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MEASUREMENT SYSTEMS AND INDICES OF MINERS' EXPOSURE TO RADON DAUGHTER PRODUCTS IN THE AIR OF MINES

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Abstract: This paper presents the classification of measurement systems that may be used for the assessment of miners' exposure to radiation in mines. The following systems were described and characterized as the Air Sampling System (ASS), the Environmental Control System (ECS), the Individual Dosimetry System (IDS), the Stream Monitoring System (SMS) and the Exhaust Monitoring System (EMS). The indices for evaluation of miners' working environments, or for assessment of individual or collective miners' exposure, were selected and determined. These are: average expected concentration (C_{AE}), average observed concentration (C_{AO}), average expected rate of exposure cumulation rate ($\dot{E}_{EXP}$), average observed exposure cumulation rate ($\dot{E}_{OBS}$), average effective exposure cumulation rate ($\dot{E}_{EFF}$). Mathematical formulae for determining all these indicators, according to the type of measurement system used in particular mines, are presented.
The reliability of assessment of miners' exposure in particular measurement systems, as well as the role of the possible reference system, are discussed.

INTRODUCTION

Scientific literature provides descriptions of various methods for measurement of radon daughter product concentration in the air of mines, as well as many methods for measuring individual miners' exposure. Some of these methods may be applied on a mass scale as they are simple and do not require any expensive equipment, e.g. miners' passive dosimeters; others that do not fulfil these conditions may be applied to a limited degree (e.g. miners' active dosimeters). A lot of more or less precise methods, however, allow us to

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measure concentration instantaneously, or provide integrated, averaged measurements covering an extended period of concentration registration (i.e. a period longer than a miner's work-day). Hence, from the hygienic point of view, the question arises as to which indicators should be used for evaluation of individual or group miners' exposure, or for evaluation of the hazards in their environment. Usually some other questions are also to be answered, e.g.: 1) which systems of measurements, i.e. measurements frequency and strategy might, or should, be used; 2) whether these systems are, or may be commensurable with, each other; and 3) which indices characterizing the radiation hazard in the working environment or miners' exposure should be calculated and, according to which mathematical formulae, in the case of various possible measurement systems.

This paper presents the indices which should be used for the evaluation of the radiation hazard in mines for each system of measurement described. There is also a discussion of a particular measurement system already applied in mines.

INDICES FOR THE EVALUATION OF THE RADIATION HAZARD IN MINES

Three groups of indices which seem to be useful for radiation hazard evaluation in mines have been distinguished. These are:

– air concentration of radon (Rn) or radon daughter products (RnDP);

– the rate of cumulation of miners' exposure to the factor considered, mentioned above; and

– the past miners' exposure during the period considered (e.g. annual).

The first group of indices includes the so called 'average effective concentration' (C_{AE}) and 'average observed concentration' (C_{AO}). Both these indices allow us to calculate the so called 'average' miner's exposure, according to the general formula:

$$E \text{ (exposure)} = C \text{ (concentration)} \cdot T \text{ (miner's work period for which exposure is to be assessed)} \tag{1}$$

They are useful in cases where it is not possible to make a direct measurement of a miner's exposure in the mine. However, both the physical character and applicability of each of these indices (C_{AE} and C_{AO}) differ, and they are calculated in mathematically different ways. The first should be used for possible determination of a miner's average exposure, or for collective exposure determination when it is indispensable to assess the probability of the expected stochastic effects in the population of miners due to their past exposure; the second one can be applied where determination of the expected most probable concentration in the mine in the period considered is needed, and hence the most probable miner's exposure in the group exposed.

Mathematical formulae which should be used for calculation of C_{AE} and C_{AO}, based on the results of measurements carried out in various measuring systems, are presented in the following chapters. The logical dependence between these indices is similar to that between arithmetic and geometric means in asymmetric distribution of values belonging to the same set.

The second group consists of three indices: 'average expected miner's exposure cumulation rate' ($\dot{E}_{EXP}$), 'average observed exposure cumulation rate' ($\dot{E}_{OBS}$), and 'average effective exposure cumulation rate' ($\dot{E}_{EFF}$). The first two indices mentioned may be applied for measurement systems based on measuring devices, or on individual dosimeters integrating the measurement result during the period determined, which is equal to a work-day, but usually longer; a week or a month. Such measurement systems provide a set of unit values obtained in short-term measurements of a miner's exposure (the length of which exposure, however, may vary). Therefore, it would be advisable to construct a set of unified exposure values, recalculated for a uniform period of exposure measured over a day, a week or a month which will later be called a set of miner's exposure cumulation rate values.

If particular measurements of miners' individual exposure (E_i) were performed during the times corresponding to them, t_i, then the set of values of exposure cumulation rate corresponding to them, ($\dot{E}_i$) is constructed according to the formula $\dot{E}_i = E_i/t_i$. The values from the new set $\dot{E}_i$ may, therefore, serve to calculate two of the indicators mentioned earlier, i.e. $\dot{E}_{EXP}$, and $\dot{E}_{OBS}$, whereas these indices allow us to calculate the miner's exposure value, namely:

$$E \text{ (exposure)} = \dot{E} \text{ (exposure rate)} \cdot T \text{ (period of time considered which exposure will be evaluated)} \tag{2}$$

The physical sense of the exposure calculated thus will depend on the sense of the value of the E (exposure rate) index used. Between $\dot{E}_{EXP}$ and $\dot{E}_{OBS}$ a similar conceptual difference and logical relationship would exist as to the case of C_{AE} and C_{AO}, described erlier.

The index $\dot{E}_{EXP}$ should be used when calculating the average or collective exposure which has lead to the consideration of the frequency of possible stochastic effects of exposure in an exposed miners' population, whereas $\dot{E}_{OBS}$ should be used when the question which value of exposure would be most frequent in the population of miners is being considered. We can observe therein the same logical relationship as between the arithmetic and geometric means in the asymmetric distribution of values belonging to the same set.

However, it is important that both these indices have a sense of the values expected, and are determined from the set of measurement values which may be treated as a set of sample measurement values. Practically, it means that these indices may and should be used, and referred to the whole group exposed when the measurement system applied in a given mine covers only a randomly selected group, considerably less numerous than the whole population of miners exposed. In practice, however, a situation may occur where the whole

Table 1. Meaning of the average values of concentrations, exposure rates and exposures used in the radiation protection in mines

Symbol	Name	Meaning
C_{AE}	Average Expected Concentration	The average value of concentrations which one can use for the evaluation of probable harmful effects among miner populations.
C_{AO}	Average Observed Concentration	The average value of concentrations which approaches the most frequently observed values of concentrations in a considered environment.
$\dot{E}_{EXP}$	Average Expected Exposure Rate	The average value of miners' exposure rates which one can use for the calculation of the average expected exposure at the assumed duration of exposure.
$\dot{E}_{OBS}$	Average Observed Exposure Rate	The average value of miners' exposure rates which one can use for the calculation of the average observed exposure at the assumed duration of exposure.
$\dot{E}_{EFF}$	Average Effective Exposure Rate	The average value of miners' exposure rates which one can use for the calculation of the effective exposure at the assumed duration of exposure.
E_{EXP}	Average Expected Exposure	The average value of miners' exposure which should be used for the evaluation of the probable harmful effects among miner populations when measurements concern a selected subgroup of miners.
E_{OBS}	Average Observed Exposure	The average value of miners' exposure which approaches the most frequently observed values of individual miners' exposures in a considered mine.
E_{EFF}	Average Effective Exposure	The average value of miners' exposure which should be used for the evaluation of the probable harmful effects among miner populations when either the exposure of each miner is measured or measurements are collected in a representative subgroup of miners.

population exposed is covered by a continuous individual dosimetry system, e.g. in small mines employing from several to several dozen workers when another index, i.e. $\dot{E}_{EFF}$, is very useful for determination of the past exposure of the whole exposed population. $\dot{E}_{EFF}$ then, is a simple summing up of all registered, past exposures, referred to the summed-up exposure periods of all detectors. The respective formula is:

$$\dot{E}_{EFF} = \left(\sum_i E_i\right) / \left(\sum_i t_i\right) \tag{3}$$

Hence, $\dot{E}_{EFF}$ may serve for the determination of actual, past collective exposure, or for calculating the averaged individual exposure, according to the general formula (2) as in the case of the indices discussed earlier. However, the conceptual difference between $\dot{E}_{EXP}$ and $\dot{E}_{EFF}$ is that the first indicator leads to obtaining the exposure $\dot{E}_{EXP}$, i.e. expected average value of individual (or indirectly collective) exposure from measurements collected in a group smaller than the whole exposed population; the second to a determination of the exposure $\dot{E}_{EFF}$, i.e. actual cumulated exposure value in the total population exposed. It must be noted, however, that for the measurement system covering the total population exposed with individual dosimetry, the values $\dot{E}_{EXP}$ and $\dot{E}_{OBS}$ may also be calculated, although in that case, these values determine expected (extrapolated) exposures which might occur if the measurements were repeated in the future covering the same population, environmental conditions and measurement system.
Characteristics of all indices discussed are presented in Table 1.

MEASUREMENT SYSTEMS FOR EVALUATION OF MINERS' EXPOSURE

The term "measurement system" in a mine, meant for the radiological protection of miners exposed to radon daughter products embraces at least three elements; 1) measurement method; 2) the objectives of measurement; and 3) measurement strategy in time and space.

There are a lot of measurement systems which may be used for the evaluation of miners' exposure to radon daughter products in mines. These systems may be grouped, according to the measurement technique and their strategy, into: the Air Sampling System (ASS), the Environmental Control System (ECS), the Individual Dosimetry System (IDS), the Stream Monitoring System (SMS) and the Exhaust Monitoring System (EMS).

Definitions and descriptions of particular systems, main characteristics and strategies are presented in Table 2. The origin of particular measurement systems is as follows:

– ASS is the oldest and conceptually the simplest system, although it is very labour-consuming and costly.

Table 2. Classification and definitions of measurement systems used for the assessment of miners' exposure to radon daughters

Classification		Definitions (important features are underlined)
Code	Name	
ASS	Air Sampling System	The system based on instant grab air sampling and suitable evaluation of concentrations of radon or radon daughters, or even both of them, at the work places of miners. The aim of the system is to evaluate the annual C_{AE} and sequentially, to evaluate the annual E_{EXP} of the considered group of miners at the assumed effective work-time.
ECS	Environmental Control System	The system based on the continuous monitoring or measuring of concentrations of radon daughters at the work-places of miners. The aim of the system is to evaluate the annual C_{AE} based on integrating continuous measurements and, sequentially, to evaluate the annual E_{EXP} of the considered group of miners at the assumed effective work-time.
IDS	Individual Dosimetry System	The system based on continuous measuring of exposure of miners wearing individual integrating dosemeters. The aim of the system is to evaluate directly the annual individual exposure of each miner, or to evaluate the E_{EXP} for a whole group of miners by using a representative subgroup of miners wearing dosemeters. The system provides coherent information on the annual C_{AE} and C_{AO} at miners' work-places.
SMS	Stream Monitoring System	The system based on continuous monitoring or measuring of concentrations of radon daughters in main streams of air exhausted from regions where miners are working. The aim of the system is to evaluate the annual C_{AE} in respective regions, by the use of a previously found correlation (R) of this system's results with the results of a chosen reference measurement system, i.e. IDS. The C_{AE} makes it possible to evaluate the annual E_{EXP} of miners considered as a group.
EMS	Exhaust Monitoring System	The system based on continuous monitoring measurements or measuring radon daughter concentrations in mine exhaust ventilation shafts. The aim of the system is the same as in the SMS but extended to the whole mine.

Table 3. Formulae for the evaluation of average concentrations and exposures in some measurement systems: ASS, ECS, SMS, EMS

No.	Formula	Meaning of Symbols
3.1	$C_{AE} = \frac{1}{n} \sum_{i=1}^{n} C_i$	C_{AE} – the Average Effective Concentration $C_{AE}(SMS)$ – the Average Effective Concentration (only for the SMS)
3.2	$C_{AE} = \frac{1}{n} \sum_{i=1}^{n} \frac{E_i}{T_i}$	E_{EXP} – the Average Expected Exposure for the whole group of miners evaluated on the basis of the results of the considered measurement system $E_{EXP}(SMS)$ – the Average Expected Exposure of the whole group of miners evaluated on the basis of the results of the SMS
3.3	$C_{AE} = \frac{\sum_{j=1}^{s} \frac{1}{n_j} \sum_{i=1}^{n_j} w_j C_{ji}}{\sum_{n=1}^{s} w_j}$	T_E – the considered period of time for which the average exposure is calculated n – the serial number of measurement C_i – the concentration measured in i-th measurement, if the system is based on the instant measurement technique
3.4	$C_{AE}(SMS) = \frac{\sum_{j=1}^{s} \frac{1}{n_j} \sum_{i=1}^{n_j} w_j \frac{E_i}{T_i}}{\sum_{n=1}^{s} w_j}$	E_i – the exposure measured in i-th measurement, if the system is based on the integration measurement technique T_i – the duration of E_i exposure w_j – the total number of miners operating in the area corresponding to the j-th stream
3.5	$E_{EXP} = T_E C_{AE}$	s – the total number of streams (areas) being under control (monitoring) in the SMS n_j – the total number of measurements done in j-th stream (area)
3.6	$E_{EXP}(SMS) = T_E C_{AE}(SMS)$	n – the total number of measurements j – the serial number of the controlled (monitored) stream (area) i – the serial number of particular measurement

Table 3.A. Formulae for the evaluation of average observed concentrations and exposures in some measurement system: ASS, ECS, SCS, EMS

No.	Formula	Meaning of Symbols
3.1.A	$C_{AO} = \left[\prod_{i=1}^{n} C_i \right]^{1/n}$	C_{AO} – the Average Observed Concentration $C_{AO}(SMS)$ – the Average Observed Concentration (only for the SMS) E_{OBS} – the Average Observed Exposure for the whole group of miners evaluated on the basis of a measurement system $E_{OBS}(SMS)$ – the Average Observed Exposure for the whole group of miners evaluated on the basis of the results of the SMS
3.2.A	$C_{AO} = \left[\prod_{n=1}^{n} \frac{E_i}{T_i} \right]^{1/n}$	
3.3.A	$C_{AO}(SMS) = \left[\prod_{j=1}^{s} w_j \left(\prod_{i=1}^{n_j} C_i \right)^{\frac{1}{n_j}} \right] \left(\sum_{j=1}^{s} w_j \right)^{-1}$	
3.4.A	$C_{AO}(SMS) = \left[\prod_{j=1}^{s} w_j \left(\prod_{i=1}^{n_j} \frac{E_i}{T_i} \right)^{\frac{1}{n_j}} \right] \left(\sum_{j=1}^{s} w_j \right)^{-1}$	
3.5.A	$E_{OBS} = T_E C_{AO}$	
3.6.A	$E_{OBS} = T_E C_{AO}(SMS)$	The meaning of other symbols: see Table 3

– ECS is an attempt to simplify ASS and decrease the costs involved owing to installing devices for continuous or periodical monitoring of the miners' working environment.

– IDS is conceptually aimed at eliminating the main shortcomings of the previous system (ECS) through a maximum limitation of the time and space difference between the measuring devices and subject of exposure evaluation, the miners.

– SMS and EMS are chiefly aimed at decreasing the costs of permanent monitoring the environment or individual dosimetry especially in those mines where the hazard is relatively small. These systems may also be an effective tool for the early survey of radiological hazards in mines.

Each of the systems considered offers also a possibility of calculating the values of the indicators mentioned earlier, characterizing miners' exposure or concentration. The respective mathematical formulae which might be applied in ASS, ECS, SMS and EMS are presented in Tables 3 and 3A, the mathematical formulae for IDS in Tables 4 and 4A.

An interesting and important question arises as to whether the indicators thus calculated would be commensurable or approximate to each other if the measurements were carried out in a mine according to the principles and

able 4. Formulae for the evaluation of average concentrations, exposure rates and exposures in the idividual Dosimetry System (IDS)

No.	Formula	Meaning of Symbols
4.1	$C_{AE} = \frac{1}{n} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{E_{ij}}{T_{ij}}$	C_{AE} – the Average Effective Concentration $\dot{E}_{EXP}$ – the Average Expected Exposure Rate, for the whole group of miners evaluated on the basis of the results of individual exposure of miners wearing dosemeters in a subgroup which does fulfil the criteria of a representative group
4.2	$\dot{E}_{EXP} = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{j=1}^{m} E_{ij}}{\sum_{j=1}^{m} T_{ij}}$	$\dot{E}_{EFF}$ – the Average Effective Exposure Rate, for the whole group of miners evaluated on the basis of the results of individual exposures E_{EXP} – the Average Expected Exposure for the whole group of miners evaluated on the basis of the results of individual exposure of miners wearing dosemeters in a subgroup which does fulfil the criteria of a representative group
4.3	$\dot{E}_{EFF} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} E_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} T_{ij}}$	E_{EFF} – the Average Effective Exposure for the whole group of miners, evaluated on the basis of the results of individual exposures T_E – the considered period of time for which the average exposures are calculated n – the total number of miners wearing individual dosemeters
4.4	$E_{EXP} = T_E \dot{E}_{EXP}$	m – the total number of measurements for i-th miner j – the serial number of particular measurement i – the serial number of the miner wearing the dosemeter E_{ij} – the value of i-th miner's exposure in the j-th measurement
4.5	$E_{EFF} = T_E \dot{E}_{EFF}$	T_{ij} – the duration of i-th miner's exposure in the j-th measurement

strategies of all considered measurement systems used simultaneously. This issue will be discussed in the next chapter but now some characteristics of the measurement systems should be considered. The first three systems (ASS, ECS and IDS) are the so-called 'direct' or 'independent' systems since the measurements thereby obtained provide information leading, in a 'direct' and 'independent' way, to obtaining the values of such indicators as C_{AO} and C_{AE} as well as $\dot{E}_{EXP}$, and $\dot{E}_{OBS}$ (or $\dot{E}_{EFF}$ in IDS), on condition that both the strategy of measurements and selection of representative groups, are strictly and correctly observed. Therefore, if this condition is fulfilled, the indices mentioned are 'independent' and 'direct'.

Table 4.A. Formulae for the evaluation of average observed concentrations, exposure in the Individu Dosimetry System (IDS)

No.	Formula	Meaning of Symbols
4.1.A.	$C_{AO} = \left[\prod_{i=1}^{n} \sum_{j=1}^{m} \frac{E_{ij}}{T_{ij}} \right]^{1/n}$	C_{AO} – the Average Observed Concentration $\dot{E}_{OBS}$ – the Average Observed Exposure Rate fc the whole group of miners evaluated o the basis of the results of individual exposures of miners wearing dosemeter:
4.2.A.	$\dot{E}_{OBS} = \left[\prod_{i=1}^{n} \frac{\sum_{j=1}^{m} E_{ij}}{\sum_{j=1}^{m} T_{ji}} \right]^{1/n}$	E_{OBS} – the Average Observed Exposure for the whole group of miners evaluated on the basis of the results of individua exposures of miners at the work time assumed
4.3.A.	$E_{OBS} = T_E \dot{E}_{OBS}$	(The meaning of other symbols: see Table 4

SMS and EMS are *a priori* the dependent systems, i.e. systems in which the principal indices (concentrations and exposure cumulation rates) calculated from measurements cannot be directly as adequate as their actual equivalents in earlier mentioned systems and require at least one control to find out whether there is a constant correlation between them. It is chiefly due to the fact that the permanent location of the measuring point, especially in EMS, may be at a considerable distance from the miners' group that there is a constant and significant difference between the actual and determined concentration values in miners' work-places.

IDS is undoubtedly a system which *a priori* provides the most reliable information on miners' exposure and effective or observed concentrations. Therefore, this system should be used as a reference system for SMS and EMS; it might be also applied for verification of each existing or newly implemented measurement system. The high costs of this system, based on 'active' dosimeters, often prevents managers from introducing and applying it constantly and widely in mines. However, it should be noted that IDS can be implemented, even on a large scale, by means of 'passive' dosimeters which significantly reduce its costs of radiation dosimetry in mines to below ASS.

IDS may be introduced for a short period, or periodically, to determine whether the existing system of miners' exposure evaluation provides results concordant and compatible with those obtained through IDS. Hence, IDS may fulfil two roles: 1) as a measurement system for miners' exposure evaluation and assessment of concentrations in working environments; and 2) as a reference system for verifying the results obtained by means of some other systems, both existing and new systems planned for introduction into the mine.

The last remark may lead to a more general conclusion that each measurement system (except for IDS) requires verification through a reference system which is *a priori* considered to be a more reliable system. Therefore, commensurability and reliability of measurement systems can be determined by the so-called systems' commensurability index (R), calculated according to formulae presented in Table 5.

Table 5. The indices of systems' commensurability

Ratio between values evaluated in the considered and reference system
$R_{AE}\ \text{(CONSIDERED SYSTEM)} = \dfrac{C_{AE}\ \text{(CONSIDERED SYSTEM)}}{C_{AE}\ \text{(REFERENCE SYSTEM)}}$
$R_{AO}\ \text{(CONSIDERED SYSTEM)} = \dfrac{C_{AO}\ \text{(CONSIDERED SYSTEM)}}{C_{AO}\ \text{(REFERENCE SYSTEM)}}$
$R_{EXP}\ \text{(CONSIDERED SYSTEM)} = \dfrac{E_{EXP}\ \text{(CONSIDERED SYSTEM)}}{E_{EXP}\ \text{(REFERENCE SYSTEM)}}$
$R_{OBS}\ \text{(CONSIDERED SYSTEM)} = \dfrac{E_{OBS}\ \text{(CONSIDERED SYSTEM)}}{E_{OBS}\ \text{(REFERENCE SYSTEM)}}$

The indices adopted allow us to determine the proportions between the particular indices considered, which are calculated, based on results of measurements performed within considered systems. In the ideal case of measurement systems conformity, the values **R** should be equal to 1 and we may then assume full commensurability of the system concerned with its reference one. However, even if the R value for the system considered differs from 1, the system may be used on condition that this value is relatively stable in time and does not undergo changes every year. This stability condition is an important one, and if it is not fulfilled then the system considered should be disqualified as one not fit for evaluation of effective concentrations in mine or miners' exposure. When **R** values are stable then all possible indices calculated in a considered system, such as: C_{AE}, C_{AO}, $\dot{E}_{EXP}$, $\dot{E}_{OBS}$ should be corrected dividing them by their respective value: R_{AE}, R_{AO}, R_{EXP}, R_{OBS}. The corrected values can be used for the determination of effective concentrations and effective or observed miners' exposure.

EXPERIMENTAL DATA ON DETERMINATION OF SYSTEMS' COMMENSURABILITY INDEX

Comparison of the measurement systems in mines differs significantly from comparison of the measuring methods only. The first condition that is to be fulfilled, when comparing measurement systems based on various measuring methods, is to ensure a commensurability of the measuring methods by basing them on credible and commensurable calibration systems. If this condition is fulfilled then it may be assumed that the systems can be subject to comparison. Currently, there are few publications dealing with this problem in presenting the results of measurement systems comparison.

The most complex comparison of results obtained by means of ASS and IDS, carried on concurrently for a period of six years in eleven mines of metal ores, was described in an earlier publication (1). In both systems considered, the principal conditions qualifying them for comparison were fulfilled: 1) both systems were based on measuring methods which were calibrated by means of the same calibration standards (2); 2) the commensurability of the methods was checked in an experimental chamber (3) and in the mines (4); and 3) the whole measuring process in both systems was controlled, and supervised by one institution (The Nofer Institute of Occupational Medicine in Lodz).

For each system considered C_{AE}^{RnDP} and E_{EXP}^{RnDP} were determined for yearly periods. (The upper index informs us of measurements related to RnDP). The

Table 6. The distribution of R — values evaluated in 62 tests of the ASS vs the IDS in 11 metal ore mines. [Data extracted from (1)]

The interval of R value	The percentage of the tests giving R — value within the interval indicated	
	when evaluating C_{AE}^{RnDP}	when evaluating E_{EXP}^{RnDP}
(0 ÷ 1⟩	54%	47%
(1 ÷ 2⟩	24%	32%
(2 ÷ 3⟩	15%	14%
(3 ÷ 4⟩	5%	2%
(4 ÷ 5⟩	—	5%
(5 ÷ 6⟩	1%	—
(6 ÷ 7⟩	—	—
(7 ÷ 8⟩	—	—
(8 ÷ 9⟩	—	—
(9 ÷ 10⟩	—	—
(10 ÷ 11⟩	1%	—
(11 ÷ 12⟩	—	—

Table 7. The distribution of error in evaluation of C_{AE} and E_{EXP} by ASS as compared to relevant values evaluated by IDS. [Data extracted from (1)]

The range of possible error in yearly evaluation of C_{AE} or E_{EXP} by ASS as compared to IDS	The number of cases at particular ranges of error	
	when evaluating C_{AE}	when evaluating E_{EXP}
(0% ÷ 10%⟩	6	6
(10% ÷ 20%⟩	5	3
(20% ÷ 30%⟩	3	3
(30% ÷ 40%⟩	6	6
(40% ÷ 50%⟩	8	8
(50% ÷ 60%⟩	1	8
(60% ÷ 70%⟩	8	3
(70% ÷ 80%⟩	5	6
(80% ÷ 90%⟩	4	5
(90% ÷ 100%⟩	1	1
(100% ÷ 150%⟩	8	6
(150% ÷ 200%⟩	1	1
(200% ÷ 300%⟩	3	2
(300% ÷ 500%⟩	1	4
(500% ÷ 1000%⟩	1	0

results obtained (1) indicate that the respective values R_{AE}^{RnDP} and R_{EXP}^{RnDP} are rarely approximate to the value 1, and that they vary greatly at different times during the six-year monitoring. Table 6 presents distribution of R values showing the percentage of the values higher or lower than the value 1. Taking into account the precision of the measuring methods, it may be taken for granted that the R value can oscillate around the value 1 in the range 0.5 to 1.5. However, only 51% of the total number of R_{AE}^{RnDP} results and 42% of the total number of R_{EXP}^{RnDP} results are within this variability range (0.5 ÷ 1.5) whereas the remaining percentage of results differs more significantly from the value 1 in both directions. Therefore, evaluation of concentrations of miners' exposure by means of ASS may be burdened with a significant error. Table 7 presents

Table 8. The discrepancy between average annual exposure of miners evaluation based on U.S. Federal inspection results and company records. [Extracted from (7)]

Year	Company Records (Average Exposure-WLM)	MESA*) Sampling Results (Average Exposure-WLM)
1975	1.07	5.68
1976	0.99	4.64
1977	0.91	4.08

*) Mine Enforcement and Safety Administration (MESA)

a number of cases in which the evaluation could be burdened with the error determined, showing that an evaluation based on ASS could lead to practically unpredictable errors ranging from several to several hundred percent. In the study mentioned (1), the causes of such a big error are thoroughly discussed. Nevertheless, using ASS, based on local measuring services, it is difficult or impossible to anticipate the annual values of C_{AE} and $\dot{E}_{EXP}$. This conclusion, resulting from investigations carried out in metal ore mines in Poland, confirms the earlier observations of federal services controlling USA mines (7). Table 8 presents differences in estimations of miners' exposure based on the results of local measuring and federal services. In that case, ASS (Federal) may be regarded as a reference system for ASS (Company) and the R_{EXP}^{RnDP} (ASS-Company) values, calculated and amounting to: 0.18, 0.21, 0.22.

Table 9. The values of R_{AE}^{Rn} (ECS) evaluated from the results of short-term measurements conducted in 4 coal mines by independently realised systems, i.e. ECS and IDS. [Data extracted from (5)]

Coal Mine	Number of measurements N		R_{AE}^{Rn} (ECS)
	N (ECS)	N (IDS)	
Mine 1	14	280	6.21
Mine 2	10	182	1.79
Mine 3	14	260	1.42
Mine 4	11	282	0.90

Scarcity of data in scientific literature about comparison of some other measurement systems with the IDS reference system makes detailed consideration of that problem impossible. However, an earlier publication of the author and his co-workers (5), allow us to make a partial comparison of ECS and IDS. The investigations carried out in four big underground coal mines in the years 1981–1983 were aimed at the comparative determination of radon effective concentration in the air of mines by means of ECS and IDS. Cassettes with passive track etch detectors were placed at miners' work stations for ECS, and the same cassettes fastened to miners' helmets (in a selected group of miners) for IDS. The detectors were exposed for a month. The results obtained allowed us to calculate the value R_{AE}^{Rn} (ECS) for each of the mines monitored (Table 9). The values of R_{AE}^{Rn} (ECS) were different in each mine. However, their stability in time has not been checked.

DISCUSSION

The presented comparison of principal indices of concentration and miners' exposure, obtained in various measurement systems, reveals that such commonly used systems as ASS and ECS are not generally commensurable with the reference system adopted, i.e. IDS. The conformity of the systems concerned with IDS obviously may occur – and it was sometimes observed – but it was accidental, as was the occurrence of R values significantly lower or higher than the value 1. Randomness and unpredictability of R values for the next measurement periods show that these systems should not be used for evaluation of effective concentrations or miners' exposure. Were these systems to be used then the error in evaluation of C_{AE} and E_{EXP} indices could reach even several hundred per cent; moreover, the error cannot be determined without introducing a reference system. Unfortunately, these systems are commonly used in mines for the evaluation of yearly miners' exposure in many countries. It is obvious that the use of these systems is a compromise solution resulting from the fear of the high costs associated with IDS introduction. However, the fear is unjustified, since the costs of IDS are high only when this system is based on individual dosimeters of the 'active' type, basing it on dosimeters of the 'passive' type considerably reduces the cost involved; e.g. the total cost of the monthly measurement of a miner's exposure in Poland does not exceed 10 US dollars, including the detecting material (Kodak LT 115, plastic cassette) and costs of developing the film and reading its exposure. It must be also stressed that, in IDS, miners' group exposure may be determined, based on the results obtained in a representative group of miners and only this group needs to be equipped with dosimeters. Therefore, it may be concluded that there are no arguments against the introduction of IDS based on 'passive' dosimeters and measurements of exposure in a representative group of miners.

The question arises as to whether ASS should be applied in mines at all and, if so, when? The answer to this question is that it should be used but for quite a different purpose. This system is used in many Polish metal ore mines concomitantly with IDS. However, it is not a basis for evaluation of miners' annual exposure but a technical aid to detect the areas where high concentrations occur. It also serves for immediate control of the effectiveness of technical methods for eliminating radon in the air of mines. ASS proved to be, in both cases mentioned, an indispensable tool as it provides the results of concentration measurements immediately, however, it thus becomes merely a measuring system for technical purposes.

When comparing the systems, attention should be paid to another important aspect i.e. total effective measuring time in the system considered. During the six-year investigations in eleven mines (1) the numbers of measurements performed were N = 20369 and N = 19543 for ASS and IDS respectively. However, due to the difference in time of unit measurement t = 5 min (ASS) and t = 170 h (IDS) ASS covered altogether 1697 hrs, whereas IDS was 3.3 million hrs. Therefore, in spite of the relatively high number of measurements carried out by means of ASS in every mine investigated (from 100 ÷ 800 measurements per year), total effective time of measurements in IDS was incomparably higher although it covered only a representative group from 20 – 50 miners (6).

Therefore, irrespective of the reasons mentioned earlier (1), another cause of ASS usual incommensurability with IDS is its incomparably shorter total effective time of measurement.

In ECS, the total effective time of measurement is comparable to that in IDS: the fact that it proved to be incommensurable in two out of four mines investigated seems to be the result of one of its inherent features, i.e. stationary location of the measuring device. Hence, this measuring system is characterized by a natural inertia with respect to the high mobility of a group of miners.

SMS and EMS are new systems whose applicability is still being studied. Currently, the values R (SMS) and R (EMS) are being determined. Determination of those values and control of their stability in various types of mines will be the subject of a separate paper.

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