

Radon concentrations and exposure levels in the Trepça underground mine: A comparative study



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ABSTRACT

This study presents the results of radon concentration measurements and radiation exposure levels in the Trepça (pronounced Trepcha) underground mine, which are important to assess the radiogenic hazards to occupational workers. Radon concentration measurements were carried out in selected locations of the Trepça mine using continuous radon monitor CRM-510 and portable radon monitor PRM-145. Results show that the radon gas concentration in the mine varied from 54 Bq/m³ to 691 Bq/m³. The radiation exposure doses of miners from radon and radon daughters were determined. The total annual effective doses varied from 0.4 mSv/y to 5 mSv/y. The effective dose has been found to be lower than the dose limits recommended by the International Commission of Radiation Protection. The comparison of indoor measurements shows that the highest time-dependent indoor values of radon concentration in the two lowest horizons decreased during the time period 2010–2015 and that their average values increased by about 10%. This means that five-year mining activities generated pathways for radon gas flow, causing the decreasing of the maximum values and increasing the average values.

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1. Introduction

The human population is permanently exposed to ionising radiation from natural sources. About 50% of the total dose belongs to radon and its decay products (UNSCEAR, 2010). Radon is a radioactive gas and spontaneously decays into many short-lived daughter progenies, among which polonium-218 (Po-218) and polonium-214 (Po-214) are very high alpha emitters and are considered environmental health hazards (Sumner et al., 1991). Since radon and its progeny are easily inhaled and can penetrate deep into the airways of the lung, the alpha particles they emit carry enough energy to cause cell DNA damage within the airways and thereby increase lung cancer risk. Epidemiological studies have indicated that the presence of radon and its decay products in inhaled air causes a health risk for lung cancer (Darby et al., 2005). After reviewing numerous studies and data sources, the WHO reported that up to 15% of all lung cancers worldwide were caused by

radon exposure (WHO, 2009). Some studies (Rosario and Wichmann, 2006) show that radiation exposure is also responsible for non-cancerous diseases like stroke, heart disease and those related to the respiratory and digestive systems.

Mining and especially underground mining have an impact to safety and occupational health of miners and people living near the mines, as well as environmental degradation and pollution (Damigos, 2006). Hence, many tools have been developed to detect and mitigate environmental effects focused in the framework of sustainable development in mining (Basu and van Zyl, 2006; Worrall et al., 2009). An important role in this aspect has national legislative and policy framework and other environmental measures relating to environmental management, as well as on the implementation capacity (Mutagwaba, 2006).

On the other hand, mining activities, has been identified as one of the potential sources of exposure to naturally occurring radioactive materials (UNSCEAR, 2000). Many surveys involving radon concentration measurements report a high radon risk in mines. The high values of radon concentrations measured in abandoned gold mines can reach about three times the upper action level recommended by the ICRP for workplaces (Anjos et al., 2010). Radon

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levels in the atmosphere of mines vary over time depending on the type of mine, geological formations, working conditions and parameters such as temperature, humidity and pressure (AGIR, 2009). Moreover, one of the most important factors responsible for radon concentration in the atmosphere of mines is ventilation (natural or mechanical). Ventilation is the most effective way of reducing the accumulation of radon gas concentrations in the mine's atmosphere (Zafir et al., 2013). In mines radon is exhaled mainly from the mine walls, broken ores, backfill tailings and mine water (Sahu et al., 2014). When a miner inhales the mine's air, radon is exhaled along with the exhaled air. However, its daughter products, which are solid decay products, may be deposited in the lung, especially in the upper respiratory tract, and continue to irradiate the lung tissues. The high concentration of aerosols can significantly affect the value of the effective dose to which the miners can be exposed (Skubacz et al., 2016). The typical activities in mines are drilling, detonation, the transportation of materials and the maintenance of equipment and the mine structure. Some of these activities can result in the release of radon gas and its daughter products. Radon levels in the atmosphere of mines are considered a key indicator of the radiation hazards. National radon concentration surveys are essential in order to set reference levels, which, if

exceeded, it is recommended to take action to reduce them. The national regulatory authorities of some countries have set reference levels for workplaces. The reference levels for the majority of countries are in the range of 400–3000 Bq/m³ (Fig. 1) (Synnott and Fenton, 2005). An analysis of recent legislation in several European countries shows that recent regulation by some countries still continues to allow high reference levels in workplaces (Pacheco-Torgal, 2012).

Many radon investigations have been performed in indoor environments or working places in Kosovo (Bekteshi et al., 2011). However, studies of the concentration levels of radon and its progeny in mines are few (Hodolli et al., 2015). The aim of the present study was to measure radon concentrations in the Trepça mine and to estimate the annual exposure of the workers. By comparing five-year span measurements, we intend also to study the temporal and spatial dependence of radon distribution in the mine.

2. Description and geology of study area

The study area, the Trepça mine in Stan Terg, located in northern Kosovo, is one of the most ramified and deep mines in Kosovo and region (Fig. 2, left) (SCA, 2016). Within the Vardar Zone of Dinaride, the Stan Terg deposit is situated in the centre of the so-called Trepça Mineral Belt, which is one of the largest lead and zinc ore areas in Europe. The ore mineralogy of the deposit is dominated by pyrite, pyrrhotite, sphalerite and galena, with typical carbonate gangue minerals and minor quartz. The ore bodies have a strike extension of 1200 m (Fig. 2, right) (Hyseni et al., 2010).

3. Materials and methods

Measurements were carried out in the Trepça mine at different locations, particularly in horizons and workplaces where large number of workers frequent them. The sites selected for sampling consist of the active areas of each horizon, in which it is expected

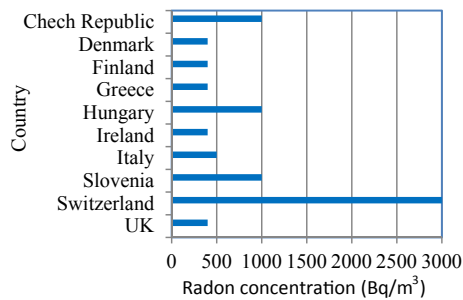


Fig. 1. Reference levels for radon gas in underground workplaces for some countries.

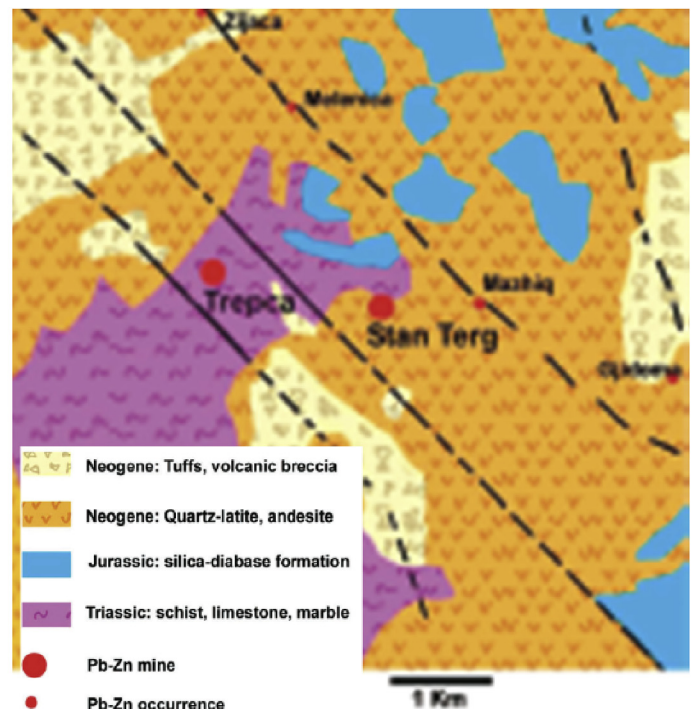


Fig. 2. Geographic map of Kosovo locating StanTerg (Pb-Zn-Ag) underground mine (left); Stan Terg regional geology (right).

that the radon concentration values would be high. The workplaces, in most cases, are at the end of the horizon, at just the place of extraction of the body ore, in some case after long walks and climbs. Most of the measurements were performed under mining conditions, i.e., underground, at high temperatures, with wetness, dust and high humidity, and in darkness. In order to review the influence of mining activities on radon distribution, measurements were also conducted in selected sites of inactive areas (horizon V) and at the ground's surface.

There are many methods and techniques for measuring radon and radon progeny in the air (for a review see: WHO, 2009). Measurements of radon concentrations were carried out with the Continuous Radon Monitor CRM-510, which operates according to the principle of the ionising chamber. This device is a fully portable continuous radon monitor that can read, record and print hourly test data for 96 h in “passive mode,” as well as other secondary parameters, such as environmental temperature, relative air humidity and atmospheric pressure. During measurements, the counter was placed at the height of the breathing organs (~1.5 m), turned on and left at least 44 h (and up to 96 h) in one position. Ambient air passively diffuses inside the chamber through a permeable membrane. As radon atoms decays, emitting alpha particles within the sensing volume of the chamber, the air becomes ionized. The flux of oriented ions so produced is recorded as a current. The number of pulses is proportional to the radon concentration. To ensure continued confidence in the accuracy of the measurements, a calibration of the instrument was performed as recommended by the manufacturer.

Instantaneous radon concentration was measured also by an active method, using portable radon monitor PRM-145. PRM-145 utilises an alpha scintillation technique for monitoring the alpha activity of radon and its short-life products. The samples were processed following standard procedures (Vaupotic et al., 1992). Air samples were collected directly into the 0.7 dm³ alpha scintillation cells. After 3 h of sampling, when radon and its short-lived decay products reached radioactive equilibrium, the activity was measured. The detection method of the PRM-145 is based on the special properties of the scintillation material, silver-activated zinc sulfide [ZnS (Ag)]. The alpha scintillation cells have inner walls coated with silver-activated zinc sulfide as a scintillator, except one, which is transparent and serves as an optical link with the photomultiplier tube. Alpha particles from radon generate photons in the scintillation cell, which the photomultiplier tube transforms into electric signals. The PRM 145 counts these electric signals, then calculates the concentration of radon in the sample, displays the

results (together with the uncertainty of the measurement) and stores them.

The annual average effective doses D_{eff} (mSv/y) received by the workers was assessed according to the dose assessment methodology (UNSCEAR, 2000):

$$D_{\text{eff}} = C_{\text{Rn}} \times F_e \times \text{DCF} \times t_{\text{avg}} \quad (1)$$

where C_{Rn} is radon concentration (in Bq/m³), DCF is the dose conversion factor (9 nSv/h per Bq/m³) and t_{avg} is the average time spent at work, whose value is 2000 h/year. The equilibrium factor F_e between radon and its decay products was assumed to be 0.4 for indoor and 0.5 for outdoor places (UNSCEAR, 2000).

4. Results and discussion

A series of 226 indoor radon measurements were carried out in representative points of 4 horizons of the Trepça mine as well as at the ground's surface. The Trepça mine comprises 11 horizons, but mining activities are conducted only in 9th, 10th and 11th horizons. The average depth of each active horizon is about 60 m. Exploitation of ore comprising lead, zinc, gold and silver now has reached approximately 800 m beneath the earth's surface (horizon XI). In order to investigate the radon distribution for different locations with different conditions in the mine, measurements were carried out also in horizon V where no mining activities took place. All horizons have natural and artificial ventilation. In order to evaluate the precision of the measurements for radon concentration, two sampling techniques were used: a pulsed ionisation chamber and the scintillation counter technique. A comparison between results of duplicate measurements obtained with both techniques carried out concurrently in the same locations and conditions is in reasonably good agreement, with variations within about 10%.

All radon measurements were completed over a period of six months (February–April and September–December 2015) under the same environmental conditions; therefore the influence of humidity and air pressure is negligible. Data are summarised in Fig. 3 in two graphs presenting the frequency distribution histogram of the radon concentration within 20 Bq/m³ intervals in the Trepça mine and the ground's surface. Graph (a) summarises the data from all locations in the mine obtained in 2010, with (in Bq/m³) the median, 262; the mean, 281; and the maximum, 748, whilst graph (b) encompasses data from same locations obtained in 2015, with (in Bq/m³) the median, 279; the mean, 286; and the maximum, 691.

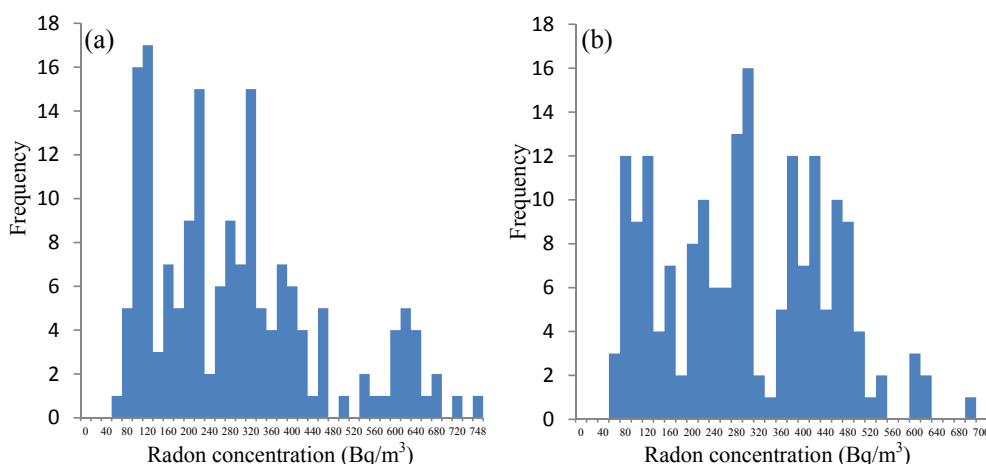


Fig. 3. Frequency distribution of radon concentration in Trepça underground mine in 2010 (a) and in 2015 (b).

Table 1

Statistical parameters of radon concentration (C_{Rn}) and the related annual effective doses (D_{eff}) in the Trepça mine (TM) and service office (SO).

Parameter	Values in 2010				Values in 2015			
	C_{Rn} (Bq/m ³)		D_{eff} (mSv/y)		C_{Rn} (Bq/m ³)		D_{eff} (mSv/y)	
	TM	SO	TM	SO	TM	SO	TM	SO
Arithmetic mean	281.4	152	2.04	1.10	286	162	2.07	1.17
Standard deviation	166.2	19.3	1.20	0.14	146	22	1.05	0.16
Geometric mean	234	151	1.69	1.09	242	160	1.75	1.16
Median (Bq/m ³)	262.5	154	1.89	1.11	279	168	2.01	1.21
Minimum	60	115	0.4	0.83	54	97	0.4	0.70
Maximum	748	197	5.4	1.42	691	185	5	1.33

The radon concentration distribution parameters are shown in Table 1. The calculated arithmetic and geometric means of radon concentrations in the Trepça mine are: 286 Bq/m³ and 242 Bq/m³, respectively. It is evident from these figures, the results fit a typical lognormal distribution well.

The spatial concentrations of radon and its decay products in the Trepça mine are very complex and time dependent. According to the results of the measurements, radon concentration varies considerably from horizon to horizon and within the same horizon of the mine. The comparison of indoor measurements from the entrance to locations deep in the mine shows in general a shift of radon peaks following the direction of deeper points in the mine. For particular horizons, radon concentrations depend on the depth of the horizons in the mine. A general trend of elevated radon concentrations was that they were found further and deeper into the horizons. Average radon concentrations were found to range from 245 Bq/m³ (horizon V) to 441 Bq/m³ (horizon XI). Most enhanced values, up to 691 Bq/m³, occurred at mining locations in horizon XI. This change of radon levels depends on many factors, especially the ventilation. Furthermore, because radon is the heaviest of all gases and about 8 times heavier than air, it tends to accumulate at lower horizons. It should be noted that the measurements reveal that radon concentration in all locations were below the actionable level of 1000 Bq/m³ for workplaces defined by the IAEA (IAEA, 2003).

The analysis of data shows that in the areas affected by mining activities (horizons X, XI) maximum indoor values decreased from 531 Bq/m³ to 472 Bq/m³ (horizon X) and from 748 Bq/m³ to 691 Bq/m³ (horizon XI), respectively, in the time period 2010–2015. This analysis also shows that their average values increased from 348 Bq/m³ to 380 Bq/m³ (horizon X) and from 402 Bq/m³ to 441 Bq/m³ (horizon XI). Considering that the same ventilation system operated during these years, the impact of ventilation on the change of radon concentration and effective dose to miners is negligible. This difference can be attributed to five-year mining activities, which

have generated pathways for radon gas flow, causing a decrease in the maximum values and an increase in the average values. Additionally, the influence of the geological characteristics of this mine should be investigated in detail.

In the second step of the study (September–December 2015), radon concentration was measured in selected sites of horizon V. This horizon is inactive, and so the radon concentrations are not influenced by the mining activities. Radon concentrations were found to range from 109 Bq/m³ to 401 Bq/m³ with an average of 245 Bq/m³. Average radon concentrations were decreased by about 5% compared with those of 2010. In all locations of the mine, the radon content was generally below the reference levels recommended by the ICRP. The minimum, average and maximum values of radon concentrations in the Trepça mine for the last five years and recent data are given in Fig. 4.

In order provide relative values for the mine and the ground surface, as well as for workers compared to the general population in the area, the radon level and annual average effective doses were estimated in the service office. The service office is located in the building near the entrance of the Trepça mine. In the service office, however, lower maximum radon concentrations were detected than in areas near the mine: 185 Bq/m³ and 398 Bq/m³, respectively (Xhafa et al., 2009). Taking into consideration that the service office has no ventilation system, it can be concluded that this is a result of the influence of other factors, mainly geological. The radon concentrations detected in the service office (median: 168 Bq/m³) were lower than inside the mine (median: 279 Bq/m³). Many surveys involving radon concentration measurements in mines have verified this phenomenon (BEIR, 1999).

The maximum annual effective dose limits should be monitored such that they do not exceed an effective dose of 20 mSv/y averaged over five consecutive years (IAEA, 2003). This exposure assessment was based on a radiation dose that could be received by any miner working in a mine for a period of one year. The effective doses received by miners, calculated using Equation (1), are given in Fig. 5. The maximum annual effective dose in the service office is

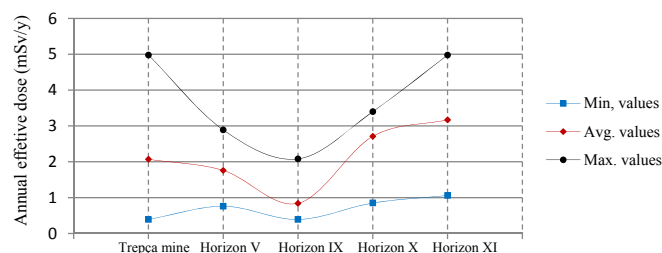


Fig. 5. Values of annual effective doses at Trepça mine and different horizons estimated for the year 2015.

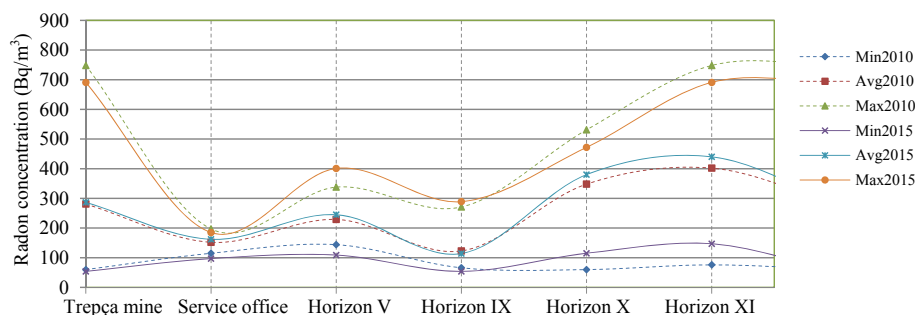


Fig. 4. Radon concentration at 2010 (dashed lines) and 2015 (solid lines) in Trepça mine, service office and different horizons. Markings and abbreviations on charts legend: Min 2010, Avg 2010, Max2010 means minimum, average, maximum values in the year 2010 and Min 2015, Avg 2015, Max2015 respective values for 2015.

1.33 mSv/y, and in the mine, it is 5 mSv/y. These values are found to be lower than the actionable levels recommended by the ICRP (ICRP, 2007).

5. Conclusion

The radon levels and annual average effective doses were estimated for 4 horizons in the Trepça mine and compared with those of 2010. The measurements of the radon concentrations were conducted using Continuous Radon Monitor CRM-510 and portable radon monitor PRM-145. From the results obtained, the following can be concluded:

- The radon concentration measured in the Trepça mine in 2015 varies from 54 Bq/m³ to 691 Bq/m³. The average and median indoor radon concentrations were 286 Bq/m³ and 279 Bq/m³, respectively. Radon concentrations at all horizon sites were below the actionable level ranges for workplaces recommended by ICRP.
- The annual average effective dose received by the miners in the examined locations was estimated to be from 0.4 mSv/y to 5 mSv/y, which means that they are lower than dose limits recommended by the ICRP. Finally, it can be concluded that the surveyed horizons are generally safe in terms of the risk to health. Nevertheless, when calculating the total dose of exposed workers, the obtained values should be added to the values outside of the mines, which means the outdoor exposure and indoor exposure in their houses. Therefore, the survey of indoor radon concentrations in workplaces should be continued.
- The analysis of the data shows that spatial concentrations of radon and its decay products are very complex and time dependent. The spatial distribution of higher indoor values varies over time and follows the direction of the mine as it gets deeper. A general trend of elevated radon concentrations further and deeper into the horizons was observed. The radon concentrations in the mine were rather high, compared to the ground's surface.
- The comparison of indoor measurements in active working areas of the mine show that the highest time-dependent indoor values of radon concentration in the 2 lowest horizons decreased over the time period 2010–2015 and that their average values increased by about 10%. The differences in the results of the recent and earlier surveys can be attributed to the mining activities. Conclusively, five-year mining activities have generated pathways for radon gas flow, causing the decreased the maximum values and increased average values.

The results of radon concentration measurements and the estimated annual average effective doses will be used as bases for the national regulatory authority to prepare Kosovo's regulatory standards.

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Abbreviations

Bq/m ³	becquerel per cubic meter
C _{Rn}	radon concentration
DCF	dose conversion factor

D _{eff}	annual average effective dose
F _e	equilibrium factor
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
mSv/y	milisievert per year
SO	service office
t _{avg}	average time spent at work
TM	Trepça mine
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

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