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RADON IN THE WATER

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Abstract: Man and his environment are constantly exposed to the effects of ionizing radiation. Most of this radiation comes from natural and artificial radionuclides and the biggest radioecological problem is the ^{222}Rn radioactive gas. Natural radioactivity comes from unstable radioisotopes that were present during the formation of the Earth, and are present today. According to the research by UNSCEAR(United Nations Scientific Committee on the Effects of Atomic Radiation) it is estimated that the radiation dose, which comes from natural radionuclides and to which man is exposed, is 2.4 mSv per year. Natural sources of radioactivity are cosmic radiation and Earth's crust that contains primordial radioactive elements including those that are sources of radon (uranium). Radon is a natural inert radioactive gas without smell and taste. It is soluble in water and can easily diffuse with the gaseous and aqueous phase and in this way forms significant concentrations. The techniques and methods most commonly used to detect and determine the activities of radon in water are alpha spectrometry, gamma spectrometry and measurement techniques on a liquid scintillation detector. Throughout epidemiological studies, the World Health Organization has provided convincing evidence of the correlation of exposure to indoor radon and the development of lung cancer. Radon and its decomposition products are considered to be the second cause of lung cancer after consuming tobacco.

Keywords: radiation, radon, water, detection, cancer.

1. INTRODUCTION

Every moment of the people's existence is accompanied with radioactivity. Radioactivity is all around us, and human body contains certain radionuclides. Radionuclides are unstable nuclei of chemical elements that are transformed to a stable state by emission of ionizing radiation. By origin they are classified into three groups: primordial, cosmogenic and anthropogenic. Primordial radionuclides are produced by nucleosynthesis like all the substances of our solar system. Cosmogenic radionuclides are produced by cosmic rays, and the human factor has influenced the formation of anthropogenic radionuclides. People can be irradiated in two ways: externally, when radioactive substances irradiate the body externally, and internally when radioactive substances are introduced into the body by inhalation and ingestion, with food and water. The dose of environmental irradiation depends on the level of contamination of the terrain and the migration of radionuclides in the ecosystem and the food chain. According to a UNSCEAR study (United Nations Scientific Committee on the Effects of Atomic Radiation), it is estimated that an average person receives a radiation dose of 2.4 mSv per year from natural radionuclides. Awareness of the harmfulness of radioactivity was not developed until the beginning of the last century. The biggest problem is the nature of radioactivity, because it is odorless, tasteless, colorless, and the consequences of exposure are slow, and it may even take generations until the effects of exposure occurs. With the expansion of the media and the internet, a wider population is increasingly educated in understanding the harmful effects and necessity of protecting against radioactivity. Radioactivity monitoring systems procedures and methods of protection against excessive radiation have become an integral part of the legislation of developed and environmentally consecrated countries.

In recent decades researches have shown that, under normal conditions, over 70% of the total annual radiation dose that the population receives comes from natural sources. 40% of radiation dose being conditioned by the inhalation and ingestion of natural radioactive gas, radon, ^{222}Rn, or its descendants. Epidemiological studies have shown that the presence

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of radon, ^{222}Rn in the environment is considered to be the second most important cause of malignant lung disease (the first cause is long-term exposure to tobacco smoke) [1]. The relationship between radon and lung cancer risk is linear, which means that if we double exposure, the risk will double as well. It is extremely important to measure the concentration of radon activity indoors, because today's human activities lead to increased potential human exposure to radon and its short-lived descendant. Those activities are reducing natural ventilation to save energy, using recycled waste materials for construction purposes. Except the building materials, one of the most important sources of radon is water drawn from underground sources. Groundwater accumulates radon formed in the Earth's crust and as a result high concentrations of radon can be measured at specific locations. When using such water, high radon concentration from the water enters the air inside the room.

The World Health Organization recommends measurement of radon concentrations wherever it is possible. Depending on the obtained results, certain measures and actions have to be taken to minimize exposure of the population to radioactive gas. It is the reason for existence of radon maps that accurately show the concentrations of radon in certain territories and, depending on the information available through radon maps, actions are organized to educate or protect the population. The importance of radon monitoring in water is not reflected only in the adoption of new measures and radiation protection, but certain measurements in hydrology, oceanography and hydrogeology are used to obtain useful and meaningful information. In hydrology and oceanography, ^{222}Rn isotope is used as an ecological marker, while in hydrogeology it provides information and origin of groundwater, contact between water and rocks, groundwater dynamics and stages of the hydrological cycle [2].

2. RADON

Radon is an inert volatile gas, odorless, colorless and tasteless. It was named by radium and discovered by German physicist Friedrich Dorn in 1898. Radon is volatile and chemically non-reactive. It is the heaviest noble gas in the periodic table of the elements. Because it has higher density than air, it is usually kept at low altitudes, in rooms with poor ventilation and in basements [3]. It is soluble in water, where it can be found as a consequence of decay of the radium present in the surrounding rocks and soil [4]. Isotopes of this radionuclide are formed during the decay of isotopes of radium from the uranium, thorium and actinium series. Radon has 27 known isotopes so far. Figure 1 shows the scheme of radioactive decay of ^{226}Ra and ^{222}Rn and its descendants.

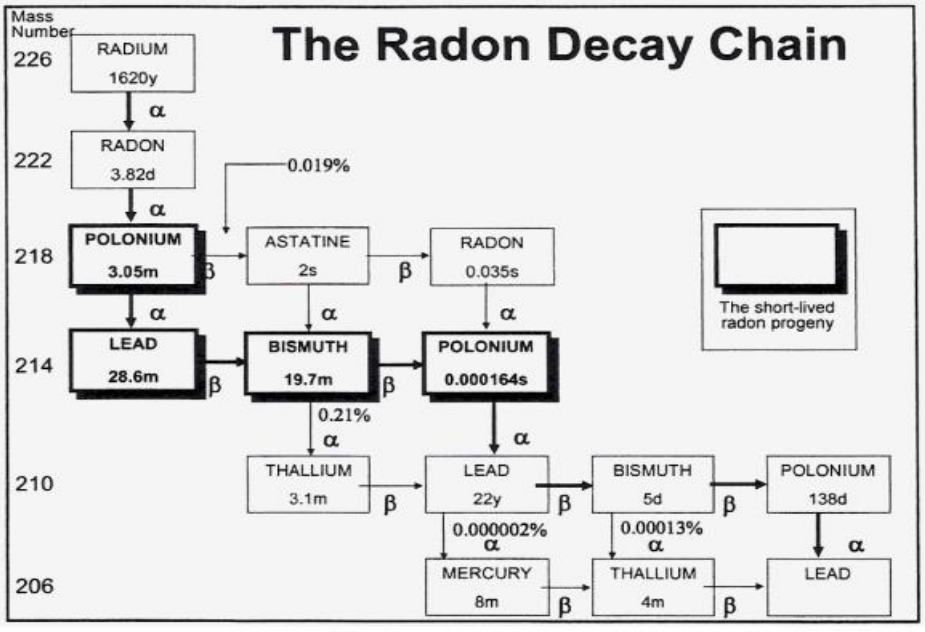

Figure 1. Scheme of radioactive decay ^{226}Ra and ^{222}Rn and itsdescendant

The radon isotope ^{222}Rn is formed by alpha decomposition of radium ^{226}Ra in the uranium series. The half-life of this radionuclide is $T_{1/2}$ = 3,824 days. Although there are more radon isotopes, it is common to refer to the name "radon" as the ^{222}Rn radioisotope.

Decay and descendants of radon, ^{222}Rn

^{222}Rn is an alpha emitter. Radon decomposes into several short-lived descendants (polonium ^{218}Po, lead ^{214}Pb, bismuth ^{214}Bi and polonium ^{214}Po, which are also radioactive [4]. During transformation, the nuclei emit appropriate ionizing radiation: α particles, β particles or γ rays, or combinations of particles and air. The following table 1shows some of the physical properties of ^{222}Rn and its short-lived descendants.

Table 1. Physical properties of Radon and its short-lived descendants.

element	Historical symbol	Basic radiation	Decays energy (MeV)	Half life
^{226}Ra	Ra	α	4,8	1,620 god
^{222}Rn	Rn	α	5,49	3,82 dan
^{218}Po	RaA	α	6	3,05 min
^{214}Pb	RaB	β, γ	1	26,8 min
^{214}Bi	RaC	β, γ	3,3	19,8 min
^{214}Po	RaC	α	7,69	164 μs

Polonium, ^{218}Po was obtained by radon ^{222}Rn alpha decay. The energy of the emitted α particle is 5.49 MeV. The atoms of this metal are sticking to dust particles. It can be deposited on surfaces, e.g. the walls of the rooms or the interior of the lungs, if they come in contact with them. The half-life of polonium ^{218}Po is $T_{1/2}$ = 3.05 min. Like radon, ^{218}Po is an α emitter and decays to lead ^{214}Pb, with an emission of α particle energy of 6 MeV. The ^{214}Pb lead is in solid state. The half-life of this radionuclide is $T_{1/2}$ = 26.8 min. It decomposes by the emission of β particles and γ rays on bismuth ^{214}Bi. Bismuth ^{214}Bi is also in solid state. The half-life of ^{214}Bi is $T_{1/2}$ = 19.8 min. With the decay of ^{214}Bi, polonium ^{214}Po was obtained. The half-life of ^{214}Po is $T_{1/2}$ = 164 μs. ^{214}Po is decayed on lead ^{210}Pb, by the emission of α particles and its energy is 7.69 MeV. Radon's descendants are attached to water molecules or other molecules in the air dimensions from 0.5 to 5 nm. They are also grouped into small diameter clusters of 0.5 nm. Depending on the concentration of ions in the air and the humidity, partial neutralization of unattached radon descendants may occur by recombination with negative ions or by merging aerosol particles to form attached radon descendants (20 to 500 nm in diameter).

Behavior of short-lived radon descendants

Knowledge of the behavior of radon descendants in the atmosphere is very significant. Its contribution to radiation health risks is much greater than that of radon itself. About 80% of newly formed descendants are positively charged and chemically active. They interact with the negative ions present in the atmosphere by attaching to natural aerosols. The first descendant of ^{218}Po exists under normal external conditions for only 20 s as a self-contained mobile ion or atom. After that it attaches to molecules of water vapor, oxygen and other gases, particles and solid surfaces.

The most pronounced negative effect has the unattached descendants floating in the air in the form of free clusters of only a few molecules. That descendants collide with each other so they merge and increase and also decay and precipitate. Deposition of radon descendants also occurs in human lungs and is more likely to precipitate free than attached radon descendants. The part of free-form radon descendants depends on several factors and ranges from 0.3 to 33%. Radioactive aerosols with diameters in the range of 0.1 to 10 nm easily deposite in human lungs. Larger aerosols are retained in nose and oral cavity without reaching the sensitive respiratory epithelium of the bronchial tree.

Radon descendants are deposited on surfaces within closed spaces. Such a deposition process is a significant mechanism for reducing the concentration of radon descendants in a closed atmosphere.

Indoors Radon

Radon easily migrates to residential buildings and accumulate indoors. Migration takes place through cracks or porous blocks of walls and floors, through water or through ventilation pipes, and from building materials (Figure 2).

If the air pressure is lower in the closed room, the radon enters the room via moving air because of pressure gradient. The factors and forces responsible for radon mobility change daily and seasonally, so the dynamic interaction of all these factors is very complex. The concentration of radium in soil depends on the concentration of uranium and thorium in the rocks and on the geochemical processes at the observed location over time. Due to the widespread distribution of radium isotopes, its descendants, radon

isotopes are also present in the fluids found in the pores of rocks and soil.

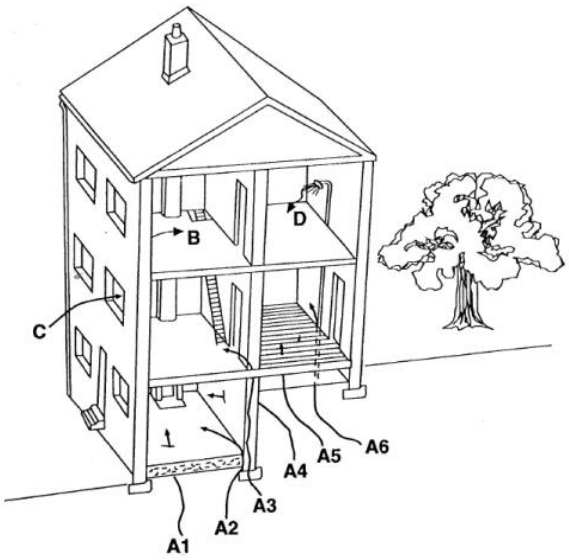

Figure 2. Migration of radon throw/fromA1, A4, A5, A6-cracs, A2-joints, A3-porous walls, B-building materials, C-outside air, D-water[5]

Mobility of radon atoms

The radon atoms are moving by diffusion. They are moving in a concentration gradient from a place of higher radon concentration to the place of lower concentration. Diffusion is not sensitive to the size of the soil pores but is very sensitive to the amount of water in the pores. With increasing soil porosity, diffusion increases. The diffuse length (the distance traveled by radon atoms) in dry soil was determined experimentally to be 1.6-1.9 m, while in soils with larger amounts of water the diffuse length was 0.01 m. [6]. Due to the pressure gradient in the fluid contained in the soil pores and cracks, convective (vertical) and advective (lateral-horizontal) flows occur. In the case of soil gases, a pressure gradient can occur in the soil air, between the soil air and the atmospheric air, or in their combination. Convection and advection depend on the internal permeability of the soil, the viscosity of the fluid moving through the pores of the soil, and on the pressure gradient driving the fluid.

Water occupies a large part of the planet Earth's surface, over 70%, of which 0.3% is water that we can drink and use daily. Water could be divided into surface and underground water. Groundwater, on its way through the earth's crust, passes by rocks containing radionuclides, where it absorbs radium and radon, easily soluble in water. Most radon is released immediately when water comes in contact with air, so surface water has significantly less dissolved radon. Surface water contains low concentrations of radon activity on average less than 4 Bq l^{-1}. Released radon increases the concentration indoors and is responsible for causing lung cancer, while a smaller amount of radon remaining in water is responsible for gastric cancer.

The highest concentrations of radon can be found in the water taken from deep wells. Concentrations that can be measured in underground and well systems are up to 104 Bq l^{-1}. The average ^{222}Rn concentration in groundwater is 20 Bq l^{-1} [7], and can vary from 3 - 80000 Bq l^{-1}. Water used from urban water supply contains significantly less radon concentration. The technological process of water purification and treatment results in the emanation of radon in contact with the air, so that very small amounts remain dissolved in the water. The concentration of radon in bottled drinking water depends most on the origin of the water, ie. the depth from which the water is pumped and the type of soil through which water flows on its way to the pumping point.

Geological characteristics have great influence on source and distribution of radon in water. Radon release from rocks and soil predominantly depend on the type of minerals in which radium and uranium are present [8]. Higher radon concentrations are often found in groundwater that is in contact with granite rocks, shales, and limestone.

Radon concentration depends on weather conditions and seasonal changes, so it was observed that higher radon concentrations are in the water during spring. A larger inflow of water dissolves radon from a larger mass of rocks with faster radon transport. Its migration from groundwater to the earth's surface is influenced by: hydrogeological properties of rocks, groundwater circulation way, temperature, pressure, presence of CO_2 or other dissolved gases and presence of ^{226}Ra and ^{238}U. It is often the case that the analyzed thermal and mineral water samples show high levels of ^{222}Rn, but not high concentrations of ^{226}Ra and ^{238}U and vice versa. This is why it seems impossible to establish a correlation between their concentrations. Solubility limits have the greatest influence on this correlation. The solubility limits of Ra and U in most groundwater are much lower than radon limits. Also, low radium concentrations can lead to high radon concentrations if the radium is adsorbed on the mineral grain surface [2].

Sampling techniques and sampling problems greatly contribute to the measurement uncertainty of determining the radon concentration activity in water. Since radon has the ability to diffuse easily, each contact of water and air causes a loss of radon. Great attention in all scientific papers is on the sampling method itself, and the technique that would give the

best results. When sampling, it would be convenient to pour the samples directly into the measuring bottles. If water is poured from the bottle into the measuring vessels, it is quite certain that some of the radon will be lost in contact with the air. The choice of the sampling bottles is also important. In the case of plastic bottles, radon is more likely to emanate, whereas in the case of glass measuring bottles it can be safely stated that radon will remain longer within the bottle volume.

During transport and storage, the samples should be at the temperature below the water temperature at the time of sample collection - the "original" temperature (but above 0 ° C) until measuring begins. The container should be protected and tightly closed. It should also be properly packed to prevent any water leakage. The transport and storage period should be as short as possible. It is recommended the samples to be analyzed as soon as possible after the equilibrium time of the radon and its descendants is reached. The time between sampling and analysis of samples should not exceed 48h [9].

Geological and hydrogeological aspect of the analysis of radon content in water

The total mass of radon in the Earth's crust is estimated to be 175 t. It is a relatively small mass that has a great impact on the Earth's surface.

Due to the variable sedimentation processes in sedimentary rocks or the processes of formation of magmatic and metamorphic rocks, different geological formations have different radionuclide distribution. The radon emanation coefficients (a fraction of the total amount of radon generated by the decay of radium released from the soil and reaching the pores of the media) vary from 5 - 70%: for soil the mean is 40%, for rocks 5%, for granite 6 - 33%. granodiorite 17 - 40%, gneiss 1 - 14%. The radon emanation coefficients of some minerals are: 0.29 - 4.17% for monacite; 0.46 - 1.04% for zircon; 0.3 - 0.76% for uranite; 1.34 - 22.5% for torit; 16.8 - 22.9% for cerite [2]. The radioactivity of magmatic rocks increases with the proportion of SiO_2 in the rock. Granite is the most radioactive acidic magmatic rock. The radionuclide concentration is influenced by hydrothermal, pneumatolytic and other post-magmatic processes leading to secondary rock alterations. Therefore, high concentrations of radioactive elements are often present in the geochemical barriers in the tectonic zone [2]. It has been observed that high concentrations of radon are present in waters in the vicinity of tectonic zones, due to the migration of radon through cracks and fractures in the ground.

Waters with high concentrations of ^{222}Rn usually have high temperature, high mineralization, or increased concentration of CO_2, so radon then can be used as an indicator of its origin from a hydrogeological point of view. Monitoring of ^{222}Rn in groundwater allows radon to be used as an earthquake indicator. In groundwater, there will be a sharp increase in the ^{222}Rn concentration if larger cracks in the rocks are opened as a result of the increase in pressure [2].

Radon in thermal spas

Research shows that exposure to low radiation doses can lead to positive effects on DNA repair and detoxification mechanisms, the immune system and its response to the development of cancerous cells. It is paradoxical, however, the link between high doses and cancerous diseases cannot be applied in the case of low doses. Low dose positive effects have been found in radon spas. Radon spas are numerous in Europe and here. Although radon solubility declines slightly with increasing temperature, the highest radon concentrations can be found mainly in thermal waters, which are often used in radon spas. The solubility of radon at 20 ° C is 0.225 $cm^3 g^{-1}$ [10].

3. MEASURING RADON IN WATER-METHODS

There are several techniques and methods used to determine radon activity in water. These include solid and liquid scintillation counters, gamma counters and ionization chambers. Preference is given to using the LSC technique which enables the analysis of a large number of samples over a relatively short period of time. The lowest detectable activity is <1 Bq l^{-1} for 20-60 min measurements with direct LSC methods, and much lower using the α / β discriminator, 0.04-0.2 Bq l^{-1}. LSC methods, however, have poor energy resolution [11]. Sampling technique is generally the main source of error in measuring radon concentration in water The water sample must be representative, tested and such that it has never been in contact with air.

LSC method

The Liquid Scintillation Counter (LSC) method is based on the occurrence of scintillation in the tested material, that is, on determining the energy of the emitted radiation. It is predominantly used to determine the α- and β-activity of samples, but it is

also used for the analysis of radionuclides emitting γ-rays, x-rays, neutrons, Auger's and conversion electrons. For this purpose, liquid scintillation detectors consisting of a scintillator, photomultiplier and electronic pulse amplification and processing device are used. Scintillation detectors use luminescence to detect radiation. The luminescence is property of a material to emit light when its atoms are excited or ionized. The problem is, most materials are not transparent to their own light. Materials that are transparent to their own light are divided into organic and inorganic scintillators. Organic scintillators come in crystalline form (naphthalene, anthracene, stilben), but can also be used in liquid form (xylene, toluene). Both crystalline and liquid scintillators are hydrocarbon compounds. Inorganic scintillators are used in the form of single crystals and the most common of these is NaI, but LiI, CsI, CsF and KI are also used.

These crystals are transparent to the light they emit in a small percentage (about 0.1%), and to increase this percentage, they add a small amount of impurities, so-called activators, that create luminescent centers. LSC technique uses scintillation cocktails that are placed in vials for measurement. The emission of radiation from the active sample excites molecules, which then generate light. Aromatic solvents are used for LSC cocktails because they have a high electron density. The scintillation cocktail completely binds radon and thus prevents it from diffusing from the sample. The processes that interfere with LSC detection are: background radiation or background, attenuation in scintillation counters, spectral overlap, luminescence, static electricity effect and wall effect.

Quantulus 1220™

The Quantulus 1220TM (Ultra Low Level Liquid Scintillation Spectrometer Wallac 1220TM Quantulus) is a liquid scintillation detector, belongs to low-phonic detectors, manufactured by Perkin Elmer, Finland. The device has very high stability and very good active and passive protection. Quantulus 1220™ device can be seen in Figure 3. Quantulus has two dual programmable multi-channel analyzers. One is active protection and the other captures spectra. *Pulse Shape Analyzer* (PSA) provides the identification of ionizing radiation particles, allowing simultaneous imaging of pure α- and β-spectra and the detection of very small α-activities in the presence of high β activity. PSA is a necessary prerequisite for the sensitivity of liquid scintillation alpha counting.

Figure 3. Quantulus 1220™

The software of this spectrometer runs on Windows 95, NT4, or Windows XP platforms, and the user interface is WinQprograme. Information stored on the hard disk was processed offline using the Easy View Spectrum Analysis software.

The measurement method for determination the concentration of ^{222}Rn activity on a liquid scintillation spectrometer has been prescribed by the US Environmental Protection Agency (EPA) [12]. The method is designed to analyze radon from groundwater and surface water sources. It involves the preparation of two-phase samples. Certain experiments have shown that, when preparing two-phase samples, the initial shaking of the samples immediately after mixing with the cocktail promotes radon transfer to the organic phase and reaching equilibrium in the vial and that the shaking time (3-40 s) is inversely proportional to the time of equilibrium reaching [13].

The advantages of Quantulus are: high stability and at long measurement time, advanced separation of alpha and beta spectra, passive attenuation of radiation and active protection against cosmic and environmental radiation, which prevents losses in detection efficiency.

Tricarb 2900

The Tricarb 2900 is a liquid scintillation detector (Figure 4). It is connected to a computer and is therefore able to automatically process data, check and evaluate the results obtained. Using Tricarb 2900 detectors, low-dose alpha, beta and gamma radiation can be detected. [14].

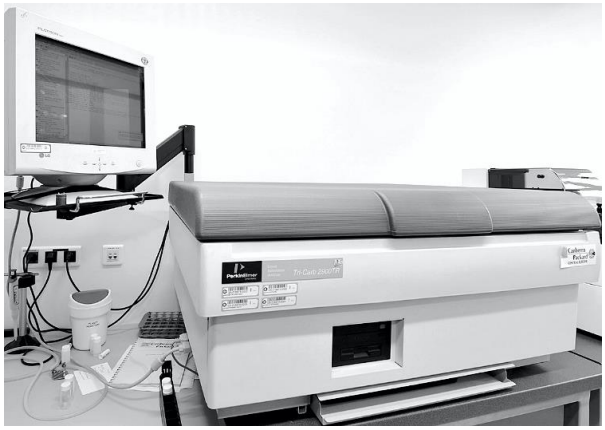

Figure 4. Tricarb 2900

As the operation of the Tricarb 2900 detector is based on scintillation, it should be used indoors away from any other device that may affect its operation. Due to the optical sensors it has, it needs to be protected from exposure to sunlight.

The scintillation cocktails used in the Tricarb 2900 detector are designed to enhance the detection of emitted photons and are selected according to the nuclide we are observing. For the ^{222}Rn test, the Ultima Gold XR scintillation cocktail turned out very well.

The software used to study the sample spectrum is QuantaSmart. It allows displaying the 2D spectrum of the sample being analyzed. Information about the number of events that occurred in the sample is obtained, as well as the energy at which these events were recorded, and can be represented in a linear and logarithmic scale [14].

RAD7 is an alpha spectrometer that can be used to measure radon concentrations in water, air and soil. The device is mobile thanks to its battery power and compact design which means it can be used both in the field and in the laboratory. The device can be seen in Figure 5. The base of this device is a 0.7 liter semi-spherical chamber lined on the inside with material that is a good electrical conductor. At the center of the semisphere is a flat silicon α detector that is ion implanted. The high voltage maintains the potential difference between the internal conductor and the detector from 2 kV to 2.5 kV, thus creating an electric field within the volume of the detector chamber. The device has an automatic pump that allows the flow of dry air at a rate of 1 l / min through the chamber. At the entrance to the chamber there is a filter that prevents the entry of radon descendants into the chamber and thus allows the measurement of radon concentration in the chamber. The ^{222}Rn radon nuclei contained within the chamber are decomposed into ^{218}Po polonium nuclei, with the polonium nuclei being positive ions and being electrically fielded onto a silicon α detector on which they are deposited. The deposited polonium ^{218}Po decays α and β decay. The α particle is detected in the volume of the detector with the specified energy α of the particle produced by the decay of polonium ^{218}Po of 6.03 MeV. All resulting β decays will not be detected, and other α decays will be detected, but with a different incident energy [15].

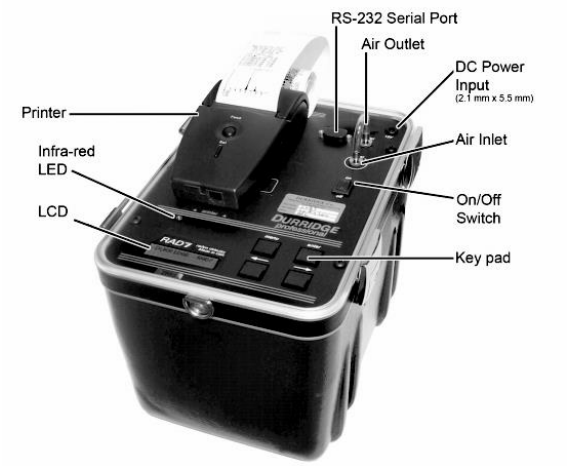

Figure 5. Alfa-spectrometer RAD 7[15]

If radon concentration in water is measured, special adapters and accessories must be added to the RAD7 for this type of measurement. A system which pump air into a water sample container is used. It is a closed-type system and a volume of air and water is constant and independent of air flow. This system quickly reaches equilibrium. The relative humidity in the chamber must be constantly checked and maintained below 10%, because if the humidity reaches a higher value the measurements are not relevant. Procedures for handling such devices and methods for sampling radon from water, air and soil are prescribed by the standard procedures of international agencies (EPA standard protocol 402-R-92-004).

Sampling techniques

The main reason for obtaining unreliable results is sampling method [16]. When sampling, it is extremely important that water is kept in contact with the surrounding air as less as possible.

Comparison of measurement techniques

Different measurement techniques (RAD7 and LSC) can be compared through the results of measurements of environmental water samples. RAD7 was used as the reference method, and several different scintillation cocktails were prepared for the LSC method [17].

Scintillation cocktails have proven to be good radon catchers. Radon has a greater affinity for the cocktail and diffuses from the sample into the cocktail. This property of scintillation cocktails allows that, if the sample is immediately prepared with a cocktail, it can stand for a long time without radon emanating from the sample. However, the use of different scintillation cocktails has produced different results. The two-phase method with UGF and OFO cocktails showed very good agreement with the reference values, respectively, with the concentrations of activity obtained by the RAD7 detector for all analyzed samples shown in Table 2. [17].

Table 2. Comparison of measurement techniques [17].

Water Sample ID	RAD7 A [Bq l^{-1}]	LSC UGAB A [Bq l^{-1}]	LSC UGF A [Bq l^{-1}]	LSC MOS A [Bq l^{-1}]	LSC OFO A [Bq l^{-1}]
Sample 1	601 ± 5	429 ± 5	612 ± 7	674 ± 11	586 ± 12
Sample 2	37.2 ± 2.4	27.6 ± 0.8	38.5 ± 1.2	41.4 ± 1.3	36.7 ± 1.3
Sample 3	6.6 ± 0.3	5.1 ± 0.3	7.1 ± 0.5	8.1 ± 0.5	6.9 ± 0.5

4. HEALTH ASPECT - RISK AND DISEASES

Radioactive contamination is one of the most significant factors affecting the environment and human health today. Radon and its descendants are thought to be another cause of lung cancer after consuming tobacco. According to the World Health Organization, epidemiological studies have provided convincing evidence of an association between indoor radon exposure and lung cancer development. The riskiest group of workers exposed to high levels of radon are miners where studies have shown an increase in the frequency of chromosomal aberrations in blood lymphocytes.

Significant as an experimental group were the miners of the former East Germany in uranium mines where chromosomal aberrations were studied as biomarkers of genetic damage in blood lymphocytes in order to assess the health risk of a given population in lung cancer [18,19,20]. In addition to mostly negative results, some studies have found a positive correlation between the incidence of adenocarcinoma in a group of women nonsmokers and increased concentrations of radon in the living room.

The main targets for the development of lung cancer are thought to be small cells e.g. segments of the bronchi and thus the lungs are the most endangered organ of the human body due to radon inhalation [21]. Inhalation of radon descendants can lead to their inhomogeneous deposition on the walls of the human respiratory tract and irradiation of the bronchial epithelium which further increases the risk of lung cancer [22].

Among the health risks of the World Health Organization, special emphasis is placed on the exposure of the population to radon reaching the body via drinking water. The reference limit according to European standards for radon activity in water is 100 Bq I^{-1}, [23]. The population is exposed to high doses of radon in the water only in the case of households that have private wells, which is mostly the case in areas with high concentrations of radium in the soil. Households supplied with water from urban water supply systems do not have such problems because the treatment of water in the city system makes radon largely eliminated, so the concentrations of radon reaching households are very low.

Studies done worldwide show that the mean annual dose that the population received through radon inhalation is 1.26 mSv, which represents practically half of the total mean dose received from all natural radiation sources (2.4 mSv), and twice the dose received from all artificial radiation sources (0.6 mSv) [24]. Figure 6 shows the radiation sources and the average exposure distribution for the world population.

Radon transits through water from soil and rocks in which ^{226}Ra isotopes decompose [25], so groundwater moving through porous rocks rich in radium will "pick up" isotopes of its descendant ^{222}Rn. The concentration of radon in water decreases as water moves to the surface due to its movement and purification. The problem arises if this water is used directly from a source in a household [26]. Figure 7 shows schematically the distribution of radon, its movement and its impact on an organism that causes health risks.

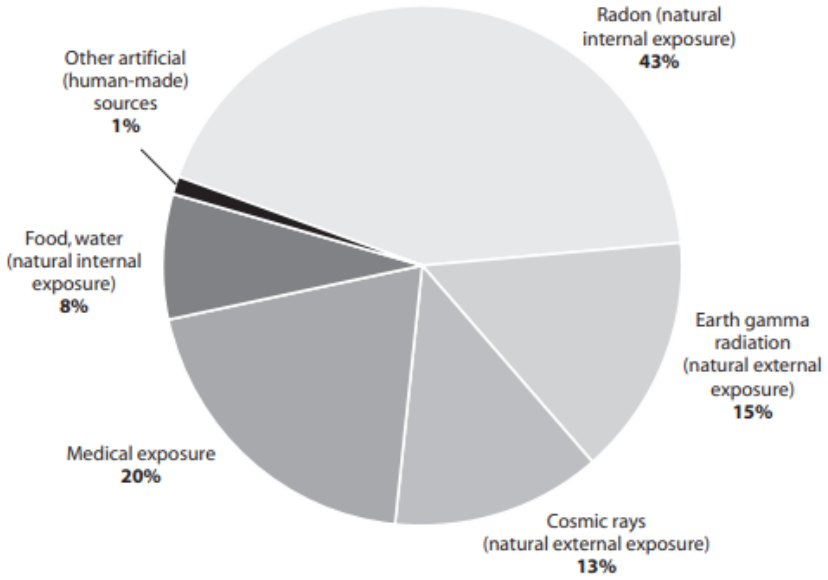

Figure 6. Sources and distribution, the average exposure of the world population

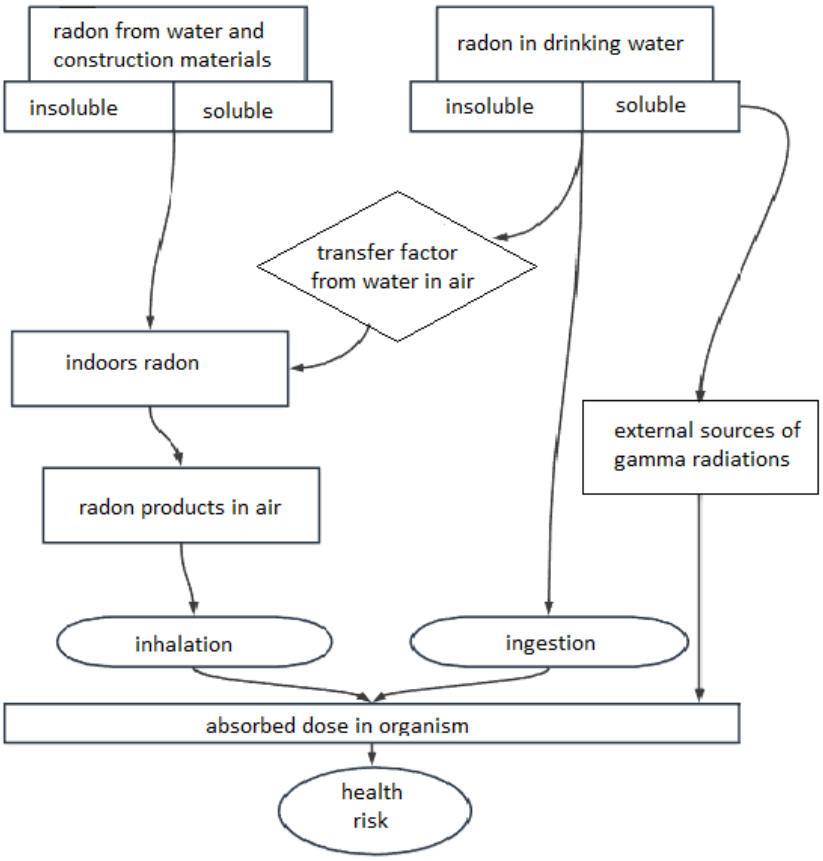

Figure 7. The distribution of radon, movement and impact on organism

In addition to lung cancer caused by radon, ingestion of water with elevated ^{222}Rn content and its direct uptake in drinking water has been a serious risk of gastric, colon, and liver cancers [27]. Within the control of population exposure to natural radiation sources, the concentration of ^{222}Rn in drinking water is a relevant parameter in terms of dosimetry, on the basis of which dose inhalation and ingestion doses are made [28]. The effective dose E used for ingestion of radon and its descendants refers to gastric tissue and is determined annually by Equation 1 [29]:

E [Sv] = $K\ C\ KM\ t$, (1)

where:

K – the applied dose conversion factor for ingestion ^{222}Rn is 10^{-8} Sv Bq^{-1} for adults and 2 x 10^{-8} Sv Bq^{-1} for children [30];

C – activity concentration ^{222}Rn [Bq l^{-1}];

KM – water consumption factor, is 2 [l day^{-1}];

t – duration of water consumption, taken as 365 [day] [7].

5. CONCLUSION

In this paper many publications and materials dealing with the concepts of radioactivity, radiation and environmental protection have been studied. Particular attention is given to radon in water, measurement techniques and the health aspect. Radon is one of the biggest radioecological problems of today and is the dominant natural source of radiation. It is soluble in water and can easily diffuse with the gaseous and aqueous phases, thus forming significant concentrations that can be very harmful to humans, as confirmed by World Health Organization research.

Wells and groundwater are used in our area, where the highest concentrations of radon can often be found. In order to protect people from these regions, it is necessary to carry out systematic measurements of radon concentrations and present the average values of radon concentrations as a map. In this way, radon folders would form, which would be of multiple use. This type of measurement would give information about the amount of radon entering households, but would also give us more accurate information about the possible health risk. The population in high-risk areas needs to be educated about the procedures for preventing radon from entering the soil in construction facilities and how to clean the wells. Awareness of the harmfulness of radioactivity and of radon as a radioecological problem in our country is still not sufficiently developed. The consequences of exposure to radiation are often not immediate and slow to observe, and this has a negative impact on raising awareness of these issues, and it is therefore necessary to educate the population more intensively in order to achieve a satisfactory level of awareness and the need for protection against radioactivity. Radioactivity monitoring systems and procedures and methods of protection against excessive radiation have become an integral part of the legislation of developed and environmentally conscious countries, and we should adopt such standards and regulations in our country as well.

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РАДОН У ВОДИ

Сажетак: Човјек и његова околина константно су изложени утицајима јонизујућег зрачења. Већина тог зрачења потиче од природних и вјештачких радионуклида, а највећи радиоеколошки проблем представља радиоактивни гас 222Rn. Природна радиоактивност потиче од нестабилних радиоизотопа који су били присутни приликом формирања планете Земље, а присутни су и данас. На основу истраживања UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radioation) процијењено је да човјек годишње прими дозу зрачења 2,4 mSv која потиче од природних радионуклида. Природни извори радиоактивности су космичко зрачење и Земљина кора која садржи примордијалне радиоактивне елементе, укључујући и оне

који су извори радона (уранијум). Радон је природан инертан радиоактиван гас без укуса и мириса. Растворљив је у води и може лако да дифундује са гасовитом и воденом фазом и на тај начин образује значајне концентрације. Технике и методе које се најчешће користе за детекцију и одређивање активности радона у води су алфа спектрометрија, гама спектрометрија и техника мјерења на течном сцинтилационом детектору. Свјетска здравствена организација је кроз епидемиолошке студије пружила увјерљиве доказе о повезаности изложености радону у затвореном простору и развоју рака плућа. Радон и његови производи распадања се сматрају другим узрочником рака плућа након конзумирања дувана.

Кључне ријечи: зрачење, радон, вода, откривање, рак.

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