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COMPUTER-AIDED METHODS FOR EVALUATING CANCER RISK IN MINERS DUE TO RADIATION EXPOSURE

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Abstract. The paper presents some aspects of radiation hazard which occurs in a non-nuclear sector of industry, namely radiation hazard in non-uranium underground mines. The radiation hazard is caused in each type of underground mine by the naturally occurring noble radiactive gas-radon (^{222}Rn) and radioactive products of its decay ^{218}Po, ^{214}Pb, $^{214}Bi/^{214}Po$ the so-called 'radon daughters' occurring in the mines' air. The paper presents the concept of how to provide a reliable system of assessment of miners' exposure by application of representative individual dosimetry, and also presents principles of computer-aided methods for interpretation of the results of miner's dosimetry useful for conversion of dosimetry data to the term of expected risk of cancer caused by exposure at miner's workplaces. The representative Individual Dosimetry system strengthened by computer-aided methods of analysis of results provided essential information on radiation cancer risk for miners employed in coal mines, metal-ore mines, chemical raw material mines in Poland. The coefficient of annual cancer risk induction is 1.5×10^{-4} year^{-1} for coal mines, 1.40×10^{-4} year^{-1} for metal ore mines and 1.5×10^{-4} year^{-1} for chemical raw material mines. The radiation risk appears to be of the same magnitude as the conventional risk of life loss at work-related accidents. The average Lost Life Expectancy coefficient for both the radiation risk and conventional risk are 0.5 and 0.3 year per each miner, respectively.

INTRODUCTION

It is presently a very well known fact that nowadays the radiation hazard for professionals and for the general population, as well, is caused by natural radiation more than by the nuclear sector of industry. Therefore, the main goal for hygienist preventing of and dealing with the radiation hazard is the problem of how to draw more attention to public opinion and scientists' efforts to the radiation hazard caused by the so-called 'technologically enhanced natural radiation'. A relevant example can be presented from Poland, entirely a 'non-nuclear' country but

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where serious problems of radiation hazard are caused by the non-uranium underground mining industry. Radiation hazard to miners is caused by the radioactive noble gas-radon (^{222}Rn), which occurs naturally in the underground mines' air. This gas decays naturally and the products of its radioactive decay appear in the form of radioactive aerosols, called radon daughters (i.e. ^{218}Po, ^{214}Pb, $^{214}Bi/^{214}Po$). Therefore, the occurrence of natural radioactive pollutants is the reason for radiation hazard to miners who work in such radioactively polluted air.

The relevant survey shows (1) that in the whole group of miners i.e. 250 000 people employed in 71 coal-mines the subgroup of ~27 000 miners employed in the seven mines can reach or surpass an annual exposure higher than the limit of the effective dose being recommended by the International Commission of Radiological Protection (ICRP) as equal to 20 mSv, and other subgroups about ~70 000 miners are exposed to levels in excess of 30% of the mentioned limit.

Both these facts create real problems for radiation hygienist, namely 1) how to provide a reliable system of assessment of miners' exposure, and 2) how to interpret the results of miners' dosimetry.

This paper presents ways which can lead to solving of both of these problems.

REPRESENTATIVE INDIVIDUAL DOSIMETRY FOR MINERS

An assessment of miners' exposure to radon daughter products, naturally occurring in the air in mines, is possible using various measurement systems which are based on different assumptions and techniques. Generally, the systems can be grouped into two classes. One of them groups systems based on environmental monitoring of radon daughter product concentrations by collecting (or filtering) air samples and analysing the radioactivity of samples (or filters). Such a class has been called the "Air Sampling System" (ASS). The other class groups those measurement systems which are based on the use of Individual Dosimetry System" (IDS), or "Representative Individual Dosimetry System" (2).

Certainly, each of these two classes has certain different inherent advantages and critical weak points. For example, the main feature of the ASS is its relatively high precision of each single measurement; however, the strategy of monitoring and the selection of the proper frequency of monitoring and the site of the system in the area of the mine still remains the weak point of the ASS. The critical point of the IDS, on the other hand, lies either in the cost of the measuring devices or in the doubtful precision of the measurement techniques.

Though a discussion on the superiority of one of these systems for the assessment of miners' exposure still remains open and calls the attention of practitioners and managers involved in decision making on radiation safety in mining, the long-term experience of the Nofer Institute of Occupational Medicine (NIOM) suggests to prefer the representative individual dosimetry as the relevant credible system for assessment of miners' radiation exposure. How does that system look and what are its technical features? The Individual Dosimetry System (IDS) is based on the use of indivifual dosimeters and is implemented as follows:

In every mine, a representative group of 10 to 50 miners, depending on the total number of miners employed, is randomly selected and equipped with individual cassettes based on the method of applying 'passive' SSNTD (Kodak LR-115) worn on the back of their helmets for one month, four times a year (once in each season of the year). These dosimeters measure the miners' monthly exposure to RnDP expressed in [$mJhm^{-3}$]. The technical details of these detectors, measurement devices and their applications have been described previously (3–9). The 'lowest measurable concentration' and 'exposure' of this method of measurement are $0.35\ Jm^{-3}$ ($17 \cdot 10^{-3}$ WL) and $0.058\ mJhm^{-3}$ ($17 \cdot 10^{-3}$ WLM), respectively, at an assumed 'confidence level' of 0.95 and at an assumed time of exposure of one month. The 'precision' of the method of measurement, i.e. the standard deviation of mean value, is 20–25% of the measured value. The men selected from such groups proportionally represent all the functions of miners employed in all regions of a given mine. From the practical experience of NIOM it is known that the most difficult procedure in applying the IDS is the distribution of the personal dosimeters and collecting them after a one month period. It has been determined that one hundred dosimeters is a number which can be optimally applied at one time in each cycle of measurements. This number yields the minimum amount of data which allows a credible assessment of collective miners' annual exposure. In this way, the representative IDS plays the role of a representative system and gives representative results of miners' exposure. The representative IDS allows the calculation of the 'average exposure' of miners as well as the 'frequency' distribution of annual miners' exposures by using the appropriate 'computer simulation technique'.

The essential argument in favour of the representative individual dosimetry system is confirmed by observations that it is almost free from the influence of methodology on the results of assessment. Let us then consider the system using some examples.

IMPACT OF METHODOLOGY ON ASSESSMENT OF RADIATION HAZARD

The first and most obligatory condition for implementation of radiation protection of non-uranium miners is the proper and reliable assessment of miners' exposure. It has been observed many times (10) that the assessment of miners' exposure conducted by local radiation officers in particular mines using the Air Sampling System (ASS) leads to completely different results as compared with results obtained when the IDS has been used. For example, Table 1 presents the comparison of average annual concentrations in some coal mines obtained by the local services in the ASS (using portable or stationary equipment) as compared to the analogous values of average annual concentrations evaluated by the NIOM when the IDS was applied.

This Table also contains an analogous comparison of the maximum values of concentrations recorded in particular mines using both these systems. The data presented in Table 1 are confirmed by an earlier study when the two different systems (i.e. the Air Sampling System (ASS) and the Individual Dosimetry System ((IDS)) were concomitantly implemented and used over 6 years in 11 mines (11). It was discovered then that the ASS is very sensitive to the strategy of measurements. Two possible effects were observed which have been called the 'hunting' effect and the 'avoidance' effect. The so-called 'hunting' effect arises when the strategy of measurements (time-frequency of measurements and their spatial locations) leads to an overestimation of real annual miners' exposure. It takes place when the radiation

Table 1. The ratio between the annual average (and maximum recorded) concentrations evaluated by local services using the ASS ($C_{MINE(ASS)}$) and by NIOM when the IDS was applied ($C_{NIOM(IDS)}$)

Name of mine	$C_{MINE(ASS)}/C_{NIOM(IDS)}$		Type of mines
	for annual average values	for maximum recorded values	
Makoszowy Mine	0.01	0.01	
Żory Mine	0.02	0.03	
Niwka Mine	0.02	0.01	
Jankowice Mine	0.02	0.03	
Jastrzębie Mine	0.03	0.01	
Krupiński Mine	0.03	0.02	
Komuna Paryska Mine	0.04	0.06	
Brzeszcze Mine	0.06	0.03	
Rydułtowy Mine	0.06	0.14	
Borynia Mine	0.07	0.09	
Piast Mine	0.07	0.05	
Bolesław Śmiały Mine	0.08	0.07	
Silesia Mine	0.10	0.11	Coal mines
Wesoła Mine	0.11	0.04	
Wieczorek Mine	0.12	0.08	
Rozbark Mine	0.12	0.16	
Pniówek Mine	0.16	0.06	
Budryk Mine	0.17	0.12	
Sosnowiec Mine	0.21	0.55	
Czeczot Mine	0.22	0.32	
Dębieńsko Mine	0.24	0.18	
Knurów Mine	0.29	0.12	
Zimowit Mine	0.42	0.92	
Chwałowice Mine	0.43	0.38	

safety officer responsible for monitoring concentrations of radon daughter products in air of the mine (using the ASS) increases the frequency of measurements when higher concentrations are temporarily or accidentaly found. The so-called 'avoidance' effect also arises from a false strategy of measurements, but is caused when the radiation safety officer responsible for monitoring in the mine simply removes measurements when higher concentrations are found. Both these effects are explained by the data presented in Fig. 1. This Figure displays the concentration of potential alpha energy of radon daughter products in the air measured simultaneously under the two discussed systems in two different mines collected during one particular year. The distribution of measured concentration obtained from personal dosimeters worn by miners under the IDS in both mines, shows a typical log-normal distribution and therefore can be recognised as reliable data corresponding to a real existing hazard. The distributions of measurement results obtained under the ASS differ from each other and differ completely in relation to data from the IDS. One can suspect on the basis of the data from the ASS regarding the Boleslaw Mine that the radiation safety officer selectively increased the frequency of measurements in states of higher concentration. Despite this, in the Polkowice

Mine the radiation safety officer probably avoided measurements in places where concentrations were higher.

One can conclude that the ASS is very dependent on man-related parameters of the system, whereas the IDS seems to be more free of them.

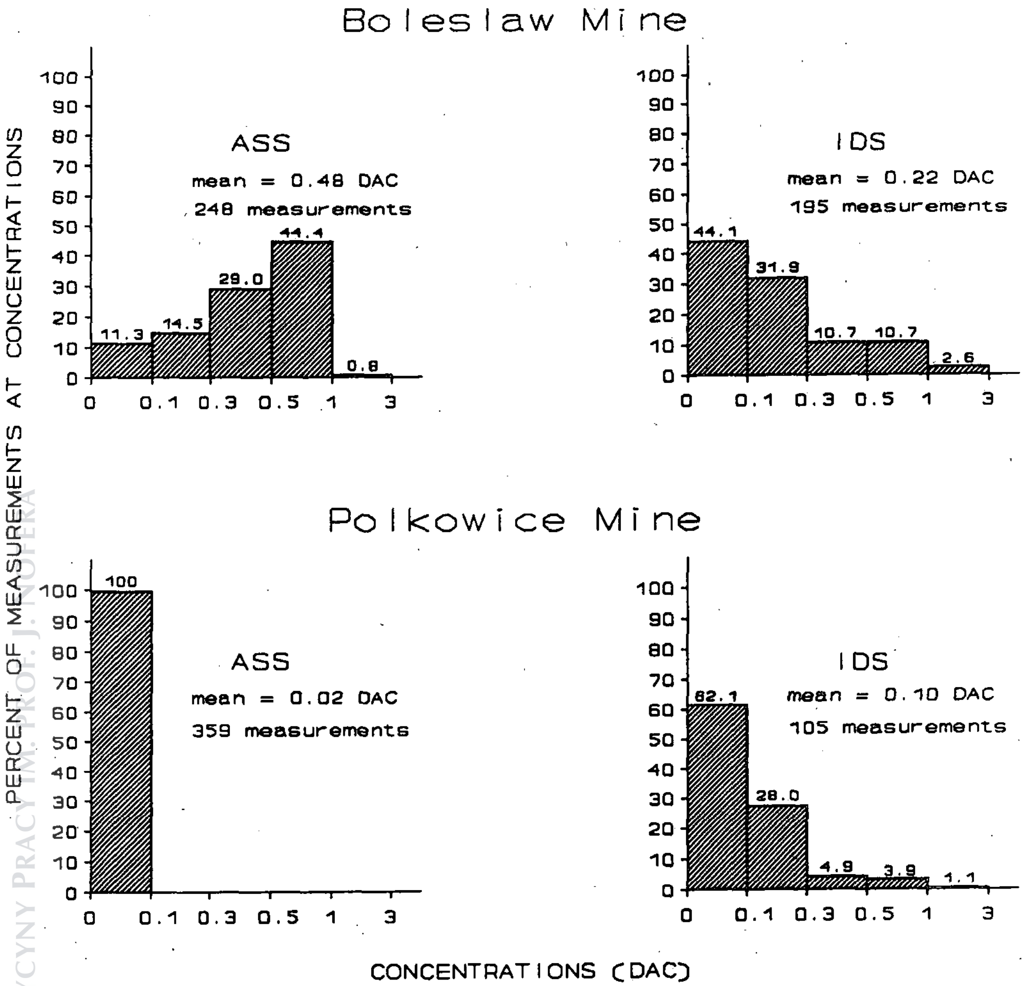


Fig. 1. The distribution of concentration of radon daughters in the air of two mines, measured under two independent systems concomitantly implemented in both mines. DAC (Derived Air Concentration) = 6.2 μJm^{-3} (0.3 WL).

COMPUTER-AIDED METHODS FOR PROCESSING INDIVIDUAL DOSIMETRY DATA

The representative individual dosimetry contains two stages in which computerised methods have to be used. The first stage is the computerised processing of dosimeters which were worn by a selected representative group of miners. The second one is the stage of adopting and transforming these results for evalutaion of values of indices which would refer to the whole group of miners employed in the mine being considered.

The first stage mentioned is relatively easy to be implemented and realised bacause it mainly concerns technical aspects of automatic read-out of a detector by computerised image analyser of films and afterwards the storing of the results in an appropriate computerised data bank (12, 13). The second stage is much more difficult since it concerns itself with the interpretation of results. The main problem occurs when interpreting the results obtained from a small group of miners (~50 persons) in relation to the whole population which sometimes reaches several thousand miners employed in a mine. On that ground, several questions arise, namely:

1. how many miners wearing dosimeters should constitute such a representative group?
2. What would be the criteria for the best selection of that group?
3. What should be the pattern for the transformation of representative individual dosimetry to the whole population of miners?
4. How to transfer the assessment of miners' exposure to the term of radiation risk for miners?

The answer to each of these questions could be the subject of a special paper, however, the concept of one of the most important and useful computerised method of evaluation of the indices of miners' exposure is presented below.

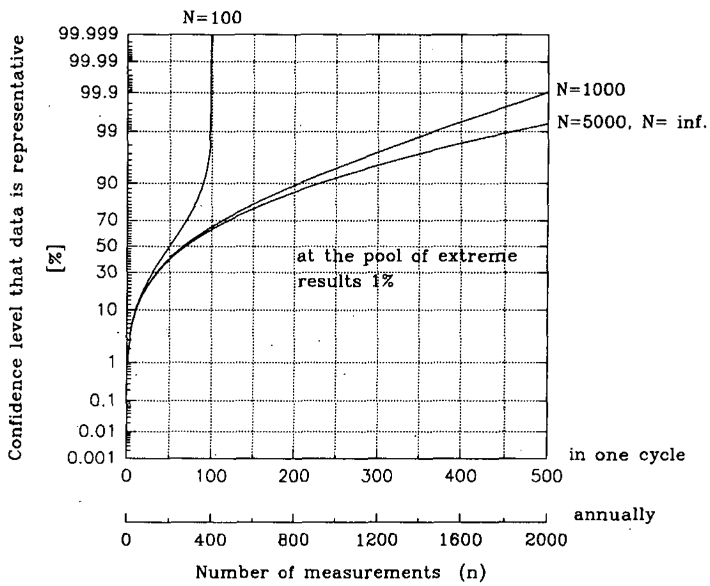


Fig. 2. The relationship between the number of measurements and respective confidence level of the data representativeness for different total (N) number of miners employed in the mine in question. The pool of the extreme results assumed to equal 1%.

The representative individual dosimetry provides the set of values of monthly individual exposures (E_i) which can be used for evaluation of the 'average annual exposure' for the whole miners' population as well as the 'frequency' distribution of

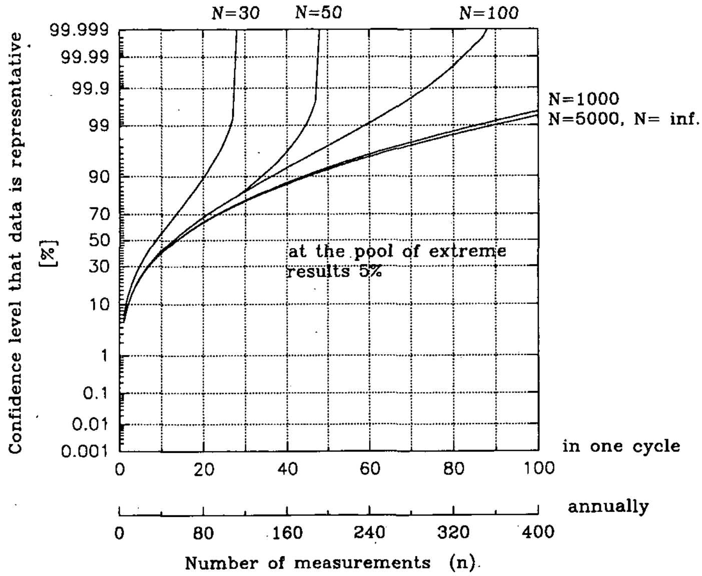


Fig. 3. The relationship between the number of measurements and respective confidence level of the data representativeness for different total number of miners employed in a mine (N). The pool of the extreme results assumed to equal 5%.

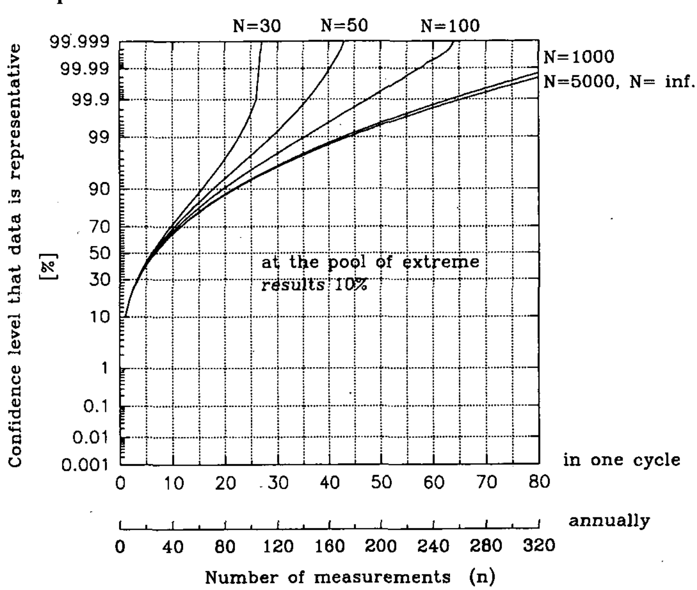
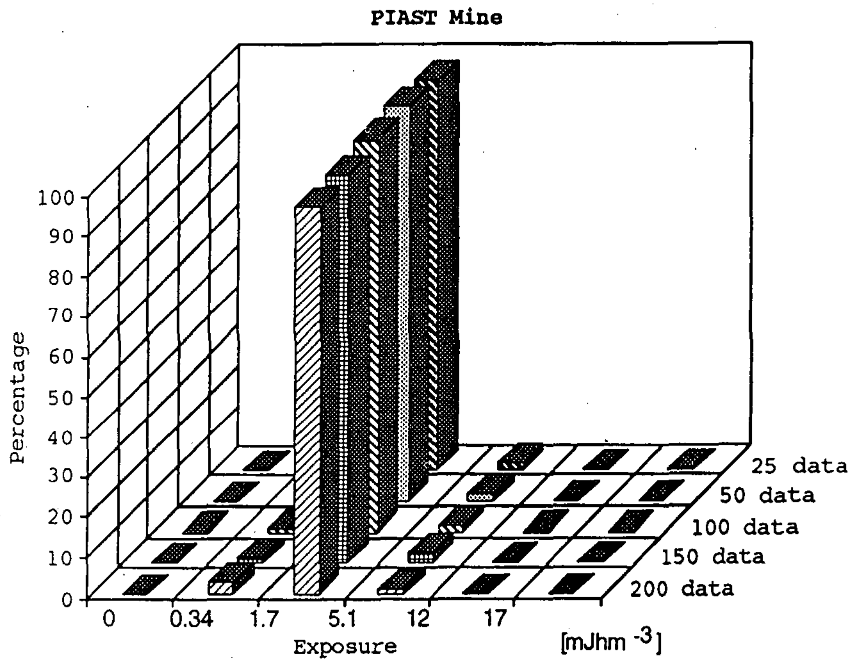


Fig. 4. The relationship between the number of measurements and respective confidence level of the data representativeness for different total number of miners employed in a mine (N). The pool of the extreme results assumed to equal 10%.

miners' exposure. The idea of such a conversion manner is to select randomly 12 of the monthly values of E_i by a computer technique based on the 'random number generator'. Twelve values were taken into account since the idea was to 'normalize' each possible single annual exposure of a miner to the standard period of employment of 2 000 hours. Since in mines a one-month period of miner's exposure



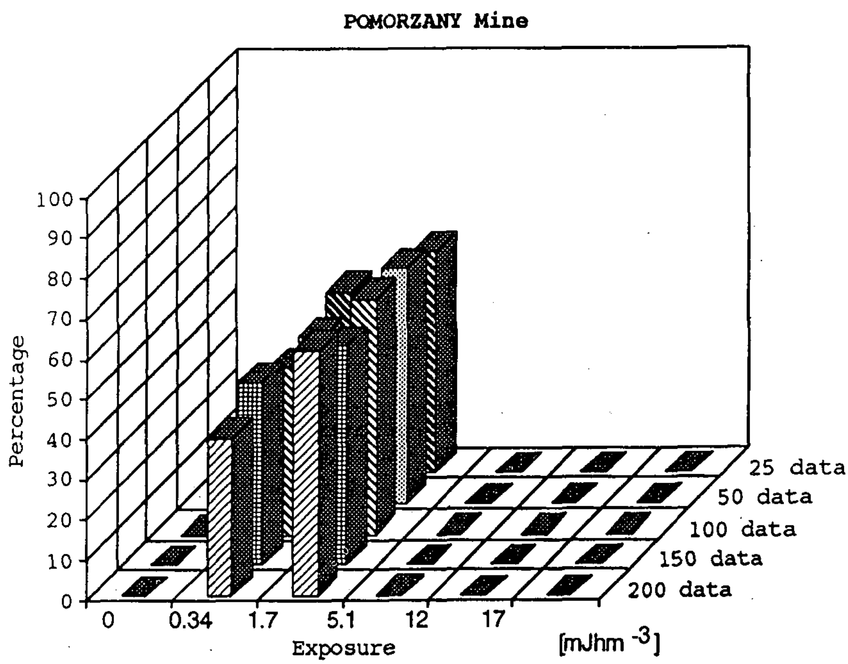


Fig. 5. Examples of two different mines where distributions of expected miners' annual exposure differ and, strongly depend (Pomorzany Mine) and are almost independent (Piast Mine) of the number of annually collected data.

is approximately 160÷170 hours, therefore, the summation of twelve of such one-month periods approximates very well the standard employment duration mentioned. Repeating that procedure many times, e.g. 10^4 times, by the computer technique, one can obtain a new set of, say 10^4 hypothetical but quite possible 'annual exposures', which one can use for evaluation of the possible 'average annual exposure', as well as for estimation of the 'frequency' distrubution of random values of possible annual exposure.

Another problem worthy of presentation is how to determine the optimal number of measurements in representative personal dosimetry. It is known, that there is a high and a frequent variability of the level of radon daughters at work in the mine. It considers both the seasonal and shift variations. In relation to the above, the number and frequency of measurements have to be correlated with all possible concentration fluctuations. It means, that there should be, at least, one measurement cycle in each season. Each one-month cycle of measurements should contain such a number of measurements, so it should be certain (in the statistical sense) that measurement data would comprise extremly high and low values.

Taking into account seasonal changes, 200 measurements must be carried out during one year, to identify the level of miners' exposure. This number of measurements (50 per one cycle) is a compromise between the technical possibilities of collecting the data and the expected accuracy of the exposure evaluation. In Figs 2 to 4 there are three sets of curves. Each of the sets is evaluated for a different pool of the extreme data and contains curves for a different total number of the underground miners (N). The horizontal axis (called 'in one cycle') is multiplied by 4 (four seasons) to get the second horizontal axis (called 'annually'). Such an amount of measurements provides a guarantee, that the miners' exposure evaluation will be free of errors due to the variability of the radon daughters concentration level. Of course, there may be mines where the seasonal and shift fluctuations are lower. In this kind of mine the number of (200) measurements may be decreased (without increasing the exposure evaluation error), which is shown in Fig. 5. But only 200 measurements (at least in a mine) during a year assure a reliable computer simulation method in any one mine being examined.

OCCUPATIONAL RADIATION CANCER RISK IN MINERS

The computer-aided method described above allows a conversion of representative personal exposure data into terms useful for evaluating an average risk of induction of lung cancers in miners due to radiation exposure. The basic data characterising exposure of miners in Polish non-uranium underground mines are presented in Table 2.

These data can be a starting point for evaluating average rates of 'radiation cancer' induction risk i.e. the probability of cancer induction in a miner due to a one year underground employment in Polish mines.

It seems to be realistic and reasonable to assume that the 'effective' period of working ability of a miner is 30 years. The term 'effective' means that even if the average period of professional activity of a single miner is less than 30 years then his possible successor who continues to be exposed constitutes a group of miners under continous exposure, during a standard period of occupational activity. In other words, if presently the total group of miners being at occupational exposure

Table 2. The weighted average expected annual exposure of miners to radon daughter products of particular types of mines in Poland in 1992

Type of mines	Number of mines	Number of miners employed	Number of records from individual dosimetry	Weighted average expected annual exposure		Maximum concentration recorded	
				$mJhm^{-3}$	WLM	μJm^{-3}	WL
Coal	71	246 580	11 852	1.8	0.53	54	2.6
Metal ore	10	17 820	1 606	1.6	0.47	17	0.8
Raw-material	13	3 080	1 237	1.7	0.50	88	4.2

1 WL (Working Level) = $21 \cdot 10^{-6}$ Jm^{-3}
1 WLM (Working Level Month) = $3.4 \cdot 10^{-3}$ Jhm^{-3}

amounts to 280 000 people then the total collective effective exposure as 'person — years' will be the product of 30 years and the total number of employed, exposed people. Therefore, assuming a long-term stability of air pollutant concentration in mines one can evaluate the rate of 'radiation cancer induction' risk. The values obtained are displayed in Table 3. Using the values presented above one can calculate the expected number of lung cancers among retired miners if the period of observation were to be continued during additional 25 years, to include all retired miners of 50—75 age group exposed in the past. The obtained values are presented in Table 4.

Table 3. The rate of 'radiation cancer induction' risk in underground miners in Poland

Mining industry	Rate of radiation lung cancer induction risk (with the inconfidency interval) [$year^{-1}$]
Coal	$1.6 \cdot 10^{-4}$ ($0.8 - 2.4 \cdot 10^{-4}$)
Metal-ore	$1.4 \cdot 10^{-4}$ ($07 - 2.0 \cdot 10^{-4}$)
Chemical raw-material	$1.5 \cdot 10^{-4}$ ($0.7 - 2.0 \cdot 10^{4}$)

Table 4. Expected number of lung cancers among the retired of non-uranium mining in Poland

Mining industry	Expected number of lung cancers (with the interval of possible inconfidency)
Coal	4 800 (3 800 — 7 500)
Metal ore	300 (200 — 500)
Chemical raw-materials	60 (30 — 70)
Total	5160 (4 300 — 8 070)

The conventional risk of fatal occupational accident among miners in Poland is statistically evaluated to be $3.1 \cdot 10^{-4}$ year^{-1}. Though this coefficient cannot be compared directly with the rate of radiation lung cancer induction risk, it is very easy to convert both of these coefficients into comparable terms, namely, into the index called the Lost Life Expectancy (LLE). The 'Lost Life Expectancy due to radiation' hazad $(LLE)_R$ is understood as the mean value of shortening of life for a miner, whereas the 'Lost Life Expectancy due to conventional' fatal accidents in mine $(LLE)_C$ means an analogous value but related to the mining occupation. Let us assume the following parameters:

– average age of miner being a victim of a conventional fatal accident	= 30 years
– average age of retired miner dying of lung cancer due to radiation hazard in mine	= 60 years
– average life span of man in the country	= 75 years
– conventional fatal accident risk rate factor	= $3.1 \cdot 10^{-4}$ year^{-1}
– radiation cancer induction risk factor per unit of annual exposure	= $0.0046/\text{mJhm}^{-3}$
(at the given inconfidence interval)	= $(0.0028 \div 0.0071)$
– the average annual exposures	(as given in Table 1).

Then, the evaluated indices of average Lost Life Expectancy per capita are as follows:

LLE_C = 0.47 year/per each miner
LLE_R = 0.30 year/per each miner.

DISCUSSION

Two aspects of radiation hazard to miners in underground mines seem to be worthy of discussion, namely, 1) how the radiation hazard to non-uranium is related to the radiation hazard to other professional groups and, 2) how to provide a reliable system of radiation protection and especially a system for assessing miners' exposure.

It seems to be a paradox that in a country which has neither nuclear nor uranium mining industries, miners are the largest group of workers exposed to ionizing radiation emitted by radon daughter products, moreover, coal miners, and other miners as well, constitute the largest group of other workers exposed to ionizing radiation at their work-places. In Poland, there are four occupational groups, (displayed in Table 5), exposed to ionizing radiation, among them the collective exposure as well as average annual personal exposure is considerably higher among miners employed in underground non-uranium mines. On the other hand, the comparison of LLE_R and LLE_C mentioned earlier emphasizes that nowadays the 'technologically enhanced natural radiation' becomes one of the essential components of human radiation exposure.

Despite high exposure to ionizing radiation, underground miners have not been given professional privileges (i.e. shorter working day, etc.) like other groups such as – X-ray workers, or, workers dealing with radioactive izotopes, even of negligible activity. This seems to be contrary to general principles of 'optimisation' of protection and prevention. It should be improved by paying more attention to problems of radiation protection in underground mines. So, the questions how

Table 5. Occupational groups in Poland exposed to ionizing radiation at their workplaces and relevant annual collective effective dose.

Group	Number of workers	Average annual dose equivalent per person [mSv]	Annual collective effective dose [man Sievert]
Underground non-uranium miners	267 480	5.0	1 337
X-ray workers	25 000	1.5	37
Isotope workers	6 900	1.5	10
Spa workers and mineral water bottling workers	1 200	1.2	1.4

to draw much more attention to natural radiation exposure in mines and how to improve the work of radiation hygienists remain open. Regarding the latter aspect one can conclude that the initial step in organising radiation protection in mines is a reliable assessment of miners' exposure which can be best accomplished by the 'passive' personal representative dosimetry for miners. However, the last but not the least conclusion regarding this matter is that the 'passive' IDS is a multi-step system which must be accomplished by a centralized system, namely, the chemical processing of dosimetric track-etch film and microscope reading of processed film used to measure radiation. Despite this, the ASS previously discussed is a typically 'decentralized' system in which commercially available equipment and one radiation safety officer can solve the problem of assessment of miners' exposure in a particular mine. However, it is only half true, since in spite of the simplicity of the ASS, it is only an apparent solution to the problem of miners' exposure assessment, in the light of data presenting the impact of methodology on the results of assessment.

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