The Nofer Institute of Occupational Medicine in Łódź

Department of Radiological Protection

dr Jerzy Olszewski

Assessment of occupational exposure resulting from exposure to radon in underground tourist routes and health resorts

Łódź, April 2019

1. Personal data

Name of author: Jerzy Olszewski

2. Education

Held diplomas, academic degrees (including the name, place and year they were obtained as well as the title of the Ph.D. dissertation):

1981 – 2001 The Nofer Institute of Occupational Medicine of Łódź Department of Radiological Protection

Title: doctor of Medical Sciences, specialty: medical biology - radiology;

Supervisor: Prof. habilitated doctor Jerzy Jankowski

Title of doctoral thesis: **Analysis of viability of an Active Dosimeter as a potential reference meter for passive methods used in mines for assessing exposure to radon derivatives by miners**

1980 - 1981 Post-graduate studies in Science and Technology Photography at the University of Warsaw.

1973 – 1981 University of Łódź Department: Physics and Chemistry, experimental physics;

Master of Physics

Title of master's thesis: **Electrochemical etching of Kodak LR-115 (II) film used as a trace detector of alpha particles**

1969 – 1973 Secondary School in Łódź

3. Past scientific employment (and the functions carried out):

06.1981 – 12.2001: assistant at the Radioactive Contamination Department of The Nofer Institute of Occupational Medicine in Łódź

01.2002 – lecturer w Department of Radiological Protection The Nofer Institute of Occupational Medicine in Łódź

Instytutu Medycyny Pracy w Łodzi

1987 – Radiation Protection Officer – IOR-3 in isotopic room categoy III

1997 – 2016: Radiation Protection Officer – IOR-3 in isotopic room categoy II in Department of Nuclear Medicine

02.2016 - President of the Radon Center - International, Non-Governmental Scientific Network

4. Indication of scientific achievement reported as the basis procedure habilitation.

a) Title of scientific achievement:

Assessment of occupational exposure resulting from exposure to radon in underground tourist routes and health resorts

b) List of monothematic publications constituting scientific achievements reported as a basis for habilitation proceedings (author/authors, title/titles of publications, publication date, name of publisher, publication reviewers).

The basis of the achievement if a cycle of 9 original publications, a monographic article 2 as well as a review article authored by the habilitant.

H1. Olszewski J., Chruścielewski W., Jankowski J., Radon on underground tourist router in Poland. International Congress Series 1276 (2005) 360 – 361, IF=0,20, pts 3

My tasks mainly consisted of carrying out measurements, detectors analysing, results analysing and preparing the manuscript. My contribution is estimated at 90%.

H2. Olszewski J., Chruścielewski W., Kacprzyk J., Kluszczyński D., Kamiński Z., Radon on selected underground tourists router in Poland. Radioactivity in the Environment, Vol. 7, 2005, 803-806 , pts 3

My tasks mainly consisted of collecting all the results obtained so far, analysing these results, making a statistical analysis of the results and writing the manuscript. My contribution is estimated at 78%.

H3. **Olszewski J.**, Chruścielewski W., Jankowski J. Radon exposure in selected underground touring routes in Poland. W: Second European IRPA Congress on Radiation Protection. Radiation protection: From Knowledge to Action. 15-19 May 2006 Paris France. Proceedings of full papers. CD-ROM. Paris: International Radiation Protection Association 2006 9 s.

My tasks mainly consisted of collecting all the results obtained so far, analysing these results, making a statistical analysis of the results and writing the manuscript. My contribution is estimated at 90%.

H4. **Jerzy Olszewski**, Małgorzata Chodak, Jerzy Jankowski, Rozpoznanie aktualnego stanu narażenia na radon pracowników uzdrowisk w Polsce. Medycyna Pracy 2008;59(1):35 – 38; , pts 6

My tasks consisted of organizing measurements and developing a measurement methodology, conducting measurements in Polish spas, statistical analysis of the results and writing the manuscript. My contribution is estimated at 91%.

H5. Mamont-Cieśla K., Stawarz O., Karpińska M., Kapała J., Kozak K., Grządziel D., Chałupnik S., Chmielewska I., **Olszewski J**., Przylibski T.A., Żebrowski A. Intercomparison of radon CR-39 detector systems conducted in CLOR's calibration chamber. Nukleonika 2010 Vol. 55 nr 4 s. 589-593; (IF_{2010}=0,321), pts 20

My tasks consisted of preparation of detectors for exposure, reading of registered radon exposure, preparation of final report and sending to CLOR for inclusion in the final report. My contribution is estimated at 10%.

H6. **Olszewski J**., Zmyślony M., Wrzesień M., Walczak K., Występowanie radonu w polskich podziemnych trasach turystycznych. Medycyna Pracy, 66 (4) str. 557-563, 2015; (IF_{2015}=0,397), pts15

My tasks consisted of development of the research concept in several dozen underground tourist routes, as well as the selection of research methodology, conducting research and analysis of results, preparation of monographs and graphic preparation for printing. My contribution is estimated at 70%.

H7. **Olszewski** J., Casus radon, W: "Ochrona przed promieniowaniem jonizującym i niejonizującym. Nowe uregulowania prawne, źródła, problemy pomiarowe. Warszawa, praca zbiorowa, PTBR, pod redakcją M. Zmyślony, Wojskowa Akademia Techniczna, Warszawa 2015

My contribution was to write a chapter based on my own and literature data. I estimate my contribution to 100%

H8. Katarzyna Walczak, **Jerzy Olszewski**, Marek Zmyślony. Estimate of radon exposure in gethemal spas in Poland, International Journal of Occupational Medicine and Environmental Health 2016;29(1):161 – 166; IF=0,780(IF_{2016}=0,780), (pts 15)

My tasks consisted of planning of the research. I made a selection of measurement methodology and carried out measurements. I also made a preliminary statistical analysis of the results. My contribution is estimated at 50%.

H9. Katarzyna Walczak, **Jerzy Olszewski**, Piotr Politański, Marek Zmyślony. Occupational exposure to radon in underground tourist routes in Poland: doses to lung and the risk of developing lung cancer. International Journal of Occupational Medicine and Environmental Health 2017;20(5):1– 8; (IF_{2017}=0,397), pts 15

My contribution consisted of planning all measurements, developing results, carrying out preliminary sttistical analysis of the results, preparation of final conclusions. I estimate my contribution at 50%.

H10. Jerzy Olszewski; The underground tourist route Kowary Drifts – An example to follow. Journal of Environment and Health Science; 2018; DOI 10.15436/2378-6841.18.1684;

My contribution consisted of collecting and re-working out all measurements carried out by me in the underground route from the beginning of its existence. Statistical analysis of the results and writing the monograph. My contribution: 100%

H11. Olszewski J., Radon w świetle prawa atomowego, W: "Ochrona przed promieniowaniem jonizującym i niejonizującym. Nowe uregulowania prawne, źródła, problemy pomiarowe. Warszawa, praca zbiorowa, PTBR, pod redakcją M. Zmyślony, Wojskowa Akademia Techniczna, Warszawa 2018

My contribution was to write a chapter based on my own and literature data. I estimate my contribution to 100%

Indicators covering the publications included in the thesis:

Total IF: **2,262**

Total points as per the Minister of Science and Higher Education**:77**

The average contribution per one paper was 84%.

c) Discussion of the scientific/artistic reasons for the above publication/publications as well as the achieved results, together with a discussion of their possible use.

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1. Introduction

Radiation is an inherent part of the natural environment. It comes from natural sources, present in the Earth crust since the beginnings of our planet, as well as from artificial sources resulting from human activity. Cosmic radiation is a constant presence as well. Out of all natural radiation sources on the surface of the Earth, radon is the largest radiological threat to humans. Currently, it is estimated that more than half of the radiation load of the Polish population results from the inhalation of radon and radon derivatives[1].

The element was discovered as early as the 19th century, by the German chemist Friedrich Ernst Dorn. At the time, he was conducting research in Halle concerning the radioactive decay of rad. When he tried to determine what happened to the mass of rad, he discovered a radioactive gas - "the radioactive air of Mrs. Curie". Dorn initially called the gas "niton". It was only in 1923 that the International Congress of Science on Radioactivity adopted the current name for the element, radon. The element is a class I carcinogen. At the same time, radiation threats are posed by radon derivatives, 218Po and 214Po, attached to aerosol particles and being deposited together with them, mainly on bronchi walls. They emit alpha particles with the energies of, respectively, 6.0 MeV and 7,69 MeV, whose energy is sufficient to irradiate the layers of basal cells of bronchi and lungs. Exposure to radon derivatives may lead to lung cancer.[2]

2. Aim and scope of the studies

Council Directive 2013/59/Euratom was issued on 5 December, 2013[3]. The document laid down basic safety standards for protection against dangers arising from exposure to ionising radiation. The directive states that protection against natural sources of radiation should be entirely included in general guidelines on radiological protection. The document contains two clauses, particularly important for protection against negative impact of radon on a human body. The first clause refers to the fact that prolonged indoor exposure to radon radiation, equal to 100 Bqm^{-3}, contributes to a significant increased risk of lung cancer. The other clause refers to implementation of the national reference level of radon concentration in indoor workplaces by member states of the EU. The reference level cannot exceed 300 Bqm^{-3} of the average yearly radon concentration in both residential dwelling and workplace air, unless it is bound to reach that level due to current conditions in a particular country.

Considering all the above, we can ask a question: Where can we expect increased levels of radon? In most cases, radon hazard is associated with underground mines, particularly uranium mines.

The aim of the habilitation dissertation was to assess health hazard of underground tourist routes, resorts and spas, caused by radioactive gas – radon, detected at workplaces.

The analyses included in the summary of professional achievements are based on studies which I conducted for above ten years. I will present consequences of implementing recommendations of the directive into legal provisions as well as I will attempt to evaluate the hazard associated with specific influence of radon on a human body.

3. Radon - properties, occurrence, measurement, hazard

In the decay chain starting with uranium ^{238}U, one of the chain's elements is radium, with half-life of 1620 years. As part of radioactive decay of radium, radon is created (^{222}Rn). Radon is an element from the noble gas group, it is an invisible gas, with no odor or taste, easily dissolved in water and certain organic solvents.[4] Radon occurs in nature in the form of three radioactive isotopes, all of which are created from radium isotopes. Radon ^{219}Rn (actinon) from radium ^{223}Ra, ^{220}Rn (thoron) from ^{224}Ra and ^{222}Rn (radon) from ^{226}Ra. The former two have short half-lives (4 and 58 seconds respectively), while radon (^{222}Rn) has a half-life of 3.8 day.[5] Radon is a gas, therefore it is capable of spreading, while the long half-life of ^{222}Rn allows it to circulate in the environment from its origin point to atmospheric air, as well as to enclosed spaces such as caves, tunnels, residential buildings etc. As a result, radon impacts the process of human respiration and, due to its radioactivity, may impact human health.

Radon resulting from the decay of radium spreads into the environment by being released from grains of soil or rock into the cracks, gaps and pores in their structures. The environment may be either air or water or, in some cases, petroleum or natural gas. After radon is released, its migration follows via cracks into the atmospheric air[6] or, in the case of underground tourist routes, into the atmosphere of the rooms on the route. Underground tourist routes may contain radon in concentrations up to several thousand Bqm^{-3}.

As mentioned before, the good solubility of radon in water means that the gas is present in nearly all water reservoirs on the surface as well as underground.

In underground waters, concentrations of radon range from a fraction of $Bq \cdot dm^{-3}$ up to several hundred thousand $Bq \cdot dm^{-3}$ and are mainly dependent on the geological makeup as well as the mineral-petroleum-geochemical characteristics of the region of the water outflow or intake[7,8]. Larger concentrations of the gas in water should be expected only in the environment of underground water. Groundwater, including highly mineralized or thermal water (that is water where solubility of gases is lower) often contain radon in concentrations exceeding several hundred, or even one thousand $Bq \cdot dm^{-3}$.

Mineral waters used for therapeutic purposes in health resorts contain mineral salts washed out from deeper layers of the lithosphere as well as soluble gases: carbon dioxide as well as the radioactive radon ^{222}Rn[9]. Radon released from water into the air may be the source of danger for workers employed in relation to the use of mineral waters.

In health resorts (there are several dozens of these in Poland), large amounts of mineral waters are in use, usually in enclosed room such as bathrooms, inhalatoriums, swimming pools etc.[10] In these conditions, radon concentrations may be high in rooms where workers are present. This phenomenon may occur when using non-radon water as well, that is to say - water containing less than 74 Bq/l (2 nCi/l) radon per liter of water.[11]

Water containing large amounts of water - the so-called radon waters - is used for therapeutic purposes as drinking water or in inhalation therapy.

In Poland, it is increasingly popular to use thermal waters for recreation purposes. There are several prospering centers (called SPAs) using natural thermal waters in Poland. Generally, research on thermal or therapeutic water in health centers focus on the concentrations of microelements or chemical elements (including radioactive ones, notably radium and radon) in the water. Large concentrations of radon in water may lead to a higher concentration of radon in the air, and consequently lead to higher susceptibility of the working personnel to radon exposure.

Measurement methods

Measurement techniques used to determine the concentration of radon, the potential energy, or both the potential energy and radon at the same time, usually take advantage of alpha radiation emitted as part of the decay or radon, as well as certain short-lived products of its decay (polonium ^{218}Po and ^{214}Po).

The energy of alpha particles emitted as part of radioactive decay means that they strongly impact the particles or atoms they come into contact with. In 1903, W. Crookes and J. Elster as well as H. Geitel simultaneously discovered the phenomenon of scintillation, that is to say the appearance of a brief light flash occurring when charged particles (e.g. alpha particles) pass through luminescent substances, the so-called scintillators. In the late 1950s, it was discovered that heavy, charged particles (e.g. alpha particles), when passing through solid-state dielectric substances - including crystals, non-organic glasses and plastics - leave microscopic marks behind. Such marks were first observed in mica in 1959 by E.C. Slik and R. S. Barnes.[12] Using an electron microscope, it was possible to observe long, line-shaped damage areas - "marks". In most detector materials, the marks are the result of the fact that the passing of a charged particles ionizes atoms in its path, which in turn damages the crystal structure. In materials sensitive to alpha particles, it is more likely that marks will result from the damaged chemical bonds.[13] The damages resulting in a detector may be observed only via an electron microscope. To make it possible to conduct observations with an optical microscope, it is necessary to subject a detector to chemical etching.[14,15,16,17]

At present, various detection equipment is used in order to measure the concentrations of radon as well as the potential energy of alpha radiation of its short-lived derivatives. These include, among others: Atmos-12D, Alpha Guard MC50, Pylon AB-5, Pylon CPRD, EML Radiometer, Sun Nuclear-1023 (radon) as well as Eberline WLM-14, Thom./Nielsen IRMP, Scintrex WLM-30, Alpha Nuclear-770A or Pylon WLx (potential energy).[18]

In the Institute of Occupational Medicine of Łódź, the following measurement instruments and methods are in use:

1. Passive dosimeters with a trace detector - for the measurement of individual exposition to radon derivatives and/or periodic concentrations of potential energy.
2. Scintillation cells for the measurement of instantaneous concentrations.

Passive dosimeter

The term "passive dosimeter" means that the registering of radiation occurs passively, without the use of supporting mechanical or electronic devices. A passive dosimeter consists of: a dosimetric cassette and a trace detector. Two types of dosimeters may be distinguished - an open one (OC-1) or an enclosed one (NRPB). For long-term measurements of radon concentrations in underground tourist routes, an enclosed dosimeter NRPB has been used.

NPRB-type enclosed dosimetric cassette is made of plastic.[19] It consists of two parts. The dimensions of the cassette are: diameter 5.5 cm, thickness 2 cm. A CR-39 trace detector is placed within the cassette. An important construction feature of a NRPB cassette is that after it is closed, only gas diffuses into it via microslits. As a result, a concentration of radon is established inside the cassette's chamber that is equal to that in the air around the cassette, regardless of the amount of radon derivatives. As a result, it is used to measure exposure to radon. If the exact measurement time is known, it is possible to calculate the average concentration of radon in the air in the period in question. An NRPB dosimeter is shown in figure 1. After finished exposure, CR-39 detectors (or Tastrak) undergo chemical treatment consisting in their etching in a 20% NaOH solution, in the temperature of 80 degrees C, for the period of 18 hours.

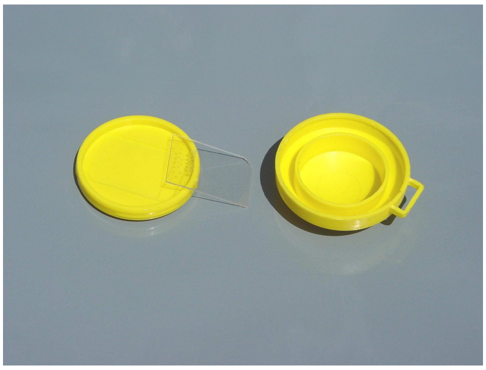

Fig. 1. Opened NRPB-type dosimetric cassette with a Cr-39 detector.

The analysis of trace detectors is conducted with the help with an image analysis system by the IMAL company[20] available in the Institute of Occupational Medicine of Łódź.

As a result of the analysis, the density of traces per mm^2 is obtained, which in turn is used to calculate the exposure that the detector was subject to. Due to the readability, the detector can record exposures up to 1 $MBqhm^{-3}$

Scintillation cells

RDA-200 gauge consisting of scintillation cells, the so-called Lucas chambers, and a registering system with a photomultiplier, produced by the Canadian company EDA, is a device whose purpose is to measure the concentration of the radioactive gas radon ^{222}Rn, present in the air.

The measurement of radon concentration is conducted on the basis of a measurement of alpha radioactivity of an air sample collected via a filter into a scintillation cell, with the use of a manual or mechanical pump. The volume of a scintillation cell is 176 cm^3. The lower detection threshold is 0.03 $kBqm^{-3}$ A set produced by the Canadian company Pylon is presented in figure 2.

Fig. 2. RDA-200 gauge by Pylon (Canada)

Hazard

Radon occurs so commonly that practically every human inhales air with radon and suspended radioactive aerosols. The human respiratory system can be divided into three parts: nasopharyngeal, trachea-bronchial and alveolo-interstitial. After a period of a second, gases and radon are removed from the body. Radioactive aerosols remain there long enough for all short-lived radon decay products to undergo decay[21]. Dust, so also radioactive aerosols which penetrated lung alveoli are absorbed by pulmonary macrophages and together with them, partially eliminated to airways and to regional lymph nodes. Due to this self-purification ability of lungs, only a slight amount of inhaled dust, i.e. about 5%, is retained in the respiratory system[22]. This process is so long that only lead, ^{210}Pb, also radioactive with life of 22.3 years, can be partially excreted from the body. Thus, decay of short-lived radon derivatives affects a dose for the respiratory system.

Harmful properties of radon were mentioned as early as in ancient times, when the cause of this phenomenon was not known. One of the oldest reports on diseases caused by work in mines can be found in a document, called "*De Rerum Natura*", dating back to 1st century B.C., written by Titus Lucretius Carus[23]. The author mentioned a harmful effect of gases coming from the underground in gold mines on the health of miners. The description refers to underground mines in ancient Thracia (Greece). We can suppose that radon and its derivatives were factors contributing to the occurrence of miners' diseases. According to the modern European atlas of radiation, this area is characterised by increased radon levels[24]. In 1556, Agricola revealed that miners working in the Scheneeberg and Jachymova regions are more susceptible to pulmonary and bronchial disorders[25]. In 1879, lung cancer appeared to be one of those diseases[26].

Calibration of measurement methods

Trace detectors are calibrated in a radon chamber before they are applied. The detectors are exposed in a few radon concentrations. In the Institute of Occupational Medicine, a two-cubic metre radon chamber is used for calibration of trace detectors. The so called "two-filter method" is a reference method, used in calibration of measurement devices and trace detectors. This method involves filtering air containing radon and radioactive aerosols through two filters[27], placed at the end of a half-meter long metal tube. The first filter retains radioactive aerosols but passes radon. The other filter retains radon derivatives which form when radon stays in the tube. Certified radon emanators, manufactured by Pylon company from Canada are used for calibration. Detectors are exposed in minimum three radon concentrations for a period of at least 8 hours. The density of traces, formed on the detectors, are the grounds for calculating coefficients enabling to converse the trace density to the magnitude of exposure of the detector[28] . When we know the exact duration of exposure, we can calculate the average radon concentration during the exposure.

A radon chamber is also used for calibration of scintillation cells. Certain radon concentration, controlled by the use of a two-filter method, is generated in the radon chamber with the application of emanators. Next, radon-filled air with is passed through scintillation cells. The calibration procedure allows to obtain the conversion coefficient which enables to converse the number of impulses, registered on a photomultiplier into instantaneous radon concentration.

Measurement apparatuses and meters for individual exposure to radon and/or potential energy have to be systematically calibrated, at least once a year.

The department has been awarded PCA AB 837 accreditation for measuring exposure to radon (radon concentration) with the use of trace detectors.

Apart from regular calibrations, inter-laboratory comparisons of measurement methods are performed systematically[29]. In 2016, such inter-laboratory comparisons were performed in the Central Mining Institute [30] in Katowice (June) and in the underground tourist route "Kowary Drifts" (September). Similar comparisons were conducted in the Central Laboratory of Radiological Protection in 2018[31].

In 2013, Polish representatives participated in the international procedure of comparing measurement methods for radon concentration, held in Prague in the Czech Republic. [32].

4. Regulations - transitional period

At the moment we are in a transitional period regarding the legal provisions regarding radon. This is due to the publication of the Directive 2013/59/EURATOM from 5 December 2013. The directive established the basic safety norms in order to protect from dangers resulting from exposure to ionizing radiation, and repealed directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom[3]. Member states are bound to introduce statutory, executive and administrative laws necessary for the implementation of the directive no later than 6 February 2018. (New Atomic Law)

The 73-page directive standardizes and updates the legislation in EU countries, taking into account the newest research and achievements in the field of radiological protection. The directive applies to any situations of planned exposure, existing exposure or exceptional exposure related to dangers resulting from exposure to ionizing radiation, which may not be dismissed from the point of view of radiation protection or in relation to the environment, taking into advantage the long-term protection of human health. This is a new approach to radiological protection that includes practically all situations where a person is exposed to ionizing radiation.

The starting point for the new approach to exposure to radon and its derivatives is the declaration that "the newest epidemiological data resulting from the research on populace in residential buildings shows that there is a statistically significant increase in risk of lung cancer as a result of prolonged exposure to radon inside buildings on the level around 100 Bq m^{-3}". (The Preamble of the directive, item 22. Item 23 points out that the combination of tobacco smoking and high exposure to radon results in a much higher risk of lung cancer in a single person than either of those factors in isolation. It also states that tobacco smoking increases the risk resulting from radon exposure on the population level. It was also determined that it is important that member countries deal with both types of health hazard.

At present, the draft Atomic Law has been submitted to the Sejm of the Republic of Poland on February 20, 2019 (print 3237). He was then referred to the 1st reading in the Committee on Environmental Protection, Natural Resources and Forestry. Deadline for submission of the report by 06-05-2019.[33]

At this point, it is probably worth quoting the most important article in the new Atomic Law.

,, Art. 23b. The reference level for the average annual radon concentration in the air at:

1) indoor work places as well

2) rooms for people's stay

- in the amount of **300 Bqm^{-3}** (becquerels per cubic meter).

5. Underground tourist routes

It is estimated that there are currently about 240[34] underground tourist routes in Poland, which may employ over 1500 people. In the year 2000, that is to say from the time I developed an interest in worker exposure in underground tourist routes, there were 27 underground routes. In the time between 2000 and now, four underground tourist routes have been systematically controlled at various times. These are, sorted by the time measurements had been initiated: the Niedźwiedzia cave (1995), the closed uranium mine in Kowary "Kowary Drifts" (2001), the closed uranium mine in Kletno (2004), the closed gold mine "Złoty Stok" (2004), the underground town Osówka in Głuszyca (2004).

The first results of measurements made in the tourist routes were published in 2005. The measurements were taken in the Niedźwiedzia Cave, the Kowary Drift and in the Uranium Mine in Kletno..[35]

In 2012, as part of the research work of the Institute of Occupational Medicine, measurements were carried out in 66 underground routes in Poland.

The results of multiannual measurements will be discussed below. I carried out these measurements personally, only for the first 5 years measurements in the Niedźwiedzia Cave were performed by other people working in the Department of Radiological Protection IMP.

Only measurements made by me will be used to analyze radon threat in Polish underground tourist routes.

5.1. The Niedźwiedzia Cave

The Niedźwiedzia Cave was accidentally discovered in 1966, during the exploitation of the Kletno III quarry.[36] In 1977, the Cave and its immediate surroundings were established as a nature preserve. In 1983, part of the cave was opened to tourists. The total length of the corridors in the cave is 2500 meters, and the length of the tourist route is approximately 400 m. The visiting time is about 45 minutes.

In the Niedźwiedzia Cave, the first ionizing radiation measurements were conducted as early as 1967. Radon concentration in water and air were measured. The results of those measurements were published in 1978[37]. The concentrations of radon at the time were to the tune of several thousand Bqm^{-3}. (e.g. 5100 Bqm^{-3} in the Lion Room). The research conducted then resulted in the conclusion that systematic research of radiation therein needed to be conducted.

However, systematic measurements did not being until 1994. From around that time, my interest in caves and other underground tourist routes developed. Passive NRPB-type (closed) dosimeters were used to measure the average monthly concentrations of radon.

The detectors were placed in points chosen by the customer, for the period of one month. In the time the measurements were taken, there were a total of 16 measurement points. Systematic measurements of radon concentrations were wrapped up by 2004/2005. After the 10-year measurement cycle, IMP conducted additional radon concentration measurements in 2006 and 2007. The average yearly concentrations were, respectively, 2.24 and 2.53 kBqm^{-3}.

In 1995, the average concentrations were 1080 Bqm^{-3}. In the following years, an increase in the radon concentration was observed. The largest yearly average concentration of radon (3400 Bqm-3) was recorded in the year 2004[38]. The average concentration of radon in a ten-year period is 2200 ± 700 Bqm-3. Figure 3 presents the results of measurements of average yearly concentrations of radon in the Niedźwiedzia Cave.

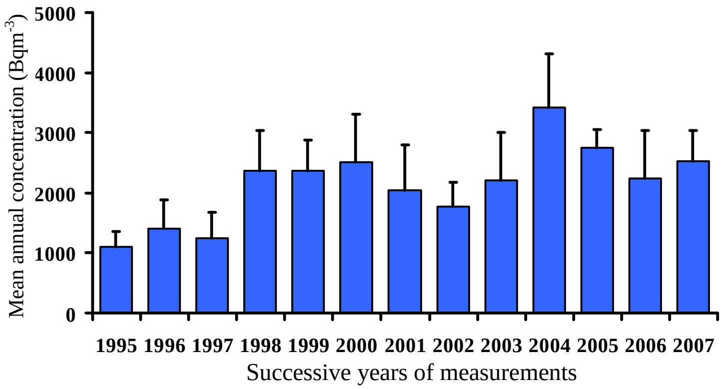

Figure 3. Results of the measurements of average yearly concentrations of radon in the Niedźwiedzia Cave[39,40].

There have been no measurements made in the Niedźwiedzia Cave to determine the individual exposure of workers managing the route. On the basis of the available data regarding the work time of the employees, it is only possible to estimate the dose they may have received. There are about 50 employees working in the cave. The average time spent by a worker, according to the data made available by the management, is 80 hours per year.

Taking into account the work time of the particular workers, and the average concentrations in the last five measurement years (2600±500 Bqm^{-3}), yearly doses have been calculated that may have been received by the workers there. The estimated average dose, assuming the UNSCEAR 2000 average exposure-dose conversion coefficient of $9nSv/Bq \cdot m^{-3}h$. The distribution of the doses is presented in figure 4.

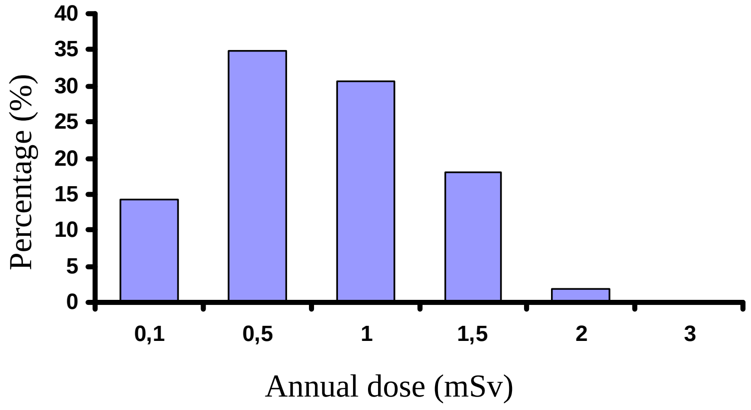

Fig. 4. The distribution of the expected yearly effective doses from radon, estimated on the basis of work times and yearly average concentrations of radon.

It should also be noted that the time spend by the workers in the Cave was relatively short, approximately 4% of the nominal working time in a year. With a significant increase in the work time, yearly doses in excess of 6 mSv should be expected, which means that the workers will belong in the A exposure category. In such a case, individual dosimetry should be introduced.

However, IMP has not made any measurements of radon concentrations in the Niedźwiedzia Cave since 2007.

5.2. Kowary Drifts

The founding and development of Kowary is connected chiefly with iron ore mining and smithing. Oral sources indicate that, in 1148, a Walloon miner named Wawrzyniec Angelus discovered iron ore on the slopes of the Rudnik mountain. 10 years later, acting on the orders of Bolesław the Curly, the Prince of Poland at the time, a settlement was established there. Kowary are situated in the valley of the river Jedlica - in the upper course of the river, between Rudawy Janowickie and the Karkonosze mountains.

Intensive development of the Kowary mining industry took place in the 19th and 20th centuries. It was then that increased extraction took place of iron ore, fluorite, zinc-lead ores, silver, copper and uranium.[41]

Exploitation of uranium ore in Kowary began before World War 2, from the magnetite deposits in the Wolność (Freedom) mine, where 70 tons of uranium in ore form were likely extracted in total. After the war, geological surveys were conducted, whose positive result led to opening the Kowary Mines in 1948. The ZPR-1 facilities were created. The R-1 industrial facilities were very large. They included all mines extracting uranium ores, among them mines from other regions of the country, e.g. in Rudki near Kielce. In Kowary, the management of the mines was situated, as well as a laboratory, a transport base, workshops. The R-1 facilities employed approximately 25-26 thousand people in the years 1948-1972. In the initial time period, all work conducted was classified. It was only in 1956 that Polish specialists were allowed to work there.

Since 1952, due to the advances in thermonuclear technology, the interest in excavating uranium ores with a fissile U-235 isotope content of about 0.7% (in relation to the sum of isotopes) became less attractive for military purposes. In 1957, the last Russian workers left the R-1 facilities. The "Wolność" mine was closed in 1962, after the last exploitable deposits had been depleted. From that time forward, the R-1 Facilities liquidated the mines, which were formally dissolved in 1973.

The mines posed typical mining threats, mainly related to dust produced when excavating and transporting the ore and rocks. There was no official discussion regarding the dangers related to radiation until 1957. In uranium ore mines, there are two kinds of danger related to ionizing radiation. These are: a heightened gamma radiation level, and the high concentration of radon and its derivatives in the air. According to the data at my disposal, the concentrations of radon reached e.g. in the third quarter of 1957, depending on the measurement point, from 18.5 up to 888 kBqm^{-3}.[42] This means that the doses from radon that the miners were exposed to may have exceeded **1 Sv**. After exploitation of the mines was terminated, excavation and exploratory adits remained, as well as heaps of excavated material and other mine-related elements.

It was as early as 1968 that the concept arose of taking advantage of excavation sites after the mine exploitation was terminated. Launching an underground radon inhalatorium (radon galleries) was planned in the former Podgórze mine, based on the inhalatorium in Bad Gastein, Austria. The first inhalation chamber was made available for treating patients in 1974; adit 19 was used for that purpose. In 1975, the concept was posed to use another adit of the

Podgórze mine, namely adit 9. It was to house a mining laboratory for the Mining Institute of the Wrocław University of Technology. Adit 9 also housed an inhalation chamber for about 20 patients. In 1989/1990, the government changes and economic conditions led to terminating all activity in the Podgórze mine, and the closing of the inhalatoriums and the laboratory. The region of adits 9 and 19 lay bare for a few years and gradually deteriorated.

What saved adit 9 and the buildings that had been built therein was the actions of the businessmen from the Wielkopolska region, Marek Jankowski and Wojciech Jabłoński[43]. Their interest in adit 9 resulted in opening, on 29 April 2000, the Underground Tourist Route "Kowary Drifts", and in 2002, the Radon Inhalatorium (radon galleries) was opened. The length of the route available for visitors is 1200 m. Tourists take about one hour to go through the route

From the moment they started executing their plans, the owners of the adit were aware that radon was present at the site, which may have been harmful to the health of the workers there.

It was before the route was opened, in 1999, that measurements were made of the radiological parameters of the environment in the underground adit 9 and 9a in Kowary - Podgórze. This was, of course, what would later become the tourist route "Kowary Drifts". The measurements included the measurement of both the instantaneous and long-term concentrations of radon.[44].

The measurements conducted showed that the presence of radiation in the excavation sites of adits 9 and 9a was mainly due to exhalation of the radioactive radon gas from the rocks, which may lead instantaneous concentration values of up to 1000 Bqm^{-3}, while the average long-term values are stabilized at the level of about 400 Bqm^{-3}, which was confirmed by two long-term measurements.

It was as early as 2000 that, as a consequence of a contract signed with the Institute of Occupational Medicine of Łódź that systematic measurements were conducted of radon exposure in the underground tourist route. The first measurements, for organizational reasons, were made between 2000 and 2001. A quarterly schedule of measurements was adopted. Six guides were included in the individual dosimetry, while environmental dosimeters were placed in 4 points along the route. The average radon concentration that the workers worked in, during the measurement period, was 560±50 Bqm^{-3}; the average radon concentration in the measurement period, measured by environmental dosimeters, was 520±140 Bqm^{-3}.

The measurements of seasonal radon concentrations were conducted in five points along the tourist route, on a quarterly basis. The results of the measurements of the yearly average concentrations of radon are illustrated by figure 5.

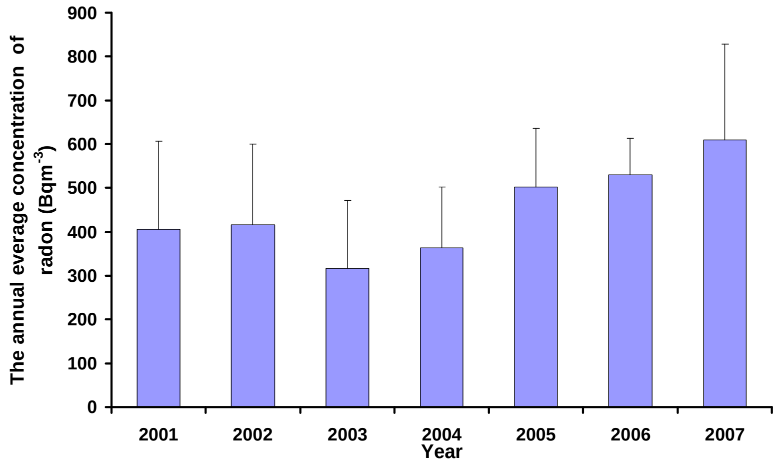

Fig. 5. Results of the measurements of the average yearly concentrations of radon in the tourist route "Kowary Drifts".

The results of the measurements conducted in 2001-2007 have shown that the average yearly concentration of radon in the adit were within the 300 to 600 Bqm^{-3} range. The average five-year concentration of radon was 450 ± 100 Bqm^{-3}.

There was a total of 17 people covered by the control of individual exposure in the years 2001-2007 (guides and service personnel). The distribution of individual doses from radon in this measurement period is presented in fig. 6. The average estimates yearly dose was 0.92±0,37 mSv. The maximum yearly dose of 1.73 mSv was registered in 2002.

Mixed radon exposure measurements were conducted in Kowary Drifts until 2008. Starting with January 2008, the number of measurements points distributed along the tourist route was increased from 4 to 12, and individual dosimetry was dropped.

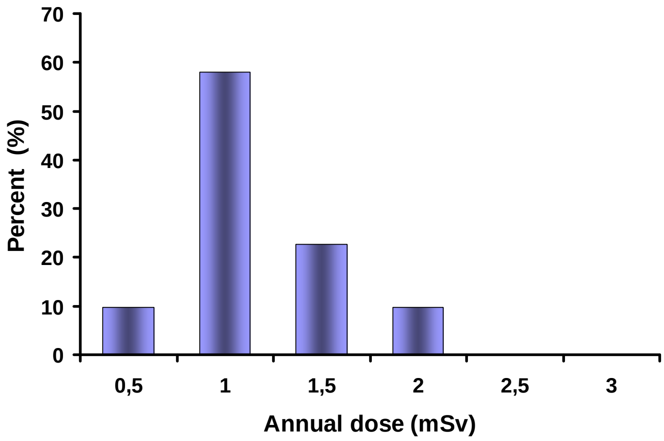

Fig. 6. The distribution of yearly doses for the workers on the tourist route in the years 2001-2007.

Figure 7 presents the measurements of the average yearly radon concentrations for the tourist route and, separately, for the radon galleries the years 2008-2015.

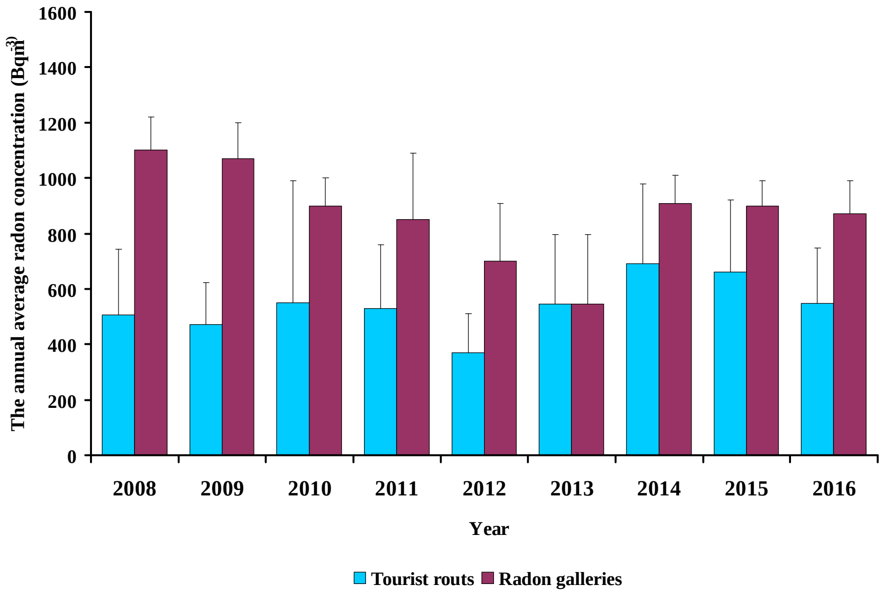

Fig. 7. Average yearly concentrations of radon measured in the rooms of the tourist route and in the radon galleries

The average yearly concentration of radon in the years 2008-2015 was: in the tourist route – 540 Bqm^{-3}, in the radon galleries m: 870 Bqm^{-3}. The highest registered concentration in the rooms of the tourist route was in 2014, at 690 Bqm^{-3}, and in the radon galleries in 2018 - 1100 Bqm^{-3}.

In the year 2010, another expertise was developed regarding radon exposure. The conclusions included as part of the expertise were as follows:

1. The measurements of radon concentrations in the tourist route Kowary Drifts, conducted over the period of many years, have shown that radon concentrations in excess of 1000 Bqm^{-3} should not be expected in the rooms made available for tourists.
2. The workers of the tourist route and the radon galleries should be included in the B[1] category of exposure to ionizing radiation.
3. Constant, long-term measurements should be conducted of the average concentrations of radon in selected points of the route and in the radon galleries.
4. The assessment of worker exposure should be conducted on the basis of environmental measurements as well as work time logs in the corridors of the route and in the radon galleries.

Complementary measurements

In addition to the above-described research in the rooms along the route, control measurements of instantaneous concentrations of radon have been conducted since 2001. Such measurements were conducted in 2001, 2004, as well as in 2010, 2011 and 2012.

The measurements of radon concentrations have been made with the use of scintillation cells.

Instantaneous measurements of radon concentration were conducted in September 2001, in six points along the tourist route. The concentration varied between 210 and 800 Bqm^{-3}, with the average at 380 ± 220 Bqm^{-3}.

Instantaneous measurements of radon concentration were conducted in June 2004, in five points along the tourist route. The concentration varied between 100 and 500 Bqm^{-3}, with the average at 230 ± 180 Bqm^{-3}.

Instantaneous measurements of radon concentration were conducted in July 2010, in fourteen points along the tourist route. The concentration varied between 100 and 890 Bqm^{-3}, with the average at 480 ± 240 Bqm^{-3}.

[1] The B category of radiation exposure means that the worker may receive a yearly dose exceeding 1 mSv, but should not receive a dose higher than 6 mSv, so she or he is not included in the A category of exposure.

The measurements conducted in July 2011 have shown that the range of instantaneous concentrations of radon, measured in the adit, was within the range of 550 to 1300 Bqm^{-3}, with the average value of 790 ± 260 Bqm^{-3}.

Instantaneous measurements of radon concentration were conducted in August 2012, in nine points along the tourist route. The concentration varied between 100 and 620 Bqm^{-3}, with the average at 390 ± 170 Bqm^{-3}.

Figure 8 shows the distribution of radon concentrations, as measured via scintillation cells. These are the so-called instantaneous measurements.

Just like in the case of long-term measurements, the instantaneous measurements have confirmed that:

1. Constant measurements should be conducted of the average concentrations of radon, over long-term periods, in selected points of the route and in the radon galleries.
2. The measurements conducted have shown a correct choice of measurement points for environmental dosimetry.
3. The radon concentrations in the radon galleries are higher than those in the tourist route.

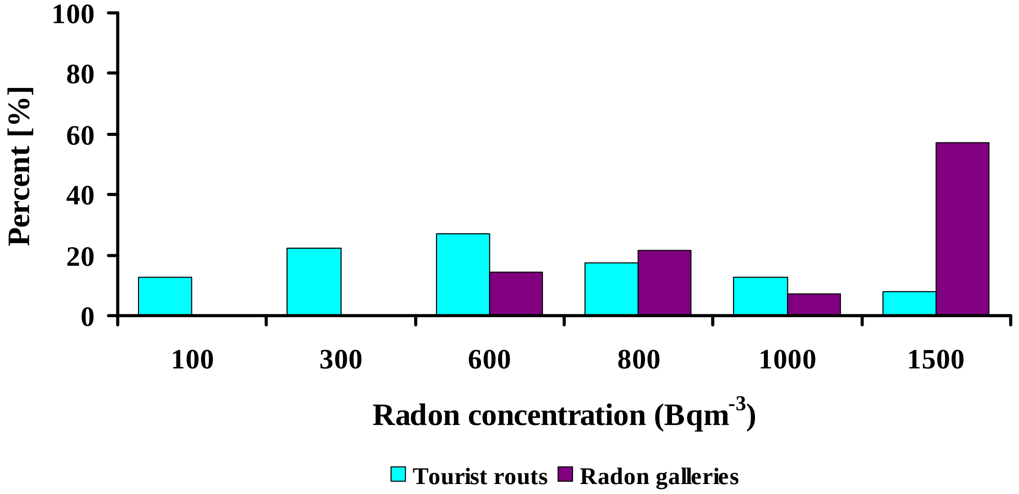

Fig. 8. Distribution of radon concentrations measured in five series of instantaneous measurements, in the years 2001-2018.

The actions described above, related to the presence of radon in the underground tourist route, may be seen as an example to follow for other tourist routes, especially ones in the design phase.[45]

In the years 2004 - 2007 I also conducted research in three underground tourist routes.[46]. The results have been discussed below.

5.3. Underground Tourist and Educational Route „Old Uranium Mine” in Kletno

In 2002, part of the excavation sites of the former uranium mine in Kletno, in the Strona Śląska administrative region, was opened for visitors. The tourists go through mine pavements for the distance of about 200 m, watching visually appealing formations of local minerals (fluorite, quartz and others) as well as a few special exhibitions. The exit is located at the place of a former tunnel inlet.

In the tourist route Kletno, due to its length (200 m), measurements are made in 1/3 and 2/3 of the length of the route, in two-month cycles. Figure 9 presents the measurements conducted in the years 2004-2005. The average concentration in this period was 1500 ± 900 Bqm^{-3}.

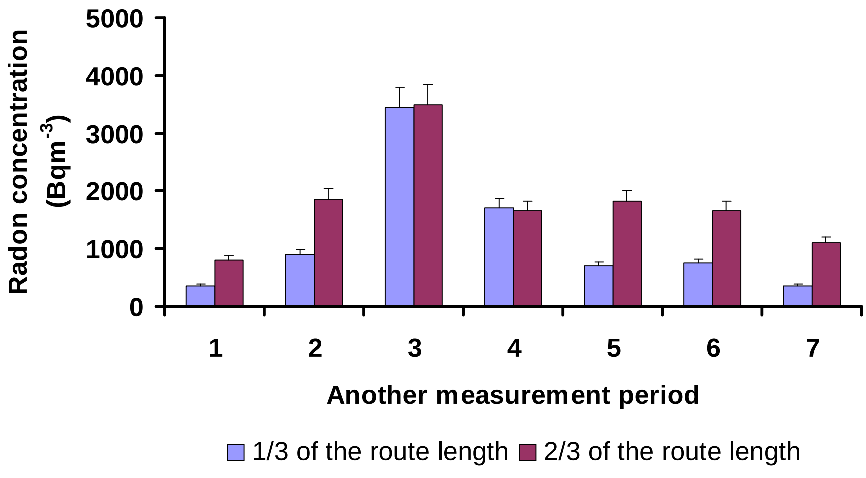

Fig. 9. Results of the measurements of average bi-monthly radon concentrations.

On the basis of the measurements conducted, as well as statistical data regarding work times in the tourist routes, the yearly doses have been estimated that the workers at the tourist route may have been subject to. The average estimated yearly dose was 0.94±0.84 mSv. The distribution of the doses is presented in figure 10.

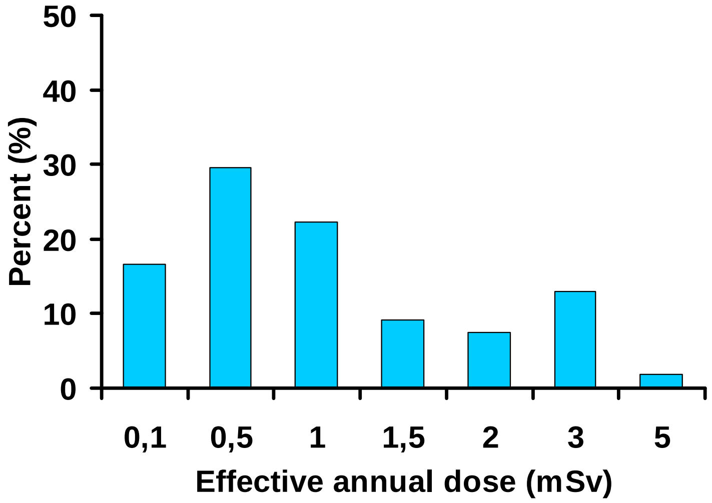

Figure 10. Distribution of the estimated doses in the Kletno tourist route.

5.4. Underground tourist route "Złoty Stok"

The gold mine in Złoty Stok functioned up until 1962, when it was ultimately closed and liquidated, for reasons not fully known today. In May 1996, the Undeground Tourist Route "Gold Mine" was opened, together with the Museum of Mining and Metallurgy in Złoty Stok. Out of the huge maze of about 300 km of underground tunnels, currently two adits are available for visiting. The visiting time is 1.5 hours.

In the tourist route Złoty Stok, measurements of radon concentrations were conducted in monthly cycles, in five measurement points. Figure 11 presents the average monthly measurements of radon concentrations.

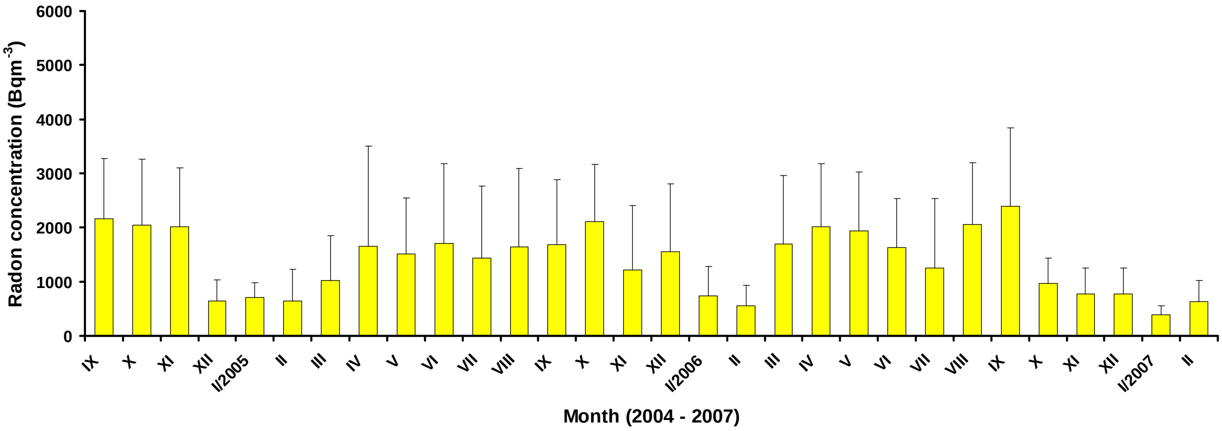

Fig. 11. Average monthly radon concentrations measured in the tourist route "Gold Mine".

The average concentration of radon in 2005 was 1400 Bqm^{-3}. The maximum monthly concentrations were measured in the point called Gertruda–Tama and was equal to 4900 Bqm^{-3}.

Based on the working times and the results of concentration measurements, the doses that a worker employed at Złoty Stok may receive were estimated. The average estimated yearly dose was 0.70±0.60 mSv. Figure 12 presents the distribution of the estimated doses.

1

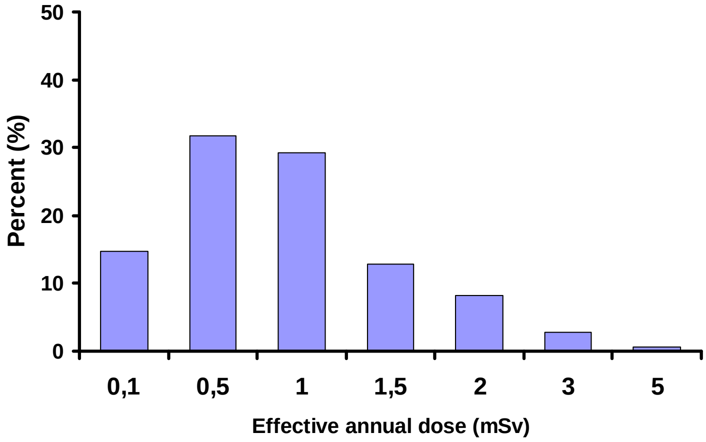

Fig. 12. Distribution of doses estimated on the basis of radon concentration measurements and the working times.

Workers at this tourist routes may receive doses in the range of 0.01 up to 5 mSv.

5.5. Undeground town Osówka in Głuszyca

The Undeground Complex Osówka in Głuszyca is located a little over one kilometer to the north-east of the town of Kolce, and a similar distance north from the Sierpnica town. Work at the site begun in mid-1943, and it resulted in creating a system of a vast system of concrete corridors, reinforced constructions and halls. The purpose of the work was kept secret. Some speculate that the site was meant for a secret headquarters for Adolf Hitler. Osówka is visited by tourists wearing protective helmets, with a guide. The visit takes one hour.

In the tourist route Underground Town Osówka, periodical measurements of radon concentration were performed in four measurement points. The measurements are realized in quarterly cycles. Figure 13 presents the distribution of the measured radon concentrations.

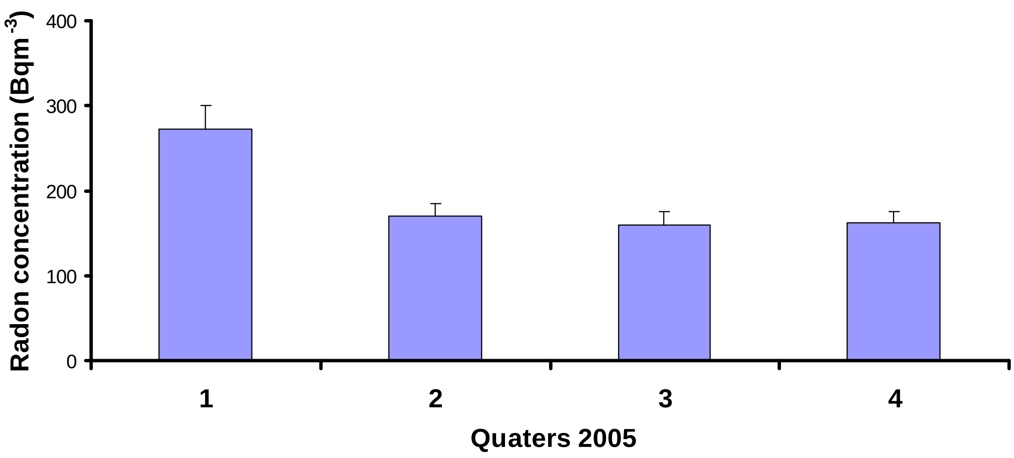

Figure 13. Average quarterly radon concentrations

The average radon concentration in 2005 was 200±100 Bqm^{-3}. Such a concentration of radon means that the workers employed in this tourist route are not in danger of exceeding the yearly dose of 1 mSv.

6. Exploratory measurement in underground tourist routes

In the year 2012, measurements of periodic radon concentrations were conducted in underground tourist routes, using enclosed dosimeters described in chapter 3.

100 tourist routes were chosen for the research, i.e. all the routes included in the book "Guide to Poland. Underground tourist routes" [47]. Out of the 100 selected underground tourist routes, IMP received back the dosimeters placed at 66 routes. In the remaining 34 routes, measurements were not conducted for the following reasons: theft of dosimeters (11 routes), refusal to place dosimeters or dosimeters being sent back with a note "not placed" (14 routes) or lack of information regarding the dosimeters sent (9 routes). 25 tourist routes (caves, grottos) and 41 artificial routes (buildings, mines) were researched. As a result of the research conducted, 259 radon concentrations measurements were obtained.[48]. The arithmetic mean of the results is 1610 Bqm^{-3}, and the maximum concentration measured - over 20 000 Bqm^{-3}. The minimum concentration is determined by the sensitivity threshold of the measurement method[49] and is equal to 100 Bqm^{-3}. The joint results are presented in Table 1.

Table 1. Results of the radon concentration measurements in underground tourist routes.

No.	Type of tourist route	Number of routes researched	Average concentration of radon [Bqm^{-3}]	Maximum concentration of radon [Bqm^{-3}]
1	All	66	1610	20980
2	Natural underground routes	25	1310	4640
3	Caves	21	1390	4640
4	Grottos	4	740	2600
5	Artificial underground routes	41	1720	20980
6	Mines	16	3030	20980
7	Military buildings	15	930	5660
8	Urban buildings	10	590	2460

The radon concentration measurements conducted in underground tourist routs have shown that its presence may pose a real threat to the health of the workers. Figure 14 shows the distribution of average radon concentrations for a given underground route.

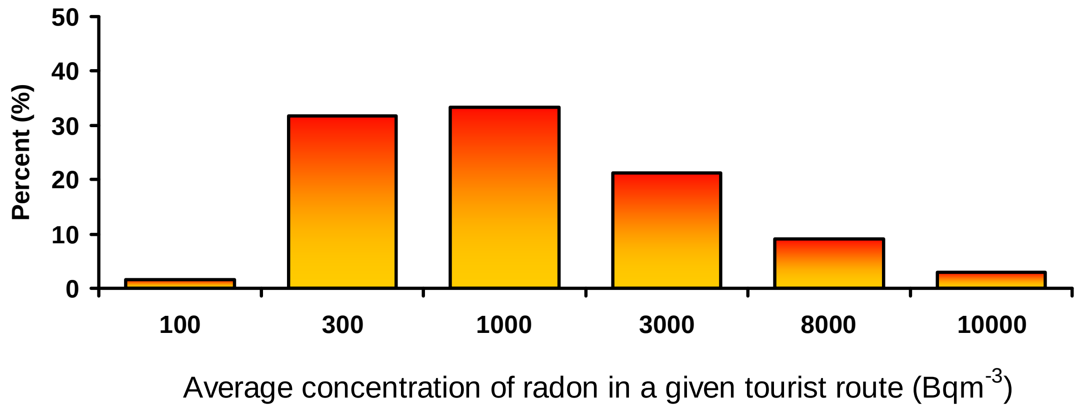

Fig. 14. Distribution of arithmetic mean radon concentrations, as measured for all underground tourist routes.

The arithmetic means of the measurements for the particular routes have shown that the concentration of radon was below the sensitivity threshold in only one of them, while in 67% of the routes, it exceeded 300 Bqm^{-3}.

The research showed as follows:

1. In a substantial majority of the underground routes, the concentration significantly exceeded 300 Bqm^{-3} (reference level proposed by the European Council). In 33% of the routes research, the arithmetic mean of the measured concentrations exceeded 1000 Bqm^{-3}.
2. Radon present in underground tourist routes may pose, for many of them, an organizational and legal problem.
3. An action plan needs to be developed in order to lower the radon concentrations in underground routes, especially those created in former mines.
4. Yearly measurements of radon concentration need to be performed, particularly in the routes where its levels are elevated.
5. The number of underground tourist routes in Poland is systematically increasing (at present, the number is approximately 200). Consequently, measurements of radon concentration need to be continued in newly created routes.

7. Health resorts and SPA

In many Polish spas, mineral waters can be found containing radon of radioactive gas (^{222}Rn). These waters are either bottled or used during balneotherapy treatments (baths, water procedures, inhalations). During all these procedures radon, which is a noble gas, can easily penetrate the environment through natural diffusion. As already mentioned, the presence of radon in the air can cause a threat of ionizing radiation of personnel working in health resorts.

In the years 1977 – 1987, the Institute of Occupational Medicine in Lodz made extensive studies which allowed to determine radon radioactivity hazard in health resort employees. In order to measure the hazard, trace detectors and mining radiometers were used. After completing the measurements, the researchers determined the yearly exposure level in 25 health resort employees[50]. It was revealed that the average exposure in the analysed resorts was 0.31 mJhm^{-3},(0.087 WLM) and maximum – 1.56 mJhm^{-3}. (0.444 WLM).

In later years, in some spas, measurements of radon derived concentrations were continued.

Świeradów health resort is the only place in Poland where the level of radon and radon derivatives concentrations have been systematically measured for many years. The measurements are made with the use of passive dosimeters, installed in a few places of the resort (swimming pool, bathrooms, radon galleries). Dosimeters are placed for one month, four times a year, every quarter. Figure no. 15 presents the distribution of radon concentrations, measured in 2002 – 20018. I analysed 2,000 working hours and the average concentration for the period of 17 years, i.e. results of measurements made between 2002 and 2018. In this way, I calculated yearly doses which Świeradów employees might have been affected by. As before, I adopted the conversion coefficient equal to 9nSv/Bq·m^{-3}h. Roczne dawki skuteczne mogły zawierać się w granicach od 2.2 mSv (2011) do 14,1 mSv (2007). Ze względu na specyficzny system pracy w uzdrowisku oszacowanie dawki skutecznej może być obarczone dużym błędem. Najlepszym rozwiązaniem byłoby wprowadzenie systemu dozymetrii indywidualnej.

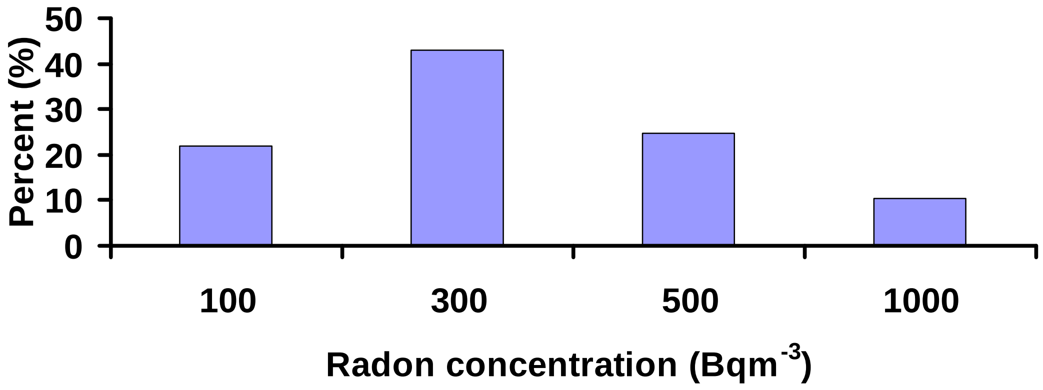

Fig. 15. Distribution of mean monthly radon concentrations measured in 2002 - 2018

Twenty years later, I proposed similar measurements, extending them to all spas (sanatoria).

In the 2007 year, 101 health resorts were each sent 5 passive enclosed dosimeters with a trace detector CR-39. The entire country was included in the research.[51]. Table 2 shows the basic data concerning the research conducted. The dosimeters were exposed for a period of one month. Figures 16 and 17 show the distribution of radon concentrations for all measurements, as well as the averages for a given health center.

Table 2. Basic data regarding the conducted research.

No.	Number characterized	Amount
1	Dosimeters sent to resorts	505
2	Resorts that received dosimeters for research	101
3	Resorts that sent the dosimeters back	81
4	Resorts that did not place dosimeters	5
5	Resorts that took part in the study	76

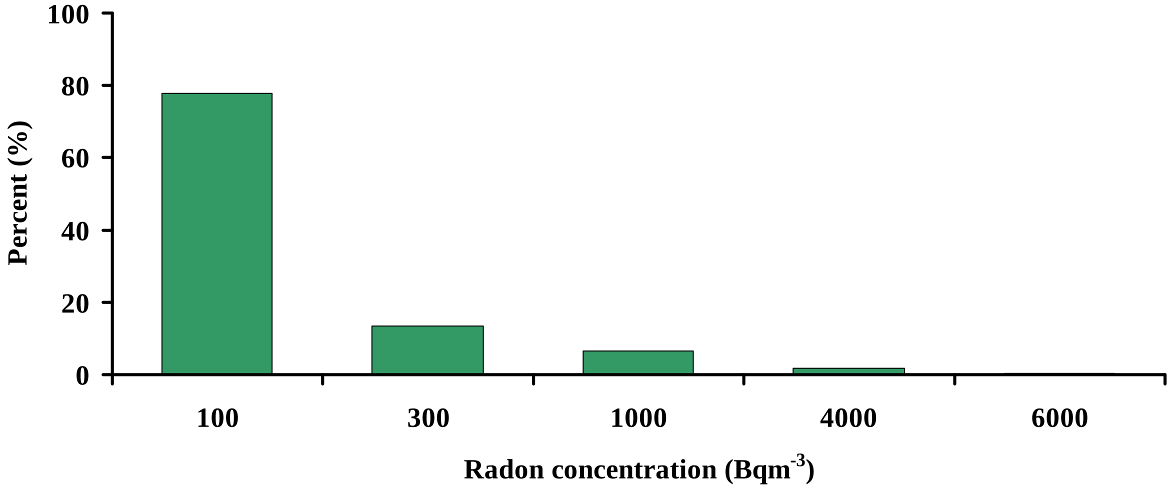

Fig. 16. Distribution of all concentration measurements conducted in the health resorts.

In 63 health centers (83% of those researched) the average radon concentration was below 100 Bqm^{-3}. In these health centers, the problem of radon does not occur and there is no danger posed thereby.

In the remaining health centers, the distribution of concentrations was as follows:

Exceeding 100 Bqm^{-3} was observed in 13 health centers, while in 6 of those concentrations were measured in excess of 300 Bqm^{-3}. A compilation of results for the highest recorded concentrations is shown in Table 3.

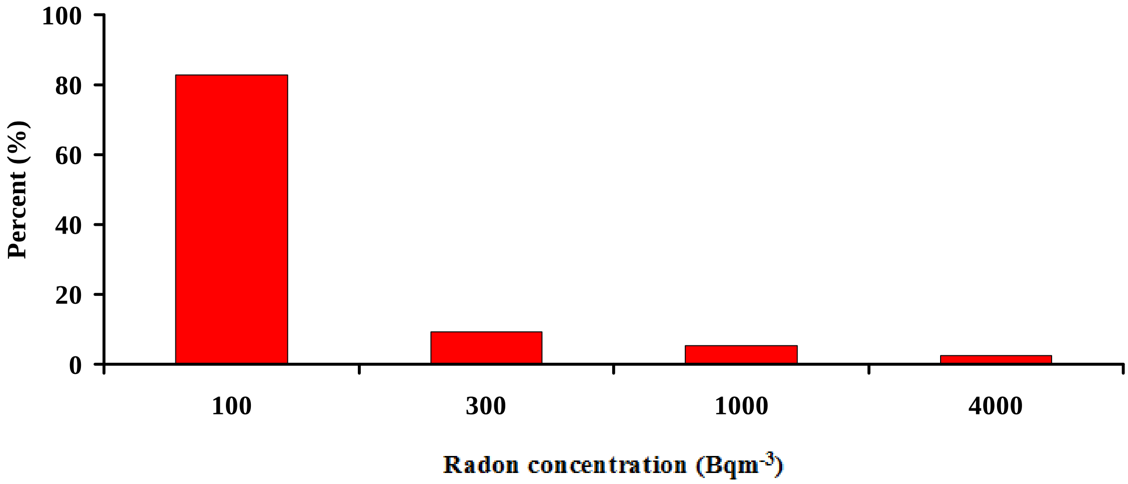

Fig. 17. Distribution of average concentrations of radon measured for the given health resort.

Table 3. Results of the measurements of radon concentration in health resorts where 300 Bqm^{-3} was found to be exceeded.

No.	Name of a resort	Monthly concentration of radon activity in the air (Bqm^{-3})		
		Average	Maximum	Minimum
1	Health resort „Świeradów – Czerniawa” Ltd., Świeradów - Zdrój	3370	13960	350
2	Health resort „Lądek – Długopole” JSC, Lądek Zdrój	900	2180	50
3	Sanatorium spa „Moniuszko”, Duszniki Zdrój	420	530	250
4	Sanatorium spa „Złocień”, Ustroń	290	660	60
5	Spa hospital for Children, Świeradów Zdrój	380	530	300
6	Sanatorium spa „Chemik” non-public medical center, Duszniki Zdrój	180	560	50

Exceeding the concentration of radon in air of 300 Bqm^{-3} may be significant from the point of view of radiological protection, in particular when there is no awareness of a potential danger from radon. Collectively, the problem of radon exposure in Polish health resorts may concern about 160 people.

SPA

In 2013, concentrations of radon were measured above the surface of geothermal waters in 9 Polish SPA resorts that use geothermal waters for recreation and therapeutic purposes (a few SPA did not allow for the measurements to be conducted)[52]. Eight of the researched facilities use geothermal waters in pools or jacuzzi. In one of the resorts, tubs filled with geothermal water are used for therapeutic purposes. The measurements were conducted with the use of Lucas scintillation cells described above. The samples were taken in the areas where workers breathe.

The radon concentration in most measurement points, with the exception of one, was below the lower threshold of detectability for Lucas cells, i.e. 100 Bqm^{-3}. This means that the maximum dose that may be received by the personnel in geothermal SPAs is no higher than 0.6 mSv/year. Only in one of the SPAs researched, the concentration of radon was within the

130 - 530 Bqm^{-3} range, i.e. the estimated yearly dose for workers may be within the 0.8 - 3.4 mSv range.

8. Assessment of professional exposure resulting from exposure to radon in underground tourist routes and health resorts/SPA

A revolutionary approach to the problem of the naturally occurring in nature radioactive gas radon was presented in the European Union Directive COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013 r. It will have substantial social and economic consequences. The first of the changes included in the directive is to make equal, in the legal sense, the exposure to all kinds of radiation present in nature. This means that work that requires being in a place where radon is present in the air and work at a nuclear power plant are equal. There are only three exceptions included in the directive when the directive's rules do not apply. These are: exposure to natural radiation, for example from radioactive nuclides present in the human body, or from cosmic radiation present at ground level; b) exposure of people from the general populace or workers other than those employed at aircraft or spacecraft, to cosmic radiation during the flight or while in extraterrestrial space; c) exposure above the surface of the Earth to radioactive nuclides present in the intact Earth crust.

There are two issues connected to the presence of ionizing radiation (which was discovered more than a hundred years ago).

1. The first issue are the actions taken in order to minimize the effects of radiation, which is to say the broadly understood protection from ionizing radiation.
2. The second is the negative impact on the human body, or the broadly understood illnesses caused by ionizing radiation, from burns to fatal tumors.

8.1. Radiological protection

Radiological protection - it is the prevention of human exposure and environment contamination, and in a situation where it is impossible to prevent such situations - limiting their impact to as low a level as reasonably possible, while taking into account economic, social and health factors.

The goals of radiological protection - prevention of deterministic effects as well as reducing the probability of stochastic effects.

The principles of radiological protection - any amount of radiation is harmful.

One of the important elements of radiological protection is the system of reducing limit doses. A dose of radiation is an amount of energy absorbed by a given object. The limit dose is the value established by regulations that sets the lower limit of the range of unacceptable doses. In radiological protection, the most important are: the effective dose and the equivalent dose.

The effective dose: it is a sum of equivalent doses originating from external and internal exposure, determined while taking into account the appropriate coefficients for organs and tissues, representing the danger to the entire body.

An equivalent dose is a dose absorbed into a tissue or organ T, taking into account the radiation type (alpha, beta, gamma and others).

In short, the limitation system may be described as follows:

Effective doses

1. The yearly dose limit for an employee working with radiation - 20 mSv
2. A worker is included in the A category of radiation threat after a dose of 6 mSv. is exceeded.
3. The dose limit per year for the general populace is 1 mSv.

Equivalent doses

1. The dose limit to the lenses of the eyes of a worker - 150 mSv per year.
2. The dose limit to the skin and limbs of a worker - 500 mSv per year.

The equivalent doses to the lenses of eyes and to the skin are limited for the general populace, as well.

The alignment of exposure to the radioactive gas radon with the exposure to radiation from other sources requires creating an algorithm that allows for the conversion of radon exposure and its equivalents to an effective (equivalent) dose.

When breathing air containing radon and its radioactive derivatives, the process of depositing radon derivatives in the lungs occurs, which results in the irradiation of the cells lining the lungs.

Knowing the concentration of radon daughters or its derivatives at a given time, exposure may be calculated.

The energy concentration of potential alpha radiation C_{α} it is the sum of the energy of the alpha particles which is emitted during the total radioactive decay of 3.7 kBq of short-lived radon derivatives contained in the unit of air volume. The unit of concentration in the SI system is [Jm-3]; The traditional concentration unit is 1 WL (Working Level).

$$1\mathrm{WL} = 2{,}1 \times 10^{-5}\,\mathrm{Jm}^{-3}$$

The unit of exposure to radon derivatives in the SI system is [Jhm-3]; the traditional unit is 1WLM (Working Level Month). The relationship between these units is as follows:

$$1\mathrm{WLM} = 3{,}51\mathrm{mJhm}^{-3}$$

In the case of knowing only the average radon concentrations in which a person resided and the residence time, the exposure can be calculated using the coefficients given in the literature[53]

For example:

Yearly work (2000 hours), with radon present in the air at a concentration of 300 Bqm^{-3} means that the lungs were exposed at the following level: 0.378 WLM.

Yearly living (7000 hours) in an apartment where the average yearly concentrations is 230 Bqm^{-3} leads to exposure equal to 1 WLM.

The information available to the owner of an underground tourist route is the yearly average radon concentration in the rooms of the route, as well as the concentration of derivatives, in the case of individual dosimetry.

The question that needs to be asked is what benefit this information gives to the employer or an inspector of radiological protection; their task is to optimize radiological protection in the workplace. The answer is - no benefit, because as has been said, the radiological protection system is based on the effective dose or the equivalent dose, expressed in mSv. Therefore, a proper exposure-to-effective dose to the lungs conversion coefficient needs to be used. There are no limits regarding the equivalent dose to the lungs. Therefore, all activities should be based on knowing the effective dose.

In order to convert the exposure to radon and its derivatives into an effective dose, the proper conversion coefficients are used. Unfortunately, the coefficients provided by various scientific panels differ, sometimes to a significant extent.

Below is the table No. 4 of conversion factors for publication in the publication ICRP 115[54].

Table 4. Conversion factors for radon exposure to annual effective doses.

ICRP Publication 115

Table 4 Published values of effective dose to an adult male from the inhalation of radon and its progeny calculated using dosimetric models.

Publication	Model type	Exposure scenario	Effective dose (mSv per WLM)	Effective dose [mSv per (mJh/m^3)]
ICRP (1987)	NEA (1983)	Indoors	6.4	1.8
		Outdoors	8.9	2.5
UNSCEAR (2000)	NEA (1983)	Indoors and outdoors	5.7	1.6
Harley et al. (1996)		Indoors and mines	9.6[a]	2.7
Porstendörfer (2001)	Zock et al. (1996)	Home[b]	8	2.3
		Workplace	11.5	3.2
		Outdoor	10.6	3.0
Winkler-Heil and Hofmann (2002)	Deterministic airway generation model	Home	7.6	2.1
Winkler-Heil et al. (2007)	Deterministic airway generation model	Mine	8.3	2.3
	Stochastic airway generation model	Mine	8.9	2.5
	HRTM (ICRP, 1994)	Mine	11.8	3.3
Marsh and Birchall (2000)	HRTM (ICRP, 1994)	Home	15	4.2
James et al. (2004)	HRTM (ICRP, 1994)	Mine[c]	20.9	5.9
		Homeb	21.1	6.0
Marsh et al. (2005)	HRTM (ICRP, 1994)	Mine	12.5	3.5
		Homeb	12.9	3.6

WLM, working level month; HRTM, Human Respiratory Tract Model.

[a] An absorbed dose of 6 mGy per WLM [1.7 mGy per (mJh/m^3)] was calculated for the bronchial region. The effective dose per unit exposure was then calculated with a radiation-weighting factor for alpha particles of 20 and a tissue-weighting factor of 0.08 ($= 2/3 \times 0.12$) for the bronchial and bronchiolar regions of the lung (ICRP, 1993).

[b] Home without cigarette smoke.

[c] No hygroscopic growth was assumed.

How will the use of the coefficient adopted impact actions related to radiological protection?

Assuming the measurements of radon concentrations taken in 66 underground tourist routes as a starting point, as well as the work data of the guides, a probable exposure distribution has been estimated to which the route workers will be exposed. The distribution is shown in fig. 18.

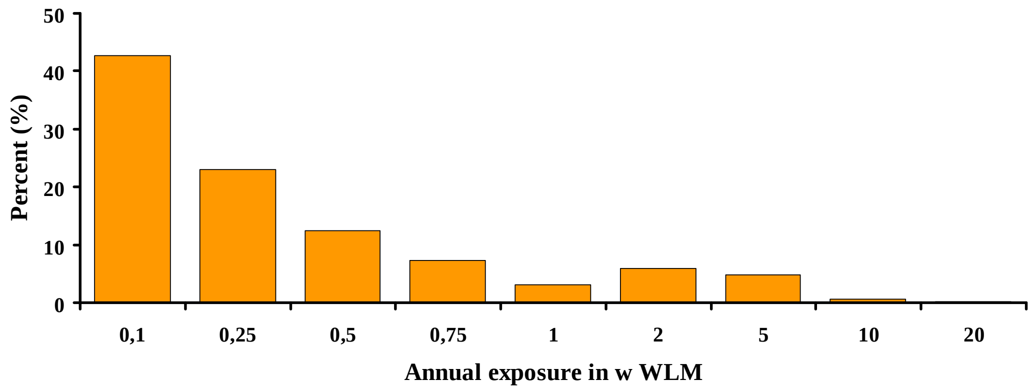

Fig. 18. The distribution of exposure estimated on the basis of measurement data and the information regarding the work time of workers in underground tourist routes.

Let us analyze the impact of the coefficient value on the scope of radiological protection needed to implement in underground tourist routes. Figure 19 presents the distribution of exposure doses for underground tourist routes depending on the coefficient adopted.

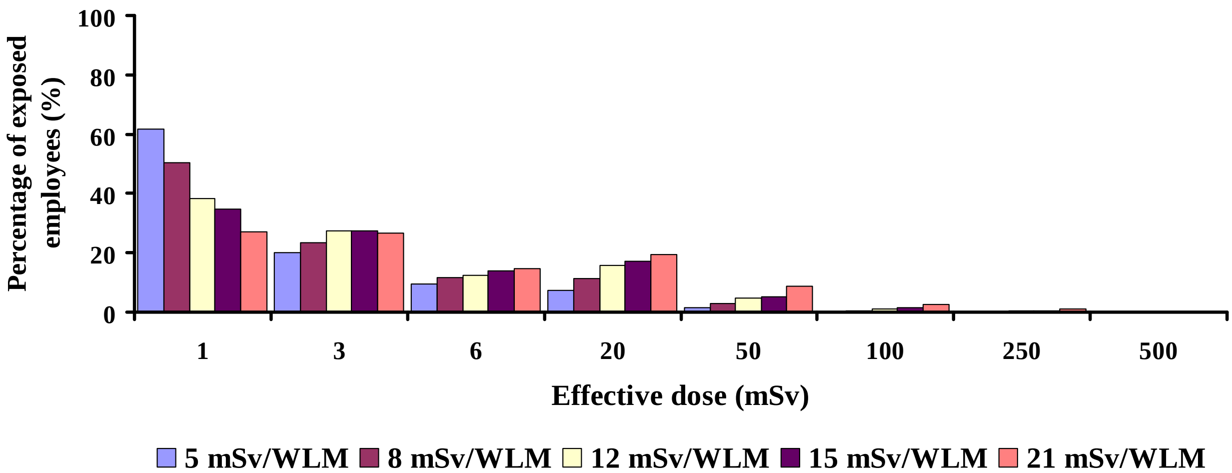

Fig. 19. Distribution of exposure dose depending on the conversion coefficient adopted.

For example, for an underground tourist route where the radon concentrations are within two to three reference levels (from 600 to 900 Bqm^{-3}), the workers in the route, depending on the conversion coefficient adopted, may be included in the B or A exposure category of radiation exposure. From the point of view of radiological protection, this entails specific financial and social consequences.

In light of the above, what coefficient should be used?

Radiological protection in light of new ICRP directives

After about a year since the 126 ICRP publications were made available during the meeting of the ICRP Main Commission (13-17, 2015 – Sydney, Australia), it was suggested that one conversion coefficient be suggested regarding the exposure dose.[55] And so, according to the present recommendations, 1 WLM exposure (3.4 $mJhm^{-3}$) will result in receiving a 12 mSv dose.

Figure 19 shows, among others, the distribution of exposure doses for a coefficient of 12mSv/WLM.

As the above graph indicates, there is, for the coefficient proposes, a possibility of exceeding the yearly dose limit (20 mSv) by more than 6% of the workers, or even the five-year dose (100 mSv).

It is why it is such an important issue that needs to be solved before the recommendations of the Directive are implemented, to assume one (maximum 2) mSv/WLM coefficients for the purpose of realizing radiological protection related to the presence of radon.

The alignment, regarding radiological protection, of work in the presence of radon with work with radioactive elements entails other, quite surprising, issues, particularly for the workers and owners of underground tourist routes.

As has been mentioned, radiological protection is an entire system of actions whose purpose is to provide the safest possible work with ionizing radiation emitted by radioactive elements (radium, radon, cesium, cobalt etc.) or equipment emitting such radiation, for example X-ray lamps.

One of the important elements of radiological protection is the so-called supervised area and controlled area. According to the provisions of the Nuclear Law:

1) Controlled area is an area where there is a possibility of receiving doses defined for A-category workers; there is a possibility of spreading radioactive pollution; or, there may be large changes in the power of a dose of ionizing radiation;

2) Supervised area is one where there is a possibility of receiving the doses defined for B-category workers, and which have not been designated as controlled areas.

In light of the above, what is the situation in underground tourist routes? By analyzing the data received as part of the above-described comparative research, it is possible to establish that controlled areas need to be introduced in 14 of the routes. The consequence of introducing a controlled area is: the need to mark with warning signs, limit access through the use of gates, locks, etc. Individual controlled dosimetry should be introduced in the controlled areas, and the employees should be covered with specialist medical examinations.

And one more aspect of the new radon regulations.

Until now, exposure to radon has been treated in a rather carefree manner. It was assumed that in Poland - as in many European countries - exposure from natural sources constitutes 73.6% of total radiation exposure, and expressed as so-called effective dose - is about 2,433 mSv / year. The largest share in this exposure has radon and its decay products, from which a statistical inhabitant of Poland receives a dose of approximately 1,201 mSv / year. It should also be noted that the exposure of a statistical inhabitant of Poland to natural radiation sources is about 1.5-2 times lower than the population of Finland, Sweden, Romania or Italy.

Exposure of a statistical inhabitant of Poland in 2015 from radiation sources used for medical purposes, mainly in medical diagnostics including x-ray examinations and in vivo tests (ie administration of radioactive preparations to patients), is estimated at 0.860 mSv. This dose consists mainly of doses obtained in the studies in which computed tomography (0.33 mSv) and conventional radiography and fluoroscopy (0.38 mSv) were used. For the annual report of PAA President for 2017.[1]

As if that was not enough, in January 2018 a summary of the ICRP recommendations for radon appeared. The publication ICRP 137[56] quoted in this publication. Occupational use of radionuclides: part 3.

The study concludes that, although radon protection is mainly based on the measurement and control of exposure levels, estimated doses are required for workers in certain situations. Dose estimates have value for protection purposes when employees are exposed to more than one source of radiation, as is the case for underground miners. In addition, estimated doses are required to estimate the sources of population exposure. In addition, conversion factors for underground tourist routes have been provided. And so it was found that: in the case of tourist caves and workplaces in rooms where employees are expected to spend two thirds of their time in motion, the dose rates are 6.7 and 5.7 mSv per $mJhm^{-3}$, respectively.

Let us come back to the above analysis of the influence of the coefficient value on the scope of radiological protection necessary for use in underground tourist routes. Figure 20 shows the distribution of the exposure doses for the coefficients given in the publication ICRP 137.

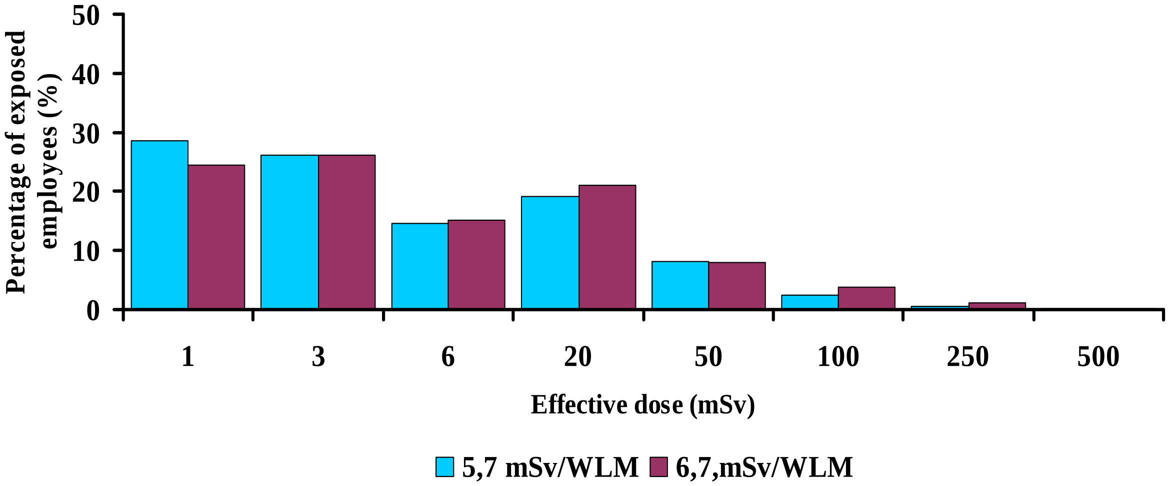

Fig. 20. Distribution of effective doses that can be obtained by employees of underground tourist routes for coefficients from ICRP publication 137.

As can be seen from the above, the development of appropriate legal provisions will be a very important element regulating the conduct of underground tourist routes. These regulations must regulate the procedure both when starting new routes and during their normal operation. The regulations will require both a system of work in underground routes and a system of controlling exposure to radon for both employees and tourists. Legal regulations will have to take into account the fact that employees of underground tourist routes will be counted among employees working with radiation. Therefore, provisions regarding radiological protection should apply, as in the case of nuclear medicine, for example.

The radiological protection system in the case of radon should be able to flexibly adapt the requirements to a specific tourist route. Of course, the general rules must be kept, and they are:

1. Workers of underground tourist routes are professionally exposed to ionizing radiation

2. Depending on the severity of the hazard, employees should be classified as A or B exposure to radiation

3. Workers will be subject to control of individual doses depending on the category of exposure.

4. Workers of underground tourist routes are subject to medical

The system for launching underground tourist routes must also be legally regulated. This system must strictly enforce specific activities consisting, among other things, in recognizing the concentrations of radon present in a given tourist route. The principles of conducting measurements and assessing the degree of exposure to radon must be developed. The scope of the procedure must be regulated depending on the results obtained and the type of touristic route. In the case of spas or SPA, legal regulations will apply to a similar extent as employees of underground tourist routes in addition to elements of health care regulations.

8.2. Health deterioration risk due to exposure to radon

The second issue related to the presence of radon and its impact on the human body is the risk of inducing cancer, and consequently, of death.

Including radon among the factors resulting in occupational risks will also entail changes in the duties and behavior of the employer.

Information regarding occupational risks is a very important part of any employment relationship. The employer is required to inform the workers (before the work begins) about the dangers present in the positions in question. The purpose of risk assessment is not only to ensure safety in the workplace, but also to prevent work accidents and occupational diseases of those employed.

Definition of occupational risk

The Ministry of Labor defines **occupational risk** as the probability of occurrence of undesirable events (danger) related to the job performed and resulting in losses, as well as their impact on the health or life of the workers, in the form of occupational diseases and work-related accidents. This means that the **occupational risk** is no different from the danger the worker faces as part of performing their duties.

Occupational risk assessment

According to the regulations of the Labor Code, the employer is required to assess and document **occupational risk** related to the workers performing their duties, as well as to taking the necessary prevention measures in order to neutralize the dangers. When conducting **occupational risk** assessment, all environmental factors need to be taken into account that occur as part of work in a given position. It is because the main goal of occupational risk assessment is to protect the health and lives of those employed.

The State Labor Inspection has specified 5 principles of conducting occupational risk assessment in workplaces, that is:

1. Collecting information needed to conduct **occupational risk** assessment;
2. Identifying the dangers. Defining the dangers present for every position;
3. Estimating the risk;
4. Determining the actions eliminating or reducing the **occupational risk**;
5. Documenting the results of **occupational risk** assessment

The legislator does not specify who is permitted to examine and assess the risk. The duty of keeping documentation is put on the employer. As a result, every person conducting economic activity and employing workers that is not required to create a Health and safety service, is allowed to conduct **occupational risk** assessment on his or her own.

Information about occupational risk

The employer's duties include **informing the persons they employ about the risk present in a given position**, as well as about the rules of protection against the risk.

The above explanation shows that, after the provisions of the Directive are implemented, employers whose workers have contact with radon will be given a number of additional duties. One of the most important will be to assess the occupational risk related to the presence of radon.

Risk has always been, for as long as civilization exists, connected to human action, both individual and working in larger groups. It was as early as 3200 BC, in the Tigris and Euphrates valley, that a group of people existed called Asipu, who counselled people who took risky, uncertain and difficult decisions. The Greeks and Romans watched causal relationships between the environmental conditions and the state of health. In the 4th century

BC, Hippocrates saw the risk to humans resulting from external conditions. In the 1st century BC, Vitruvious has discovered the toxicity of lead.[57]. In mid-20th century it was determined that it was not radon itself, but its short-lived derivatives, forming radioactive aerosols together with the dust in the air that are deposited in the lungs, that was responsible for the incidence of lung cancer.[58,59,60]

The impact of ionizing radiation on biological systems may lead to stochastic and deterministic effects. The stochastic effects are changes in the particular cells. They may result in malignant neoplasms or hereditary (genetic) changes present in the offspring. On the other hand, deterministic effects occur only after a certain threshold dose is exceeded. These are irreversible changes in the tissues and organs that may lead to their inability to function properly (temporarily or permanently), in extreme cases leading to the death of the irradiated organism.

The stochastic effects of ionizing radiation may be described using the following terms:

1. Relative Risk (RR) is defined as RR=O/E where O – number of cancer occurrences observed in the population surveyed, and E is the number of expected cancer occurrences in the population if the population had not been exposed.
2. Extra Risk (ER) defined as ER=O-E
3. Excess relative risk: ERR= RR-1 = (O-E)/E

Microrisk - is the risk of one death per million inhabitants as a result of performing (by every person out of the million) the same, specified action. Such a microrisk will appear when anyone performs a regular action, such as smoking one cigarette.

The risk of inducing lung cancer as a result of breathing in radon and its derivatives.

The most important epidemiological research regarding people exposed to ionizing radiation as part of their professional work are concerned with exposure to radon (^{222}Rn) and its short-lived fission products (RaA, RaB, RaC’, that is to say ^{218}Po, ^{214}Pb, ^{214}Po). It was as early as 16th century that high death rates were observed among the miners in the Schneeberg i Jachymowa (Rudawa) mines, due to lung cancer.

The source of over ninety percent of the equivalent dose to the respiratory organ of a human is the alpha radiation ^{218}Po, ^{214}Po. The dominant part of decay products of Rn is absorbed in the dust particles present in the mine atmosphere, which are stopped when breathing in approximately 30-40% in the bronchi, bronchioles and pulmonary vesicles. These nuclides, in the form of free ions (the so-called fraction unconnected to aerosols) are stopped almost entirely in the bronchial tree. The largest dose of alpha radiation is absorbed in the epithelium covering the large bronchi (bronchial, segmental) and it is where usually - but not exclusively - malignant tumors of the respiratory system develop after many years (lung cancer).

The death rate due to lung cancers in miners exposed to large concentrations of radon and its derivatives in mines extracting uranium and other metals, as well as other types of minerals, has been followed closely for the last several dozen years in many countries.

The common occurrence of radon means that not only miners are endangered by its effects, but also the inhabitants and workers who are employed in other underground places, such as tunnels or underground tourist routes.

In the 115 ICRP publication, the results of epidemiological research have been shown. Three common analyses are presented that were conducted on the basis of data from Europe (Darby et al., 2005), from North America (Krewski et al., 2005, 2006), and from China (Lubin et al., 2004). Each of the particular analyses has shown that the risk of lung cancer increases with accumulated exposure at home to radon. The exposure time in North America and China was at least 30 years before the diagnosed lung cancer, and 35 years between the diagnosis for Europeans. In each study, the concentration of radon was estimated 5 years before the cancer was detected. It was assumed that the minimum induction time of the cancer was 5 years, on the basis of the data from studying underground miners (NRC, 1999). And so: the estimated raised relative risk of contracting lung cancer with multi-year exposition to radon at 100 Bqm-3 concentration is, for Europe (Darby et al., 2006) 1.08; for North America (Kreaski et al., 2006) 1.10; and for China (Lubin et al., 2004) 1.13.

On the basis of the analysis results of the European data it was determined that continuous smoking of cigarettes means that the risk of lung cancer emergence is approximately 25 times higher than the risk for non-smokers. (Darby et al., 2006).

A very interesting analysis of the effect of radiation on the human body is presented in the publication by DM Parkin and SC Darby titled: „Cancer in 2010 attributed to the effect of ionizing radiation in Great Britain"[61] The presented estimation implies that in 2010, there were 5807 instances of cancer diagnosed, of which 1170 are spontaneous cancer (not caused by radiation, 1861 resulted from radiological diagnostics, 1380 from using radiotherapy, 19 were caused by nuclear medicine, and 1376 were caused by radon.

As the above shows, with long-term exposure to radon, its negative effects can be expected, in the form of induced cancer. Poland, fortunately, is not among the areas with particularly heightened radon concentrations, however its occurrence and impact on the human body may lead to an increase in deaths due to lung cancer.

The measurements I have conducted in previous years in health centers and SPAs, non-ferrous metal mines and residential buildings have shown that yearly concentrations not only exceed 100 Bqm^{-3}, but in many cases the reference level, which is to say 300 Bqm^{-3}.

In non-ferrous metal mines the measurements of radon concentrations have been conducted by the Institute of Occupational medicine for many years. Based on the measurements in the year 2010, the exposure of miners was estimated in four non-ferrous metal mines.[62]. And so, in the years 1998–2009, the average effective dose was 2.1 ± 0.9 mSv. In the years 2010-2015, the yearly average radon concentrations in the controlled mines were from 300 to 800 Bqm^{-3} [63]

In residential buildings in the city of Łódź, the measurements of radon concentrations have been conducted by the Institute of Occupational Medicine three times:

1. In the period of 01 July 1998–31 December 2000, as part of the subject „Analysis of the viability of radon exposure assessment using the measurement of ^{210}Pb lead content in adits", project no.: 4P05D 069 16 (Committee of Scientific Research).
2. In 2005, as part of celebrating the World Physics Day 2005.
3. In the period of 01 March 2008–01 March 2009, as part of the subject „Seasonal changes in radon concentrations in residential buildings", realized by the Medical University of Białystok, application no. N N506 1127 33.

The conducted measurements of average periodical concentrations of radon in residential buildings in Łódź have shown that the average yearly concentration of this element in 1998/1999 was at the level of 91 Bqm^{-3}, and in 2008/2009 it was at the level of 75 Bqm^{-3}. The average half-year concentration in 2005 was 52 Bqm^{-3}. As a curiosity, it may be noted that in two cases, the yearly average radon concentration exceeded 100 Bqm^{-3}. [64]

The measurements of radon concentration in Łódź using Pico-Rad. were also conducted by the University of Technology of Łódź the years 1988-199l.[65]. The average concentration in the measured 486 apartments, located at the ground floor and the first floor, was 23.4 Bqm-3. The maximum measured concentration was 170 Bqm^{-3}.

The above-mentioned research, conducted as part of the grant realized by the Medical University of Białystok, allowed for an estimation of the range of variation of radon concentration in buildings located all over Poland. The measurements have shown that the concentration of radon is higher than thought before in residential buildings. The average concentration of radon in Poland was 170 Bqm^{-3}, and the highest values of average yearly radon concentrations were recorded in buildings located in the Sudety mountains (850 Bqm^{-3})[66].

On the basis of this research, coefficients have also been developed allowing for the conversion of average monthly concentrations of radon in apartments into yearly average concentrations, which should be used when creating a radon map of Poland.[67]

Of course, there are other areas that are hardly recognized in respect of radon presence, e.g. kindergartens or schools. For example, the radon concentration measurements taken in 2011, in kindergartens in Kalisz and Ostrów Wielkopolski have shown that the average radon concentrations are below 100 Bqm^{-3}, (respectively 46.0 and 48.9 Bqm^{-3}); however, the maximum concentrations were 194 and 219 Bqm^{-3}.[68]

The data presented above implies that the radon problem should not be disregarded. In the case of carcinogenic assessment, it is important to know the coefficients allowing the calculation of the probability of inducing cancer depending on exposition to radon and its derivatives.

It was in this case as well that various scientific commissions suggested various approaches towards calculating the risk of inducing cancer, basing on the same or different cohorts of people exposed to the influence of radon. The importance of risk factors is larger for the general populace than for a single person.

The table below shows various risk factors, calculated for three models. The below Table 5 is included in the ICRP 65 publication.[69]

Table 5 Excess lifetime relative risk and lifetime probability of fatal lung cancer for the 'Male Reference Worker', attributable to chronic occupational exposure to radon (^{222}Rn) progeny from age 18 to 64 (baseline risk $R_o = 0.042$)

		Projection model[a]		
Risk quantity	Annual exposure mJ h m^{-3} (WLM)	PRR model ICRP 50 (1987)	TSE model BEIR IV (1988)	TSE model GSF (1992)
Excess relative risk	3.5 (1.0)	0.35	0.29	0.31
	7.0 (2.0)	0.68	0.56	0.62
	14.0 (4.0)	1.33	1.12	1.19
Excess absolute risk	3.5 (1.0)	0.015	0.012	0.013
	7.0 (2.0)	0.029	0.024	0.026
	14.0 (4.0)	0.056	0.047	0.050

[a] The excess relative risk coefficients underlying these models have been modified by a factor of 0.83 from the original values used in the models (see text).

Table 6 below shows the risk factors provided in ICRP publication 115.[54]

Table 6 Summary of excess relative risk (ERR) per 100 working level months (WLM) published from combined analyses of miner studies.

Reference	No. of cohorts	No. of miners	Person-years	ERR per 100 WLM	SE	95% CI
ICRP (1993)	7	31,486	635,022	1.34		0.82–2.13
Lubin et al. (1994)	11	60,570	908,903	0.49		0.20–1.00
NRC (1999)	11	60,705	892,547	0.59	1.32	
UNSCEAR (2009)	9	125,627	3,115,975	0.59		0.35–1.00
Tomášek et al. (2008)	2	10,100	248,782	1.60		1.00–2.30

SE, standard error; CI, confidence interval.

As can be seen from the above, it is not easy to define one risk factor, and the problem is further complicated by the synergic impact of cigarette smoking on the incidence of lung cancer.

To illustrate the problem, below is presented an analysis of the impact of radon exposure of workers employed in underground tourist routes. The analysis used the BEIR VI **(Biological Effects of Ionizing Radiation IV).**

The analyses were conducted on the basis of radon concentration measurements taken in underground tourist routes. The equivalent doses to the lungs, and the relative risk (RR), the lung cancer incidence among the workers in the selected tourist routes in Poland, were determined on the basis of the measured radon concentrations and the information regarding work times in those concentrations.[70]

A short summary of the research conducted in the underground tourist routes in Poland is as follows: in 98.5% of the researched Polish underground tourist routes, the average concentration of radon exceeds 100 Bqm^{-3}, in 67.7% it exceeds the reference level 300 Bqm^{-3}, and in 1.5% it exceeds 10 $kBqm^{-3}$. Among the 66 routes researched, only 31 employed workers.

The equivalent doses to the lungs of the workers in the tourist routes were calculated using the coefficients calculated by et al., in relation to the human model of the respiratory system. The coefficient of equivalent dose to the lungs from radon was calculated as equal to 8.95·10-5 (mSv·m3)/(Bq·h), (dose coefficient to the lungs =35,8 mSv/Bq·h, taken from [Kendall] (Table 2), was converted to 1 Bq/m3 and 1 h/year)[71]. The relative risk (RR) is the ratio between the probability of lung cancer occurrence in the people who were subject to the influence of the sum of natural and professional exposure to radon, to the probability of contracting lung cancer among the people who had no professional risk. The relative risk of contracting lung cancer was calculated using the model created by the BEIR VI committee **(Biological Effects of Ionizing Radiation IV)**[72].

This model is based on the total exposure to radon and its derivatives, expressed as WLM (in the SI system, 1 WLM = 3.51 $mJhm^{-3}$ of exposure to radon and its derivatives). The model assumes that other factors have a varied impact on the increase of relative risk of contracting long cancer from radon exposure - the risk is lowered with longer time since exposition and increases with age. The model by the BEIR IV committee was selected, because it does not assume the risk to be dependent on cigarette smoking, and our research did not include an analysis of risk dependence on smoking. According to the model it was assumed that exposure received during the previous 5 years before the analysis does not increase the risk of contracting lung cancer. The model defines various exposure time intervals before dying of cancer, and as such, the sum of exposure from radon is the sum of exposure in three time windows: 5-14, 15-24, and 25 years or more, before reaching the current age (that is w5-14 means the average exposure received in the period between 5 years before reaching the current age, and 14 years before reaching the current age). The model is as follows:

’ $$RR = 1 + \beta(w_{5-14} + 0.78w_{15-24} + 0.51w_{25+})\theta_{age}\lambda_z$$

where

- β is the slope factor of the exposure-risk relationship (β=0.0768); w5-14 , w14-25, w25+ show the sum of exposure to radon (expressed in WLM) received in the time period of respectively 5-14 years, 15-24 years and 25 years or more, before reaching the current age. The values before each 'w' in the first equation are the parameters taken from BEIR VI for the exposure-age-concentration model (Table 3-3). WLM includes the sum of exposure to radon in both: the workplace (the worktime is between 40-2200 hours/year, and depends on the policy of each underground route), at work (5000 hours in the concentration of radon estimated at 100 Bq/m^3) and outside (number of hours reduced by the time spent at home and at work; it was assume that the concentration of radon outside is 10 Bq/m^3);
- θ_{age} is a factor dependent on the age reached (its values are as follows: $\theta_{age<55}$=1. $\theta_{age55-64}$=0.57, $\theta_{age\ 65-74}$=0.29, $\theta_{age\ 75+}$=0.09)

and

- λ_y represents the exposure level (λ_y=1).

All calculations of relative risk assumed that the age of workers is no higher than 64 years.

In order to estimate the efficient doses received by people employed in underground tourist routes, the dose conversion factor was used proposed by the International Agency of Atomic Energy in report no. 331[73].

The dose distribution for the workers in underground tourist routes is as follows:

In 13 routes, the effective dose was over 1mSv/year (n = 161 people). In three routes, the effective dose exceeded 6 mSv/year (n = 27 people).

In 5 routes (34 workers) the equivalent dose to the lungs was over 100 mSv/year, and in once case it was as high as 490 mSv / year (3 people).

Among all the analyzed tourist routes, in 22.6% of the cases the relative risk factor RR after 40 years of work (average value for each route) was higher than 2.

In one case, RR reached as high as 5.2 (radon concentration - 6790 Bq·m3, work time at 800 h/year).

This means that in 22.6% of the workplaces discussed above (56 workers), the risk of contracting lung cancer among the workers is approximately twice as high as that for an average person living in Poland, and in the case of one tourist route (3 workers), it is 5 times higher.

Statistical data indicates[74] that within 40 years, approximately 2.2% of the population of Poland will contract lung cancer. It can be estimated that within 40 years of professional life, approximately 31 out of 1400 people (1400 - our estimate of the number of workers in the underground tourist routes) will develop lung cancer. The analysis of relative risk leads to the conclusion that in this 31-people group, 42.3% of cases of lung cancer (13 people) would be caused by radon exposure.

To sum up, the relative risk of contracting lung cancer is higher for people working in underground tourist routes, compared to the general population. The workers in underground tourist routes should be monitored from the point of view or radon exposure.

The measurements taken in health resorts and SPAs have shown that in only seven cases there are concentrations in excess of 300 Bqm^{-3}. At the same time, there are concentrations exceeding 1000 Bqm^{-3}. When conducting a similar exposure analysis, it can be estimated that in 40 years of professional life, among those health resort and SPA workers there would be one case of lung cancer caused by radon exposure.

9. Summary

The analysis presented above has shown that ubiquitous presence of radon in underground tourist routes may cause a problem from the organizational, legal and health perspective. Currently, steps are being taken in order to make Polish law conform to international norms. It is especially important to implement executive rules, with special attention paid to the problem of underground tourist routes. As we know, underground tourist routes can be divided into artificial and natural ones. The drafted regulations must take into account these specific features of the routes. The Nuclear law will (likely) include the provision that the reference level for concentrations of radon present in underground workplaces shall be 300 Bqm^{-3}.

Reducing the level of radon concentration in artificial hiking routes can be achieved by damaging the places from which radon flows or increasing the ventilation of the routes. What problem may be the uncontrolled opening of underground tourist routes, let us show the following example.

Podgórze Mine - tourist route in a former uranium mine

The Podgórze Mine was one of the first uranium ore mines collectively known as the so-called Kowary Mines. The mine operated in the years 1950-58. Uranium ore was excavated in the main fault area as well as its branches, mainly in intersection points with the main layer and secondary layers of shales. The deposit reached 529 m in depth. The mine was ventilated with fresh air and, if necessary, with a ventilation duct[75].

The dangers posed by mines were not discussed much in that time period, but e.g. measurements of radon concentrations were, in fact, performed. The first measurements showed that the radon concentrations exceeded 3 MBqm-3. After ventilation systems were introduced, the concentration at excavation sites was constant at a 370 kBqm^{-3} level. The Podgórze Mine was closed in 1958. In 1974, an inhalation chamber was opened in adit 19 of the Podgórze Mine. In the late 1980s, the therapeutic activity at the Podgórze site was terminated. The entrance to adit 19 and 19a was protected from entry by trespassers.

In 1995, as part as realizing the research subject 0837/S4/93/04, a measurement of radon concentration was taken at the exit of adit 19[76]. The result, 50 kBqm^{-3}, confirmed the presence of high concentration of radon in the mine.

In 2009, an attempt was made to launch an underground tourist route in adit 19. However, it was only in 2011 that the Institute of Occupational Medicine was commissioned to measure the concentrations of radon in the mine's excavation sites. The average measured concentration in the route was 30.7 kBqm^{-3}, and the maximum concentration measured in the so-called "feast hall" was 60.3 kBqm^{-3}. Unfortunately, the site's managers ignored the presence of radon and did not install the appropriate fans. It was only after getting acquainted with the measurement results that they installed a fan pushing fresh air into the adit.

The measurements were repeated in November of the same year, after the fans were installed. The results were relatively satisfactory. The average concentration in the adit was 8.3 kBqm^{-3}, and the maximum was 10.4 kBqm^{-3}. In April of next year, the measurement results were satisfactory as well. The average concentration in the adit was 3.0 kBqm^{-3}, and the maximum was 8.9 kBqm^{-3}. In September 2011, one more cycle of measurements was taken. The average concentration in the adit was 2.9 kBqm^{-3}, while the maximum was 4.4 kBqm^{-3}. Unfortunately, reaching such a concentration required turning on the ventilation for a few days, which in the case of this route proved to be very costly. For this, as well as other economic and organizational reasons, the route was soon closed.

Unfortunately, in early 2015 another group tried to reopen the underground tourist route. Another mistake was made then in ignoring the danger posed by radon, despite the previous results being known. The lack of ventilation in the adit was completely ignored.

It was only in July of that year that the first measurements of radon concentration were taken. The results showed that the adit still had high concentrations of radon, which of course could have been predicted. In the so-called inhalatorium, the concentration of radon reached a level as high as 300 $kBqm^{-3}$. Similarly to when the route was first opened, mechanical ventilation was introduced (with the difference that two fans were used). One fan was placed at the entry to the adit, another at the end of the route, as a support fan. Its role was to push the air into venting adits.

The measurements taken after the fans had been installed proved their efficiency. The average concentration in the route dropped by a factor of almost one hundred and reached the level of 6.5 $kBqm^{-3}$.

Due to the high radon concentrations, the route requires intensive ventilation; in October 2015, measurements were taken in order to show the changes in radon concentration in the route depending on the time of turning on or turning off the fans. The figure 21 below shows an analysis of this research. In order to illustrate the problem, the same graph shows the reduction in average radon concentration in the route, measured at the time the route was first opened. At the time, only one fan had been installed, with half the power.

Unfortunately, when starting the route, radon problem was completely neglected both at the first and the second time. For many weeks during the preparatory period, the route was run in very high concentrations of radon, which may result in negative effects in the future (lung cancer). The route was also started without the necessary measurements in this case. The route has not been prepared in terms of radiation safety - damming unseen tunnels and installing adequate ventilation. Measures taken after the measurements are made are provisional and did not provide a sufficient level of security. Status for 2016.

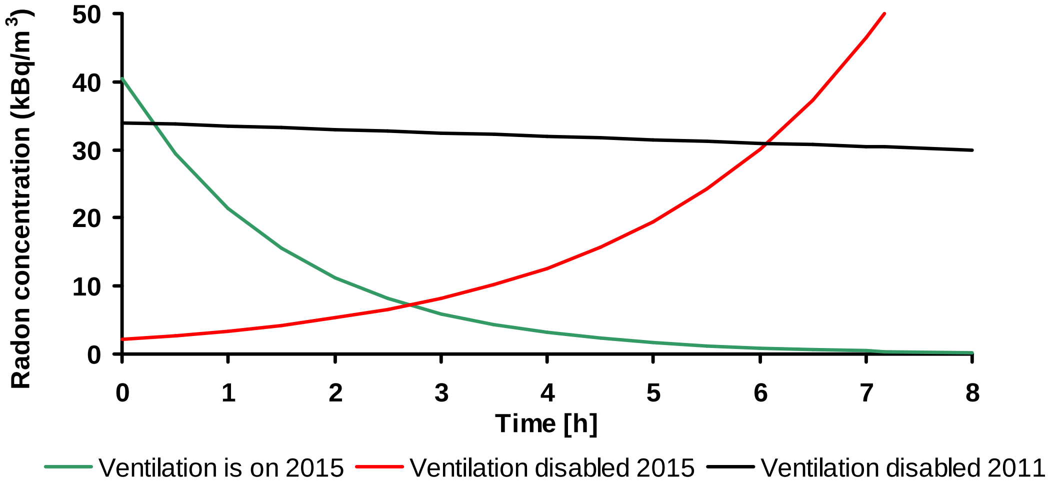

Fig. 21. Changes in average radon concentrations in the underground route "Podgórze" depending on the ventilation system used in the adit.

10. Conclusions

The year 2019 has not yet brought, contrary to expectations, the adoption of the Atomic Law. It probably means a two-year delay in adopting the act in relation to the provision in the Directive. How important the society will be to pass the law showed the information contained in the text[77]. They can be summarized as follows:

The extension of radiation protection to natural radioactive elements, including radon, sometimes has consequences that are difficult to predict.

This new, revolutionary platform must be taken into account in the entire human life, that is, at work and at home, and wherever it is. In the presented dissertation, I presented the problem of radon in two work places: underground tourist routes and health resorts. Also, do not forget about digging and tunnels and other workplaces. A separate issue will be the exposure of people from radon in homes or other places of stay connected, for example, with science.

In further work related to the occurrence of radon, the following issues should be considered:

1. legal regulations taking into account the specificity of the issue
2. conducting further epidemiological studies on the influence of radon on the human body

3. determining the rules of radiological protection also taking into account the specificity of radon, in particular verification of coefficients allowing for the calculation of an effective dose from radon
4. Radon is also used as a therapeutic agent, which should also be included in further proceedings enforced by the adopted Directive

Research conducted for many years by me and the analysis presented showed that employees of underground tourist routes and in some health resorts should be treated as professionally exposed to ionizing radiation. All regulations governing work with ionizing radiation should be applied to them.

The nearest planned activities

Continuing research into the exposure of miners to radon its derivatives. Development of implementing regulations, instructions and recommendations for underground tourist routes related to the radon present in the framework of the IMP and Radon Center activities. Research on radon threat areas.

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5. Discussion of other scientific and research achievements

Before the doctorate

I started my professional work at the Institute of Occupational Medicine by carrying out research on the electrochemical etching of trace detectors, which resulted in obtaining a master's degree. Then, my activities focused primarily on the dangers of radon in underground excavations of hard and brown coal, non-ferrous metals and chemical raw materials. I have carried out research allowing for the classification of hard coal mines in terms of radiation hazard from radon. I was a co-founder of two grants. The first grant assessed the level of threat to the environment and people resulting from the remains of uranium mines in Poland. The implementation of the second grant examined the possibility of assessing the radon exposure by measuring the lead content of Pb-210 in the shafts.

I participated in two international intercalibration methods for radon concentration measurements (France, USA).

I developed, built and tested an individual dosimeter to measure exposure to radon derivatives.

I was a lecturer at the School of Public Health and at the Postgraduate study of Work Hygiene and Environmental Protection.

I was also a lecturer at a number of courses on radiological protection in the work environment.

I also did a training internship at the Leningrad Scientific-Research Institute of Radiation Hygiene.

I was the author or co-author of 27 publications, including 6 in journals from the Journal Citation Reports database

I participated in 17 congresses or conferences, including 3 foreign ones. I gave a total of 12 papers, including one in English, and presented 14 posters.

In the period from 1981 to 2001, I was the manager or contractor of 12 research topics carried out at the Institute of Occupational Medicine.

Since 1987 I have been performing the function of the Radiological Protection Inspector at the Institute of Occupational Medicine in Łódź, and from 1997 to 2016 I performed this role in the isotopic laboratory class II located in the Department of Nuclear Medicine in Lodz.

After PhD

I continued research on mine workers exposure in non-ferrous metal mines. At the same time, I directed my interests towards exposure to ionizing radiation from radioactive sources and X-ray machines. I participated in the introduction to the routine use of thermoluminescent detectors for the control of doses on the hands. For my work on this issue, I received two awards: the Chief Labor Inspector and the Honorable Mention of the Minister of Labor and Politics.

Research into the exposure of hands in nuclear medicine laboratories resulted in the recommendation of workers' cancer being included in the legal provisions. The ordinance (D.U from 2006 No. 4, 180, item 1325) recommends the use of digital finger dosimetry for daily work using a technetium isotope of more than 1 GBq of activity. I received a second degree team award in the field of radiation hygiene for the publication "Hand exposure to ionizing radiation of nuclear medicine workers" of the Polish Society for Radiation Research. Maria Skłodowska-Curie - 2010.

I cooperated in the implementation of the grant "Seasonal changes in the concentration of radon in residential buildings" carried out by the Medical University of Bialystok.

I carried out measurements of radon concentrations in residential buildings in Łódź and the surrounding area, as well as in Kowary.

I was a lecturer on a number of radiological protection courses in the work environment.

I have completed four trainings: 2002 Germany, 2005 Lithuania, 2013 Germany and 2017 Italy.

I have completed 16 research topics, including 8 related to radon.

I am the author or co-author of 37 publications, including 26 in journals from the Journal Citation Reports database. I participated in 45 congresses or conferences, including 8 foreign ones. I gave a total of 35 papers and presented 14 posters. In the period from 2002 to the present I was (am) the manager or contractor of 17 research topics carried out at the Institute of Occupational Medicine.

I participated as an expert in the PAA commission to prepare the implementation of the EU Directive to the Atomic Law.

Jerzy Olszewski