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ORIGINAL PAPERS

FIELD MONITORING VERSUS INDIVIDUAL MINER DOSIMETRY OF RADON DAUGHTER PRODUCTS IN MINES

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Abstract. The paper presents the results realised simultaneously by two different and independent systems of measurement of an assessment of miners' exposure to radon daughter products which naturally occur in the air of mines. The first one, called the Air Sampling System (ASS), was based on the field monitoring of radon progeny in air, the second one, called the Individual Dosimetry System (IDS), was based on the individual dosimeters worn by miners. Experimental comparison of these two systems has been conducted for six years in eleven Polish underground metal-ore mines. This study reveals that no correlation exists between the concentration and annual miners' exposures evaluated by the ASS and IDS. The ratio ASS/IDS for mine population varies from 11.0 to 0.14 in respect of annual concentration means, and in respect to annual exposures, this ratio varies from 4.5 to 0.14.
The conclusion to be drawn from six years' observation and comparison of both systems is that correct and true evaluation of miners' exposure to radon progeny can be made only by the use of the Individual Dosimetry System, since the Air Sampling System is too sensitive and too dependent on the Strategy of sampling and its radiation.

INTRODUCTION

Assessment of miners' exposure to radon (222-Rn) 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 system has been called the "Air Sampling System" (ASS). Another class groups those measurement systems which are based on the use of individual dosimeters worn by miners. This class has been called the "Individual Dosimetry System" (IDS).

Certainly, each of these two classes has certain different inherent advantages and critical weak points. For example, the main feature of the ASS is usually the relatively high precision of each single measu-

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rement; 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.

Thus, a discussion on the superiority of either 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.

This paper presents the results of a long-term comparison of the two independent systems, i.e. the ASS and the IDS, implemented and tested simultaneously in Polish underground metal-ore mines.

Measurement Systems

Air Sampling System. The ASS, based on the air sampling and determination of the gross alpha activity of radon daughter products collected on an 'absolute' membrane milliporous filter (4), was implemented in all Polish underground copper and zinc-lead ore mines between 1981 and 1983 (7).

In all of these mines, the special local two or three-men services, responsible for radiation monitoring and safety, were organized and equipped with portable radiometers suitable for sampling and measuring the concentrations of alpha potential energy of radon daughter products in the air. The above-mentioned services, who were either technicians or engineers and were called the radiation safety services, were part of the ventillation section of particular mines. All the men included in the radiation safety services had been trained, examined and then registered and licensed as the radiation safety officers. The radiometers, called WL-meters, used in every mine are registered, calibrated and tested once a year in the Institute of Occupational Medicine in Lodz, which generally oversees radiation safety in the mining industry in Poland under the special recommendations and authorization of the Polish Atomic Agency in Warsaw.

The crucial point of the ASS, i.e. the strategy of monitoring and sampling, was thoroughly considered, discussed and finally approved by the Institute of Occupational Medicine before the implementation of this system. It was decided that the radiation safety services should measure and register all the measured concentrations of alpha potential energy of radon daughter products in air, all year long, in order to perform from a few tens to several hundred single measurements a year. It was strictly recommended that measurements should be performed in the sites where miners work and in the local air stream outlet. Also, unoccupied regions of a mine and unventillated caves and corridors where the concentrations are naturally higher were not to be used. Moreover, the instruction specified that only technically correct measurements i.e. those made when the radiometers were working correctly, were allowed to be registered.

The method in which measurements of alpha potential energy of radon daughter products in mine air were performed is presented in Fig. 1. The details of the measurement method used in the ASS are displayed in Table 1.

Individual Dosimetry System. The IDS (sometimes called the Helmet Cassette System), based on individual dosimeters worn by miners on the back of their helmets (Fig. 2) (6) was introduced in all the mines under consideration in the period between 1977 and 79 (1). This system is based on the use of small cassettes containing track-etch detector foil sensitive to alpha particles emitted by radon daughter products (2, 3, 11). The detector passively registers alpha particles which produce the 'tracks' which are visible and ready to be scored after

Fig. 1.

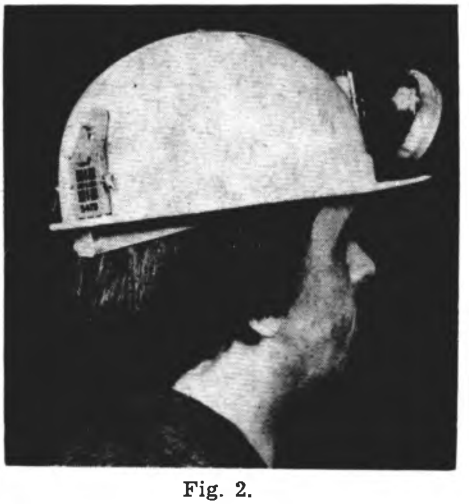

Fig. 2.

Fig. 1. The measurement of radon daughter concentration in air dose under the 'Air Sampling System'.

Fig. 2. A miner wearing a helmet cassette for the evaluation of the exposure to the radon daughter concentration under the 'Individual Dosimetry System'.

TABLE 1. Characteristics of measurement methods used in the Air Sampling System and Individual Dosimetry System

Feature	ASS	IDS
Kind of detectors	Semiconductor sensitive to alpha particles	Track-etch detector sensitive to alpha particles, LR-115 KODAK
Type of instrument	Radiometer RGR-13	Cassette OC-1
Duration of single measurement	5 minutes	Approximately 170 hours
Volume of air samples	10÷25 liters	Permanent contact of detector with ambient air
Lowest measurable concentration at the confidence level of 95%	0.4—0.9 10^{-3}	17 10^{-3} WLM (for 170 hours of exposure it is equal to 17 10^{-3} WL)
Precision *	< 1%	< 30%

* Variability of measurement in a series defined as the value of standard error and expressed as a percentage of the mean value.

suitable chemical processing of the foil and whose surface density can easily be recalculated, after suitable chamber calibration, as the miner's exposure. The cassettes are exchangeable and after one-month's exposure they are replaced by new ones by the radiation safety officers in every mine covered by this system. The IDS is realised centrally (results scored and registered) by the Institute of Occupational Medicine (8). Unfortunately, the working capacity of the computerised centre located in the IOM, does not exceed 5000 films for processing and scoring. Since it is the only centre in the country, it is impossible to cover all the considered mines which employ more than 15 000 miners by comprehensive IDS. Therefore, at the time of implementing the IDS it was resolved to select representative groups of miners in every mine and to equip them with helmet cassettes. The men selected to form such groups proportionally represent all the functions of miners employed in all regions of a given mine. In this way, the present IDS plays the role of a representative system and gives representative results of miners' exposure in all the considered mines. This representative IDS is officially regarded as a system of evaluation of average annual exposure of miners employed in metal-ore mines in Poland.

The details of measurement method used in the IDS are presented in Table 1. Figure 2 presents the type of measurements realised under the IDS.

Technical Compatibility of Methods used in the ASS and IDS. The compatibility of measurement techniques used in the two systems makes it possible to compare the results collected using them. The compatibility is provided and proved by a thoroughly arranged system of calibration of measurement techniques applied in both systems. The principal idea of calibration is to use a comparatively large experimental radon chamber, to create conditions closely corresponding to those characteristic of mine air and also to conduct instantaneous measurements of the concentration of radon progeny using the techniques applied in the ASS and IDS.

So, a large volume chamber (1000 liters) — comparable to the volume of a single air sample in the ASS — was used for such calibration experiments (5). The equilibrium (radon/progeny) during calibration experiments corresponded to conditions frequently occurring in mine air. Radon and radon daughter products were obtained by the use of calibrated, certified generator sources, and were estimated by comparison with 'first class' sealed standard sources of radium (226-Ra), manufactured by the Radiochemical Centre Amersham (Great Britain).

Therefore, calibrations conducted with the use of an experimental chamber and measurement techniques based on certified reference sources, should provide full compatibility of the methods used in both systems, i.e. the ASS and IDS.

Nevertheless, the authors decided to prove compatibility not from the results of the chamber experiments alone but also taking into account special auxiliary field experiments which were conducted in one of the mines. In these experiments, instantaneous calibrations were conducted in the mine atmosphere, instead of the chamber, to see whether the results obtained under 'field' conditions are close to those obtained in chamber calibration. The positive results of this 'field' test prove the technical compatibility of methods used in the ASS and IDS.

Results of measurements

Field monitoring under the ASS system was conducted in 5 copper mines and 6 zinc-lead mines, starting in 1981, 1982 or 1983 depending on a given mine. The number of measurements made under this system in particular years after its implementation are given in Table 2. In that table the numbers of respective measurements done under the ASS and IDS are also presented. The results of measurements collected in both systems can be compared in respect to the mean value of annual concentration of alpha potential energy of radon daughter products in air, and secondly, in respect to the mean value of the annual exposure of miners.

TABLE 2. The numbers of measurements conducted under the Air Sampling System and under the Individual Dosimetry System

Code of mine (Year of implementation of ASS)	Year after implementation of the ASS; (ASS) (IDS)						Type of mine
	1st	2-nd	3-rd	4-th	5-th	6-th	
LUB (1981)	324	369	522	588	570	541	
	375	409	464	441	342	396	
RUD (1982)	104	354	436	325	320	*	
	71	329	628	317	275	418	
KON (1982)	55	34	72	29	*	*	Copper mines
	243	292	556	260	493	435	
POL (1981)	359	578	286	432	396	435	
	105	182	104	227	203	224	
SIE (1983)	612	492	356	260	265	210	
	109	287	236	207	222	104	
BOL (1986)	248	227	604	326	747	*	
	195	294	340	163	260	331	
OLK (1981)	233	105	268	334	413	513	
	88	176	245	220	229	239	
TRZ (1981)	112	102	186	117	268	173	
	298	286	243	290	255	226	Zinc-lead mines
DAB (1981)	200	217	279	258	241	176	
	217	457	661	260	459	354	
MAR (1981)	206	208	158	116	150	153	
	248	399	290	259	199	207	
POM (1981)	193	431	612	792	823	856	
	189	306	418	433	404	456	
Total	2646	3117	3779	3577	4193	3057	All the miners
	2138	3417	4185	3072	3341	3390	

* Regular measurements under the ASS were not continued in this year

Table 3 presents 'annual' mean values obtained under the ASS and IDS, of the alpha potential energy of the radon daughter product concentration in mine air, whereas Table 4 presents the ratio between these two means. The numerical values displayed in Table 3 are expressed as fractions of the so-called 'Derived Air Concentration' (DAC), i.e. the concentration which is 'derived' from the value of the Authorized Limit (AL) for miners' annual exposure to radon daughters progeny. The value of the Authorized Limit adopted in Poland is 3.5 WLM (12 10^{-3} J m^{-3} h) which corresponds to the Derived Air Concentration of 0.3 WL (6.2 10^{-6} J m^{-3}). Tables 5 and 6 refer to the miners' annual exposure evaluated by the IDS and calculated using results collected by the ASS. Table 5 presents values of the miners' annual exposure expressed as

TABLE 3. The 'annual' mean values of the radon daughter concentrations of results collected under the Air Sampling System and under the Individual Dosimetry System; expressed as fractions of DAC

Code of mine	Year after implementation of the ASS; (ASS) (IDS)						Type of mine
	1-st	2-nd	3-rd	4-th	5-th	6-th	
LUB	0.13	0.12	0.13	0.12	0.14	0.12	Copper mines
	0.038	0.051	0.070	0.097	0.10	0.075	
RUD	0.036	0.027	0.027	0.024	0.030	*	
	0.050	0.090	0.081	0.097	0.10	0.078	
KON	0.44	0.12	0.12	0.078	*		
	0.04	0.05	0.14	0.15	0.21	0.17	
POL	0.025	0.025	0.023	0.029	0.029	0.028	
	0.10	0.13	0.11	0.20	0.19	0.11	
SIE	0.13	0.093	0.090	0.085	0.069	0.024	
	0.15	0.13	0.23	0.090	0.11	0.056	
BOL	0.48	0.41	0.35	0.39	0.44	*	Zinc-lead mines
	0.22	0.20	0.25	0.41	0.33	0.24	
OLK	0.20	0.27	0.12	0.12	0.13	0.20	
	0.17	0.16	0.22	0.21	0.20	0.27	
TRZ	0.14	0.10	0.064	0.048	0.087	0.10	
	0.039	0.025	0.047	0.065	0.090	0.65	
DAB	0.17	0.17	0.13	0.078	0.079	0.070	
	0.030	0.070	0.058	0.082	0.14	0.13	
MAR	0.51	0.45	0.47	0.43	0.43	0.46	
	0.19	0.21	0.19	0.26	0.29	0.20	
POM	0.13	0.16	0.14	0.14	0.14	0.16	
	0.073	0.092	0.12	0.14	0.26	0.15	

* Regular measurements under the ASS were not continued in this year

a fraction of the Authorized Limit, whereas Table 6 presents the ratio (mean ASS)/(mean IDS). Figure 4 displays the distribution of concentrations of alpha potential energy of radon daughter products in air, measured simultaneously under the two discussed systems in two diffe-

TABLE 4. The ratio of 'annual' means of the radon daughter concentrations according to results collected under the Air Sampling System and under the Individual Dosimetry System, i.e. the ratio (mean ASS)/(mean IDS)

Code of mine	Year after implementation of the ASS;						Type of mine
	1-st	2-nd	3-rd	4-th	5-th	6-th	
LUB	3.4	2.3	1.9	1.2	1.4	1.6	Copper mine
RUD	0.72	0.30	0.33	0.25	0.30	*	
KON	11.0	2.4	0.86	0.52	*	*	
POL	0.25	0.19	0.21	0.14	0.15	0.25	
SIE	0.86	0.69	0.39	0.94	0.62	0.43	
BOL	2.2	2.0	1.4	0.95	1.3	*	Zinc-lead mines
OLK	0.85	1.7	0.54	0.57	0.65	0.74	
TRZ	3.6	4.0	1.4	0.74	0.97	1.5	
DAB	5.7	2.4	2.2	0.95	0.55	0.54	
MAR	2.7	2.1	2.5	1.7	1.5	2.3	
POM	1.8	1.7	1.2	1.0	0.54	1.0	

* Regular measurements under the ASS were not continued in this year

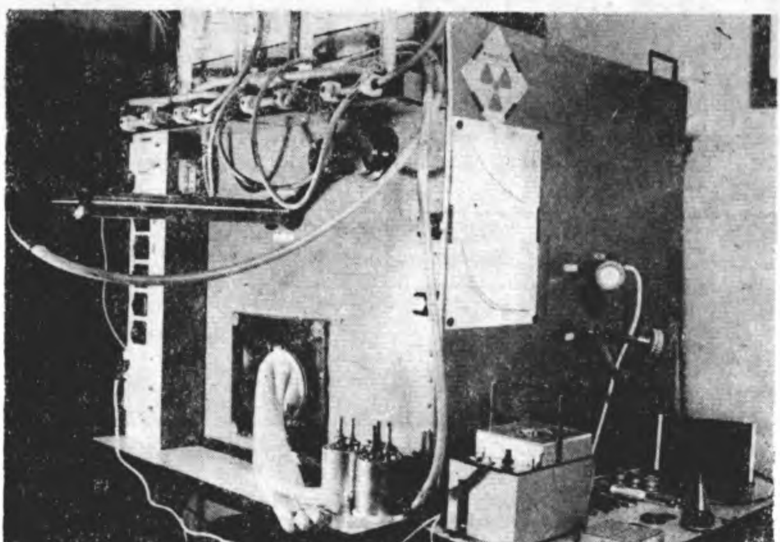

Fig. 3. The experimental radon chamber for calibrations of portable radiometers and track-etch detectors used in the ASS and IDS, respectively.

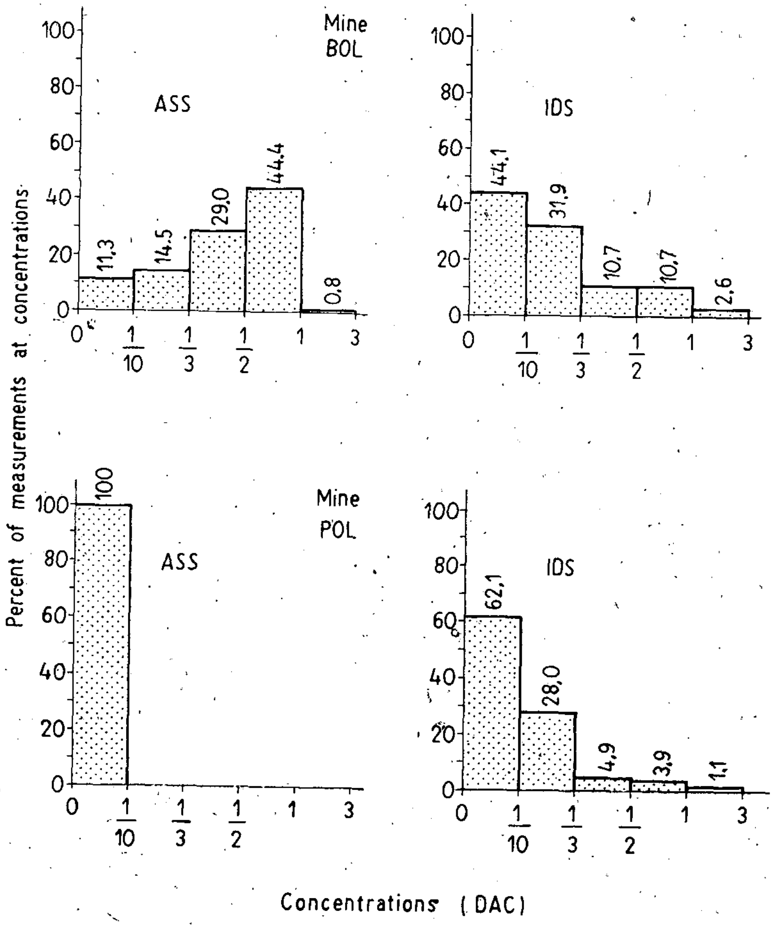

Fig. 4. The distribution of concentrations of alpha potential energy of radon daughter products in air of two different mines coded BOL and POL. Concentrations were measured under two independent systems, i.e. the ASS (left diagrams) and the IDS (right diagrams).

rent mines and collected during the first year after the implementation of the ASS. The diagrams present typical effects called the 'hunting' effect and the 'avoidance' effect which are discussed below.

DISCUSSION

Thousands of measurements conducted simultaneously in eleven metal-ore mines under two technically compatible, but entirely independent, long-term systems of radiation exposure assessment have brought results which have lead to important conclusions concerning the reliability and validity of these systems.

The first general effect which is reflected by the results in Table 4 and 6 is that these systems yield inconsistent results. Thus, the general question arises as to which of the systems is the more reliable and practicable. Before giving an answer, let us discuss several aspects of the matter in the light of observed similarities.

The ratio of annual concentrations, i.e. (mean ASS)/(mean IDS), shown in Table 4, varies in value from 11 to 0.14, depending on the mine and the year of implementation of the ASS. Thorough analysis of results given in that table indicates that certain similarities exist, namely, that, in nine out of the eleven mines, the mentioned ratio has its highest values in the first year after the implementation of the ASS, and that these values gradually decrease even to less than 1 in the following years and become relatively stable usually after the second

TABLE 5. The mean values of 'annual' miners' exposures measured under the Individual Dosimetry System and values evaluated from results collected under the Air Sampling System; expressed as fractions of AL

Code of mine	Year after implementation of the ASS; (ASS) (IDS)						Type of mine
	1-st	2-nd	3-rd	4-th	5-th	6-th	
LUB	0.13	0.12	0.13	0.12	0.14	0.12	Copper mines
	0.030	0.050	0.070	0.096	0.10	0.076	
RUD	0.036	0.027	0.027	0.024	0.030	*	
	0.075	0.087	0.081	0.12	0.13	0.075	
KON	0.44	0.12	0.12	0.078	*	*	
	0.096	0.066	0.12	0.23	0.20	0.16	
POL	0.025	0.025	0.022	0.029	0.029	0.028	
	0.095	0.12	0.13	0.20	0.19	0.12	
SIE	0.13	0.093	0.090	0.085	0.069	0.024	
	0.15	0.12	0.20	0.093	0.10	0.052	
BOL	0.48	0.41	0.35	0.39	0.44	*	Zinc-lead mines
	0.20	0.20	0.25	0.35	0.32	0.24	
OLK	0.20	0.27	0.12	0.12	0.13	0.20	
	0.14	0.17	0.22	0.21	0.20	0.27	
TRZ	0.14	0.10	0.064	0.048	0.037	0.10	
	0.038	0.022	0.043	0.062	0.087	0.062	
DAB	0.17	0.17	0.13	0.078	0.079	0.070	
	0.036	0.072	0.057	0.081	0.14	0.13	
MAR	0.51	0.45	0.47	0.43	0.43	0.46	
	0.17	0.21	0.19	0.25	0.27	0.19	
POM	0.13	0.16	0.14	0.14	0.14	0.16	
	0.067	0.091	0.12	0.13	0.25	0.15	

* Regular measurements under the ASS were not continued in this year

year. The existence of this phenomenon lies, presumably, in the policy of air sampling. Since the technique and policy of sampling are very important, inherent features of the ASS, relatively soon after its implementation, the effect which the authors call the 'hunting for results' takes place and dominates during sampling. It may well be attributed to the fact that radiation safety officers or dosimetrists look for places where concentrations will be higher, or, in other words, they 'hunt' for results, neglecting the strict instruction given them during the training course before the implementation of the ASS.

The opposite effect, revealed by results collected in two other mines (the mine coded RUD and especially mine POL), can be called the 'avoidance' of inconvenient results'. For five or six years (in these two mines) the discussed ratio is relatively constant but exceptionally low, which means that the mean annual concentration evaluated under the ASS is always much lower than the one measured under the IDS. The authors suspect that in these cases, the radiation safety officers or dosimetrists probably tried to hide results which would increase the mean value or, they simply avoided places in which miners work at relatively higher concentrations. Indeed, the same effects and similarities, albeit of a slightly different intensity, exist in relation to miners' exposure, as presented in Table 6. In this case, in the mines coded RUD and POL the 'avoidance' effect is apparent, whereas the other six mines present clearly the 'hunting' effect.

TABLE 6. The ratio of 'annual' means of miners exposure evaluated by measurements made under the Air Sampling System and under the Individual Dosimetry System, i.e. the ratio (mean ASS)/(mean IDS)

Code of mine	Year after implementation of the ASS;						Type of mine
	1-st	2-nd	3-rd	4-th	5-th	6-th	
LUB	4.3	2.4	1.9	1.2	1.4	1.6	Copper mine
RUD	0.48	0.31	0.33	0.50	0.23	*	
KON	4.5	1.8	1.0	0.56	*	*	
POL	0.26	0.21	0.17	0.14	0.15	0.23	
SIE	0.87	0.77	0.45	0.91	0.69	0.46	
BOL	2.4	2.0	1.4	1.1	1.4	*	Zinc-lead mines
OLK	1.4	1.6	0.54	0.57	0.65	0.74	
TRZ	3.7	4.5	1.5	0.77	0.42	1.6	
DAB	4.7	2.3	2.3	0.96	0.56	0.54	
MAR	3.0	2.1	2.5	1.7	1.6	2.4	
POM	1.9	1.8	1.2	1.1	0.56	1.1	

* Regular measurements under the ASS were not continued in this year

Both the above-mentioned effects distort the real picture of both concentrations and miners' exposure. The 'hunting' effect appears to be disappearing over the years, but it sometimes turns into to the 'avoidance' effect, whereas the 'avoidance' effect seems to be much more serious, since it seems rather entrenched.

The authors recongnised both these effects immediately after the implementation of the ASS, however they did not officially oppose the potentially incorrect practices of radiation safety services in particualr mines, since, in Poland, the earlier described IDS, which was introduced in 1977, is still the legally accepted system for the assessment of miners' exposure. Therefore, the miners' exposure assessment has simply been provided independent of the findings of the ASS without any intervention concerning the incorrect realization of the ASS system. So, during the period between 1981 and '88, the authors observed radiation safety officers and dosimetrists in particular mines who were repeatedly instructed and periodically retrained.

Surprisingly, the 'avoidance' effect still persisted and did not decrease its intensity throughout the whole period of observation.

The observations and study described in this paper were made possible as the authors had the reference dosimetric system at their disposal, namely the IDS which is inherently more reliable in miners' exposure assessment than the currently implemented ASS. Therefore, one may well ask why the ASS has been implemented at all. The ASS was implemented in order to equip the local radiation safety services with instruments which are both useful and necessary for the current control of radon progeny in mines. However, mine managers, as well as technical staff have urged the opinion that the IDS is an expensive and quite useless system as compared to the ASS. The results presented in this paper have undoubtedly revealed that the ASS is unreliable and would distort the real appearance of the radiation hazard, since it seems to be too dependent on air sampling policy and its practical realisation.

Nevertheless, the ASS should not be entirely abandoned since it is obviously better than nothing, and it can play another positive and useful role, especially as a tool for technical preventative actions aimed at fighting against or for the technical control of radon progeny in mines. In this respect, the ASS based on the instant measuring method would appear to be irreplaceable.

Last, but not least, a comment concerning the results presented and their possible impact and contribution to the discussion on the value of the radiation mortality risk factor seems to be called for. It is commonly known that this factor was evaluated in a study of the epidemiological lung cancer of American miners as several times lower than in analogous study of Czechoslovakian miners (10, 12). This known discrepancy between risk factor values has been, and still remains, the subject of scientific speculation, reevaluations, discussions, etc. However, so far, the reason behind the discrepancy has not been clearly established as the essential inherent incompatibility of the measurement systems which provided the necessary data on exposure to radon daughters during miners' employment. In the Czechoslovakian miner study, the exposure of miners was evaluated basing on the radon concentration data, collected under the ASS, conducted for many years and apparently consistent (13, 14). In this case the 'hunting' effect was probably minimalized or had possibly even ceased to exist at all. The evaluation of miners' exposure was the weakest point in the American study (9, 12). Sometimes, the concentrations were measured under the ASS only in a few places in particular supervised mines covered by the study, sometimes dosimetrists measured the concentration of radon progeny only once, and this is basis on which the exposure of the group of observed miners was evaluated. It is almost undeniable that the 'hunting' effect would play a significant role in such a collection of samples, and this would lead to an overestimation of miners' expected exposure and, consequently, to the obtaining of a lung cancer risk factor with a value several times lower than the one obtained by the Czechoslovakians.

Summing up, the authors declare the following opinion: 1) the post-irradiation lung cancer risk factor due to exposure to radon daughters should be thoroughly reconsidered in the light of the discovered effects, and 2) the correctness of the assessment of miners' exposure can be provided only by the Individual Dosimetry System.

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