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COST-BENEFIT ANALYSIS OF PREVENTION OF RADON RISK IN POLISH MINES

ANALIZA KOSZTÓW ZAGROŻENIA RADONOWEGO I NAKŁADÓW NA JEGO PREWENCJĘ W POLSKICH KOPALNIACH

Radon is the most important source of radiation hazard in underground mining. Polish experience from this field shows, that doses caused by the exposure of miners to radon progeny are the biggest in comparison with doses due to other natural sources of radiation in mines. On the other hand, enhanced radon concentration can be present everywhere in underground mines, being a source of the radiation hazard for whole mining crews. In late 90's complex investigations of the possible preventive measures have been finished in coal mining industry and in this paper the analysis of profits and costs of the mitigation measures against radon progeny is described. It has been shown, that costs of the prevention are much lower than costs of health detriments, generated by this hazard in the population of miners.

Key words: radon, mines, prevention, cost analysis.

Radon stanowi największe źródło zagrożenia promieniowaniem jonizującym w podziemnym środowisku pracy. Z kilkunastoletniej praktyki kontroli tego zagrożenia w Polsce wiadomo, że górnicy kopalń węgla kamiennego z tego właśnie źródła mogą otrzymywać największe dawki indywidualne, a ponadto — narażona na to zagrożenie jest praktycznie cała załoga podziemnego zakładu górniczego.

Ten stan rzeczy spowodował, że w latach dziewięćdziesiątych przystąpiono do opracowania kompleksowego systemu przeciwdziałania temu zagrożeniu. W rezultacie, opracowano zarówno wytyczne projektowania wyrobisk i pracy w warunkach zagrożenia, jak i metody techniczne przeciwdziałania temu zagrożeniu w konkretnych sytuacjach, m. in. przez izolację zrobów czy filtrację z powietrza aerozoli promieniotwórczych. Wszystkie wymienione metody, a także wytyczne, uzyskały stosowne zatwierdzenia i dopuszczenia do stosowania w podziemnych zakładach górniczych.

W artykule porównano nakłady na zastosowanie poszczególnych metod prewencji z kosztami, jakie może przynieść narażenie na długotrwałą ekspozycję górników na krótkożyciowe produkty rozpadu radonu. Przy analizie kosztów uwzględniono najnowsze

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opracowania dotyczące epidemiologii schorzeń jakie może wywołać ekspozycja na pochodne radonu, a także analizy kosztów (m. in. leczenie, renty) jakie schorzenia te powodują w skali globalnej.

Wykazano, że nakłady na prewencję są zdecydowanie niższe od kosztów, jakie to zagrożenie niesie z sobą. Stwierdzono też, że w obecnej sytuacji, gdy dostępne są metody prewencji, możliwe jest obniżenie ryzyka powodowanego przez pochodne radonu przynajmniej do poziomu ryzyka tolerowalnego ($10^{-3}-10^{-5}$).

Słowa kluczowe: radon, kopalnie, prewencja, analiza kosztów.

1. Natural sources of the ionising radiation in the natural environment

Any being, living on the Earth, is exposed to the ionising radiation. Part of this radiation comes from the cosmic spaces (so called "cosmic radiation"), whilst another component is related to the "cosmogenic isotopes", created in interactions of cosmic rays with atmospheric nuclei. Radionuclides, incorporated in the Earth's crust, are another source of radiation — these isotopes are known as "primordial radionuclides". To this group belong isotopes from uranium and thorium series as well as radioactive isotope of potassium — ^{40}K. ^{238}U is a parent isotope of the uranium series — as a result of several consecutive decays different radionuclides are created, while ^{232}Th is a primary isotope of the thorium series. Contribution of primordial radionuclides is the major part of the total dose equivalent for people.

Due to the present knowledge, the annual dose equivalent for a person, living in so called "normal region" (see Fig. 1), is equal 2.9 mSv (Jagielak J. et al., 1998). The major contribution in this dose is caused by radon or more strictly, by short-lived radon progeny.

The radiation hazard is one of the natural hazards in all types of the underground mines. In Polish coal mines the main sources of natural radiation are as follows:

— short-lived radon progeny;

— radium-bearing mine waters;

— deposits with enhanced radioactivity, precipitated out of radium-bearing waters.

The main factor of the radiation hazard for miners is the exposure to short-lived radon progeny, present in the air (see Fig. 2). Therefore in the further part of the paper, this problem will be described more precisely.

In underground galleries radon and radon progeny concentrations are higher, because that are places with limited ventilation, confined by rock body with many cracks and fissures. Typical radon outdoor concentration is of about 8 Bq/m^3, but in coal mines in Upper Silesia region the radon concentrations up to 15000 Bq/m^3 were measured, moreover in mines of Lower Silesian Coal Basin radon concentrations up to 150000 Bq/m^3 were found (Skowronek J., 1992).

In monitoring of radon progeny in mines rather seldom concentrations of particular short-lived decay product of radon are measured. Usually the term of potential alpha energy concentration (PAEC) is used. The PAEC values are expressed in joules per cubic meter and this term can be explained as the total energy, released during decay of short-lived radon progeny with alpha particles until their complete disintegration. PAEC describes in the best way the exposure of men to radon progeny, due to the fact, that in this particular case the influence of beta and gamma radiation is negligible.

Till now, the highest value of PAEC, measured in Polish coal mines, was equal 63 $\mu J/m^3$, but this measurement was made close to old uranium workings. In coal mines of Upper Silesian Coal Basin (USCB) the highest PAEC values never exceeded 15 $\mu J/m^3$.

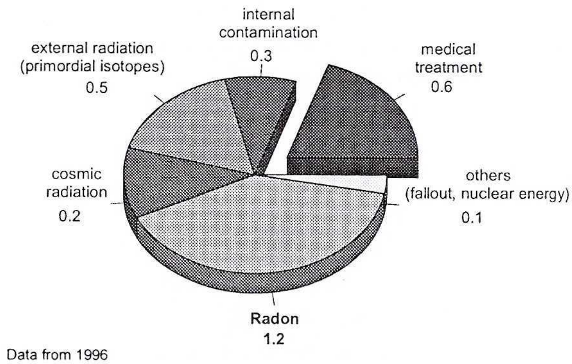

Fig. 1. Components of the average annual dose of ionising radiation, mSv

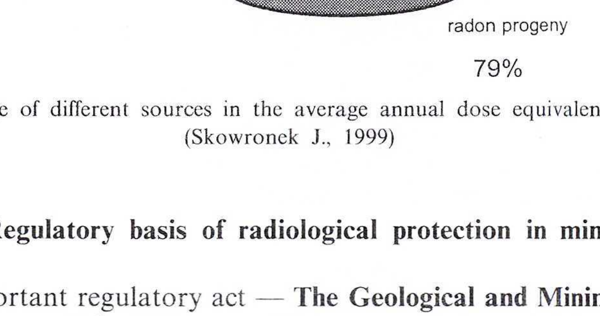

Fig. 2. The percentage of different sources in the average annual dose equivalent for Polish miners (Skowronek J., 1999)

2. Regulatory basis of radiological protection in mines

The most important regulatory act — **The Geological and Mining Law** (Ustawa, 1994) — was issued on 14th of February 1994. Accordingly to this law, criteria of the hazard assessment, also natural ones, must be established by the President of State

Mining Authority in co-operation with Ministry of Economy. Additionally, in case of radiation hazard, all regulations must be co-ordinated with President of Polish Atomic Energy Agency. The safety requirements for underground workings were issued by Ministry of Economy, acting within the agreement with the President of State Mining Authority.

Criteria of the assessment of radiation hazard in Polish mining industry were described in the Decree of the President of State Mining Authority, concerning all natural hazards (Zarządzenie, 1994). Additionally, in the Decree of the Ministry of Economy, issued in agreement with the President of Polish Atomic Energy Agency, requirements for protection against artificial and natural radionuclides in mining industry, prevention measures and monitoring of radiation hazard are included (Rozporządzenie, 1995). Appendix 14 to the mentioned above Decree contains the description of the monitoring methods and its frequency. Both decrees were prepared in comprise with new international recommendation.

In the Decree of the President of State Mining Authority underground galleries with enhanced radiation risk were divided into two classes:

Class A — for galleries, where the annual dose equivalent is within the range 5 to 20 mSv;

Class B — for galleries, where the annual dose equivalent exceeds 20 mSv.

In the Decree the methods and frequency of monitoring are stated for the classifying of undergound galleries. The following indicators of the radiation hazard from natural radionuclides have been defined:

— potential alpha energy concentration of short-lived radon progeny;

— gamma dose rate;

— concentration of radium isotopes in waters and sediments.

In the Decree of Ministry of Economy requirements for radiological protection against artificial and natural radioactivity are stated. But the following chapter will be focused only on requirements for natural radioactivity.

In the Decree the following statement is included:

"...In galleries with enhanced radiation hazard, located in underground mines, the employer must undertake efforts to change the work organisation and to reduce the radiation risk in such way to ensure conditions for employees, in which there is no possibility to go beyond the annual limit of dose equivalent (50 mSv), but no more than 100 mSv in 5 consecutive years. (...)"

In the Decree two advisory levels were defined:

— inspection level, equal 2 mSv/y, above which the employer must guarantee the thorough monitoring of the working environment;

— action level — 5 mSv/y — beyond this level the employer should start mitigation and prevention measures, to diminuish or liquidate the radiation hazard at workplaces.

Monitoring of the radiation hazard in galleries from the particular class must fulfil following requirements:

— in class A galleries monitoring of the working environment must be done;

— in class B galleries not only monitoring of the environment must be performed but also individual dosimetry should be applied.

3. Assessment of the hazard, caused by radon progeny in underground mines

Accordingly to mentioned above law regulations, the duty of the monitoring lays upon the employer (mine management). In practice, monitoring is performed by specialised laboratories, hired by mines to provide the full service, concerning radiation hazard. Therefore the biggest database of radiation monitoring results are gathered in such institutions for particular branches of mine industry.

For instance, data from coal mines are published annually as a special report by Central Mining Institute in Katowice (Skowronek J. et al., 1999). For other branches, like copper mines, lead and zinc mines etc., results of monitoring are published in annual report of Polish Atomic Energy Agency (Informacja, 1998), concerning general status of nuclear safety and radiological protection in Poland.

In table 1 maximum and average doses, caused by the exposure of miners to radon progeny, are shown for the period 1994–1998. Additionally, the collective doses for all underground coal miners have been included into this table.

It can be seen that during last few years a systematic decrease of doses for coal miners from radon progeny is observed. The main reason of such situation is application of prevention measures in mines. On the other hand, it must be taken into account, that the period of the incubation of lung cancer is stated as at least ten years.

TABLE 1

Maximum, average and collective dose equivalent for Polish coal miners, caused by radon progeny, during last five years

	1994	1995	1996	1997	1998
Maximum value, mSv/y	14	4.7	4.9	7.2	4.8
Average value, mSv/y	0.55	0.55	0.4	0.3	0.3
Collective dose equivalent, manSv/y	118	115	77	56	50

In the report of PAEA, the collective dose for miners of metallic ore mines is quoted as 25 man-sieverts per year, with the number of miners of about 14670 persons. It gives roughly a dose equivalent 1.7 mSv/y per miner, so higher than the average dose equivalent in coal mining industry.

4. Methods of radiation risk reduction

The Geological and Mining Law and accomplished decrees contain only general regulations and requirements concerning prevention against radiation hazard caused by radon progeny. The efforts were focused on development and application into practice *"Guidelines of the planning of underground workings, planning of the ventilation system as well as running the exploitation under the conditions with enhanced concentrations of radon progeny"* (Skowronek J. et al., 1999).

In these guidelines, for the planning stage of exploitation fields and for driving of new galleries, the requirements of the application of ventilation systems and other methods of prevention are described. For the stage of exploitation of the coal seams, the requirements concerning identification of radon sources, prevention measures as well as recommendation for ventilation systems are given. Additionally, needs of the prevention against radon exhalation from radium-bearing waters and deposits have been emphasised. In **Guidelines** sketch plans of ventilation systems are also included as well as the latest achievements in technologies and instrumentation for protective measures, like technique of goaf's insulation and the device for removal of radioactive aerosols from the one air UFAR-300 (Skowronek J., 2000).

The insulation of goafs (Skowronek J., 1999a) is of the main elements of the prevention against enhancement of radon progeny levels in the areas of long-walls. This technique is based on the principle, that reduction of the ventilation rate of goaf area leads to lower exhalation of radon and radon progeny to air. Investigations, performed in one of coal mines, proved this thesis — after the isolation of the exploited out area the PAEC dropped down from the level 6 $\mu J/m^3$ to values below 1 $\mu J/m^3$. Due to the continuous insulation of goaf's area in this region a significant improvement has been achieved — the PAEC value never exceeded the level 1 $\mu J/m^3$.

Experience, gathered during investigations of goaf's insulation in coal mines, leads to the conclusion, that different insulating materials can be used for this purpose, but materials, characterised by high value of aerodynamic resistance, should be preferred. The isolation might be done in these galleries, where it cause a decrease of the amount of air flowing into goaf, as well as on the opposite side of goaf's — to reduce the exhalation of radon and other gases into ventilation air.

In some cases, the air, ventilating particular workplaces, may contain enhanced radon and radon progeny concentration due to the earlier contact with radon sources, like goafs or radon-bearing waters. Than the filtration of air should be applied to reduce the radiation hazard as well as dust content. Typical devices, used in mining industry for the filtration of the air, are designed for the removal of respirable fraction of the dust (with diameter below 10 μm). The size of aerosols, connected with atoms of radon progeny, is usually lower than 1 μm. Therefore application of typical filtration devices to remove radon progeny from air is not efficiently.

For this purpose a special filtration device was developed. At first, a proper filtration material was chosen and tested in the radon chamber. Later a new design of a filter was prepared, which can be used in vent fans. This device, called UFAR-300, was accepted by State Mining Authority for use in all underground galleries, even at workplaces with methane or explosion hazards.

5. Risk assessment

Risk, caused by exposure to radon progeny, reveals an enhanced probability of cancer of the respiratory tracts: lung cancer or larynx cancer. It must be point out, that radon progeny is not the only one cancerigenous compound for this type of cancer. On the other hand, simultaneous exposure for several cancerogenic substances increases the probability of the incubation of cancers, moreover in the multiplying, not additive, way.

Currently, for the risk assessment of lung cancer incubation, the following formula, recommended by International Committee of Radiological Protection (ICRP, 65), is used:

$$P_\alpha = H_{ef} \bullet 8 \bullet 10^{-4},$$

$$N_\alpha = H_{ef} \bullet N \bullet 8 \bullet 10^{-4},$$

where:

P_α — probability of cancer incubation during one year
N_α — estimated number of lung cancers among exposed population
H_{ef} — the annual dose equivalent, mSv
N — number of people in the population, exposed to radon progeny.

Taking into account the number of miners, working under the conditions of enhanced radon progeny concentration as well as other data from radiation monitoring in mines the number of additional casualties of lung cancer among Polish miners can be calculated (see table 2). For the assessment, results of monitoring in year 1998 were used — the lowest values within the period of last few years. The number of casualties varies in range 48–52 per year, it depends on the method of the assessment — the lower value (48) was calculated with application of the average dose equivalent for while population and higher value (52) was obtained for calculations made for weighted average. It can be seen that 65% of cancers are induced by low doses, even below the action level.

It is very difficult to calculate the costs of the risk for the population. Basing on the datas of the Oncology Centre in Gliwice, the life expectancy of a man, for which lung cancer was detected, is of about 6–7 months only (Zemła et al., 1999). On the other hand, the incubation period for lung cancer, induced by radon progeny, is stated as 10–15 years. Therefore in some cases the cancer may appear before the retirement of the particular miner. For the calculation of the costs of the disease not only costs of medical treatment must be included but also the value of the loss in the productivity.

TABLE 2

Probability of the appearance of the lung cancer and the total number of estimated casualties among Polish miners due to the exposure to radon progeny in 1998

The branch of mining industry	The type of a dose equivalent	The annual dose equivalent [mSv]	The crew [persons]	Annual probability of lung cancer	Estimated number of lung cancers among miners
Coal mining	Average annual dose equivalent for all miners	0.3	200,000	0.00024	48
	Average annual dose equivalent for miners from workplaces without radiation hazard $H<2$ mSv	0.2	192,000	0.000144	31
	Average annual dose equivalent for miners from workplaces with low radiation hazard 2 mSv $<H<5$ mSv	2.5	6,000	0.002	12
	Average annual dose equivalent for miners from workplaces with enhanced radiation hazard $H>5$ mSv	6	1,800	0.004	9
The metal ore mining	Average annual dose equivalent	1.7	14,670	0.00136	20

The simplest way of the costs estimation is to make an assumption, that all cancers are terminally illnesses and the cost of the cancer is equal to the cost of the mortal accident — 830,000,– zł (Hebda A., 1999). For 70 cancers per year among all miners in Poland the total loss is equal:

$$70 \bullet 830{,}000,\!- = 58{,}100{,}000,\!- \text{ zł.}$$

The calculation of the costs, with taking into account medical treatment and early retirement, is far more complicated. It is very difficult to assess the cost of the medical treatment, because it depends of the type of a lung cancer. It can be assumed, that this cost is equal to the cost of heavy accident with disability pension (916,000,–zł).

In the scale of a whole year the total loss can be calculated as:

$$70 \bullet 916{,}000,\!- = 64{,}120{,}000,\!- \text{ zł.}$$

It can be seen, that overall costs due to the exposure of coal miners to the radon progeny is estimated as 58 to 64 million złoty per year.

6. Cost-profit analysis of the radon risk in mines

Each year enhanced PAEC values have been measured in underground galleries of several coal mines, but of course, usually that type of radiation hazard is related to areas near longwalls. In table 3 expenses on typical prevention measures are quoted.

TABLE 3

Costs of basic prevention measures against radon progeny hazard

The type of prevention measure	Unit cost	Expected span of prevention	Expected total cost
Changes in the ventilation net (drilling of new galleries)	2,800,– zł/running metre	10,000 metres of new galleries	28,000,000,– zł
Insulation of goafs	300,– zł/running metre	10,000 metres	3,000,000,– zł
Filtration of the air	100,000,– zł/year	10 devices	1,000,000,– zł

In mentioned above analysis the total loss for mining industry, caused by radon progeny hazard, was estimated as at least 58 million zł. Reduction of small doses from radon is very difficult because they are on the level compatible with the environmental one. But it is possible and rather easy to reduce the doses higher than inspection level — 2 mSv/year. In this case, we reduce estimated number of lung cancer among the miners at about 40 cases. Even in the case, the reduction of costs at least 33 million zł in all mining industry (17 million zł in coal mining industry) is possible.

The comparison of the loss with the predicted costs of the prevention shows, that mining industry could achieve significant profits due to the implementation of mitigation measures.

Due to the latest recommendations for mining industry (Niczyporuk Z. T., 1996), concerning safety problems, the maximum tolerant risk of mortal accident in this industry should be not higher as 10^{-3} of deaths per year and person. The exposure to radon progeny may lead to the incubation of lung cancer. This disease is characterised by very short life expectancy for the casualties — for men is only of about 6–7 months. Therefore the lung cancer must be treated as terminally illness, and for the risk analysis the criteria of the individual mortal accident should be applied. So, the risk above 10^{-3} must be treated as inadmissible risk. In table 4 the comparison of risk limits for mining industry with probability of the lung cancer, due to the exposure to radon progeny, is shown.

The results of that analysis show, that the action level for radon progeny in Polish coal mines, equal currently 5 mSv per year should be lower. The reason is that for this value of annual dose equivalent the probability of the lung cancer is higher than the maximum admissible risk of death, proposed for mining industry.

TABLE 4

The comparison of risk limits and probability of cancer disease among Polish coal miners

The type of risk	The range of risk	Probability of the incubation of lung cancer;	The range of annual dose equivalents related to the risk values
	deaths/year and person	casualties/year and person	
Inadmissible risk	$>10^{-3}$	$2\cdot10^{-3}$	Annual dose equivalent within the range 2–5 mSv
		$4\cdot10^{-3}$	Annual dose equivalent above 5 mSv
		$1.36\cdot10^{-3}$	Average annual dose equivalent in metal ore mines
Admissible risk	$10^{-5}-10^{-3}$	$2.4\cdot10^{-4}$	Average annual dose equivalent in coal mines
Accepted risk	$<10^{-5}$		no occurrence in mining industry

7. Conclusions

• Comparing the risk, caused by radon progeny in mines with the permissible limit of death risk -10^{-3} per year and person, it can be clearly seen, that current limits of radiation protection in mining industry in Poland enable exceeding of that risk.

• Cost-benefit analysis of the prevention measures and social costs of medical treatment, earlier retirements etc. leads to the conclusion, that expenses on mitigation measures are lower or similar to social costs.

• Implementation of different methods of prevention has been started in Polish coal mines few years ago. The effect of the mitigation is the permanent decrease of the radiation hazards during 90's. The same trend could be observed in the future, but current limits in radiation protection must be lower.

• The novelty of the Geological and Mining Law and related decrees gives the opportunity to apply in the regulation latest achievements in prevention of radon risk as well as ALARA principle — to keep the radiation risk of miners *as low as reasonable achievable.*

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