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VARIATION OF INDOOR RADON CONCENTRATION WITHIN A RESIDENTIAL COMPLEX

Teofana Sferle[1], Gabriel Dobrei*,[1], Tiberius Dicu[1], Bety-Denissa Burghele[1], Nicoleta Brişan[1], Alexandra Cucoş (Dinu)[1], Tiberiu Catalina[1,2], Andrei Istrate[1,2], Alexandru Lupulescu[1], Mircea Moldovan[1], Dan Niţă[1], Botond Papp[1], Istvan Pap[1], Kinga Szacsvai[1], Ştefan Florică[1,3], Ancuţa Ţenter[1] and Carlos Sainz[1,4]
[1]Babeş-Bolyai University, Faculty of Environmental Science and Engineering, "Constantin Cosma" Radon Laboratory (LiRaCC), Cluj-Napoca, Romania
[2]Technical University of Civil Engineering of Bucharest, Faculty of Engineering Installations, Bucharest, Romania
[3]Babeş-Bolyai University, Faculty of Biology and Geology, Department of Geology, Cluj-Napoca, Romania
[4]University of Cantabria, Department of Medical Physics, Faculty of Medicine, Santander, Spain

*Corresponding author: gabriel.dobrei@gmail.com

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A recent challenge in research dedicated to residential exposure to radon comes from the growing number of houses retrofitted to reduce energy consumption. Efficiently insulated buildings and modern architectural solutions can lead to the accumulation of high levels of indoor pollutants. A systematic analysis was conducted in a residential complex (consisting of six houses) in order to assess the annual radon concentration and to evaluate the intensity of the relationships with various factors, such as the indoor-outdoor temperature differences, wind speed and wind direction. Three types of occupational behaviour, influencing the ventilation rate of the dwellings and, implicitly, the indoor radon activity concentration were observed. By calculating the partial correlation coefficient between the radon concentration and the wind direction, with the wind speed as the control variable, for all six houses the correlation coefficient presents negative values.

INTRODUCTION

Exposure to indoor radon is identified as the main source of natural radiation exposure to the population(1). Radon is a risk factor that can be controlled and reduced with reasonable costs(2–4). In the field of protecting buildings against radon, several factors that could control the source and the behaviour of indoor radon should be carefully studied. In most case studies, the main source of radon in homes is the soil its built upon. Through migration and transport processes, radon can reach the house where it can accumulate. The migration and transport of radon from the ground or building materials to indoor air depends on a number of factors, such as porosity and type of material, humidity, indoor–outdoor air temperature or pressure differences, wind speed and wind direction(5). A positive correlation was found between indoor–outdoor temperature differences and indoor radon(5, 6). As was pointed out by Riley *et al.*, the wind speed could have a positive impact due to over-pressure on the transport of radon from soil inside the building(7).

In addition to these data, the current policy on energy efficiency turned out to cause unexpected effects on indoor air quality, like an increase of indoor radon concentration after energy retrofit compared to the concentration before applying this measure(8). Increasing the sealing of the building, associated with the lack of adequate ventilation, can lead to an important increase in indoor air pollution(9).

This paper aims to present the impact of indoor and outdoor factors, as well as user's behaviour on indoor air quality in six houses with thermal insulation. Several chemical and physical parameters of the indoor air have been measured in this sense. The outdoor parameters were obtained from the nearby weather station.

MATERIAL AND METHODS

Site description

The study area is located in Floreşti, Cluj County, Romania, in the meadow of the Şomeşul Mic River at a distance of 300 m from the riverbed. The residential neighbourhood consists of eight houses, six of them making the subject of the present study. The six houses are aligned along 100 m.

From a geological point of view, the entire area is characterised by a Precambrian age-old crystalline foundation covered by sedimentary formations with the oldest deposits belonging to the Upper Cretaceous, followed in a stratigraphic succession of Paleogene, Neogene and Quaternary deposits.

In terms of construction, the houses are built on a concrete foundation with Porotherm bricks, double or triple glazed PVC doors and windows, ceramic roof tiles and 10-cm polystyrene outdoor insulation. The construction phase took place between 2010 and 2014. Although the same real estate developer built the houses, some differences were identified. Houses I–IV are identical in terms of construction plan and materials (ground and first floor, triple glazed PVC doors and windows). House VI is designed as ground and first floor, but with double glazed PVC doors and windows. House V has just ground floor and double-glazed doors and windows. There are no cellars, basement apartments or crawl spaces under the studied houses.

Radioactivity measurements

Passive indoor radon measurements

The indoor radon measurements for the present survey were performed with the help of nuclear track detectors provided by Radosys Ltd. (Hungary), which uses CR-39 chips. Solid-state nuclear track detectors were placed indoor for two consecutive 6 months campaigns. Two passive detectors were placed in each building, in rooms selected based on occupancy factor.

Continuous indoor air monitoring

In order to monitor the time variation of the indoor air quality, an integrated monitoring system, namely ICA was used. This device can simultaneously monitors several parameters, such as: radon, CO, CO_2, volatile organic compounds, as well as temperature, relative humidity and pressure. The data were transmitted every 2 min over the Wi-Fi to a designated server. A detailed description of the system is made elsewhere[10].

Radon in soil gas measurements

Radon activity concentration in soil was measured *in situ* using two devices: RM-2 (Radon v.o.s., Czech Republic) and LUK 3P radon and thoron detector, which is based on a scintillation technique using Lucas cell (Jiří Plch-SMM, Czech Republic). The devices were submitted to an intercomparison exercise before and after the study and all results were harmonised. The use of two devices was strictly related to convenience.

The sampling of soil gas was based on Neznal method[11]. A steel pipe with 1 m length and 1 cm diameter was inserted into the soil to a given depth (80 cm regularly). For soil gas sampling, a Janet syringe was used, with a volume of 145 ml (equal with the volume of the detection cell). Soil permeability measurements were carried out using RADON-JOK (Radon v.o.s., Czech Republic)[12] to assess the radon potential (RP) of the building site. The equipment allows the calculation of soil permeability using the air flow through the sampler, represented by a rubber sack. The air from the soil is pumped out by attaching known weights to the bottom of the sack. Knowing the volume of air, respectively measuring the pumping time, the airflow through the probe can be computed. According to the model, the categories of radon index are as follows: if $RP < 10$, the radon index is low; if $10 < RP < 35$, the radon index is medium and if $RP > 35$, the radon index is high[13].

Radon exhalation rate

The radon exhalation rate was performed on the ground floor of each house using the RAD7 radon monitor (Durridge Company Inc., USA), based on semiconductor detection technique. The instrument draws air from an accumulation chamber (with a volume of 0.005 m^3) through a desiccant filter into the detection chamber and then back to the accumulation chamber. For generating the radon growth curve, the data were taken every 30 min, for 3 h. The methodology is described by Tuccimei and Soligo[14]. The detection limit was computed to 10 Bq m^{-2} h^{-1}. The exhalation rate was determined on the floor in order to establish the radon permeability of the house flooring.

Radon in leakages measurements

The method is composed on the collection of the air samples in places, where visible leakages may appear and then measuring radon concentrations from collected samples using the same instrumentation as for the determination of radon concentrations from soil gas[11]. The samples of air were collected using a needle connected to Janet syringe from all visible cracks, in the slab, at the interface between the floor and the walls or at the entrance of the pipes in the room.

Statistical analysis

The statistical analysis of the data was performed using OriginPro 2018b software (USA). If not otherwise mentioned, the data are presented as arithmetic means. In order to evaluate the intensity of the relationship between the examined variables, the Spearman non-parametric correlation coefficient (r_S) was calculated. The significance level of α was chosen at 0.05.

Table 1. Preliminary indoor screening using passive method in the six investigated houses.

House	Indoor radon concentration depending on the measurement period (Bq m^{-3})					
	January–June		July–December		Annual average	
	Living	Bedroom	Living	Bedroom	Living	Bedroom
I	464	449	299	299	382	374
II	404	349	316	274	361	312
III	511	492	322	280	407	396
IV	509	392	361	260	435	326
V	280	237	158	155	216	194
VI	431	375	238	176	338	279

RESULTS AND DISCUSSIONS

Preliminary screening

A preliminary screening using passive measurements with CR-39 detectors over a period of 1 y was conducted from January to December 2017. For the screening process, a pair of CR-39 detectors was set up in each house, one on the ground floor (living area) and one on the first floor bedroom. In house V, booth detectors were placed on the ground floor (living and bedroom). Table 1 shows the results of the preliminary screening. Five of the six analysed houses had an average of annual indoor radon concentration above the recommended level of 300 Bq m^{-3}[15].

The only house with a lower average concentration is house V that differs significantly (in terms of construction) from all the others.

Even if the radon concentrations in the first campaign are between 1.3 and 2.1 times higher than in second campaign, these ratios are justifiable, taking into account the monitored period. In fact, by applying seasonal correction factors, the average of the ratios between the two campaigns is 1.1. The ground level radon concentrations were only up to 20% higher than on the first floor. This result can be explained by the existence of open spaces (open staircases) between the ground floor and the first floor, which allows a continuous air circulation between the two levels of the houses.

In the summer of 2018, detailed screening was conducted in order to evaluate the RP and radon index in soil. The radon concentration in soil was measured in the hot season choosing 15 points for each location. The arithmetic and geometric mean, as well as the standard deviation and third quartile were calculated for each house in order to assess the RP and radon index in soil. The results indicate an overall average of radon concentration in soil of 30 kBq m^{-3} (third quartile of 36 kBq m^{-3}; Table 2). The recorded values, ranging between 10 and 54 kBq m^{-3}, are comparable to those reported in previous studies[16].

The medium-to-high radon index, determined for the building sites lead to additional measurements, made in order to assess the degree of radon infiltration from soil into the indoor air. Table 3 shows the results of radon exhalation rates, as well as the number of leakages identified at the interface between the ground and the floor or the floor and the walls, as an infiltration path of radon from the soil.

Examining the exhalation rates and the number of leakages, as well as the maximum radon concentration found in the leakages, it could be concluded that for houses I and IV, the main pathway for radon from soil is the cracks in the concrete floor. The RP at houses I and IV is 25, respectively 17, resulting in a medium radon index, while the annual indoor radon concentration was 382 and 435 Bq m^{-3}, respectively. Also comparing the results from the soil screening with those from the indoor screening, the most likely way of entrance for house II is represented also by cracks in the concrete floor. The absence of leakages with a radon concentration over 1 kBq m^{-3} at houses III, V and VI indicate the presence of efficient construction works, creating an airtight space between walls and floors. However, the exhalation rates in houses III and IV showed that the floors are not impermeable to radon, this suggesting the existence of a transfer path of radon from soil into the houses (Table 3). In house V, the exhalation rate was below the detection limit, which, corroborated with the reduced number of cracks identified, can explain the low value of indoor radon concentration.

All of these measurements were performed before the installation of the ICA continuous monitoring prototype developed under the SMART-RAD-EN project[17]. The ICA system was installed with the main purpose to raise awareness among residents regarding indoor air quality by providing continuous real-time measurements.

Continuous monitoring and behavioural patterns

An ICA system was installed in each of the six houses. The device represents the first attempt to collect in real-time continuous data (radon, carbon dioxide, carbon monoxide, temperature, humidity

Table 2. Radon in soil gas measurements.

House	Radon in soil gas concentration (kBq m^{-3})					Radon potential	Radon index
	Min	Max	AM ± SD	GM	3rd quartile		
I	13	49	27 ± 11	25.2	31	25	Medium
II	33	54	42 ± 6	41.5	43	48	High
III	10	32	19 ± 8	17.5	26	32	Medium
IV	12	43	26 ± 10	24.6	33	17	Medium
V	23	48	33 ± 8	32.9	40	34	Medium
VI	17	46	31 ± 10	30.4	42	40	High

Table 3. Indoor radon screening by exhalation rates and leakage measurements.

House	Exhalation rate (Bq m^{-2} h^{-1})	Leakage analysis	
		Radon maximum concentration (kBq m^{-3})	No. of cracks over 1 kBq m^{-3}
I	63	4.9	10
II	12	3.2	7
III	24	0.8	0
IV	16	4.4	10
V	BDL[a] (6)	0.9	0
VI	24	0.8	0

[a]BLD: below detection limit.

and atmospheric pressure) in Romanian dwellings. The data collected between 1 December 2018 and 26 March 2019 were analysed in the present study. The typical time evolution of radon concentration along with outdoor temperature fluctuations is shown in Figure 1. The curve is smoothed out by using a moving average with 24 h step. A moderate inverse correlation was obtained between the indoor radon concentration and the outdoor temperature ($r_S = -0.64$, $p < 0.05$).

The descriptive statistics for parameters monitored with ICA system are shown in Table 4. The means of radon concentration obtained as continuous measurements are about 30% higher than those obtained in Table 1 with passive detectors. Despite the fact that the radon sensors, as a part of ICA system, were calibrated before installation, it is difficult to say whether this difference is due to the measurement method used or interannual variations of radon concentration inside the buildings. An important difference was noticeable in terms of radon concentration between house V and the rest of the investigated houses. The increase in CO_2 concentration observed during the evening and weekend represents an indicator of occupational patterns. The mean of carbon dioxide concentrations by house ranged from 787 to 1064 ppm, the overall average being 907 ppm.

As ICA system was primarily developed to help inhabitants to monitor and act to improve indoor air quality, the behavioural patterns in the six houses were investigated. Figure 2 shows the diurnal variation of indoor radon concentration for the period January 1–March 26 (December was excluded due to holidays and different behaviours of the owner of the house). Areas in burgundy and red indicate high concentrations of radon, while in blue are marked the concentrations below 300 Bq m^{-3}. Besides the diurnal variation, i.e. low radon concentrations in the afternoon and increased values during mornings, an important difference induced by the behaviour of the owner, respectively the house characteristics can be notice.

After applying the Fast Fourier Transform (FFT) of the time series of radon concentrations (Figure 2) for each of the six houses, three types of behavioural pattern were identified within 24-h intervals.

First pattern consists of a long period of ventilation, in the morning. This pattern is consistent during workdays, in the weekend no clear pattern was identified, taking into account the short monitoring period. Houses I, III and VI were consistent to this pattern. For the house V, the ventilation takes place in the evening.

A second pattern was identified in house IV and it consists of ventilation in the morning, followed by an accumulation period during the day and then a brief period of ventilation in the evening, usually between 5 and 7 PM. For the weekend, again no consistent pattern was identified.

The third pattern identified only in for house II, consists of small, insignificant ventilations periods during the morning (maybe just by open windows up on hinges).

The diurnal variation of indoor radon concentration is in agreement with the indoor–outdoor temperature difference that shows the maximum values during the night, the minima being reached after lunch. An inverse behaviour was observed for the wind speed, the maximum peak being reached at

Table 4. Continuous indoor air quality measurements during 1 December 2018–26 March 2019 using ICA system.

House	Radon concentration (Bq m^{-3})			CO_2 (ppm)	t (°C)	p (hPa)	rH (%)
	A.M.	S.D.	Max				
I	714	238	1587	850	20.8	973.97	37
II	825	290	2397	900	19.3	974.02	37
III	662	181	1301	953	22.2	973.57	33
IV	618	242	1255	787	20.5	973.50	37
V	248	110	607	1064	20.6	973.31	41
VI	728	220	3083	915	18.1	973.23	40

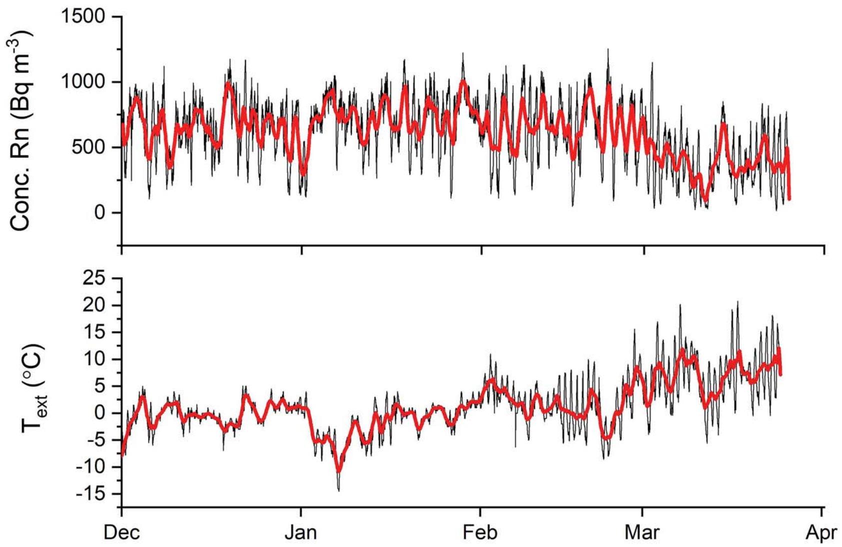

Figure 1. The hourly variation of indoor radon concentration (top) and outdoor temperature (bottom) from 1 December 2018 to 26 March 2019.

1 PM, while the minimum values are reached during the night (data not shown).

Correlation with meteorological parameters

A general positive correlation between the indoor radon concentration and the indoor–outdoor temperature differences was obtained by calculating the Spearman correlation coefficient. However, at the individual house level, the values of the correlation coefficient were in an extremely large range. As such, no correlation was found between radon concentration and temperature differences in house II ($r_S = 0.06$), while for house V the correlation coefficient was moderate ($r_S = 0.53$). A strong correlation was achieved for houses I and IV ($r_S = 0.6$ and 0.73, respectively). Generally, a weak correlation (up to 0.3) was obtained between radon concentration and indoor–outdoor pressure differences. A positive correlation was found between the radon concentration and the wind speed for house II ($r_S = 0.13$), III ($r_S = 0.12$) and VI ($r_S = 0.21$), while for the houses I ($r_S = -0.44$), IV ($r_S = -0.36$) and V ($r_S = -0.27$) a negative correlation was obtained. By calculating the partial correlation coefficient between the radon concentration and the wind direction, with the wind speed as the control variable, the correlation coefficients present negative values, being statistically significant for houses I and IV ($r_S = -0.41$), respectively III and V ($r_S = -0.36$). The lack of correlation between indoor radon and wind direction for houses II and VI could be explained by to the fact that other buildings from all sides surround these houses. As mentioned before, the houses share the same architecture (except for the house V) and, with minor differences, the same building materials. Despite these aspects, the way the houses are spatially positioned, as well as the fact that some houses are surrounded by other buildings (houses II and VI), while houses III and IV have

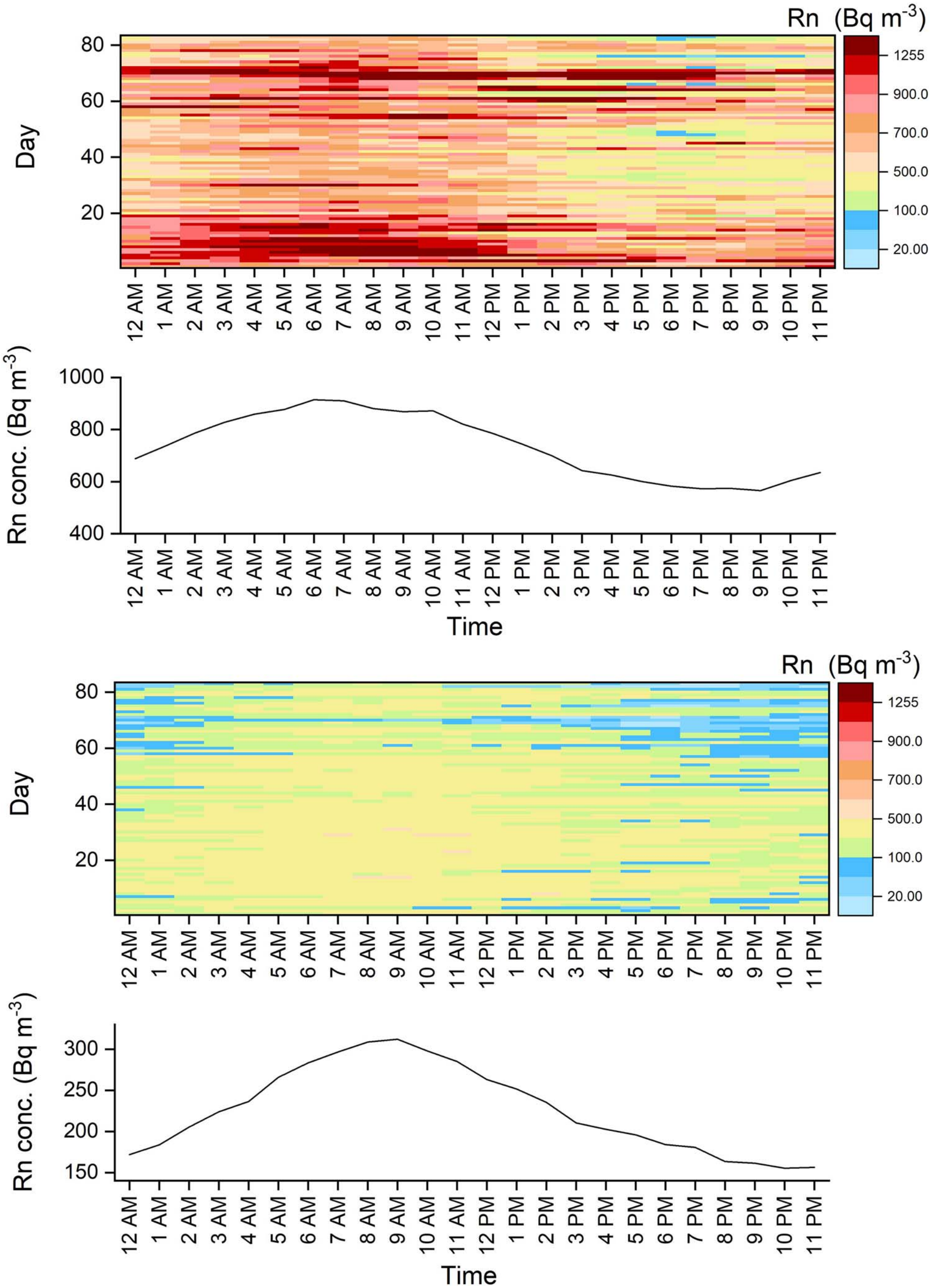

Figure 2. The diurnal variation of radon concentration for house VI (top), which is also typical for houses I and III, respectively for house V (bottom). Each ‘pixel’ on the map shows the hourly average radon concentration for a certain day.

open yard behind the house, it can cause different effects of meteorological parameters on the transport of radon from soil into the buildings. Rigorous simulations are necessary to evaluate the weight of each investigated factor on radon accumulation inside the buildings.

CONCLUSIONS

Radon measurements in six houses of a residential complex revealed an average of indoor radon concentration above the recommended level of 300 Bq m^{-3} in five houses. Radon mitigations are required for the five mentioned houses in accordance with national and international regulations. If the developer would have carried out radon measurements in soil (RP and radon index) before building the residential complex, he could have applied prevention measures during the construction phase, which would have reduced the costs and the risk of exposure to indoor radon.

After studying the time evolution of radon concentration, as well as the FFT of the radon data for all of the six investigated houses, three types of behavioural patterns were identified and correlated with indoor radon concentration. When reducing radon concentration by applying mitigation techniques, it is necessary to take into account the behaviour of the inhabitants of the house, which will considerably influence the indoor radon concentration, as well as weather conditions of the area where the houses are built.

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