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RADIOLOGICAL CLASSIFICATION OF POLISH UNDERGROUND MINES AND RECOMMENDATIONS OF SURVEILLANCE

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Abstract. The paper presents the most recent data, collected 1987 – 1989, on concentrations of ^{222}Rn products in the air of all Polish underground non-uranium mines, and data on the exposure of the miners employed there. The concentrations and exposure of miners were evaluated by using 'passive' dosimeters, based on the track-etch solid state nuclear track detector, worn as small individual casettes on helmets of representative groups in every mine for one month, four times a year (once in each season of the year). The paper contains the average annual exposure of miners in coal-, metal-ore-, and chemical raw materials ore-mines. The paper, also presents expected 'frequency' distributions of individual miners' exposure in particular types of mines, as well as the computer simulations of 'relative frequency' distributions of expected miner's exposure when the Annual Limit of Exposure would be adopted at the level 17, 12, 8.6, 6.9 and $3.4 \cdot 10^{-3}$ Jhm^{-3} (5.0, 3.5, 2.5, 2 and 1 WLM).

The concept and criteria of classification of mines according to the radiation hazards are presented and discussed. According to that concept, all mines in Poland have been considered and classified into four classes of mines with a different level of radiation hazard. The appropriate radiological surveillance to the respective class of mine is proposed and discussed.

INTRODUCTION

Nowadays in Poland there are the following underground mines: 71 coal mines, 11 non-uranium metal ore mines and 14 mineral raw material mines, employing 280,000, 21,000 and 3,600 miners, respectively. The first survey of radiation hazard was conducted during the period of 1966 – 70 applying, the so-called, grab 'Air Sampling System' (ASS) which was based on instant

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measurements of concentrations of potential alpha energy of radon (^{222}Rn) daughter products in the air (7). The results revealed, that in many mines, especially in metal ore mines, the concentrations substantially exceeded the 'concentration limit', called the Derived Air Concentration (DAC), adopted at that time as the value equal to $6.2 \cdot 10^{-6}$ Jm^{-3} (0.3 WL).

Some technical measures undertaken instantaneously in many mines brought a rapid decrease of average concentration levels, observed between 1970 and 1972 (7). In 1975 a permanent system, called the 'Environmental Control System' (ECS) was implemented in the most hazardous metal ore mines, and later in 1977 this system was replaced by the 'Individual Dosimetry System' (IDS). Both these systems were based on the application of 'passive' cassettes with track-etch 'solid-state nuclear track detectors' (SSNTD). During the study cassettes were placed, either at the miners' work-posts (in ECS), or were fixed on miners' helmets (in IDS).

A lot of coal mines remained out of supervision and any control until 1980–81, because of low work-efficiency of the eye-reading technique of SSNTD, which was applied before 1984. Therefore, only one provisional survey of radon daughter concentrations in coal mines was conducted in 1980–81, applying the strategy, called the 'Stream Monitoring System' (SMS) (3) but based on the track-etch SSNTD technique. It revealed that the radon concentrations could be quite substantial in the air of many coal mines (2). Since 1986, a new computerised system of reading of SSNTD used in miners' dosimeters has been implemented (13–14).

Finally at the end of the eighties, it was decided to conduct again a comprehensive survey in all mines existing in the territory of Poland, using individual dosimetry based on SSNTD worn on miners' helmets. The main aims of that study (described in this paper) were: 1) to provide results of present average concentrations of ^{222}Rn – daughter products (RnDP) in the air of mines; 2) to evaluate the miners' populaton exposure and its 'frequency' distribution; 3) to consider the possibility of classification of mines according to the radiation hazard caused by radon daughter products in air; and 4) to consider by appropriate computer simulations of the expected 'relative' frequency distributions where the Annual Limit of Exposure (ALE) could be adopted at different levels from 17 to $3.4 \cdot 10^{-3}$ Jhm^{-3} (5.0 to 1.0 WLM).

MATERIALS AND METHODS

In every mine, a representative group of 10 to 50 miners, depending on the total number of miners employed, was randomly selected and equipped with individual cassettes based on SSNTD track-etch dosimeters worn on their helmets for one month, four times a year (once in each season of the year). The technical details of those measurement devices and their applications were described earlier (1, 10, 12, 13, 14). The 'lowest measurable exposure' of that method of measurement are $0.35 \cdot 10^{-6}$ ($17 \cdot 10^{-3}$ WL) and $0.058 \cdot 10^{-3}$ Jhm^{-3} ($17 \cdot 10^{-3}$ WLM), respectively, at the assumed 'confidence level' equal to 0.95, and at the assumed time of exposure equal to one month. The 'precision' of the method of measurement, i.e. standard deviation of mean value, is 20–25% of measured value. Using those devices, it was possible to evaluate the exposure of the detector (E_i), during the time passed (T_i). Therefore, it was possible to obtain and evaluate for each detector the relevant 'average effective concentration' C_i, which is the simple ratio: $C_i = E_i/T_i$. Using the set of newly obtained values C_i it was possible to evaluate the indices characterising the miner's environment, i.e. the 'average expected annual concentration'. The values E_i, were used also for evaluation of the 'average annual exposure' for considered miners' populations as well as the 'frequency' distribution of miners' exposure.

The idea was to select randomly 12 of the monthly values of E_i by the 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 2000 hours. Since in Polish mines the one-month period of miner's exposure was approximately $160 \div 170$ hours, therefore summation of twelve of such one-month periods approximates very well the standard employment duration mentioned. Repeating that procedure a large number of 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 to average for evaluation of the possible 'average annual exposure', as well as for estimation of the 'frequency' distribution of random values of possible annual exposure.

RESULTS

Results have been collected for each of the underground mines existing in the territory of Poland. Considering the brevity of this paper, the results obtained in this study do not contain data concerning each particular mine, but they have been summarised and presented for three different types of underground mining, namely, coal-, metal-ore- and chemical raw material-ore mining. The detailed results for particular mines are published separately in a special technical report (8). The terms and their abbreviations used in the present paper for presentation of results are compatible with the terms explained and described earlier (3).

Table 1 presents the characteristics of the considered types of mining industries, and relevant results of measurements obtained.

Table 2 presents the 'frequency' distribution of expected, individual miners' exposure in mines of different types obtained by the above-mentioned computer technique simulation. The considered borders of intervals of the level of miners' annual exposures, i.e. 1/10 and 1/50 of ALE, were arbitrarily selected since they seem to be characteristic values for the description of exposure to ionizing radiation. Obviously, the computer technique of annual exposures simulation described makes it possible to select any other interval's border. These three intervals of levels of miners' exposure, considered in Table 2, have been named as the 'category of exposure' and arbitrary numbered A, B, and C.

TABLE 1. The weighted average expected annual exposures of miners to radon daughter products and maximum concentrations recorded in particular types of mining.

Type of mining	Number of mines	Number of miners employed	Number of records from individual dosimeters	Weighted average expected annual exposure; (E_{EXP}) 10^{-3} Jhm^{-3}	WLM	Maximum concentration recored 10^{-6} Jm^{-3}	WL
Coal	71	282 000	12 077	1.07	0.315	40.3	1.92
Metal-ore	14	121 000	2 173	0.547	0.161	5.14	0.245
Other	12	3 500	1 467	0.255	0.075	8.88	0.423

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

TABLE 2. The 'categories' of miners' exposure and 'frequency' distributions of individual expected annual miners' exposures (E_i) in different types of mining.

Category of exposure	Level of individual miner's annual exposure	Expected number and percentage of miners at relevant levels of annual exposure		
		Coal	Metal-ore	Other
A	$E_i > \frac{1}{10}ALE$	48 500 (17.2%)	200 (1.0%)	300 (8.6%)
B	$\frac{1}{50}ALE \leqslant E_i \leqslant \frac{1}{10}ALE$	194 000 (68.8%)	15 800 (75.2%)	700 (20.0%)
C	$E_i \leqslant \frac{1}{50}ALE$	39 500 (14.0%)	5 000 (23.8%)	2 500 (71.4%)

ALE (Annual Limit of Exposure) = $17 \cdot 10^{-3}$ Jhm^{-3} = 5 WLM

DISCUSSION

The obtained measurement data allow us to discuss two different, separate matters, namely, 1) the practicability of a possible decreased level of the Annual Limit of Exposure (ALE), and 2) the concept of possible classification of mines, according to the radiation hazard to miners employed, caused by radon daughter products in air.

The International Committee on Radiological Protection (ICRP) is just considering a previously recommended value of ALE for radon daughter products in air (9). The previously recommended, and still valid, value is equal to $17 \cdot 10^{-3}$ Jhm^{-3}, which corresponds to the value equal to 5 Working Level

Months (WLM), when expressed in traditional units. However, scientific considerations based on the 'risk vs. exposure' correlations as well as the precedent practice of local authorised recommendations in some countries lead to the opinion that the value of ALE should be decreased (11). Therefore, the individual data of miners' exposure collected in this study were used for the appropriate computer simulations aimed at the estimation of 'relative' frequency distributions of expected annual exposures of miners, where ALE could be adopted at different levels. The results obtained are presented in Figs. 1, 2

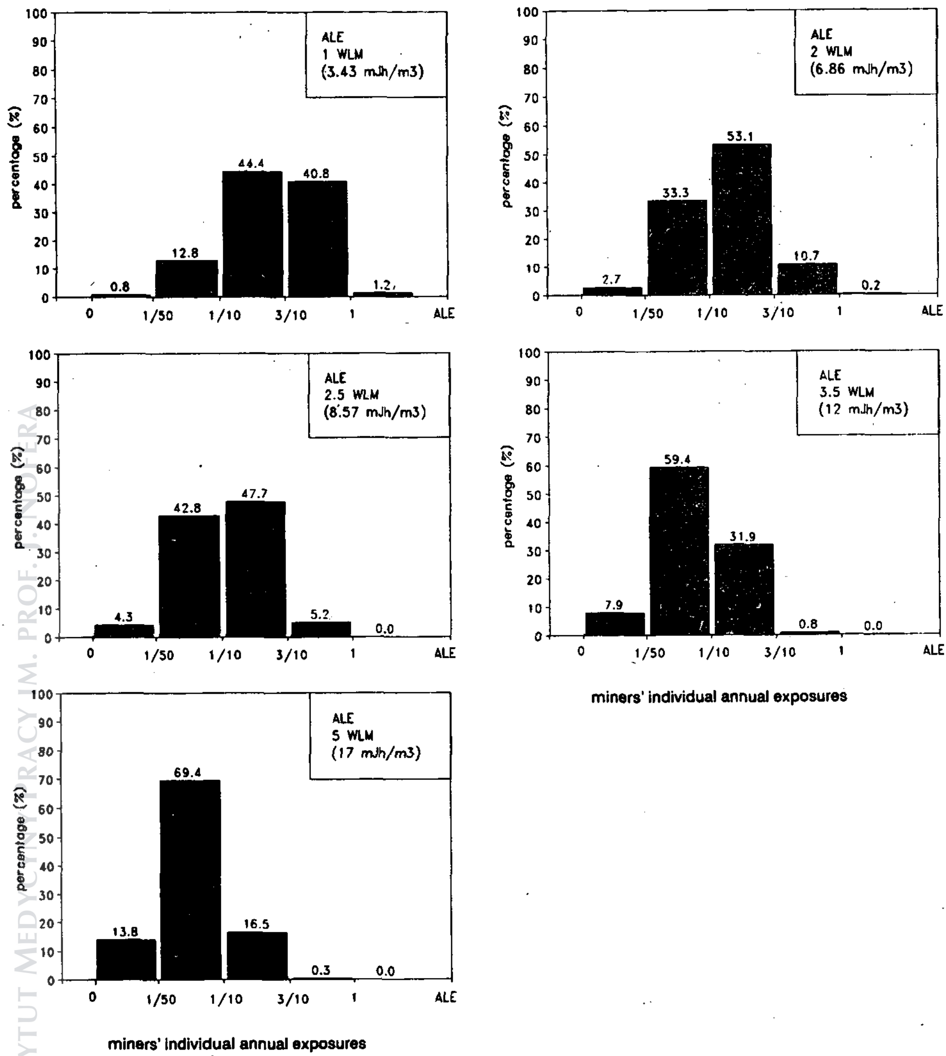

Fig. 1. The frequency distribution of possible annual miners' exposures in coal mines, expressed as a fraction (or a multiple) of Annual Limit of Exposure (ALE), when ALE would be adopted at different levels. (Computer simulation from 12 077 data of individual miners' exposures)

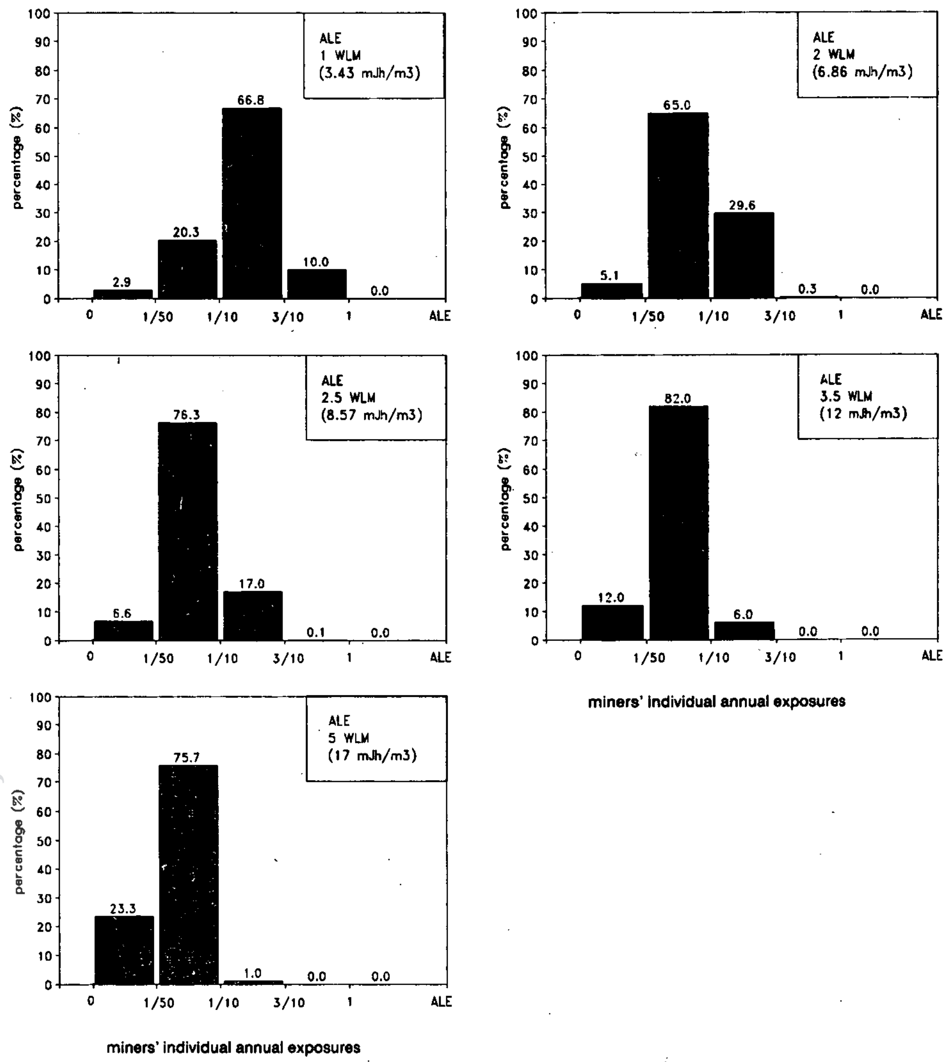

Fig. 2. The frequency distribution of possible annual miners' exposures in metal-ore mines, expressed as a fraction (or a multiple) of Annual Limit of Exposure (ALE), when ALE would be adopted at different levels. (Computer simulation from 2 173 data of individual miners' exposures)

and 3, for coal-, metal-ore-, and raw chemical-ore mines, respectively. The diagrams present the percentage of individual miners' exposures, within relevant intervals of fraction or multiples of ALE, where ALE could remain at the level $17 \cdot 10^{-3}$ Jhm^{-3} (5 WLM), or where it could be adopted at the levels 12, 8.5, 6.9, $3.4 \cdot 10^{-3}$ Jhm^{-3} (3.5, 2.5, 2.0, 1.0 WLM). Results of these computer

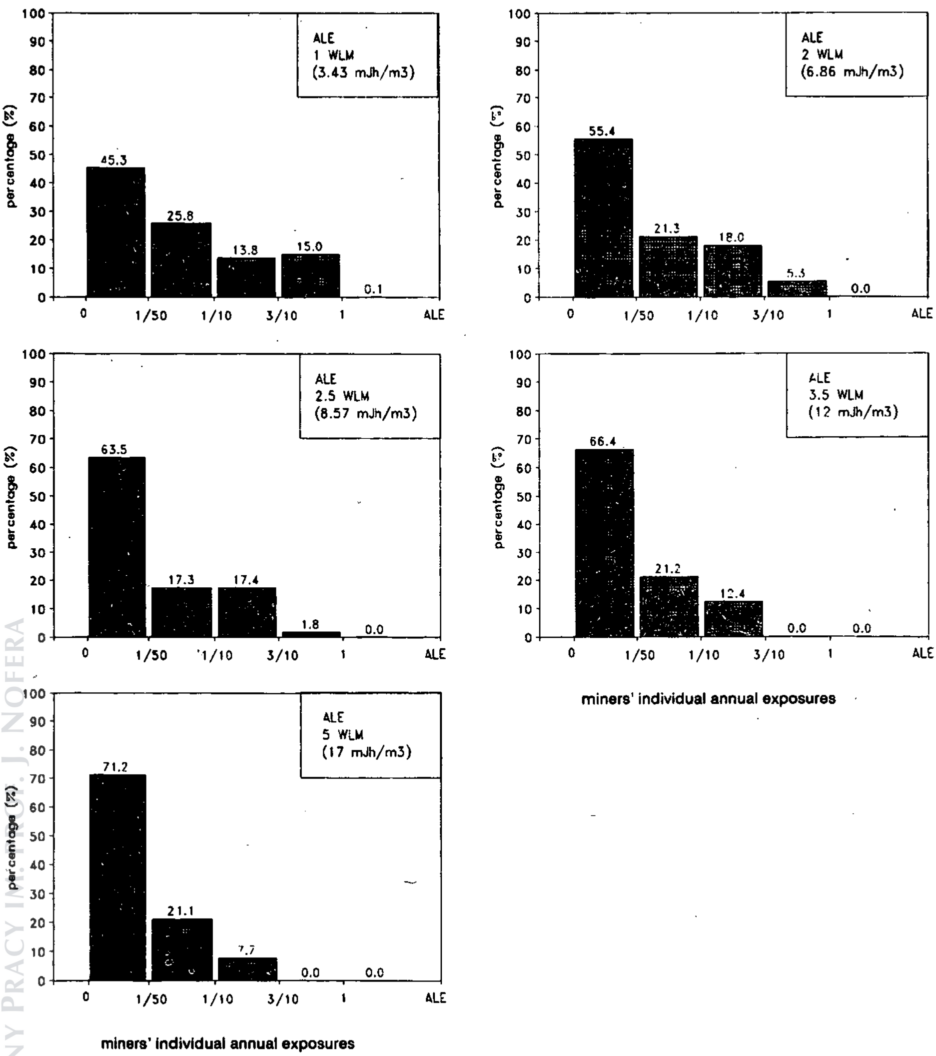

Fig. 3. The frequency distributions of possible annual miners' exposures in chemical raw materials mines, expressed as a fraction (or a multiple) of Annual Limit of Exposure (ALE), when ALE would be adopted at different levels. (Computer simulation from 1467 data of individual miners' exposures)

simulations show that for Polish underground mines it could be quite practicable to adopt ALE at a level at most $6.8 \cdot 10^{-3}$ Jhm^{-3} (2 WLM) or even $3.4 \cdot 10^{-3}$ Jhm^{-2} (1 WLM), since only a small percentage 1.2% of miners would pass the annual exposure, which could exceed the newly considered ALE. On the other hand, such a newly authorised limit would play the role of a 'constraint limit' (9) and would probably cause concentrations and exposure of miners to drop in the near future. Fifteen years ago the exposure limit, authorised in Poland for miners, was adopted at a level lower than the value recommended (8) at that time by ICRP (i.e. $12 \cdot 10^{-3}$ Jhm^{-3} = 3.5 WLM versus $17 \cdot 10^{-3}$ Jhm^{-3} = 5 WLM), and this decision constrained the present satisfying situation in the Polish mining industry. Therefore, the authors hold the opinion that the adoption of an authorised level of ALE at the level equal to $6.8 \cdot 10^{-3}$ Jhm^{-3} (2 WLM) is quite practicable presently, and presumably will bring positive effects in radiation protection in mining.

The concept of classification of mines according to the radiation hazard to miners employed there seems useful, since certain relevant recommendations of radiological surveillance could be generalised for mines included in considered classes. The principles of classification are as follows: 1) the class of mine is temporarily attributed to a previously considered mine and is based on the credible evaluation of maximum annual exposure (E_{iRAN}) which can occur to any random miner employed full-time in this mine during the considered year; 2) the class of mine should be periodically proved by reliable measurements, and the class could be either confirmed or changed, if this could be justified by those measurements.

What intervals of E_{iRAN} should be adopted for that classification is a very important question. However, it seems reasonable to adopt the following intervals: $[0 \div 1/50]$, $(1/50 \div 1/10]$, $(1/10 \div 3/10]$, $(3/10 \div 1]$, and values higher then ALE. These intervals are commonly used in radiation protection recommendations and practice. The exact criteria of classification, as well as recommendations relevant to the class of mine, are described in Table 3. The most controversial and arbitrary term used there is a 'reliable' radiological survey, though no measurement system is recommended explicitly for classes: I, II and III. It should be explained that the proper understanding of that term means that any measurement system, could be used for conducting a radiological survey for mines of these classes; however, such a measurement system should be free from some negative effects which would falsify the evaluation of average and maximum possible annual exposure. It means that the measurement system should not be suspected of the presence and influence of effects like the so called 'hunting' and 'avoidance' effects described earlier (6). Obviously, the individual dosimetry system, temporarily applied, is thought to be the best one. The frequency of repetition of the survey is another important but very debatable question. The frequency recommended for class I and II seems obvious and practicable; the frequency for classes III and IV recommended as 'every three' and 'every five' years, respectively, seems justified by the fact that in non-uranium mines, especially in mines that are territorially large, the environmental conditions might be remarkably changed only during a rather long period and too frequent repetition of the survey seems unneccessary.

TABLE 3. Criteria of classification of mines according to the radiation hazard and relevant *recommended radiological surveillance.*

Class of mines	**Criteria of classification** Recommendations of radiological surveillance
IV	**Mines, where the possible random individual annual miner's exposure (E_{iRAN}) will not reach the level of 1/50 of the annual limit of exposure (ALE).** Reliable radiological survey should be repeated every five years, for proving the class of considered mine.
III	**Mines, where the possible random individual annual miner's exposure (E_{iRAN}) may exceed the level of 1/50 of ALE, but none of miner's exposures will reach the level of 1/10 of ALE.** A reliable radiological survey should be repeated every three years, for proving the class of considered mine.
II	**Mines, where the possible random individual annual miner's exposure (E_{iRAN}) may exceed the level of 1/10 of ALE but none of miners' exposures will reach the level of 3/10 of ALE.** A reliable, (i.e., seasonally repeated, four times a year, once in each season of the year) radiological survey should be conducted every year. The aim is to prove the class of mine and evaluate and record the expected average annual exposure of miners.
I	**Mines, where the possible random individual annual miner's exposure (E_{iRAN}) may exceed the level of 3/10 of ALE.** Permanent, monthly repeated, full — or well-representative individual dosimetry system (IDS), or a reliable grab air sampling system (ASS) should be implemented. The aim is to control continuously the class of mine and to evaluate and record the average expected annual exposure of miners and to evaluate the probability of exceeding ALE by random individual miners.

The results of classification of underground Polish mines which were conducted according to the above-mentioned principle are presented in Table 4.

Let us now, consider the costs which would be attributed to recommendations specified in Table 3 if they were implemented in the Polish mining industry. Moreover, let us assume that the representative 'passive' individual track-etch SSNT dosimetry would be applied. For those considerations it is necessary to introduce a new term, namely, the 'scale of representation' (SOR). SOR means the ratio between the number of miners equipped with individual dosimeters, to the total number of miners employed and exposed at that time to radon daughter products in the air of the considered mine. Table 5 presents the expected numbers of individual measurements of miners' exposure which should be realised annually in Poland if and when the recommendations specified in Table 3 are approved and implemented. It is obvious that the reasonable value of SOR should be adopted. In the previous primary survey the SOR adopted was usually equal to 1/100 ÷ 1/20, therefore in the Table mentioned, there are considered several variants of SOR from 1/100 to 1/10. The numbers shown in Table 5 should be compared with the work-ability of the laboratory and real efficiency of the computerised system

TABLE 4. Expected numbers of mines of relevant classes of radiation hazard and expected numbers of miners employed in these mines.

Class of mines	Interval of random individual annual exposure of a miner (E_{iRAN})	Expected number of mines of relevant class, and miners employed there		
		Coal	Metal-ore	Other
IV	$0 \leqslant E_{iRAN} < 1/50$ ALE	0 0	1 1 000	4 1 800
III	$1/50$ ALE $\leqslant E_i^{RAN} < 1/10$ ALE	22 88 000	4 14 200	5 1 200
II	$1/10$ ALE $\leqslant E_{iRAN} < 3/10$ ALE	42 174 700	7 5 800	4 500
I	$3/10$ ALE $\leqslant E_{iRAN}$	7 19 300	0 0	0 0

ALE (Annual Limit of Exposure) $= 17 \cdot 10^{-3}$ $\text{Jhm}^{-3} = 5$ WLM

TABLE 5. The excepted numbers of individual measurement of miners' exposure which could be realised yearly by the representative individual dosimetry system at an assumed 'scale of representation' (SOR).

Class of mines	Expected round numbers of individual measurements of miners' exposure at an assumed 'scale of representation'				
	1/100	1/75	1/50	1/25	1/10
IV	6	8	12	23	60
III	345	460	690	1 380	3 450
II	7 240	9 653	14 480	28 959	72 400
I	2 316	3 088	4 632	9 264	23 160
All classes	9 867	13 209	19 814	39 626	99 070

used for reading of films of miners' casettes, which is equal to the 60,000 per year, maximum. Therefore, it seems to be reasonable to propose as follows:

– the value of SOR for mines included in the classes II, III and IV should be equal to 1/25; whereas

– the value of SOR for mines of the class I should be equal to 1/10.

The expected possible annual cost of such surveillance for mining industry and the structure of it is thus presented in Table 6. The values prove the rationality of the above-mentioned proposals; moreover, an 'optimum' proposal can be identified which corresponds to the above-mentioned work-ability

TABLE 6. The expected annual cost of proposed 'optimum' radiological surveillance which would be performed in the Polish mining industry.

Class of mines	SOR	Number of mines included	Number of miners employed	Proposed number of individual measurements per year	Expected annual cost of radiological surveillance (USD)	Expected averaged annual cost of radiological surveillance per each miner employed (USD)
IV	1/25	5	28 000	23	230	0.08
III	1/25	31	103 400	1 380	13 800	0.13
II	1/25	53	181 000	28 959	289 590	1.60
I	1/10	7	19 300	23 160	231 600	12.00
All classes		96	306 500	53 522	535 220	1.75

SOR – mean the 'scale of representation'
USD – US dollar

of the computerised system and efficiency of the laboratory designed for reading and recording of miners' exposures.

Although the average cost of radiological surveillance is equal to less than 2 US dollars per miner, when counted on a scale of the whole underground mining industry in Poland, it seems a 'reasonable optimum'. Now, let us consider again what could be the 'reasonable minimum' cost if the value of SOR would be adopted at a lower level but still remained as 'reasonable'. So, let us formulate another variant of the proposal, called the 'reasonable minimum', namely:

– the value of SOR for mines included in the class IV remains equal to 1/25,
– the value of SOR for mines of the classes III and II could be equal to 1/75; whereas,
– the value of SOR for mines of the class I could be equal to 1/25.

In this newly considered variant the value of SOR for the class IV remains the same, since the contribution of cost spent for the surveillance of mines included in this class is relatively very small. Despite this, the cost of surveillances of the classes III and II has a substantial contribution, and therefore, in this variant, the value of SOR is mainly reduced, whereas the reduction of the cost of surveillance of the class I is intended not to be so drastic.

The justification of the above is, that from the radiological point of view, the class I is most important. On the other hand, miners usually work in teams of 10 ÷ 25 men: therefore the value of SOR equal to 1/25 proposed for this class seems to be the reasonable minimum which would be adopted and justified, since it corresponds to the idea of one dosimeter per group of miners working, more or less, in the same conditions.

The costs of annual radiological surveillance at such, say, minimum proposals are presented in Table 7. It is obvious that the cost then becomes substantially reduced and the work which would be required for such a level of surveillance does not consume the work capability of one centralised laboratory of individual miner's dosimetry.

TABLE 7. The expected annual cost of considered 'minimum' radiological surveillance which could be realised in the Polish mining industry.

Class of mines	SOR	Proposed number of individual measurements per year	Expected annual cost of radiological surveillance (USD)	Expected averaged annual cost of radiological surveillance per each miner employed (USD)
IV	1/25	23	230	0.08
III	1/75	460	4 600	0.05
II	1/75	9 653	96 530	0.54
I	1/25	9 264	92 264	4.78
All classes		19 400	194 000	0.64*)

SOR – means the 'scale of representation'
USD – US dollar
*) – this value is obtained like the value presented in Table 6

The general conclusion which one can derive from this study is that the feasible cost which should be covered by Poland for the reasonable permanent radiological supervision of the whole mining industry in the country oscillates between two hundred and half million US dollars per year, which yields as average value equal to $0.5 \div 1.8$ US dollars per miner per year, when counted on the scale of the whole country.

This paper and the discussion presented above is thought to be a starting point for the selection and research into the most effective possible system of radiological surveillance of underground mines, where radon daughter products cause the radiation hazard to miners. The results of the estimation, presented in this paper, will be compared with the expected cost of surveillance based on another system, namely the system of measurements, called the Exhaust Monitoring System (EMS), in which the permanent monitoring of air streams exhausted from underground mines is intended to be utilised for radiological surveillance purposes.

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