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# **Levels of Radon Activity Concentration and Gamma Dose Rate in Air of Coal Mines in Bosnia and Herzegovina**

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Additional information is available at the end of the chapter

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## **Abstract**

Radon is a unique natural element because it is an inert gas and at the same time radioactive in all of its isotopes. It is known fact that exposure of the population to high concentrations of radon gas leads to irradiation of primarily respiratory organs which can cause lung cancer. Radon is a subject of intense research around the world in order to, among other reasons, assess the risk of exposure and develop appropriate standards of protection and its control. By coal mining and exploitation, radioactive radon gas, which is captured in natural geological structures, is relocated from the deep coal layers. Hence, it is concentrated in the depots and coal seams of the mines or being transported to the surface of the earth where it can significantly change the levels of radioactivity in the working premises and residences. This chapter presents the results of a 3-year research of radon activity concentration and gamma dose rate in the air in underground and surface coal mines of Bosnia and Herzegovina.

**Keywords:** radon activity concentration, gamma dose rate, air, coal mines, Bosnia and Herzegovina

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## **1. Introduction**

Coal, as well as majority of natural materials, contains natural radioactive elements [1]. The concentrations of natural radionuclides in coal are generally lower than those in the earth's crust; however, sometimes higher concentrations of uranium and thorium and their decay products in different layers of coal can be found, as a result of leaching of uranium and thorium from uranium- and thorium-rich volcanic rocks.

In many mines, the presence of radioactive materials such as uranium and thorium in the surrounding rocks may lead to increased concentrations of the isotopes of radon and to an increase of radon decay products produced in the mine atmosphere. The atmosphere in the underground mines contains, in gaseous form or in form of aerosols, all natural chain of radionuclides originated by the decomposition of thorium and uranium. As a result, the concentration of certain radionuclides, especially radon and its decay products, can achieve high levels of concentration which can be dangerous to workers' health [2].

Coal mining and its combustion in thermal power plants is potentially the most important process for creating technological elevated levels of natural radioactivity. Opening of large surface mines leads to accelerated emanation of radon from the deeper layers of the earth's crust [3]. Similarly, in coal mines, increased accumulation of radon can be caused due to its inflow through cracks and fractures in land and particular via the underground water systems.

Dangers caused by radon and its decay products are identified in the seventeenth century and in the last century, radon is considered responsible for the increased incidence of lung cancer among miners who were exposed to radon. For this reason, there was a need for atmospheric research in underground mines, as well as for dosimetry monitoring of miners involved in these activities. Dosimetry monitoring in the coal mines is needed to assure that the activities in mines do not generate radon in quantities that exceed the limit values defined by the appropriate regulation.

Although there is no any information on the emission of radon from coal mines (surface and underground mine), the UNCSEAR Committee has judged that annually 30–800 TBq of radon is released from mines around the planet, resulting in annual collective effective doses from 0.5 to 10 Sv per man, respectively. In the report UNSCEAR 2000, the Committee estimated that the average concentration of  $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$  in coal is 50, 20, and 20 Bq/kg, respectively. This estimate is based on the analysis of coal samples from 15 countries, and especially important is to mention that the value of certain radionuclides varies up to two orders of magnitude.

Bosnia and Herzegovina (B&H) is rich in coal, which represents one of its most important energy sources. The total geological reserves of coal in B&H are estimated at 5.647 billion tons, of which 2.540 billion tons are balance; 1.437 billion tons of lignite and 1.103 billion tons of brown coal. In coal mines in Bosnia and Herzegovina in 2015, approximately 9.2 million tons of coal is produced, of which approximately 85% of total coal production have been taken by power plants. Thus, the coal industry in Bosnia and Herzegovina is a potential source of danger of radioactive contamination of the environment, especially in cases when certain coals are used in power plants which indicate an increased content of natural radionuclides.

This chapter presents the results of 3-year research of radon activity concentration and gamma radiation in underground and surface coal mines in Bosnia and Herzegovina.

## **2. Coal mines in Bosnia and Herzegovina and general characteristics of coal**

Economically, important coal deposits were formed at different stages of historical and geological development of the Earth and on large number of sites (more than 100). Brown coal

deposits were formed mainly in the lower and middle Miocene and lignite in the upper Miocene and lower Pliocene. Weather and creation conditions of economically important coal deposits determined their rank and regional deployment. Coal basins in B&H are long been known and geologically largely explored. In some of them, mining has been done for over 100 years. The major reserves of brown coal are located in the following basins: Central Bosnia (deposits: Kakanj, Zenica, Breza, Bila), Banovici (Seona, central basin, Djurdjevik), Ugljevik (Bogutovo Selo, Ugljevik-Istok, Glinje). The most important lignite reserves are located in the basins of Kreka, Gacko, Stanari, Bugojno, Livno, and Duvno.

Coal mining in B&H coal mines is being done in two ways: surface mining and underground mining (pits). Mine sites are located directly at the bearings. **Figure 1** provides a geographical presentation of active coal mines in B&H, and in **Table 1**, general characteristics of the mines which were the subject of research are shown.



**Figure 1.** Position of coal mines and thermal power plants in Bosnia and Herzegovina.

Name of coal mine	Type of coal	Shelf	Top
Surface exploitation			
PK "Cubric" Mine "Banovici"	Brown coal	Sand, marl and freshwater limestone	Gray-yellow and gray marl, marly limestone and clay
PK "Dimnjace" Mine "Gracanica"	Lignite	Sandy clay and limestone marl	Sandy clay, sandy marl
PK "Drage" Mine "Tusnica"	Lignite	Clay, clay marl	Sandstones and conglomerates
PK "Vrtliste" Mine "Kakanj"	Brown coal	Marl-sand clay	Sandstones and different conglomerates
Underground exploitation			
Pit "Glavni sloj" Mine "Mramor"	Lignite	Sand	Marl clay
Pit "Djurdjevik"	Brown coal	Sandstone, clay-marl clay	Marl, marly limestones
Pit "Haljinici" –Mine "Kakanj"	Brown coal	Marl-sand clay	Sandstones and different conglomerates
Pit "Stara Jama" Mine "Zenica"	Brown coal	Marl clay, clayey marl	Layered limestone
Pit "Raspotocje" Mine "Zenica"	Brown coal	Marl clay, clayey marl	Layered limestone

Table 1. General characteristics of coal mines in Bosnia and Herzegovina.

The coal industry in Bosnia and Herzegovina is a potential source of danger of radioactive contamination of the environment, especially in cases when certain coals are used in power plants which indicate an increased content of natural radionuclides. For these reasons, in recent years, in accordance with the relevant regulations, the Public enterprise Elektroprivreda of Bosnia and Herzegovina composed of TPP Kakanj and TPP Tuzla carried out annual level monitoring of radioactivity in the two thermal power plants. Monitoring included checking the level of radionuclides in coal used for power generation, the content of radionuclides in ash and slag, and measured levels of radon and gamma radiation at locations in the vicinity of thermal power plants.

Table 2 presents the results of measurements (mean value) of specific activities of natural radionuclides in coal mines which were the subject of these investigations.

In Figure 2, a comparative graphical representation of the average specific activity of radionuclides in coals from different mines is provided.

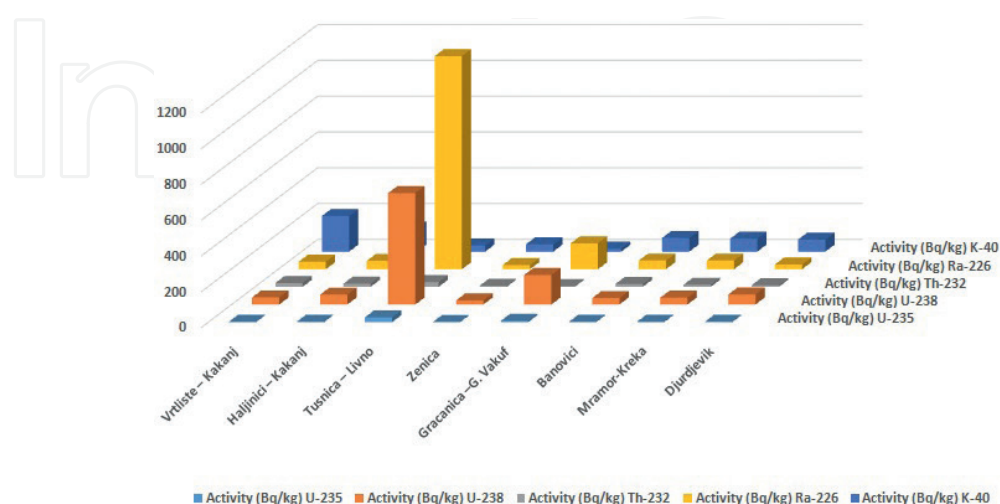
Highest specific activity of natural radionuclides, uranium and radium was measured in the coal mine Tusnica—Livno with a value of  $26.68 \pm 1.07$  Bq/kg for U-235,  $623.03 \pm 23.32$  Bq/kg for U-238, and  $1191.34 \pm 4.83$  Bq/kg for R-226. The highest values of Th-232 are measured in the coal mine Tusnica—Livno with value of  $26.67 \pm 1.86$  Bq/kg, whereas the highest values of potassium in coal mines were measured in mine Vrtliste—Kakanj. If it is known that, under appropriate regulation, the maximum activity for R-226 is 400 Bq/kg or 300 Bq/kg for U-238;

Coal mine	Activity (Bq/kg)				
	U-235	U-238	Th-232	Ra-226	K-40
Vrtliste—Kakanj	$1.82 \pm 0.21$	$39.58 \pm 6.63$	$21.78 \pm 1.00$	$42.05 \pm 1.24$	$199.09 \pm 6.84$
Haljinici—Kakanj	$2.54 \pm 0.31$	$55.08 \pm 6.64$	$17.69 \pm 0.81$	$46.62 \pm 1.27$	$129.57 \pm 5.82$
Tusnica—Livno	$26.68 \pm 1.07$	$623.03 \pm 23.32$	$26.67 \pm 1.86$	$1191.34 \pm 4.83$	$33.92 \pm 7.20$
Zenica	$1.08 \pm 0.18$	$23.36 \pm 3.84$	$5.61 \pm 0.47$	$23.44 \pm 0.71$	$40.68 \pm 3.39$
Gracanica—G. Vakuf	$7.62 \pm 0.86$	$165.41 \pm 10.07$	$4.25 \pm 0.63$	$145.14 \pm 1.74$	$16.92 \pm 1.86$
Banovici	$1.67 \pm 0.28$	$36.17 \pm 6.05$	$16.50 \pm 0.76$	$48.40 \pm 1.79$	$76.30 \pm 3.28$
Mramor-Kreka	$1.75 \pm 0.34$	$38.09 \pm 7.35$	$11.93 \pm 0.57$	$48.52 \pm 1.77$	$71.67 \pm 3.08$
Djurdjevik	$2.58 \pm 0.40$	$56.00 \pm 8.69$	$9.03 \pm 0.44$	$26.51 \pm 1.02$	$67.37 \pm 17.92$

**Table 2.** Specific activity of natural radionuclides in coal [4].

then from the **Table 2**, it can be concluded that brown coal from Tusnica has significantly increased levels of natural radionuclides in these two elements (2–3 times). Because of this knowledge, the percentage of coal from the mine Tusnica in electricity production in TPP Kakanj has been reduced, and thus the total level of natural radionuclides in coal used by the power plant is below the maximum levels.

Comparing these values with average values of radionuclides in coals of some European countries (UNSCEAR report 2000), it can also be concluded that the brown coal from the mine “Tusnica” has a significantly elevated level of natural radionuclides. These results of gamma spectrometry analysis were the main reason for conducting thorough research activity of concentration level of radon and gamma dose rate in coal mines in Bosnia and Herzegovina.



**Figure 2.** The mean specific activity of radionuclides in coals.

### 3. Research methods and instrumentalization

For creation of the experimental part of this work, the most advanced and most modern research methods of detection and dosimetry of ionizing radiation were used: a method of solid-state nuclear track detector (SSNTD) and method of measuring radiation ionization chamber. In addition to these measurements on the test sites, measuring of gamma radiation dosage was also conducted.

Measurement of radon concentration using nuclear track detectors was performed with Radon system (Radosys, manufactured in Hungary). The basic components of this system are diffuse dosimeter with the detector type CR-39; system for chemical analysis of detectors; and system for automatic reading of detectors. We used detectors made of poly-allyl-diglycol-carbonate, known as CR-39, with dimensions  $10 \times 10 \times 1$  mm, sensitivity to alpha tracks of 2.9 tracks per  $(\text{cm}^3 \text{ kBq h})/\text{m}^3$ . Limit saturation is greater than 12,000 kBqh/ $\text{m}^3$ . This method is based on registration of traces of particles from the radioactive decay of radon in the dielectric detector. Detection of charged particles using these detectors is performed with the tracks of the particles into which they penetrate the detector (latent traces). With this method, radon activity concentration was measured exclusively in the mine atmosphere and the measurement of the concentration of its decay products was avoided. **Figure 3** schematically shows the process of measuring radon using “RadoSys” system.

Error in the measurement of radon activity concentration by nuclear track detectors is calculated according to formula below:

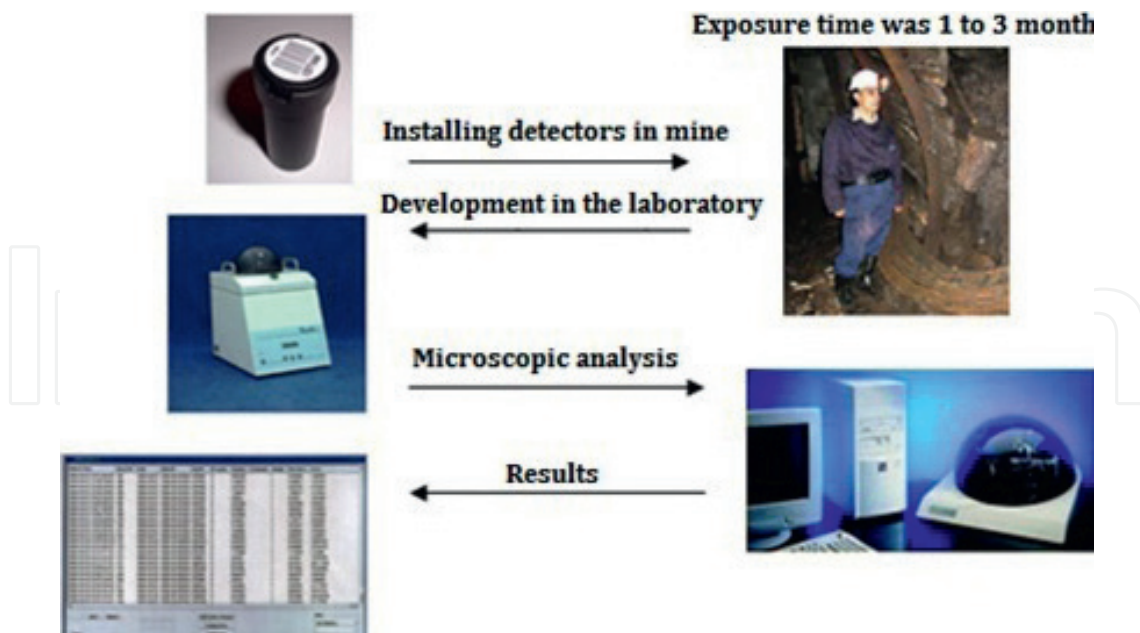
$$\sigma = A \sqrt{\sigma_{\rho}^2 + \sigma_K^2 + \sigma_{\tau}^2} \quad (1)$$

where  $A$  is the radon activity concentration,

$$\sigma_{\rho} = \frac{1}{\sqrt{N}} + 0.004$$

where  $N$  is the number of traces of  $\alpha$  particle in a detector,  $\sigma_K$  is the calibration error coefficient (for CR-39  $\sigma_K = 0.18$ ), and  $\sigma_{\tau}$  is error due to transport of dosimeter:  $\sigma_{\tau} = \frac{\text{duration of transport}}{\text{duration of exposure}}$ .

For the second method, which was done as a comparative research method, measuring system AlphaGUARD PQ 2000 PRO/MC503 was used (Genitron Instruments, made in Germany), whose work methodology is based on the principle of ionization [5]. The device can operate in two operating modes: diffusion and pump mode. In diffusion mode, radon diffuses into the ionization chamber through a glass fiber filter that prevents the entry of radon decomposition products or aerosols while for the pumping regime, “AlphaPUMP” is used. Measuring range of radon activity concentration of this product is  $2\text{--}2 \times 10^6$  Bq/ $\text{m}^3$ , while the temperature range of  $-10$  to  $50^{\circ}\text{C}$ . Calibration error of  $^{222}\text{Rn}$  is 3%. AlphaGUARD cylindrical ionization chamber device has an active volume of  $0.56 \text{ dm}^3$ . The basic configuration of this system are AlphaGUARD Radon Monitor and “Data Expert” software packages (**Figure 4**).



**Figure 3.** Order of measurement processes of radon in mines using “RadoSys” system.

To measure the dosage of gamma radiation in the mine atmosphere and at the location around the mine, ADL Gamma Tracer system was used, the latest product of Genitron Instruments GmbH, Frankfurt, Germany. Complete electronics and power supply are located in hermetic housing. The basic technical characteristics of ADL Gamma Tracer are: Detector Geiger-Muller tube, the measurement range of 10–10 Sv/h, the energy dependence of 45–1300 keV, the sensitivity is  $2 \times 0.2$  counts/s for 100 nGy/h; the measurement cycle can be set to 1, 2, 5, 15, 30, 60, and 120 min (specified by user); data capacity is 12,800 measurement points (4–1060 days). Through interactive infrared port, the registered values could be dislocated at any time. Gama professional software program for the usable communication and as a software for analyzing, guarantees an easy, fast, and secure access to the accumulated data and their visualization. In **Figure 5**, the most important components of Gamma Tracer system are given.



**Figure 4.** AlphaGUARD PQ 2000 PRO (manufacturer: Genitron Instruments).

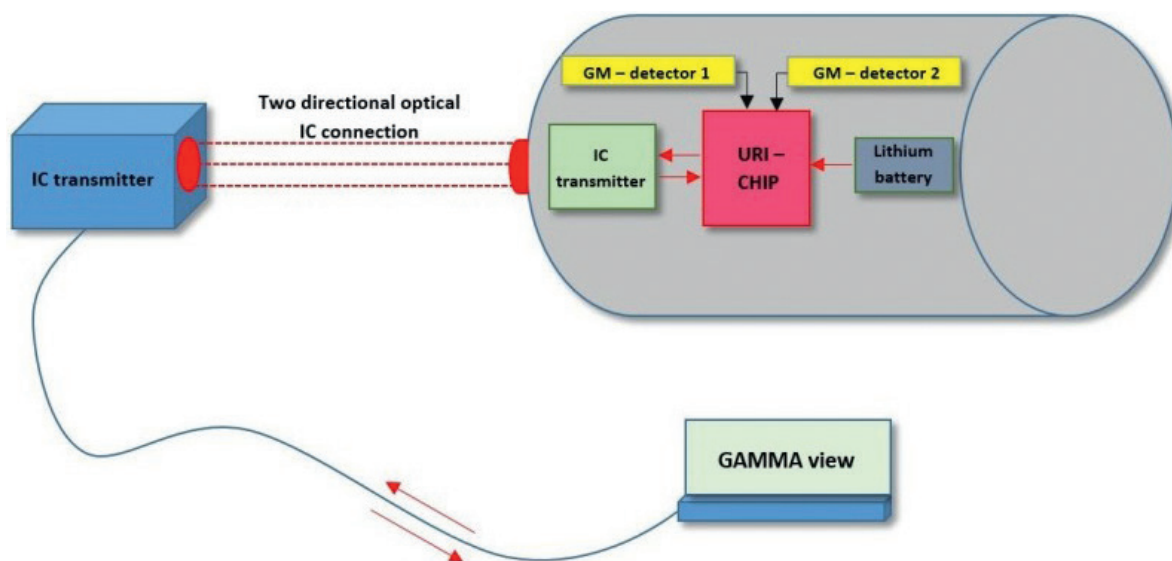


Figure 5. Basic components of Gamma Tracer system.

## 4. Results and discussion

In order to better and clearer perceive the contribution of natural radiation from technologically modified natural radioactivity, measurements of activity concentrations of radon were carried out, in most cases, during the most intensive work at surface of coal mines, when the layers and interlayers of coal and tailings on the surface mines were opened, as well as in all the activities that are performed daily in the underground coal mining. In addition to the mine site, for comparison, studies were also carried out in the immediate vicinity, as well as in the smaller (and sometimes larger) urban core.

Measurement sites were chosen after extensive analysis of all parameters that would be of importance for the research results. Also, for all measuring points on all test locations, following items have been taken into account:

- Setting of dosimeters was conducted immediately after their assembling, and thus reducing the effect of background values of radon.
- During transport, dosimeters were protected with aluminum foil.
- Reading of dosimeters was performed at the Laboratory for Dosimetry and Radiation Protection (LDDZZ) at Faculty of Sciences of the University of Tuzla.
- Measurement of radon concentration using an AlphaGUARD PQ 2000 PRO was done twice, the first time while placing dosimeters at the test site and the second time while taking the dosimeter after completing measurement.
- All measurements of radon concentration in air using an AlphaGUARD PQ 2000 PRO were carried out in the time interval of 10 min.

The research results are presented in **Tables 3–5**.

Name of coal mine	Number of measurement locations	RAC (Bq/m³)		
		Minimum	Maximum	Average
Surface exploitation				
PK “Cubric”	10	5 ± 2	44 ± 9	22 ± 5
PK “Dimnjace”	16	12 ± 4	45 ± 10	21 ± 6
PK “Drage”	10	19 ± 5	50 ± 10	24 ± 6
PK “Vrtliste”	10	7 ± 3	36 ± 8	20 ± 5
Underground exploitation				
Pit “Glavni sloj”	30	7 ± 2	71 ± 14	32 ± 7
Pit “Djurdjevik”	20	25 ± 6	76 ± 16	52 ± 11
Pit “Haljinici”	10	13 ± 4	50 ± 11	27 ± 7
Pit “Stara Jama”	20	910 ± 3	106 ± 21	27 ± 7
Pit “Raspotocje”	20	12 ± 3	38 ± 8	20 ± 5

**Table 3.** Results of RAC measurements at the workplaces of coal mines in B&H using nuclear track detectors.

Name of coal mine	Number of measurement locations	RAC (Bq/m³)		
		Minimum	Maximum	Average
Surface exploitation				
PK “Cubric”	10	5	111	35
PK “Dimnjace”	16	15	55	32
PK “Drage”	10	26	60	38
PK “Vrtliste”	10	14	33	21
Underground exploitation				
Pit “Glavni sloj”	30	12	92	43.5
Pit “Djurdjevik”	20	5	3420	279.5
Pit “Haljinici”	10	24	835	82.5
Pit “Stara Jama”	20	5	78	34.5
Pit “Raspotocje”	20	9	32	17.5

**Table 4.** Results of RAC measurements at the workplaces of coal mines in B&H using AlphaGUARD PQ 2000 PRO device.

As it can be seen from **Table 3**, the maximum mean concentration of radon (RAC) was measured using nuclear track detectors on the surface pit at PK "Drage" of coal mine Tusnica—Livno and the value is  $24 \pm 6$  Bq/m<sup>3</sup>.

Name of coal mine	Number of measurement locations	Gamma radiation equivalent dose rates in air (nSv/h)		
		Minimum	Maximum	Average
Surface exploitation				
PK “Cubric”	10	44	254	134.0
PK “Dimnjace”	16	73	108	87.0
PK “Drage”	10	80	106	91.0
PK “Vrtliste”	10	68	112	90.0
Underground exploitation				
Pit “Glavni sloj”	30	38	125	72.0
Pit “Djurdjevik”	20	48	180	97.5
Pit “Haljinici”	10	56	184	97.0
Pit “Stara Jama”	20	24	152	83.0
Pit “Raspotocje”	20	45	109	89.5

**Table 5.** Gamma radiation equivalent dose rates in working places of coal mines in Bosnia and Herzegovina.

No.	Site	RAC (Bq/m <sup>3</sup> )
1	Entrance to the old mining-1	27 ± 6
2	Entrance to the old mining-2	29 ± 6
3	Separation-1	25 ± 6
4	Separation-2	26 ± 6
5	Old warehouse Martinovac	19 ± 5
6	Warehouse of administration building	46 ± 10
7	Entrance desk (entrance to the mine)	44 ± 9
8	Spring Mandek-Novakovac. Water intake for water supply Tusnica	50 ± 10
9	Near place (about 200 m from mine)	45 ± 9
10	Administration building "Mine a coal Tusnica" in Livno-cellar	73 ± 14
11	Administration building "Mine a coal Tusnica" in Livno—first floor	43 ± 9
12	Livno—periphery (private house)	57 ± 11

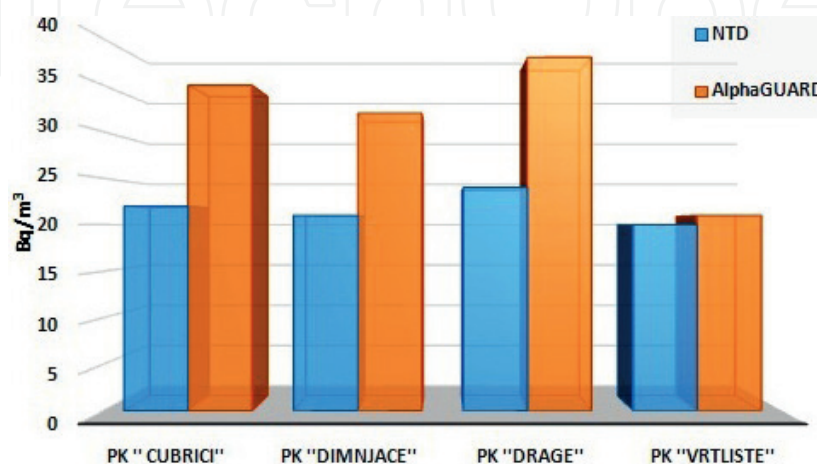
**Table 6.** Measurement results of radon activity concentration obtained using nuclear track detectors at pit PK Drage (near and far surrounding).

If we take into account all measurement sites at the locality of PK Drage (**Table 6**), it can be seen that the maximum concentration of radon in the air at this location was  $50 \pm 10 \text{ Bq/m}^3$ . Among other reasons, the reason for such a huge concentration of radon can be found in the fact that coal from this mine contains the largest percentage of radionuclides of uranium and radium with whose disintegration occurs radioactive gas radon, which is transported by diffusion from the depths to the surface. Regardless of this, the value of radon concentration in the air at the mine surface and at other mines are slightly higher than usual, which can be measured in most European countries, ranging from 10 to  $20 \text{ Bq/m}^3$ .

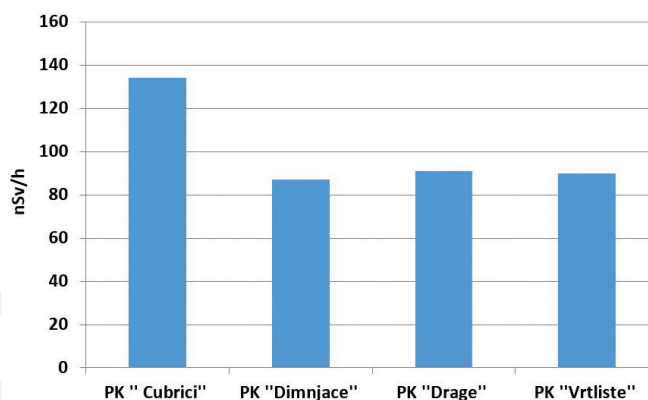
Short-term measurements of RAC using AlphaGUARD PQ 2000 PRO (ionization chamber) conducted at this open pit show some greater value than those obtained with nuclear track detectors (**Table 4**), which can be attributed with variety of weather conditions prevailing at the time of measurement (temperature, pressure, humidity, speed of moving air, etc.). The maximum value of measured radon activity concentration in the PK "Cubrici" was  $111 \text{ Bq/m}^3$ , while the highest mean radon activity concentration was measured in the PK "Drage." In **Figure 6**, a comparative graphical representation of the means of RAC for opencast mining measured by these methods is presented.

**Table 5** shows that the mean value of equivalent dose strength of gamma radiation in the working environment in open pits PK "Cubrici" is  $134 \text{ nSv/h}$  or  $1.174 \text{ mSv/y}$ , which is less than the global effective annual dose of natural resources. On the basis of UNSCEAR-1993rd results, the effective equivalent dose of average radon concentration is  $40 \text{ Bq/m}^3$  in buildings and  $10 \text{ Bq/m}^3$  in an open space, and for its decay products is  $1.2 \text{ mSv/y}$  and  $1 \text{ mSv/y}$  for other natural radioactive sources. In **Figure 7**, a graph of the mean values of intensity of an equivalent dose of gamma radiation in the working environment of open pits is given.

Based on the obtained results of measured radon concentration in coal mines (pits) B&H, which are given in **Table 3**, it can be concluded that concentration is insignificant. The highest average value of RAC measured by nuclear track detectors was  $52 \pm 11 \text{ Bq/m}^3$  in the pit "Djurdjevik," whereas the maximum RAC measured at one measurement location was  $106 \pm 21 \text{ Bq/m}^3$  in the pit "Stara Jama" of brown coal mine "Zenica." Although the average value of RAC in the pit "Djurdjevik" is significantly higher compared to other



**Figure 6.** Graphic presentation of medium value of RAC obtained using both nuclear methods.



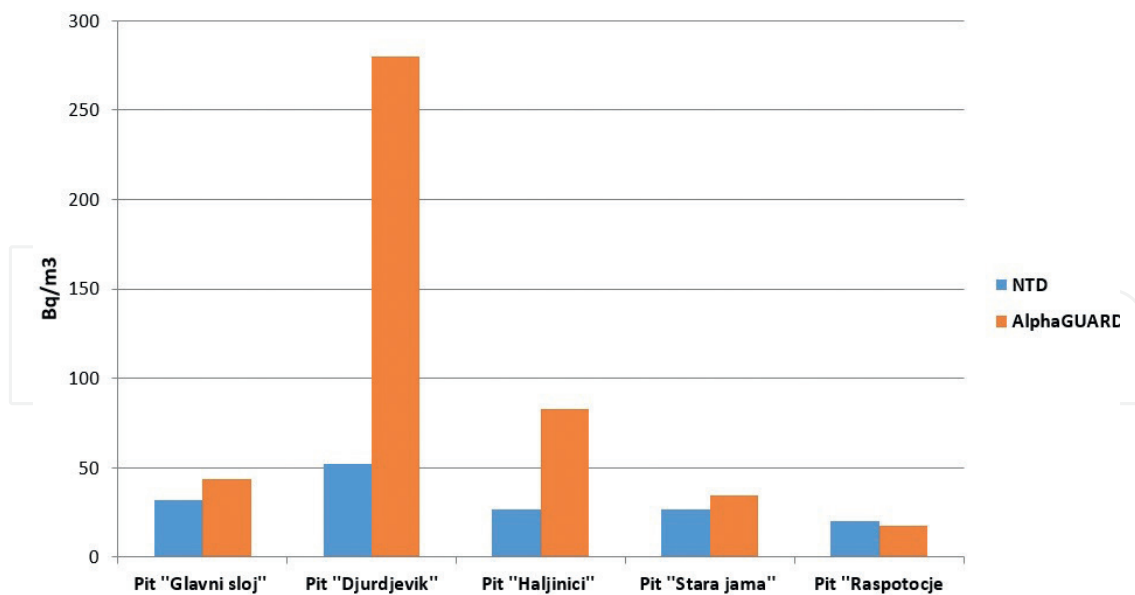
**Figure 7.** Graphic presentation of mean value of the equivalent dose rate of gamma radiation in working environment of open pits.

pits (somewhere twice), but in general it can be concluded that all these values are below the levels which are measured in the coal mines of some European countries. Causes of an increased concentration of radon in the air of pit "Djurdjevik" need to be sought in the geological structure of the tops and shelves of mines, and large quantities of underground water which were present in the pit during the measurements. Geology of the pit shelf varies from place to place, usually there are conglomerates, clay-marl clay, carbonaceous clay, while the tops of the pits consist of thick series of marls and marly limestone (**Table 1**). Having in mind that a very compact crystal structures represent an ambience with small penetration of radon gas (which is not the case with sand pits and rocks with cracks and fractures) and that a thick layer of clay is not only badly leaking the gas radon but also can change the direction of movement, then the values of RAC in the air of the cave "Djurdjevik" have their justification.

Measurements of RAC using an AlphaGUARD PQ 2000 PRO in the pits and surface mines also show something of greater values than those obtained with nuclear track detectors (**Figure 8**). These results variations can be attributed not only to different meteorological conditions prevailing at the time of measurements (temperature, pressure, humidity, speed of moving air, etc.) but also to the geological characteristics and mining operations during the measurement (drilling, blasting, dredging, transport, etc.).

The maximum RAC (**Figure 9**) measured by this method was  $3420 \text{ Bq/m}^3$  and had been measured in the pit "Djurdjevik," on the measuring site which was located near to the work site (coal excavation). This current value of increased RAC can be explained that during the excavation, there was a sudden release of radon that was trapped in the coal seams, which resulted in increasing the current RAC. That this was a current value of RAC, it was proved with repeated measurements with both methods of measurement. The same case happened in the pit "Haljinici" where at one measuring site measurement shows value of  $835 \text{ Bq/m}^3$ . Overall, the largest mean RAC was measured in the pit "Djurdjevik" and amounted to  $279.5 \text{ Bq/m}^3$ .

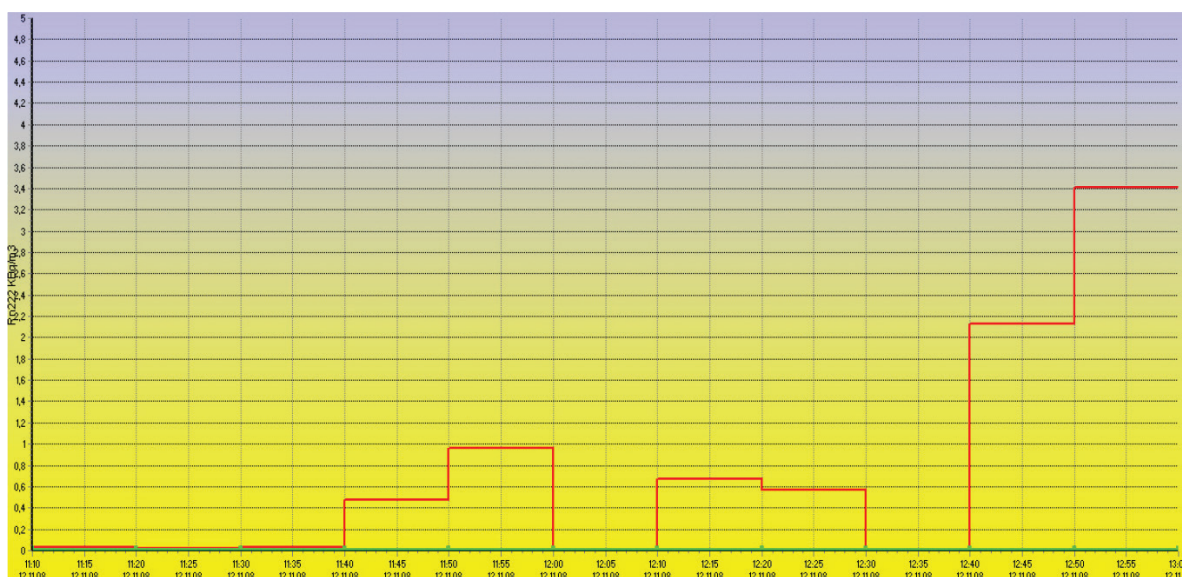
The first measurement of radon using an AlphaGUARD PQ 2000 PRO in the pit "Djurdjevik" and in its immediate vicinity was conducted in November. When on some locations obtained



**Figure 8.** Graphic presentation of RAC values in the mine pits in BiH.

values of RAC were high, additional measurements were conducted at the same locations in April. The measurement results show that the current values of RAC can vary considerably from one location to another and can range from 48 to 3420 Bq/m<sup>3</sup> at the first measurement and from 5 to 475 Bq/m<sup>3</sup> in the second measurement, which can best be seen in **Table 7**.

**Figure 10** shows a graph representation of the mean rate of the equivalent dose of gamma radiation in the air of coal mines with pit exploitation. The highest mean rate of the equivalent dose of gamma radiation was detected in the pit "Djurdjevik" and amounted 97.5 nSv/h, which is also less than the global annual effective dose from natural sources.



**Figure 9.** Graphic presentation of RAC [Bq/m<sup>3</sup>] in the air of pit "Djurdjevik".

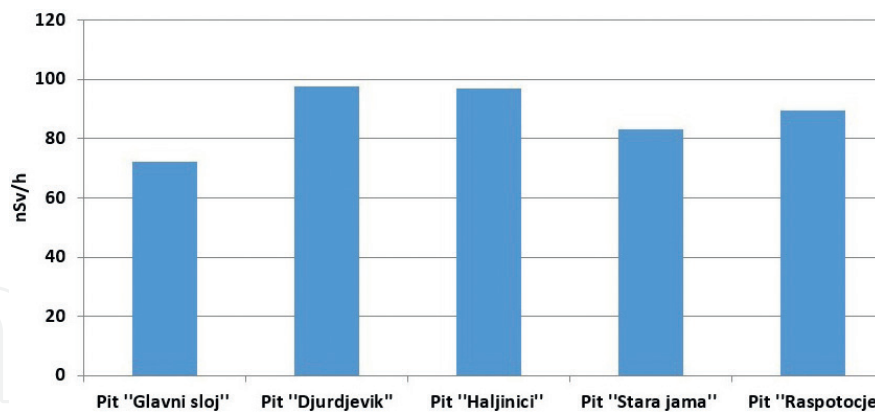
No.	Location (description)	RAC (Bq/m <sup>3</sup> )	
		First measurement	Second measurement
1	GDN 1	60	260
2	Level 180	48	475
3	GDN – Level 165	60	5
4	GDN – Level 137	60	5
5	GDN – Level 106	480	5
6	GDN – Level 90	770	5
7	Kota 55	48	12
8	Intersection GDN DH 25	670	12
9	Intersection TU 35 – DH 25	670	25
10	DH 25 between TU 35 and VU 6	580	25
11	VH 6 – on top	54	25
12	TH 18 – Intersection TN – (-2)	54	25
13	Explosion storage number 8 – TM (-2)	2340	55
14	Work site 1 – Preparation 36	3420	55
15	TH 18 – Intersection DP 18	220	40
16	TH 18 – Intersection IP 20	220	40
17	Intersection DNA – 2	54	46
18	Chamber tape – 2	54	38
19	TH 106 – by Vitla	60	18
20	GTN – entrance to the pit	60	30

**Table 7.** The values of radon concentration in the air of pit “Djurdjevik” obtained by AlphaGUARD PQ 2000 PRO device.

The calculation of correlation factor,  $r_{xy}$  is performed according to known statistical formula [6]:

$$r_{xy} = \frac{\sum_i x_i y_i - \frac{1}{n} \sum_i x_i \sum_i y_i}{\sqrt{\left[ \sum_i x_i^2 - \frac{1}{n} \left( \sum_i x_i \right)^2 \right] \left[ \sum_i y_i^2 - \frac{1}{n} \left( \sum_i y_i \right)^2 \right]}} \tag{2}$$

which enables further analysis of the obtained results. A significant correlation exists if the ratio is  $r_{xy} \geq 0.5$ . By calculating a linear correlation coefficient  $r_{xy}$  between the radon activity concentrations measured by nuclear track detectors in two different time periods (spring and autumn) in the mine Djurdjevik, considerable correlation between the two measurements is observed



**Figure 10.** Graphic presentation of mean value of the equivalent dose rate of gamma radiation in workplace pit mine a B&H.

( $r_{xy} = 0.64$ ). In the same mine, significant correlation was also observed between the radon activity concentration measured using AlphaGUARD device and the equivalent dose strength of gamma radiation measured in spring ( $r_{xy} = 0.64$ ), while the poor correlation is revealed by the first series of measurements conducted in autumn ( $r_{xy} = 0, 11$ ), which can be attributed to current weather conditions (temperature, pressure, humidity, air speed moving, etc.). A similar correlation ratio was observed with the results of measurements on the pit surface "Drage" of coal mine "Tusnica."

## 5. Calculation of effective dose

Assessment of the mean annual effective dose for workers who work on the surface and pit mines due to exposure to radon and its decomposition products can be calculated using a simple model (Annex B of the report UNSCEAR 2000) [3].

$$E = k_1 T C_{Rn} + k_2 F T C_{Rn} = (k_1 + k_2 F) T C_{Rn} \quad (3)$$

wherein,  $k_1 = 0.17 \text{ nSv}/(\text{Bq}/\text{m}^3 \text{ h})$  and  $k_2 = 9.0 \text{ nSv}/(\text{Bq}/\text{m}^3 \text{ h})$  are the conversion factors,  $T$  is the residence time in hours per year in the atmosphere with the concentration of radon  $CR$ , and  $F$  is the factor of balance.

Taking into account the results of measurement of RAC in the previous tables, and having in mind that a worker at the workplace on an average spends 8 hours a day (2920 hours per year), and using that  $F = 0.4$  for indoors and  $F = 0.6$  for outdoors, medium effective dose for workers in coal mines in B&H can be assessed. The results of these calculations are given in **Table 8**.

According to the UNSCEAR 2000 report, the average radon concentration amounts  $40 \text{ Bq}/\text{m}^3$  for indoors, and  $10 \text{ Bq}/\text{m}^3$  for outdoors. Substituting these values in the relation (3) provided that the values of other parameters are unchanged, the average annual effective dose originating from radon and its decay products in an enclosed space is obtained and amounts  $0.440 \text{ mSv}/\text{y}$ ,

	Coal mine	Effective dose (mSv)	
		Interval	Average
1	Cubrici	0.055–0.484	0.242
2	Dimnjace	0.132–0.495	0.231
3	Drage	0.209–0.550	0.264
4	Vrtliste	0.077–0.396	0.220
5	Glavni sloj	0.077–0.782	0.352
6	Djurdjevik	0.275–0.837	0.572
7	Haljinici	0.143–0.550	0.297
8	Stara Jama	0.110–1.167	0.297
9	Raspotocje	0.132–0.418	0.220

**Table 8.** Values of the annual effective dose for workers on the surface and pit mines as a result of exposure to radon and its decomposition products (nuclear track detector).

respectively 0.163 mSv/y for indoors. Comparing these values to the values from **Table 8** it is seen that the workers of mine “Djurdjevik” were exposed to somewhat higher dose than the usual, and to almost twice higher dose in the mine area where drilling and excavation are carried out, where we measured the maximum value.

Assessed values of the effective dose of employees at surface pit “Drage” of coal mine “Tusnica,” as a result of exposure to radon and its decomposition products are ranged from 0.209 to 0.550 mSv/y, with average value of 0.264 nSv/y.

## 6. Conclusions

During digging and coal mining, radioactive radon gas, which is contained in natural geological structures, is being redistributed from the depth of coal beds. Thus, this gas can be concentrated in depots and stopes of mines or can be transported to the surface of the earth, which can significantly change the levels of radioactivity and radioecology picture in the working and living spaces. This chapter presents the research results of activity concentration level of radon and gamma radiation in the air in a coal mine in Bosnia and Herzegovina, as on the surface coal mines and in the pits, obtained with most contemporary measuring devices. On the basis of all knowledge about radon and its decomposition products, a methodology was defined and research was done in mines with nuclear measuring methods which are world-wide mostly used for measuring radon in mines: nuclear track detectors method (passive method), a method of measuring radiation with ionization chamber (control method). At the same locations in the mine atmosphere, simultaneous measurement of intensity of gamma radiation using an “ADL Gamma Tracer” system is performed. Based on the obtained results,

assessment of the mean annual effective dose for workers who work in underground mines as a result of exposure to radon and its decomposition products was carried out.

With respect to the property of radon that it dissolves very well in water, influence of the amount of precipitation, intensity and underground waters to the levels of radon in the mine was noticed. Studies carried out in this chapter show that there are variations in the concentration of radon gas structure of coal, in the atmosphere and in other ambient media correlated to the characteristics of geologic structure, in function of the technology of obtaining coal and weather and climate changes. During the tests, with special attention, currently installed ventilation system at pit coal mining, as well as the presence of ground-water, was considered.

Mean values of radon activity concentration measured by nuclear track detectors in mines where surface exploitation is done are insignificant. The highest mean value of RAC obtained for PK "Drage" of coal mine "Tusnica" – Livno was  $24 \pm 6$  Bq/m<sup>3</sup>. The main reason why this mine showed the highest value of RAC is that the coal from this mine contains the largest percentage of radionuclides of uranium and radium with whose break-up radioactive gas radon is produced.

Preliminary measurements of RAC in housing and other facilities that are located in the immediate vicinity of open pit mines show that the mean values of RAC are ranged from  $33 \pm 7$  Bq/m<sup>3</sup> in the closer environment of the mine "Banovici" to  $50 \pm 11$  Bq/m<sup>3</sup> in the closer environment of surface pit "Dimnjace" of coal mine "Gracanica," are below the limits established by international organizations.

Short-term measurements of RAC performed using an AlphaGUARD PQ 2000 PRO device showed somewhat higher values than those obtained with nuclear track detectors on all surface mines, which can mostly be attributed to the different meteorological conditions during measurements (temperature, pressure, humidity, speed of movement of air, etc.).

On the basis of obtained results of RAC measured using nuclear track detectors in the pits of coal mines in Bosnia and Herzegovina, it could be concluded that the highest mean RAC measured in the pit "Djurdjevik" was  $52 \pm 11$  Bq/m<sup>3</sup>, which is below the values measured in some mines of European countries. Geology structure of rocks (sandstones, clay-marl clay, carbonaceous clay) and shelves (marls and marly limestone) of pit "Djurdjevik," as well as large quantities of underground waters (which were present in the pit during the measurement), are the main reason why the highest mean values were obtained from all other considered pits. The maximum value of RAC measured by this method is registered in the pit "Stara Jama" of coal mine "Zenica" and amounted  $106 \pm 21$  Bq/m<sup>3</sup>. The location where the maximum value was obtained was a location where a collision of input (fresh) and output (exhausted) air currents happens and where a high humidity in the air was registered.

Activity concentrations of radon measured using an AlphaGUARD PQ 2000 PRO device in the pits show that the current values can vary significantly from one location to another, which is particularly characteristic for the pit "Djurdjevik" (48 to 3420 Bq/m<sup>3</sup>) and for the pit "Haljinici" of coal mine "Kakanj" (25 to 835 Bq/m<sup>3</sup>). Proof that these results are presenting

current values were repeated measurements which didn't register significant values. Such large variations of RAC in some pits are proof that coal excavation can suddenly release trapped radon in coal layers, and as a results are current increases of RAC. It is impossible to accurately identify and even predict when it will come to a sudden release of radon during coal excavation, but the measurements carried out in this chapter showed that it really can happen.

Based on the research results of RAC in the pit coal mines of Bosnia and Herzegovina, it is possible to determine the efficiency of ventilation systems for each pit separately. It has been established that currently installed ventilation system does not allow the retention of radon gas in the pit, but using it, radon is being removed from the pit and thus can increase the RAC out of the pit, and thus affect the overall radioactivity of the environment. Measurement of RAC can be used as a good indicator of the quality of the ventilation systems in the pit of the mine.

In any coal mine, radon concentration dependency of the depth is not noticed, suggesting that radon does not come from the earth depth. In fact, RAC dependence of the rocks composition that is in the environment of set dosimeters was noticed. Radon concentrations are higher where the surroundings are slates, which have a higher content of uranium.

The measured intensity dose of gamma radiation in the working environment of surface and pit mining operations using autonomous device ADL Gamma Tracer system show a slight increase compared to the level of natural background from an unspoiled natural environment, and in general it can be said that they are within the limits of normal values measured and many European countries. Measurements clearly show that there are differences between levels of the undisturbed natural environment radiation from selected measurement locations that were served for comparison and the level of natural radioactivity in the impact zone of mining operations at the considered coal mines. These differences in values of gamma radiation dosage are lower than 10%.

On the basis of all conducted research in this chapter, it is evident that every mine, every house, and every residential or other object has its own specific "life" of radon. Therefore, it is not enough to measure the RAC in only one lignite or brown coal mine and on that basis make a general conclusion, it is necessary, with a number of aspects, investigate each mine, and only then make a conclusion that is peculiar to it alone.

The estimated values of annual effective doses for employees on most workplaces at considered mines as due to exposure to radon and its decomposition products for 8 hours of work per day (2920 hours per year) were within normal values.

Having in mind the conditions in which the researches were done, especially when it comes to measurements carried out in the pits, it can be concluded that the achieved knowledge and the results obtained in this study represent a significant contribution to the creation of the initial database for mapping and forecasting geogenetic potential of radon in coal bays of Bosnia and Herzegovina, as well as creating maps of radon and natural radioactivity in Bosnia and Herzegovina.

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