MULTIYEAR INDOOR RADON VARIABILITY IN A FAMILY HOUSE – A CASE STUDY IN SERBIA

by

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The indoor radon behavior has complex dynamics due to the influence of the large number of different parameters: the state of indoor atmosphere (temperature, pressure, and relative humidity), aerosol concentration, the exchange rate between indoor and outdoor air, construction materials, and living habits. As a result, indoor radon concentration shows variation, with the usual periodicity of one day and one year. It is well-known that seasonal variation of the radon concentration exists. It is particularly interesting to investigate indoor radon variation at the same measuring location and time period, each year, due to estimation of individual annual dose from radon exposure. The long-term indoor radon measurements, in a typical family house in Serbia, were performed. Measurements were taken during 2014, 2015, and 2016, in February and July, each year. The following measuring techniques were used: active and charcoal canisters methods. Analysis of the obtained results, using multivariate analysis methods, is presented.

Key words: radon variability, multivariate regression analysis, multi-seasonal radon measurements, indoor radon

INTRODUCTION

The research of the dynamics of radon in various environments, especially indoors, is of great importance in terms of protection against ionizing radiation and in designing of measures for its reduction. Published results and development of many models to describe the behavior of indoor radon, indicates the complexity of this research, especially with models for prediction of the variability of radon [1-3]. This is because the variability of radon depends on a large number of variables such as local geology, permeability of soil, building materials used for the buildings, the state of the indoor atmosphere (temperature, pressure and relative humidity), aerosol concentration, the exchange rate between indoor and outdoor air, construction materials, as well as the living habits of people. It is known that the indoor radon concentration variation has periodicity of one day and one year. It is also well-known that the seasonal variation of the radon concentration exists. This is why it is particularly interesting to investigate indoor radon variation at the same measuring location and time period, year after year, in order to estimate the individual annual dose from radon exposure. In that sense, we performed long-term indoor radon measurements in a typical family house in Serbia. Measurements were taken during the 2014, 2015, and 2016, in February and July, each year. We used the following measuring techniques: active and charcoal canisters methods. The detailed analysis of the obtained results using multivariate analysis (MVA) methods is presented in this paper.

First, MVA methods were tested on the radon variability studies in the Underground Low Background Laboratory in the Institute of Physics, Belgrade [4, 5]. Several climate variables: air temperature, pressure, and humidity were considered. Further advance was made by using all the publicly available climate variables monitored by nearby automatic meteorological station. In order to analyze the dependence of radon variation on multiple variables, multivariate analysis needs to be used. The goal was to find an appropriate method, out of the wide spectrum of multivariate analysis methods that are developed for the analysis of data from high-energy physics experiments, to analyze the measurements of variations of radon concentrations in indoor spaces. Previous

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analysis were done using the maximum of 18 climate parameters and use and comparison of 8 different multivariate methods. In this paper the number of variables is reduced to the most important ones and new derived variables, like vapor pressure, simple modeled solar irradiance and simple modeled precipitation, which were introduced in the multivariate analysis.

INDOOR RADON MEASUREMENTS METHODS

Depending on the integrated measurement time, methods of measurement of the indoor radon concentrations may be divided into long-term and short-term ones. The device for the performed short-term radon measurements is SN1029 radon monitor (manufactured by the Sun Nuclear Corporation, NRSB approval-code 31822) with the following characteristics: the measurement range from 1 Bqm^{-3} to 99.99 $kBqm^{-3}$, accuracy equal to +25 %, sensitivity of 0.16 counts hour per Bqm^{-3}. The device consists of two diffused junction photodiodes as the radon detector which is furnished with sensors for temperature, barometric pressure, and relative humidity. The sampling time was set to 2 h. The method for Charcoal Canister used is: EERF Standard Operating Procedures for Radon-222 Measurement Using Charcoal Canisters [6], also used by major laboratories which conduct radon measurements in Serbia [7]. Exposure time of the charcoal canisters was 48 h. The connection between short term and long term measurements has attracted some interest previously [8].

The family house, selected for the measurements and analysis of variations of radon concentrations, is a typical house in Belgrade residential areas, with requirement of existence of cellar. House is built on limestone soil. Radon measurements were carried out in the living room of the family house, which is built of standard materials (brick, concrete, mortar) and isolated with styrofoam. During the period of measurements (winter-summer 2014, 2015, and 2016), the house was naturally ventilated and air conditioning was used in heating mode at the beginning of the measurement period. During the winter period measurements, the electrical heating was used in addition to air conditioning. Measured radon concentrations, room temperature (*T*_id), atmospheric pressure (*P*_id) and relative humidity (*H*_id) inside the house, were obtained using radon monitor. Values of meteorological variables, in the measurement period, were obtained from an automatic meteorological station, located near the house in which the measurement was performed. We used the following meteorological variables: external air temperature (*T*), also at height of 5cm, pressure (*P*) and humidity (*H*), solar irradiation, wind speed, precipitation, temperature of the soil at depths of 10 cm, 20 cm and 50 cm. The natural ventilation routine was not monitored. Since the ventilation is of crucial importance for the level of radon indoors [9], Multivariate regression analysis was used mainly for winter periods.

MULTIVARIATE REGRESSION ANALYSIS

In many fields of physics, especially in high-energy physics, there is the demand for detailed analyses of a large amount of data. For this purpose, the data analysis environment ROOT [10], is developed. ROOT is modular scientific software framework, which provides all the functionalities needed to deal with big data processing, statistical analysis, visualization and storage. A specific functionality gives the developed Toolkit for Multivariate Analysis (TMVA) [11]. The TMVA provides an environment for the processing, parallel evaluation and application of multivariate regression techniques.

TMVA is used to create, test and apply all available regression multivariate methods, implemented in ROOT, in order to find methods which are the most appropriate and yield maximum information on the dependence of indoor radon concentrations on the multitude of meteorological variables. Regression methods are used to find out which regression method can, if any, on the basis of input meteorological variables only, give an output that would satisfactorily close match the observed variations of radon concentrations. The output of usage of multivariate regression analysis methods has mapped functional behavior, which can be used to evaluate the measurements of radon concentrations using input meteorological variables only. All the methods make use of training events, for which the desired output is known and is used for training of Multivariate regression methods, and test events, which are used to test the MVA methods outputs.

RESULTS

Measurements were performed during February and July in 2014, 2015, and 2016 using radon monitor and charcoal canister measurements. The descriptive results are summarized in tab. 1. The measurements using radon monitor and charcoal canisters are in good agreement.

Previous work done by researchers from the Low Background Laboratory, Institute of Physics, Belgrade, using the MVA analysis in search of connections between radon concentration and meteorological variables, included only one period of measurement, February or July 2014 [4]. Now the MVA analysis is using all the measured data February/July 2014-2016. New variables introduced in MVA analysis are modeled solar irradiance, modeled precipitation and vapor

Table 1. Descriptive results of February and July 2014, 2015, and 2016 measurements, using radon monitor and charcoal canisters (only in February)

Results of measurements	2014		2015		2016	
	Feb.	July	Feb.	July	Feb.	July
Minimal radon activity using radon monitor [Bqm^{-3}]	15	0	28	0	12	3
Maximal radon activity using radon monitor [Bqm^{-3}]	1000	286	915	88	1013	262
Median radon activity using radon monitor [Bqm^{-3}]	418	25	524	22	412	28
Arithmetic mean of radon activity using radon monitor (standard deviation) [Bqm^{-3}]	402 (216)	40 (41)	508 (207)	27 (18)	423 (214)	39 (32)
Room temperature using radon monitor (standard deviation) [°C]	20.4 (0.8)	24.7 (0.9)	21.2 (0.6)	24.9 (0.8)	22.3 (0.6)	24.6 (0.8)
Relative humidity using radon monitor (standard deviation) [%]	67.4 (5.7)	67.8 (4.8)	68.2 (4.8)	51.5 (4.7)	64.0 (6.4)	58.9 (7.5)
Radon activity using charcoal canister (standard deviation) [Bqm^{-3}]	432 (10)	/	518 (6)	/	407 (5)	/

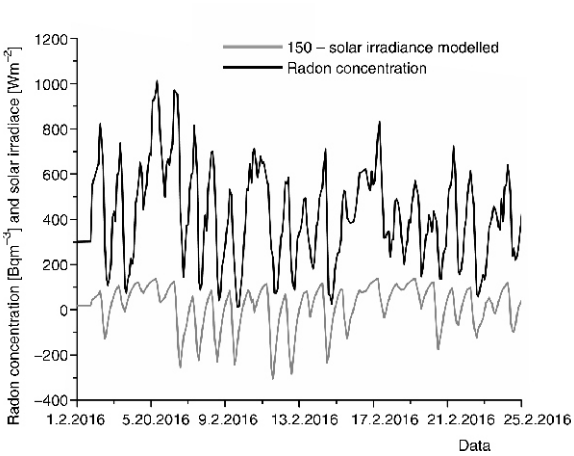

Figure 1. Modeled solar irradiance in comparison with measured radon concentration during February 2016

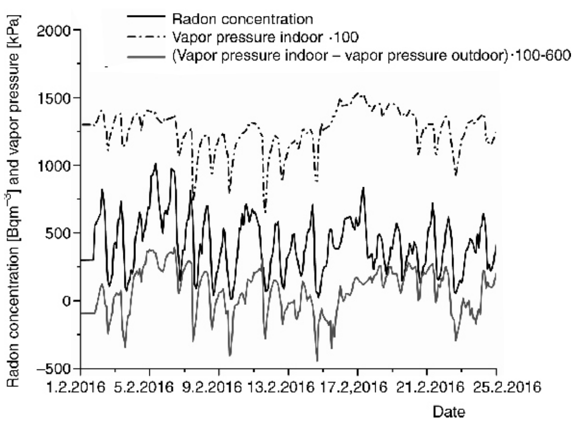

Figure 2. Vapor pressure in comparison with measured radon concentration during February 2016

pressure. In order to make use of intensity of solar irradiance during the whole day and night, the solar irradiance is modeled so that it includes 80 % of solar irradiance value from the previous measurement (previous hour) with addition of solar irradiance value for the actual hour of measurement (fig. 1). The value of 80 % is chosen so that the modeled solar irradiation has the best correlation with the radon measurements. Similar model of precipitation was used in this analysis. The next new variable is vapor pressure. The vapor pressure variable is calculated using the slope s(T), of the relationship between saturation vapor pressure and air temperature and is given by [12, 13], so that the vapor pressure equals relative humidity times saturation vapor pressure, fig. 2.

Before the start of training of Multivariate regression methods using TMVA toolkit in ROOT, the description of input meteorological variables is performed, mainly by looking into inter-correlations of input variables and their connections with the measured radon concentrations. The MVA is using all the measured data. Table 2 presents the meteorological variables and their module value of correlation with the measured radon concentrations (target), which is indicative in finding linear dependence of radon measurements and input variables. The second column in tab. 2 presents us with correlation ration values which indicate if there are some functional dependence (not only linear) between input variables and radon concentration, and the last column presents the mutual information which indicates if there is a non-functional dependence of input variables and radon measurements [11].

From tab. 2 it can be noticed that linear correlated values are not the only ones which can be used in MVA analysis, for example variable solar irradiance has high mutual information with the radon measurements.

In the data preparation for MVA training the whole dataset is consisting of many events. An event includes time of measurement, radon measurement and meteorological variables. The dataset is randomly split in two halves, one half of the events will be used for training of multivariate regression methods, and the other half of events for testing of methods, mainly to compare the measured and MVA evaluated values for radon concentration.

It turns out that the methods best suited for our purpose is the Boosted Decision Trees (BDT) method. This means that BDT gives the smallest difference be-

Table 2. Input variable rank and values for correlation, correlation ratio and mutual information, all with the measured radon concentrations (target) for February and July 2014-2016 measurements

Variable	Correlation with target		Correlation ratio		Mutual information	
	Rank	Value	Rank	Value	Rank	Value
Soil temperature depth 20 cm [°C]	1	0.87	1	0.60	13	1.48
Soil temperature depth 50 cm [°C]	2	0.86	2	0.57	14	1.31
Soil temperature depth 10 cm [°C]	3	0.82	3	0.54	9	1.84
Temperature outdoor [°C]	4	0.82	5	0.53	8	1.85
Vapor indoor – vapor od [mbar]	5	0.81	9	0.41	11	1.73
Temperature od – temperature id [°C]	6	0.80	4	0.53	6	1.92
Temperature height 5 cm [°C]	7	0.77	8	0.48	7	1.91
Vapor od [mbar]	8	0.76	10	0.41	5	1.92
Temperature id [°C]	9	0.75	7	0.49	17	1.16
Solar irradiance [Wm^{-2}]	10	0.61	6	0.50	2	2.23
Humidity indoor [%]	11	0.45	11	0.26	1	2.26
Humidity outdoor [%]	12	0.31	13	0.20	10	1.76
Air pressure outdoor [mbar]	13	0.27	17	0.07	12	1.55
Wind speed [ms^{-1}]	14	0.22	16	0.01	16	1.28
Air pressure indoor [mbar]	15	0.17	18	0.04	15	1.31
Humidity od – Humidity id [%]	16	0.10	14	0.19	4	2.11
Precipitation [Lm^{-2}]	17	0.01	15	0.19	18	1.13
Vapor indoor [mbar]	18	0.002	12	0.02	3	2.17

tween the measured radon concentration from test sample and the evaluation of value of radon concentration using input variables only. This can be seen in fig. 3, which shows the distribution of BDT and BDTG regression method outputs (evaluated values) in comparison with the measured radon concentration during February 2016.

Since TMVA has 12 different regression methods implemented, only some of those will give useful results when evaluating the radon concentration measurements. Table 4 summaries the results of MVA analysis. It shows the MVA methods RMS of difference of evaluated and measured radon concentration. Also, tab. 4 shows the mutual information of measured and MVA evaluated radon concentration. Besides BDT, the Multi-Layer Perceptron (MLP) [10], an implementation of Artificial Neural Network multi variate method, also gives good results.

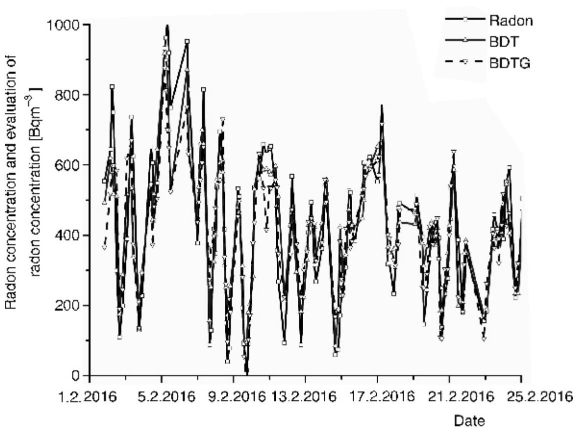

Figure 3. Comparison of MVA evaluated radon concentration and measured one from the test sample of events during February 2016

The MVA regression analysis results in mapped functional behavior and, as opposed to possible existence of theoretical modeling, which is independent of the number of measurements, MVA depends on the number of events. More events, the better mapped function we get as a result. In this sense, if the number of measurements is not great, multivariate analysis can be used only as help, to indicate which variables are more important to be used in theoretical modeling, for comparison of mapped and modeled functions, and modeled function test.

CONCLUSION

Indoor radon variation at one location in the same periods (February and July), was investigated for three years. Long-term indoor radon measurements show intense seasonal variation. The results obtained with different measuring methods are in good agreement. The radon behavior in the house is almost the same and shows good reproducibility year by year. The small variations in the year by year dynamics are originated mostly from the variations in meteorological variables during winter seasons and mostly due to ventilation habits during summer season. Ventilation habits were not monitored nor taken into account in MVA regression analysis. The preliminary results using multivariate analysis methods in TMVA are shown. Main output of Multivariate regression analy-

Table 3. Input variable correlation with the measured radon concentrations for February and July 2016

Correlation with target			
February 2016		July 2016	
Variable	Value	Variable	Value
Vapor id-vapor od [mbar]	0.58	Soil temperature depth 20 cm [°C]	0.46
Humidity id [%]	0.54	Soil temperature depth 50 cm [°C]	0.42
Vapor id [mbar]	0.52	Solar irradiance	0.32
Solar irradiance [Wm^{-2}]	0.48	Temperature id [°C]	0.30
Temperature od – temperature id [°C]	0.46	Soil temperature depth 10 cm [°C]	0.24
Temperature [°C]	0.44	Temperature od [°C]	0.21
Soil temperature depth 10 cm [°C]	0.43	Humidity od [%]	0.20
Soil temperature depth 20 cm [°C]	0.42	Humidity id [%]	0.19
Humidity [%]	0.38	Air pressure [mbar]	0.17
Temperature height 5 cm [°C]	0.32	Precipitation [Lm^{-2}]	0.17
Temperature id [°C]	0.29	Temperature od – temperature id [°C]	0.16
Air pressure od [mbar]	0.23	Air pressure_id [mbar]	0.16
Air pressure id [mbar]	0.21	Humidity od – humidity id [%]	0.14
Soil temperature depth 50 cm [°C]	0.20	Wind speed [ms^{-2}]	0.13
Precipitation [Lm^{-2}]	0.19	Temperature height 5 cm [°C]	0.12
Humidity od – humidity id [%]	0.15	Vapor id [mbar]	0.06
Vapor od [mbar]	0.08	Vapor od [mbar]	0.03
Wind speed [ms^{-1}]	0.05	Vapor id – vapor od [mbar]	0.02

Table 4. RMS of MVA method's evaluation error and mutual information; February/July 2014-2016

MVA method	RMS [Bqm^{-3}]	Mutual information
BDT	85.5	1.477
BDTG	92.1	1.614
MLP	101	1.401

sis is the initial version of *mapped* function of radon concentration dependence on multitude of meteorological variables. Simplification of MVA methods can be made by choosing only the most important input variables and exclude the other variables.

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AUTHORS' CONTRIBUTIONS

The idea for this paper came as a result of discussions of V. I. Udovičić, R. M. Banjanac, D. R. Joković, A. L. Dragić, and D. M. Maletić. Gathering climate data and MVA analysis was done by D. M. Maletić and V. I. Udovičić. Performed indoor radon measurements were done by V. I. Udovičić and S. M. Forkapić. Writing of the paper was done by D. M. Maletić and V. I. Udovičić. A. L. Dragić gave idea about using MVA methods in cosmic and radon measurements. N. B. Veselinović and M. R. Savić analyzed and validated climate data. J. Z. Živanović helped with MVA analysis. D. R. Joković helped with data analysis and paper technical preparation.

REFERENCES

[1] Collignan, B., *et al.*, Development of a Methodology to Characterize Radon Entry in Dwellings, *Building and Environment, 57* (2012), Nov., pp. 176-183
[2] Li, F., Baixeras, C., The RAGENA Dynamic Model of Radon Generation, Entry and Accumulation Indoors, *Science of the Total Environment, 307* (2003), 1-3, pp. 55-69
[3] Jelle, B. P., *et al.*, Development of a Model for Radon Concentration in Indoor Air, *Science of the Total Environment, 416* (2012), Jan., pp. 343-350
[4] Maletić, D., *et al.*, Comparison of Multivariate Classification and Regression Methods for Indoor Radon Measurements, *Nucl Technol Radiat, 29* (2014), 1, pp. 17-23
[5] Udovičić, V., *et al.*, Radon Problem in an Underground Low-Level Laboratory, *Radiation Measurements, 44* (2009), 9-10, pp. 1009-1012
[6] ***, EPA 520/5-87-005, Gray D.J, Windham S.T, United States Environmental Protection Agency, Montgomery, 1987
[7] Živanović, M. Z., *et al.*, Radon Measurements with Charcoal Canisters, *Nucl Technol Radiat, 31* (2016), 1, pp. 65-72
[8] Stojanovska, Z., *et al.*, Prediction of Long-Term Indoor Radon Concentrations Based on Short-Term Measurements, *Nucl Technol Radiat, 32* (2017), 1, pp. 77-84
[9] Nikolić, M. D., *et al.*, Modelling Radiation Exposure in Homes from Siporex Blocks by Using Exhalation Rates of Radon, *Nucl Technol Radiat, 30* (2015), 4, pp. 301-305
[10] Brun, R., Rademakers, F., ROOT – An Object Oriented Data Analysis Framework, *Nucl. Inst. Meth. in Phys. Res., A 389* (1997), 1-2, pp. 81-86

[11] Hoecker, A., *et al*., TMVA – Toolkit for Multivariate Data Analysis, PoS ACAT 040, arXiv:physics/070 303, 2007
[12] Murray, F. W., On the Computation of Saturation Vapor Pressure, *J. Applied Meteorology, 6* (1967), 1, pp. 203-204
[13] Tetens, O., About Some Meteorological Aspects (in German), *Z. Geophys, 6* (1930), pp. 207-309

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СТУДИЈА СЛУЧАЈА ВИШЕГОДИШЊЕ ВАРИЈАБИЛНОСТИ РАДОНА У ПОРОДИЧНОЈ КУЋИ У СРБИЈИ

Понашање радона у затвореном простору има сложену динамику због утицаја великог броја различитих параметара који утичу на његову варијабилност: метеоролошких (температура, притисак и релативна влажност), концентрације аеросола, брзине размене између унутрашњег и спољашњег ваздуха, грађевинских материјала и животних навика. Као резултат, концентрација радона у затвореним просторијама показује варијацију, уз стандардну периодичност од једног дана и једне године. Годишња варијабилност је добро позната сезонска варијација концентрације радона. Посебно је интересантно пратити вишегодишње варијације концентрације радона на истој мерној локацији и временском периоду, пре свега због процене индивидуалних годишњих доза од изложености радону. У типичној породичној кући у Србији извршена су дуготрајна мерења радона у дневном боравку. Мерења су рађена током 2014, 2015, и 2016. године, у фебруару и јулу, сваке године. Коришћене су следеће мерне технике: активна и метода коришћења угљених канистера. Добијени резултати анализирани су коришћењем мултиваријантне регресионе анализе.

Кључне речи: варијабилност радона, мултиваријантна регресиона анализа, радон у затвореним просторијама, вишегодишње мерење радона