annual miners' exposure to radon daughters. Therefore, complex calculations must be carried out, the results of which, however, are not always reliable (1). It is associated with a great number of independent regulatory parameters which may

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affect the results. The best way to solve this problem seems to be the apllication of the stochastic method. It can be used for estimating the group hazards of miners, when the values of individual exposure need not be considered. To do this, several assumptions have to be made, namely:

a) The mine is homogenous with regard to the potential radiation hazard as it can be divided into sectors for which this condition is true;

b) The average concentration of the potential energy during the measurement time T is assumed to be the measured quantity;

c) All of the measurements are independent of each other;

d) In the mine the distribution (its parameters) of radon daughter concentration is known;

e) For each of the miners k measurements are carried out during a year;

f) The measurement strategy is optimal, i.e. there are no "hunting" – and "avoidance" – effects (5, 6).

The continuous estimation of the radiation hazard requires m consecutive measurements according to the formula:

$$m = \frac{T_Y}{T} \tag{1}$$

where $T_Y$ – annual duration of miners' work.

The average concentrations of the potential energy $C_i$ ('i' stands for the i-th measurement for a miner) are available, so the annual exposure can be calculated from:

$$E = \sum_{i=1}^{m} C_i T \tag{2}$$

If continuous measurements of exposure were carried out for all the miners, it would be possible to evaluate the distribution of annual miners' exposure. On the other hand, if only the distribution of the concentration is available, the expected annual exposure distribution can be determined *a priori* (i.e. its parameters: $\mathbf{E}(E)$ – expected value and $\mathbf{D}^2(E)$ – variance). The values of $\mathbf{E}(E)$ and $\mathbf{D}^2(E)$ can be associated with the following parameters from the measurements: expected value $\mathbf{E}(C)$ and variance $\mathbf{D}^2(C)$ of the concentration distribution.

$$\mathbf{E}(E) = \mathbf{E}\left(\sum_{i=1}^{m} C_i T\right) \tag{3}$$

$$\mathbf{E}(E) = mT\mathbf{E}(C) \tag{4}$$

since $mT = T_Y$ then:

$$\mathbf{E}(E) = T_Y \mathbf{E}(C) \tag{5}$$

and then:

$$\mathbf{D}^2(E) = \mathbf{D}^2\left(\sum_{i=1}^{m} C_i T\right) \tag{6}$$

$$\mathbf{D}^2(E) = mT^2\mathbf{D}^2(C) \tag{7}$$

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$$\mathbf{D}^2(E) = \frac{T_Y^2}{m}\mathbf{D}^2(C) \tag{8}$$

The equations (5) and (8) describe the expected value and variance of the annual exposures distribution reflected by equation (2). If for each miner k measurements are made (k < m), non-continuous monitoring conditions will be provided. In this case the value of $E_p$ for a single miner can be determined according to:

$$E_p \overset{\text{def}}{=} T_Y \frac{\sum_{i=1}^{k} C_i T}{kT} \tag{9}$$

$$E_p = \frac{T_Y}{k}\sum_{i=1}^{k} C_i \tag{10}$$

and as follows from the above:

$$\mathbf{E}(E_p) = \mathbf{E}\left(\frac{T_Y}{k}\sum_{i=1}^{k} C_i\right) \tag{11}$$

$$\mathbf{E}(E_p) = T_Y\mathbf{E}(C) \tag{12}$$

and:

$$\mathbf{D}^2(E_p) = \mathbf{D}^2\left(\frac{T_Y}{k}\sum_{i=1}^{k} C_i\right) \tag{13}$$

$$\mathbf{D}^2(E_p) = \frac{T_Y}{k}\mathbf{D}^2(C) \tag{14}$$

The comparison of equations (5) and (12) with (8) and (14), respectively, results in the following:

$$\mathbf{E}(E_p) = \mathbf{E}(E) \tag{15}$$

and

$$\mathbf{D}^2(E_p) = \delta\mathbf{D}^2(E) \tag{16}$$

where:

$$\delta \overset{\text{def}}{=} \frac{m}{k} \tag{17}$$

From equations (15) and (16) the following conclusions can be drawn:

a) When an optimal measurement strategy is assumed, the expected value of annual exposures derived from equation (9) is equal to the expected value of annual exposures determined on the basis of continuous measurements.

b) The variances of distributions of both the exposures (E and $E_p$) are proportional, and the so-called "fill coefficient" δ is the measure of that proportionality. It is a ratio between the theoretical maximum time-period which can be used to carry out measurements for a single worker during one year (continuous measurements) and the actual time period of measurements for this worker during a one-year period.

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c) The theoretical maximum value of the "fill coefficient" δ is for example:
– for grab sampling (T = 5 min, $T_Y$ = 2000 h) δ = 24000,
– for dosimetric measurements (T = 167 h, $T_Y$ = 2000 h) δ = 12.

## EXPERIMENTAL DATA

The coefficient δ from equation (17) is dependent on the actual and theoretical time of the measurements, which are or can be carried out for one worker during a year. Let us assume that a single measurement was made for each of the miners. The time of the measurement is 5 min (for example grab sampling). In this case δ = 24000 (m = 24000, k = 1) 99% of measurements lies between 0.01 WL* and 0.5 WL (5). It is possible to calculate the distribution of exposures $E_p$ with an expected value $\mathbf{E}(E_p)$ = 1.12 WLM** and variance $\mathbf{D}^2(E_p) = 0.96\ (WLM)^2$. Using a "fill coefficient" δ and equations (15) and (16), the distribution of expected annual exposures can be found. The expected value **E**(E) and variance $\mathbf{D}^2(E)$ of this distribution area 1.12 WLM and $3.6 \cdot 10^{-5}\ (WLM)^2$, respectively. In the case of a log-normal distribution it would mean that 99% of the measuremenents' results are in the interval between 1.10 WLM and 1.14 WLM, which is inconsistent with the values of observed distributions of the annual exposures. Taking into account the actual distributions of radon progeny concentration and annual exposure distribution, the coefficient δ reaches its maximum value in the range of 20 to 30. The above value differs in the magnitude of one thousand from the theoretical value (24000). The reason for that difference is probably a process of variation of the measured concentration during the period of measurement. It was assumed that each 5 min measurement brings different results. However, if the concentrations which occur in the mines are assumed to be constant or nearly constant during a given period of time (for example two weeks), the decrease of the time between measurements to less than two weeks does not seem to be effective (Fig. 1). It has no influence on the estimated expected value **E**(C) and the variance $\mathbf{D}^2(C)$. Allowing a two-week period of possible concentrations variation the δ coefficient assumes a value in the order of 30 which is the same magnitude as the theoretical value for a one–month period of dosimetric measurements (δ = 12).

The statistical analysis of dosimetric measurements carried out in Polish metal-ore mines during the years 1977–1987 (2) reveals considerable changes of δ during that period. The dosimetric measurements consist of the individual dosimetry of a representative subgroup of miners in each metal-ore mine. Detectors are changed once a month. The following information can be obtained:

a. distribution of annual exposure of the representative subgroup of miners,
b. distribution of the average one – month concentration in the mine.

In this case, according to the definition of "fill coefficient" δ should reach the value of = 12, but Tables 1 and 2 demonstrate that δ decreases during the year from a value of about 12 to a stabilized value of about 3 (mean value of δ in 1987 is 3.21 and 3.53 for zinc-lead- and copper-mines, respectively). The observed trend in the

*Traditionally used unit (WL – Working Level)
1 WL = 20'8 $\mu Jm^{-3}$.
**Traditionally used unit (WLM – Working Level Month)
1 WLM = 3.5 $mJhm^{-3}$.

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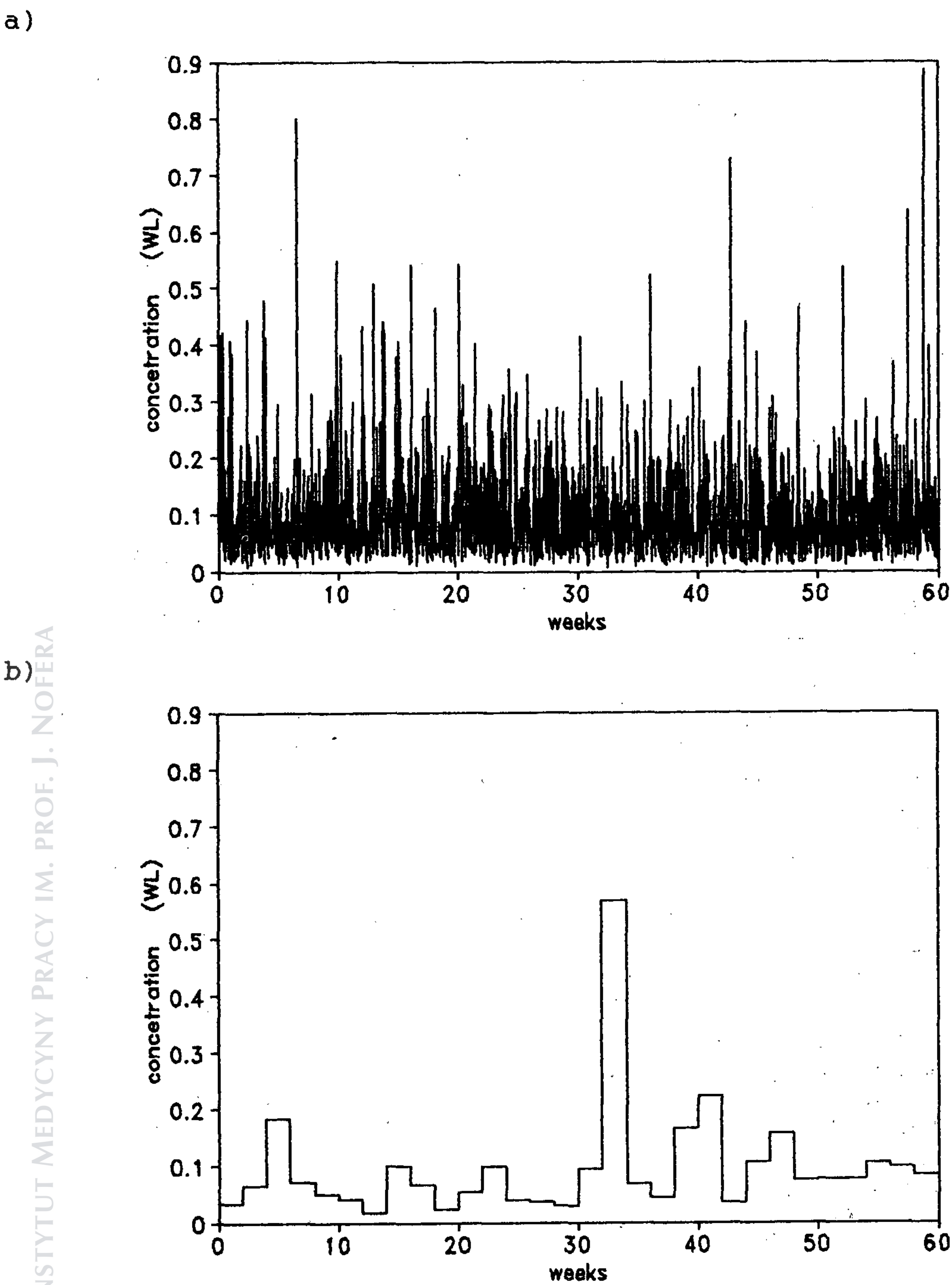


**Fig. 1.** The computer simulation of two types of concentrations' distributions with the same variances and expected values.
a) – concentration varies in 5 min period.
b) – concentration varies in two-week period.

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Table 1. "Fill coefficient" δ in lead-zinc mines.

| Year | Arithmetic mean | Range of results from – to | 95% confidence interval for arith. mean |
|---|---|---|---|
| 1977 | 6.79 | 3.98 – 10.20 | 4.16 – 9.41 |
| 1978 | 6.43 | 2.08 – 9.13 | 3.82 – 9.05 |
| 1979 | 16.93 | 0.47 – 64.05 | 0.00 – 41.95 |
| 1980 | 3.90 | 1.70 – 7.87 | 1.54 – 6.27 |
| 1981 | 5.74 | 2.31 – 9.79 | 3.04 – 8.45 |
| 1982 | 3.68 | 1.47 – 6.11 | 1.61 – 5.74 |
| 1983 | 4.30 | 2.19 – 8.59 | 1.74 – 6.86 |
| 1984 | 4.15 | 2.70 – 6.25 | 2.75 – 5.55 |
| 1985 | 3.82 | 2.05 – 6.22 | 1.99 – 5.66 |
| 1986 | 2.23 | 0.76 – 4.10 | 0.98 – 3.47 |
| 1987 | 3.21 | 1.70 – 4.87 | 1.85 – 4.58 |

Table 2. "Fill coefficient" δ in copper mines.

| Year | Arithmetic mean | Range of results from – to | 95% confidence interval for arith. mean |
|---|---|---|---|
| 1977 | 7.85 | 4.22 – 12.71 | 1.88 – 13.81 |
| 1978 | 5.12 | 0.76 – 9.38 | 0.00 – 10.88 |
| 1979 | 15.31 | 2.02 – 26.90 | 0.00 – 34.87 |
| 1980 | 7.15 | 2.61 – 11.80 | 1.09 – 13.21 |
| 1981 | 4.46 | 3.23 – 5.42 | 2.96 – 5.95 |
| 1982 | 4.58 | 1.83 – 5.84 | 1.63 – 7.52 |
| 1983 | 7.56 | 3.57 – 12.40 | 3.09 – 12.02 |
| 1984 | 7.80 | 2.65 – 11.20 | 3.85 – 11.75 |
| 1985 | 3.17 | 1.95 – 4.74 | 1.66 – 4.67 |
| 1986 | 3.42 | 2.75 – 4.17 | 2.77 – 4.07 |
| 1987 | 3.53 | 1.73 – 7.43 | 0.70 – 6.36 |

changes of δ coefficient is connected with the modifications of the ventilation network in the mines. If the air flow is not under full control, the "fill coefficient" is higher, whereas a controlled air flow brings about lower values of the δ coefficient. The stabilization on level 3 for both types of the mines shows that it has reached an optimal state, which is connected only with seasonal changes. The average value of δ during the years 1985–1987 was 3.09 for zinc-lead mines and 3.37 for copper mines. It is characteristic that in 1979 δ reached the highest value for both zinc-lead- and copper mines. This conclusion requires further studies.

Because the real δ value is lower then 12 and naturally lower than 24 000 (instant measurements), the distributions of results of the measurements (instant and dosimetric) should be equal. Obviously, the above is true if proper measurement strategies are assumed. In the radiological praxis, δ equal 12 for dosimetry, or δ equal 1 for instant measurements are often used to evaluate annual exposures.

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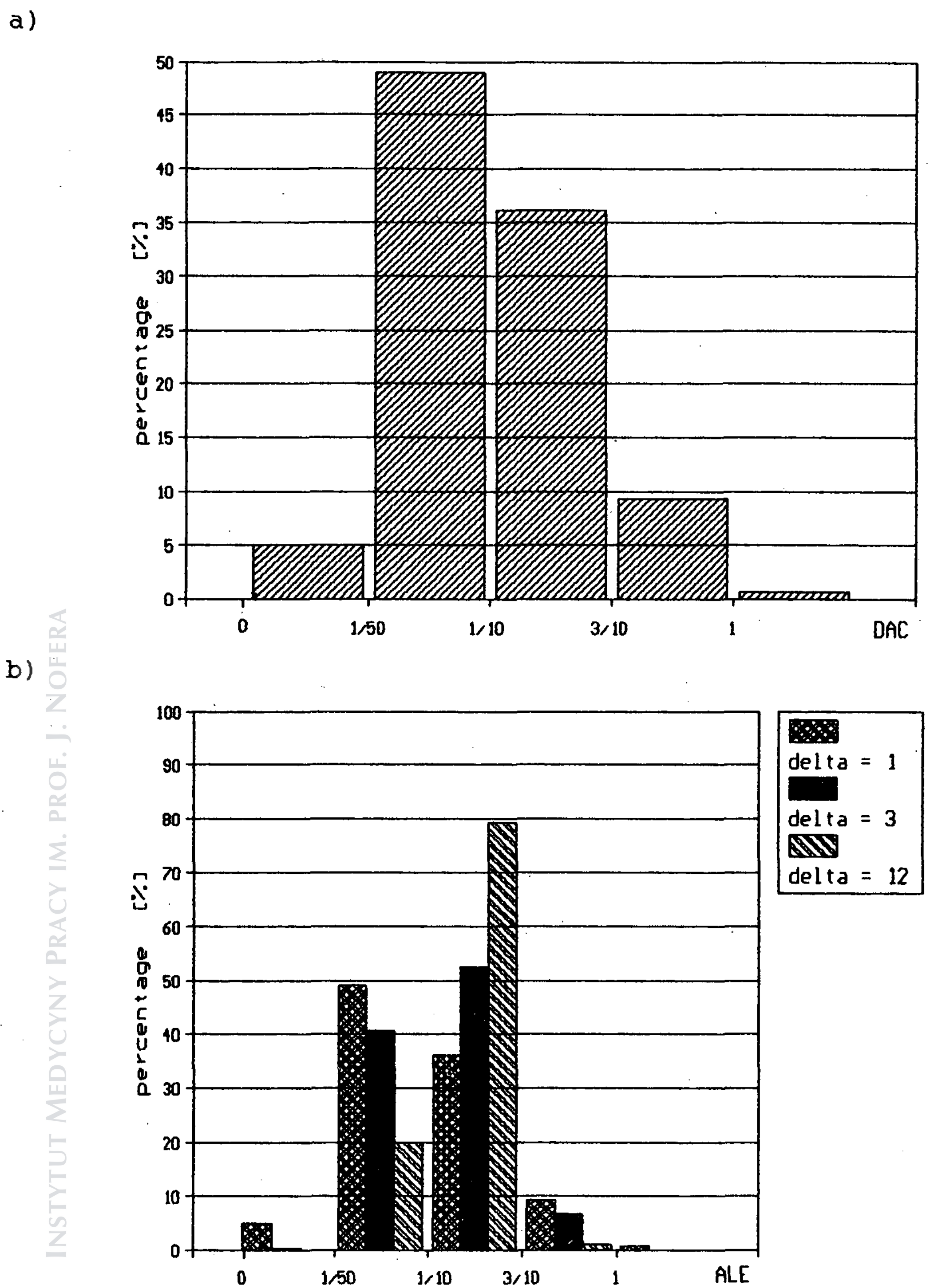


**Fig. 2.** The hypothetical concentrations' distribution in a mine (a) and corresponding annual exposures' distributions for $\delta = 1, 3, 12$ (b).

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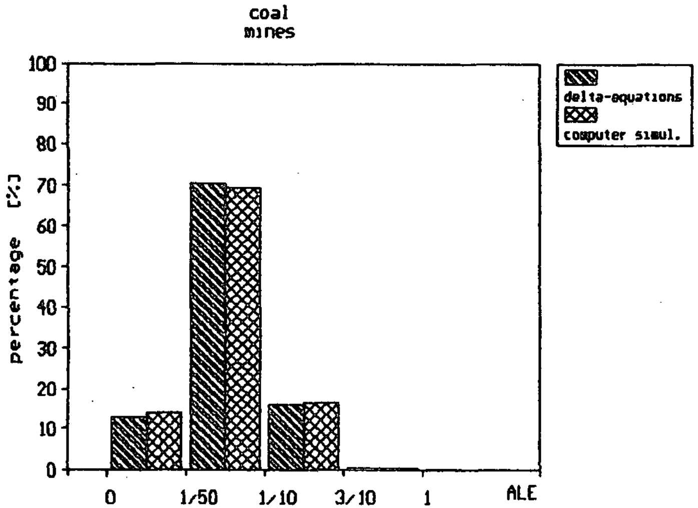


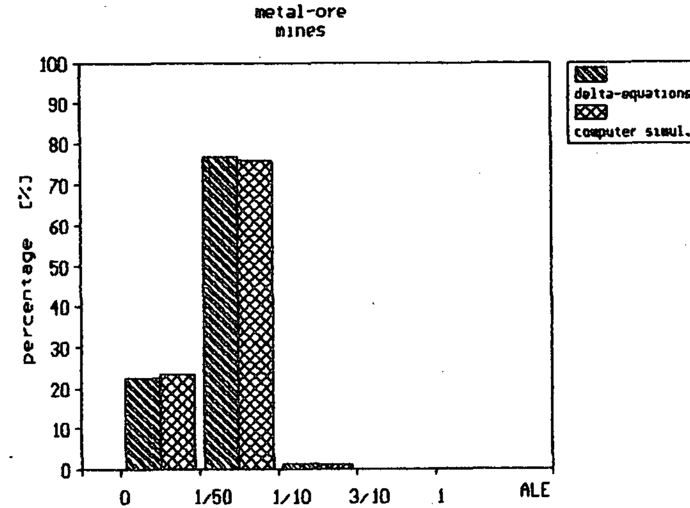


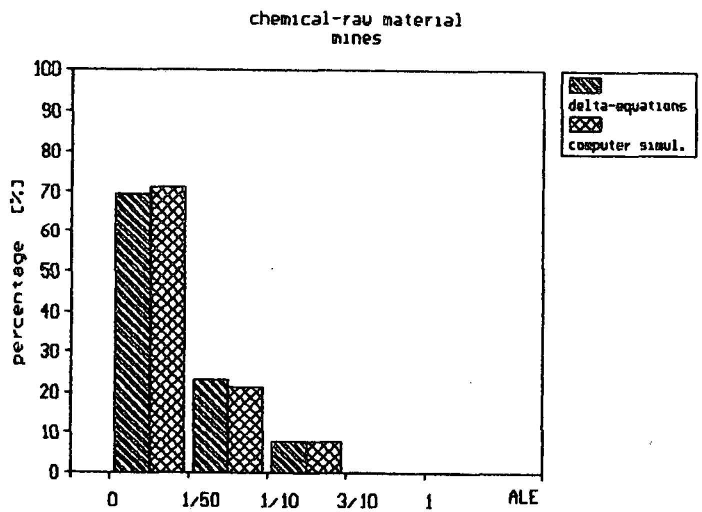


**Fig. 3.** The comparison of the hazard estimation between two techniques: computer simulation and δ – equations. Both exposures' distributions were created from a known concentrations' distribution.

When the distribution of the potential energy concentration Fig. 2a) is known, different values of $\delta$ give different estimation of the radiation hazard (Fig. 2b), i.e.:

a. for $\delta = 1$ (frequently used for instant measurements) about 46% of results of estimated annual exposures exceed 1/10 ALE *,

b. for $\delta = 3$ (approximate value for metal-ore mines) about 59% of results of estimated annual exposures exceed 1/10 ALE,

c. for $\delta = 12$ (theoretical value for one-month measurements) about 80% of results of estimated annual exposures exceed 1/10 ALE.

The other concentrations' distribution assumes other proportions exceeding the level of 1/10 ALE.

The formal correctness of the above equations can be proved by comparing them with the results obtained from computer simulation (4). The principle of the procedure is as follows: from the pool of one-month exposure results, the values of annual exposures are calculated by summing up the twelve randomly selected concentration's values. The distribution of annual exposures obtained thus should bring results comparable with parallel calculations from equations (15) and (16), assuming $\delta = 12$. Both of these distributions are presented in Fig. 3.

## CONCLUSIONS

1. The method discussed in the paper makes it possible to obtain directly the distribution of annual exposures of the miners on the basis of non-continuous measurements or grab sampling results. The connector between these two sets of results is the so-called "fill coefficient" $\delta$.

2. In the actual mines' conditions $\delta$ coefficient may reach a value of 20 – 30. It would indicate that the main contribution to the value of annual exposures have the long-term fluctuations (about two weeks) rather than the short-term variations of the concentration of potential energy in the mine's atmosphere.

3. The data from dosimetric measurements of monthly and annual exposures in metal-ore mines reveals that the real value of $\delta$-coeffiecient is about 3. Higher values of $\delta$ reported in all mines in 1979 require further studies.

4. The recorded average $\delta$-value of 3 indicates that the concentrations' distributions as obtained from long-term and instant measurements should be equal, on condition that there are no "avoiding" – and "hunting" effects in the measurement strategy. The observed differences in the estimation of exposures are caused by applying instant techniques for purposes other than risk assessment.

5. The exposure distributions obtained from both the computer simulation and the $\delta$-equations are equal.

6. The different calculating procedures frequently bring about differences in risk classification. It is connected with the measurement techniques used (Fig. 2).

* In Polish Law Regulations for radon daughters in mines:
DAC = 6.2 $\mu Jm^{-3}$ = 0.3 WL
ALE = 12 $mJhm^{-3}$ = 3.5 WLM
Dosimetry Level = 1/10 ALE.

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## ACKNOWLEDGEMENTS

This study was carried out under the Research Project of the Nofer Institute of Occupational Medicine No IMP-5.4/1992.

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Received for publication: February 26, 1992
Accepted for publication: March 10, 1992

INSTYTUT MEDYCYNY PRACY IM. PROF. J. NOFERA