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ГЛАСНИК ОДЈЕЉЕЊА ПРИРОДНИХ НАУКА, 17, 2007.

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INDOOR RADON CONCENTRATIONS IN THE CAPITAL OF MONTENEGRO

Abstract

The systematic indoor radon measurements in Podgorica, the capital of Montenegro, were performed in 2002/03, in the frame of the national radon survey program. Using CR-39 track-etch detectors, radon concentrations were measured in 89 dwellings during 6 months in the summer and 6 months in the winter period. The obtained annual mean concentrations of radon in dwellings range from 6.4 Bq/m^3 to 557 Bq/m^3, with a median value of 33.2 Bq/m^3. They belong to a lognormal distribution, with a geometric mean of 36.4 Bq/m^3 and a geometric standard deviation of 3.0. Only in one case the annual mean concentration (557 Bq/m^3) exceeded the action level (400 Bq/m^3). The maximum radon concentration of 851 Bq/m^3 was measured in one of the sampled dwellings in the winter period.

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The results of these measurements are in a good agreement with a previous investigation of indoor radon in Podgorica, and they are comparable with indoor radon concentrations in the other European countries.

INDOOR KONCENTRACIJE RADONA U GLAVNOM GRADU CRNE GORE

Izvod

Sistematska mjerenja *indoor* koncentracija radona u Podgorici, glavnom gradu Crne Gore, realizovana su 2002/03 godine u okviru programa istraživanja i mapiranja radona u stanovima u Crnoj Gori. Koristeći CR-39 detektore tragova, koncentracije radona mjerene su šestomjesečno u 89 stanova u ljetnjem i u zimskom periodu. Mjerenjima je nađeno da je opseg srednjih godišnjih koncentracija radona u stanovima u Podgorici (6.4–557) Bq/m^3, sa medijanom 33.2 Bq/m^3. Ove koncentracije slijede lognormalnu raspodjelu, sa geometrijskom sredinom 36.4 Bq/m^3 i geometrijskom standardnom devijacijom 3.0. Samo u jednom slučaju je srednja godišnja koncentracija radona (557 Bq/m^3) bila iznad akcionog nivoa (400 Bq/m^3). Maksimalna koncentracija radona od 851 Bq/m^3 izmjerena je u jednom od uzorkovanih stanova u zimskom periodu.

Dobijeni rezultati su saglasni sa ranijim istraživanjem radona u Podgorici i uporedivi sa *indoor* koncentracijama radona u drugim zemljama Evrope.

INTRODUCTION

The radon action levels adopted in Montenegro are in accordance with the international recommendations [1], i.e. 400 Bq/m^3 for existing houses, and 200 Bq/m^3 for future buildings. However, they were adopted without knowing the real situation regarding exposure to radon in Montenegro, the country with an area of 13.812 km^2, population of 620.527, and 173.887 inhabited dwellings (by the Census 2003). Therefore, the first systematic long-term indoor radon measurements in Montenegro started in 2002, in the frame of the national radon survey program, where measurements in about 1000 houses all over the country were planned.

Podgorica, as the capital of Montenegro and the biggest town in the country, with 143.479 inhabitants and 40.142 inhabited dwellings (by the Census 2003), has a special importance within this national radon program. That is why the selection of dwellings in this town for the radon survey was carried out very carefully. The sampling criteria were geological and pedological characteristics of the town area, types and construction materials of the houses, local density of population in the town districts, and the final selection, in accordance with all mentioned criteria, was fully random. The basic 750 m grid square for the town of Podgorica was chosen on the basis of geological and pedological criteria, with one sampled dwelling in each of the 73 squares covering the urban area. Number of the sampled homes in a square was then eventually increased depending on the density of dwellings in that part of the town. From a total number of 94 dwellings selected in that way in the town of Podgorica, radon concentrations in 89 of them were measured in both the summer and winter period.

EXPERIMENTAL

Home-made passive time-integrating dosimeters for radon monitoring in the air were used. Our plastic dosimeter is of the well-known Karlsruhe type. It presents a diffusion chamber equipped with a CR-39 solid state nuclear track detector. As a protection of the moisture which might collect on the detector surface, a special paper filter was placed under dosimeter lid.

Dosimeters were regularly located in dwellings on the ground floor or the first floor, in the living room or bedroom, in a place which is away from windows and doors, about 1.5 m above the floor and 0.5 m distant from the wall. In order to control the consistency and accuracy of dosimeter response, at each tenth measuring location two of our dosimeters were placed together and, again at each tenth (but the other) location, beside our dosimeter, the Slovenian dosimeter [2] was also placed.

Long-term indoor radon concentration at the same place was measured twice a year. The detectors were exposed in the period from April to September 2002 (the summer period) and from October 2002 to March 2003 (the winter period).

Latent image of α-particle tracks in a detector foil was transformed to visible tracks with etching technique (6.25N NaOH, 70 °C, 7 hours), while track density was determined by the TRACOS automatic image analysis system [3], developed in the Laboratory for nuclear tracks at the Institute Jozef Stefan - Ljubljana, Slovenia.

We calibrated our dosimeter using the radon chamber at the Institute Jozef Stefan, and the response of the dosimeter to radon was determined as k_1 = 0.167 tracks·cm^{-2}/Bq·m^{-3}·d (see Fig. 1). Then, we performed intercalibration of our dosimeters with the Slovenian ones, and obtained k_2 = 0.165 tracks·cm^{-2}/Bq·m^{-3}·d (see Fig. 2). Therefore, we adopted the value k = 0.166 tracks·cm^{-2}/Bq·m^{-3}·d, as the arithmetic mean of the two mentioned values, to calculate radon concentrations from α-track density, using the formula:

$$\rho = \rho_0 + kCt, \tag{1}$$

where is:

C - radon concentration,

ρ - density of α-tracks,

ρ_0 – background track density,

t – detector exposure time.

For an estimation of the lowest detectable radon concentration, the following formula is used

$$C_{min} = \frac{L_D}{kSt}, \tag{2}$$

where is:

L_D – lower limit of counted tracks for a qualitative detection,

S - scanned area of the detector.

For a well-known blank, defined as the signal resulting from an experiment in which conditions are identical to the experiment in question except that no radon gas is present, the definition of L_D is [4]:

$$L_D = 2.71 + 3.29\sigma_B, \tag{3}$$

where σ_B is the standard deviation of the blank, which is defined as [5]:

$$\sigma_B = \sqrt{(\rho_b + \mu_b t)S + (sS)^2}, \tag{4}$$

where is:

ρ_b - background track density,

μ_b - mean rate of background radiation tracks,

s - constant that describes variation of background track density due to variations in detector sensitivity, etching and counting technique.

In our case, an average detector exposure time was t = 180 d, and $\rho_b = \rho_0 = 422$ tracks/cm^2, $\mu_b \cong 0$, $s = 2$ cm^{-2}, S = 2.25 cm^2, $\sigma_B \cong 31$, $L_D \cong 105$, k = 0.166 tracks·cm^{-2}/Bq·m^{-3}·d. With these values we obtain that $C_{min} \cong 1.5$ Bq/m^3, which indicates a good sensitivity of our dosimeter.

The comparison of track densities in our detectors which were paired at each tenth location, as well as the results obtained with pairs of our and Slovenian dosimeters placed together, confirmed a good consistency and accuracy of our dosimeters which we used for indoor radon concentration measurements. Generally, the results were very similar, and a discrepancy appeared only in the cases when concentrations were very low, i.e. for summer exposures of the detectors.

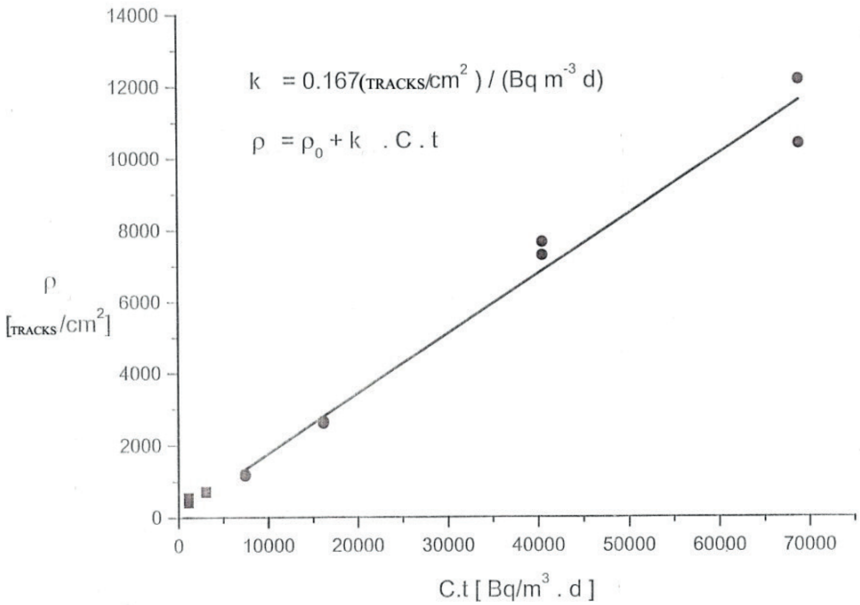

Fig. 1. The response k_1 obtained from dosimeter calibration in radon chamber.

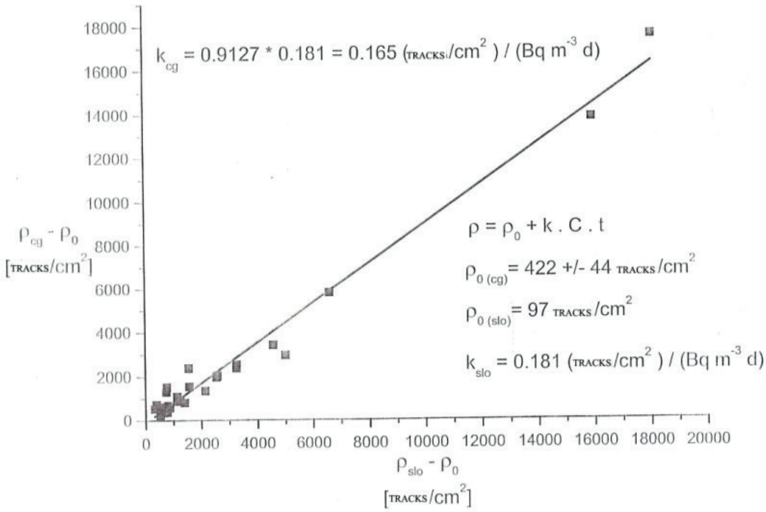

Fig. 2. The response k_2 obtained from intercalibration of dosimeters. Index "cg" is related to our dosimeter, and index "slo" to the Slovenian dosimeter.

RESULTS

Statistics of the results of radon measurements performed during summer period in 94 dwellings in Podgorica is given in Table 1, while Fig. 3. presents the histogram of frequency distribution of summer indoor radon concentrations.

As it was expected, indoor radon concentrations in the winter period are higher than in the summer period. They were measured in 90 dwellings, and the obtained results are presented in Table 2. and in Fig. 4.

Table 1. Statistics for indoor radon concentrations in the summer period.

No. of dwellings	AM [Bq/m^3]	SD [Bq/m^3]	GM [Bq/m^3]	GSD	MIN [Bq/m^3]	MAX [Bq/m^3]	Median [Bq/m^3]
94	34.9	41.3	21.8	2.6	2.9	262	21.6

AM - arithmetic mean, SD - standard deviation, GM - geometric mean, GSD - geometric standard deviation, MIN - minimum measured radon concentration, MAX - maximum measured radon concentration.

Table 2. Statistics for indoor radon concentrations in the winter period.

No. of dwellings	AM [Bq/m^3]	SD [Bq/m^3]	GM [Bq/m^3]	GSD	MIN [Bq/m^3]	MAX [Bq/m^3]	Median [Bq/m^3]
90	107	162	47.8	3.4	5.3	851	39.3

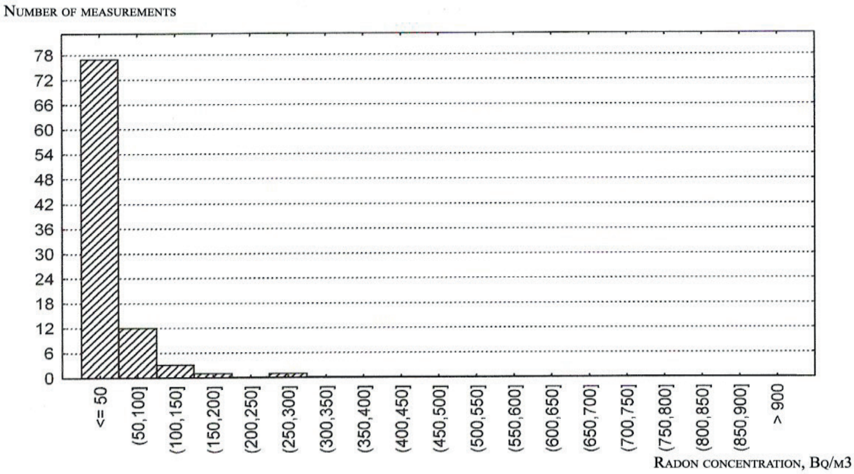

Fig. 3. Frequency distribution of summer radon concentrations in 94 dwellings in the town of Podgorica.

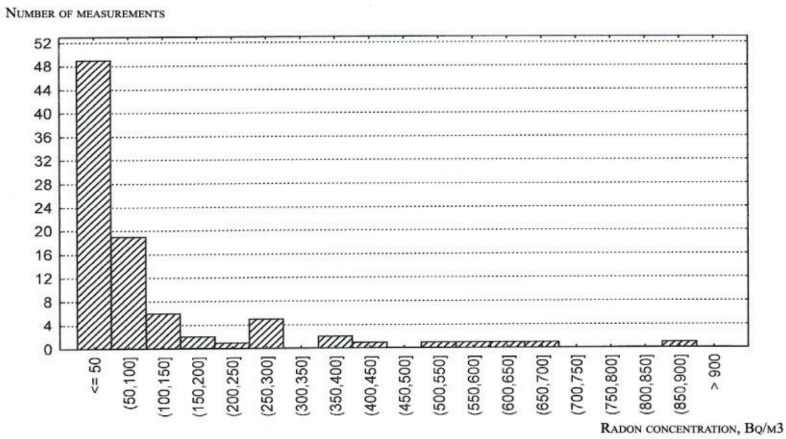

Fig. 4. Frequency distribution of winter radon concentrations in 90 dwellings in the town of Podgorica.

Table 3. Statistics for the annual mean concentrations of indoor radon.

No. of sampled dwellings	AM [Bq/m^3]	SD [Bq/m^3]	GM [Bq/m^3]	GSD	MIN [Bq/m^3]	MAX [Bq/m^3]	Median [Bq/m^3]
89	70	97	36.4	3.0	6.4	557	33.2

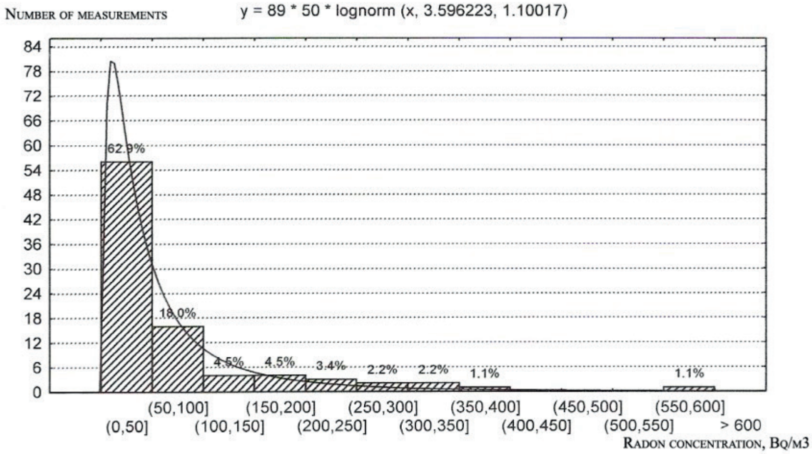

Fig. 5a. Frequency distribution of the annual mean concentrations of indoor radon in the town of Podgorica (89 dwellings): histogram, lognormal fit (μ=3.596, σ=1.100), percentages.

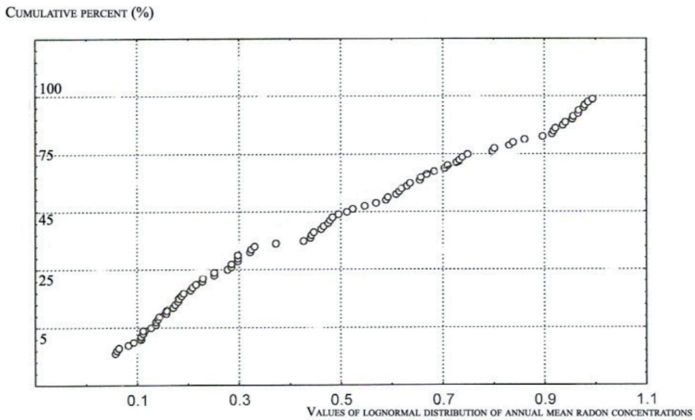

Fig. 5b. Cumulative percent of the annual mean concentrations of indoor radon in Podgorica.

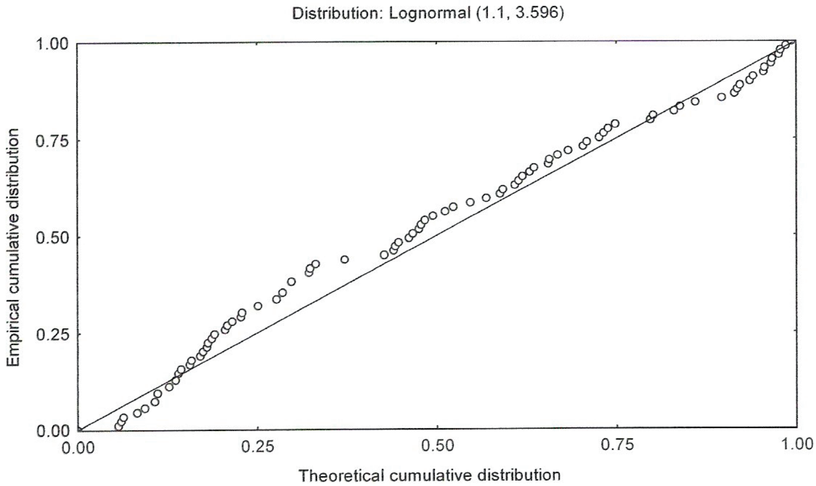

Fig. 5c. Probability-probability plot of the annual mean concentrations of indoor radon in Podgorica (for lognormal distribution μ=3.596, σ=1.100).

The annual mean concentrations of indoor radon are determined for 89 dwellings, as the arithmetic means of the two measurements - in the summer and in the winter period. Statistics of these results is presented in Table 3. and in Fig. 5. Fig. 5c. clearly proves that the distribution of the annual mean concentrations of radon in dwellings in the town of Podgorica is lognormal (with geometric mean of 36.4 Bq/m^3 and geometric standard deviation of 3.0), which is a well known fact for radon concentrations in both dwellings and workplaces worldwide.

DISCUSSION AND CONCLUSIONS

As Fig. 3 shows, summer indoor radon concentrations measured in Podgorica were mostly below 50 Bq/m^3 (82 %), and in only five cases above 100 Bq/m^3. None of them exceeded the action level of 400 Bq/m^3.

For the winter period, 76.6 % of the results were below 100 Bq/m^3 (see Fig. 4). Radon concentrations above 400 Bq/m^3 were found in six dwellings.

The annual mean concentrations of indoor radon were mostly in a range (0 – 50) Bq/m^3 (56 of 89 dwellings, or 63 %). In only one case the annual mean concentration exceeded the action level. This concentration of 557 Bq/m^3 was found in the town district Masline, in a ground floor living room of a detached family house made of stones, which is electrically-heated and naturally ventilated. The summer indoor radon concentration measured in that room was 262 Bq/m^3, and the winter one 851 Bq/m^3, which is the maximum value found during this indoor radon survey in Podgorica.

The annual mean radon concentration of 399 Bq/m^3 measured in the district Stara Varos (Old Town Podgorica), in a bedroom of an one-story family house made of bricks, is on the brink of the intervention level. In that room, the summer indoor radon concentration was 148 Bq/m^3, and radon concentration during the winter period 651 Bq/m^3.

Beside these two results, several measurements in the winter period have shown concentrations above the intervention level. The winter radon concentration of 639 Bq/m^3 (and the summer one of 26.7 Bq/m^3) was found in the town district Pobrezje, in a house made of bricks and wood. The winter concentrations of 596 Bq/m^3, 509 Bq/m^3, 436 Bq/m^3, and 397 Bq/m^3, were found in dwellings in the town districts Drac, Tolosi, Dahna, and Nova Varos. The summer concentrations in the same dwellings were 44.3 Bq/m^3, 27.5 Bq/m^3, 107.9 Bq/m^3, and 69.8 Bq/m^3, respectively.

According to UNSCEAR [6]), the arithmetic mean of annual indoor radon concentrations in dwellings at middle geographic latitudes in the world is 40 Bq/m^3. In European countries, the median values of indoor radon concentrations range from 9 Bq/m^3 to 60 Bq/m^3, though some individual radon concentrations are at the level of a few hundred Bq/m^3, rarely of a few thousand Bq/m^3. The results of our measurements of indoor radon in the town of Podgorica are in good accordance with these previously mentioned data.

In an earlier investigation of indoor radon in Podgorica [7, 8], when a similar radon measurement method was applied, and 110 town houses selected on the basis of their construction materials and techniques were surveyed, statistics for the radon concentrations measured in them during three winter months was as follows: AM=77.4 Bq/m^3, GM=43.6 Bq/m^3, MIN=8 Bq/m^3, MAX=906 Bq/m^3, Median=52.8 Bq/m^3. If we compare this data with those from our recent radon survey presented here in Table 3, and take into account that previous results are related to the winter radon concentrations only, which are generally higher than the annual mean concentrations, we can conclude that two indoor radon surveys in the town of Podgorica produced results which stand in a good mutual agreement.

Indoor radon measurements presented here are performed systematically all over the territory of the town of Podgorica, and they provide confident results for radon concentrations. Two independent six-month measurements of winter and summer indoor radon concentrations give a realistic estimation of annual mean concentrations of indoor radon, and a good insight in the exposure to radon in the town dwellings.

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