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SPECIAL ASPECTS OF CALIBRATION OF IONIZING RADIATION DETECTORS USED FOR SOIL RADON MONITORING

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The results of calibration of $\alpha-$, β- and γ-radiation detectors mounted into a borehole at the depths of 0.5 and 1 m, which are destined for soil radon monitoring, are represented and analyzed. The radon isotope radiometer RTM 2200 (SARAD GmbH, Germany) was used for calibration. It was determined that time variations of α-radiation flux density at the depths of 1 m poorly reflect the soil radon dynamics, both the diurnal variations and their amplitudes, and in the case with γ-radiation, they do not reflect it at all. Good synchronism between flux density dynamics of β-radiation at 0.5–1 m depth that of α-radiation at 0.5 m depth and radon volumetric activity dynamics measured at the same depths was found for diurnal and synoptic scales. Nevertheless, for certain days a small time shift between α- and β-flux densities and radon time series was observed. Recommendations for the conditions and the procedure of calibration of soil ionizing radiation detectors were developed.

Key words: radon, soil, monitoring, detector, ionizing radiation, calibration

Introduction

Methods of control for soil radon on α-, β- or γ-radiation in boreholes are the most widely spread to make earthquake forecast, to investigate the issues of gaseous exchange between lithosphere and atmosphere [1]-[9]. In these methods, ionizing radiation detectors operating in the count mode are mounted into boreholes at some depth. In this case, the processes of gas transfer in soil are not disturbed in comparison to the methods with forced air pumping from a borehole for the following analysis.

The reasons of the change of radiometers for α-, β- or γ-radiation detectors, mounted into boreholes are the simple maintenance and the capability of remote automated continuous monitoring of soil radon. Moreover, they are 1-2 orders cheaper than the

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methods applying α-spectrometry which makes it possible to use them widely. Thus, the number of sites for simultaneous monitoring may be significantly increased, extending the observation area. The main advantage is that they allow us to receive, process and analyze data in quasi-real scale.

Validity of the results and reliability or the methods of radon direct registration in a borehole applying ionizing radiation detectors has not been investigated in detail and over long periods of time. The conversion of pulse counting rate measured by detectors into radon volumetric activity (VA) value is carried out by multiplication by a correction coefficient which is usually determined by an indirect method of comparison of the data with the results of single (in the best case, not continuous) measurements by a certified radiometer for radon.

Frequently, the analysis of soil radon dynamics for “anomalies” to make earthquake forecast is performed according to the results of monitoring without the conversion of the measured pulse counting rate into the radon VA value, arguing that only relative variations are important in such tasks.

Nevertheless, analysis of the results of numerical modeling [8, 9] allowed us to suppose that for the conversion of ionizing radiation (IR) flux densities (FD) the correction coefficients will not be proportional to radon VA in the soil air, and will likely be the functions from one or several parameters. Moreover, the conversion of measurement results into absolute values may be useful in the following calculation of radon transfer in soil-atmosphere system and in specification of model coefficients, as well as in the study of the issues on gaseous exchange, air mass and air electricity transfers and so on.

To verify the possibility of radon measurement by direct registration in the soil (borehole) by one or several IR and to determine the correction coefficients, a series of long-term calibration experiments has been carried out in Tomsk laboratory of radioactivity and ionizing radiations (TORII).

Instrumentation and methods

To monitor soil radon, highly sensitive intellectual detector blocks, BDPA-01 (2 units), 2 BDPB-01 (2 units) and BDKG-03 (ATOMTEX, Belarus), where chosen. They were installed on TOPII experimental test field, in 5 separate boreholes 0.5 and 1 m deep according to the scheme shown in Fig. 1a. The external view of the complex for the calibration of soil detectors of ionizing radiation by radon and thoron radiometer RTM 2200 (SARAD, Germany) is shown in Fig. 1b. The calibration of soil detectors was carried out from May 28 to July 28 and from October 5 to November 21, 2011.

To realize the calibration, 2 holes were made in the upper part of a plastic pipe (Fig. 1a) projecting above the surface to connect the tubes with the radiometer. The air together with gases cumulated inside a borehole were constantly pumped out (with the velocity of 1 l/min) by a built-in air pump via the 1st connecting tube from the lower part of a borehole and got inside the test radiometer volume. During the time of gas motion from a borehole into the radiometer, thoron almost decayed. Thus, the developed scheme allowed us to analyze only soil radon. After the test volume, the air together with radon was pumped back into the upper part of a borehole through the 2nd connecting tube.

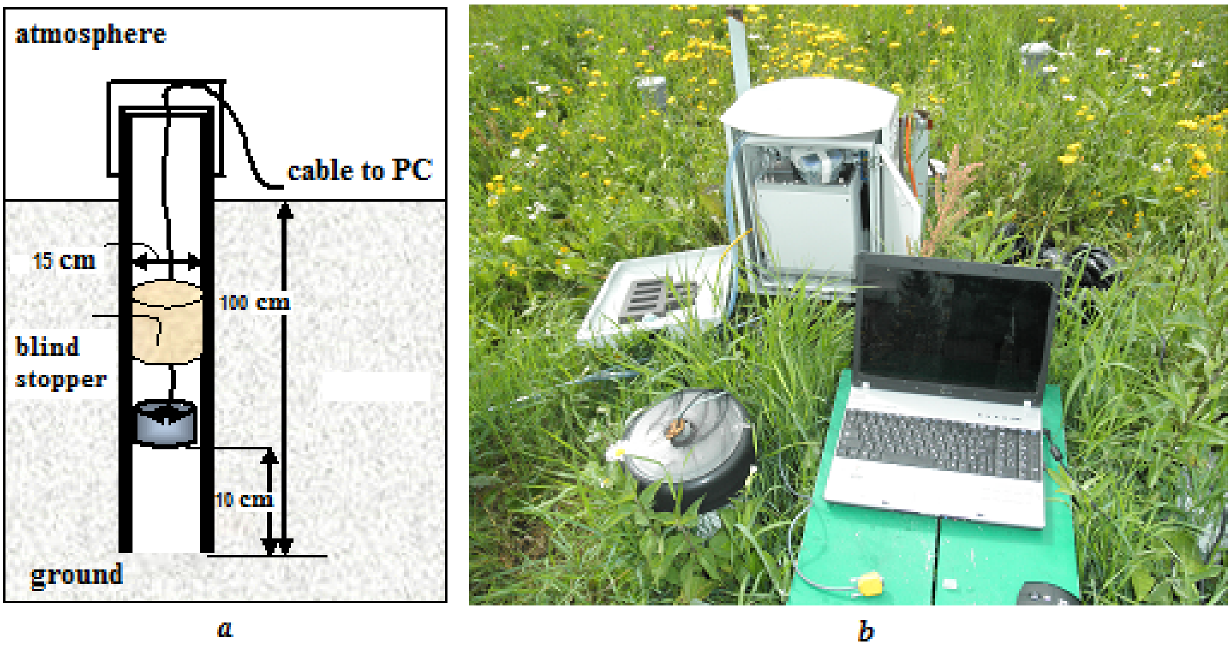

Fig. 1. Scheme for mounting of soil IR detectors (*a*), and the complex (*b*) for their calibration by radon radiometer RTM 2200

Results and analysis

Let's first analyze the differences in the regions for data collection of γ-radiation photons, β- and α particles formed during radio active decay of soil radionuclide, radon isotopes and their daughters (D). Consider the schemes of mounting of detectors for photons (Fig. 2 a) and charged particles (Fig. 2 b and c). It follows from the schemes that the regions for charged particles and photon collection differ significantly.

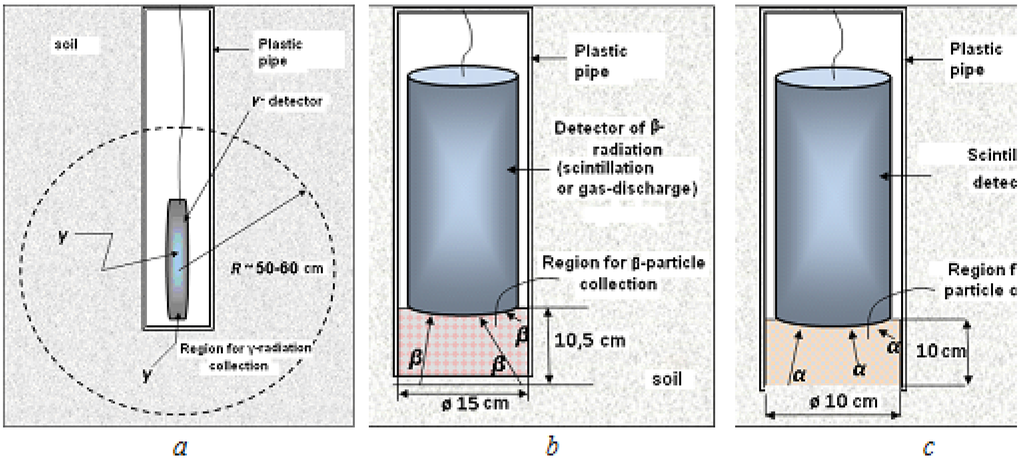

Fig. 2. Region for collection of γ-radiation photons (*a*), β-particles (*b*) and α-particles (*c*), formed during radio active decay of soil radionuclide and radon isotopes and their daughters

Collection of γ-radiation photons by a detector takes place within the radius of 50-60 cm depending on the borehole size. Taking into account that the borehole for γ-detector is hermetically sealed at the bottom, the detector registers only the photons generated in the soil. Collection of α-particles is performed from a small air volume limited by plastic pipe walls with an open base and the distance to soil corresponding to the length of maximum range of α-particle path in the air determined by the size of detector sensitivity area, maximum α-particle energy (8.8 MeV) and energy threshold of scintillation detector (3 MeV).

β-particles get into the detector from the same air volume plus from the soil layer about 0.5 cm thick. The change of weather conditions causes the change of radon concentration in the soil. In this case, time delay of the reaction response of the whole "soil-air inside a borehole" system or its separate parts is possible. It will be determined by the differences in time of radioactive equilibrium between α-, β-radiating decay products.

Thus, the differences in the regions for collection of IR, characterized by different sizes and characteristics of included media, allow us to expect differences in the dynamics of different types of IR characterizing the changes in soil radon concentration.

The results of calibration in the borehole at the depth of 1 m with α–detector are shown in Fig. 3. The upper diagram shows experimental series of radon VA (Rn 1 m) and the radon VA (Alpha 1 m) recovered by multiplication by the correction coefficient $K_{\alpha 1m}$. The lower diagram of the figure illustrates temperature changes on the earth surface.

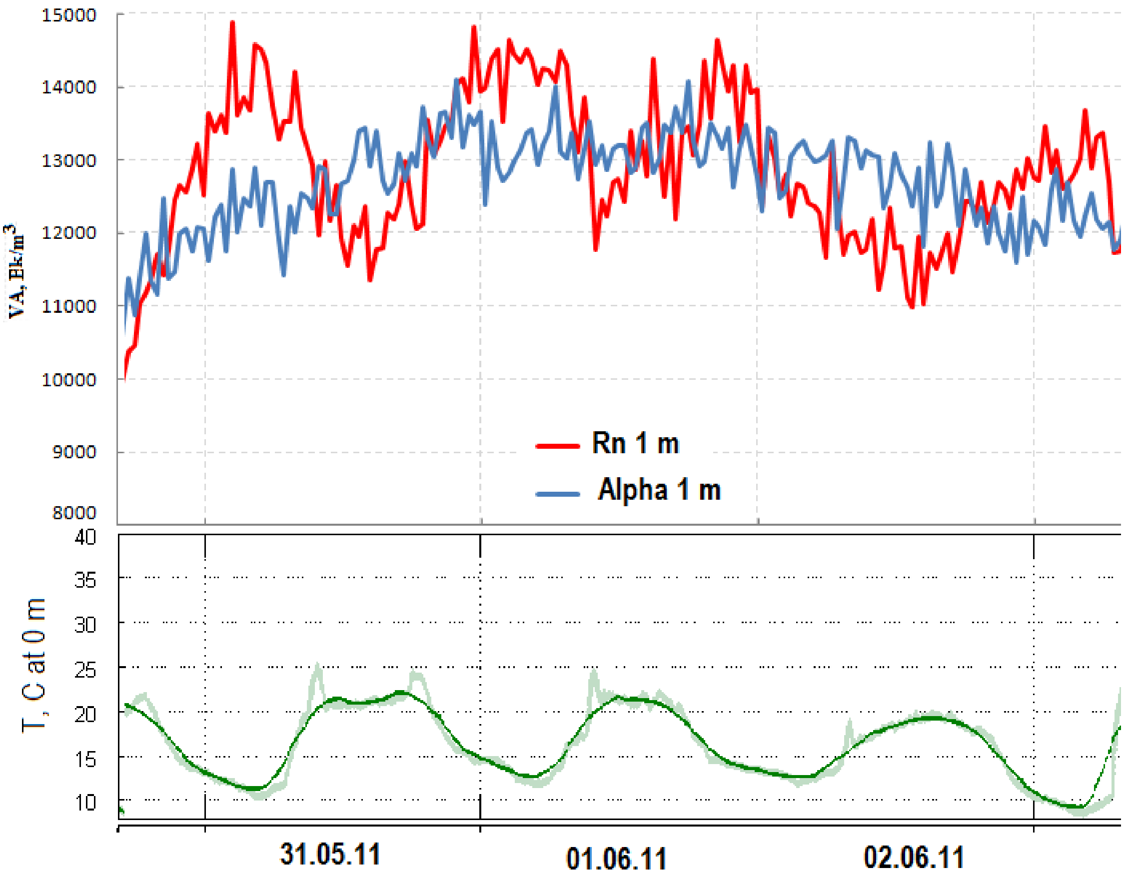

Fig. 3. Dynamics of temperature and radon VA at the depth of 1 m

The correction coefficient $K_{\alpha 1m}$ was determined by the division of radon VA average for the observation period by the average pulse counting rate registered by the detector.

Analysis of the real and recovered series of radon VA showed that the α-detector at the depth of 1 m reflects inadequately the real change of radon VA in a borehole, there are no diurnal variations which are registered by radon radiometer.

Then the calibration of α-detector was carried out in the borehole at the depth of 0.5 m from June 3 to 10. The results of calibration in the borehole 0.5 m deep with α-detector are illustrated in Fig. 4.

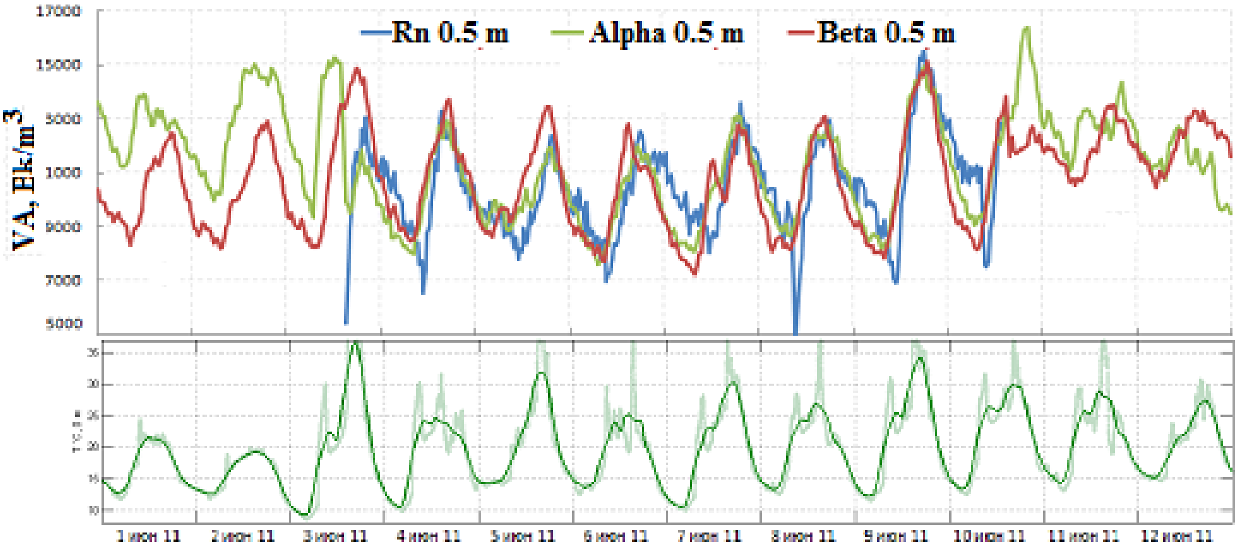

Fig. 4. Results of calibration by α-detector in the borehole 0.5 m deep

It shows the series of radon VA (Rn 0.5 m) measured by the radiometer and those (Alpha 0.5 m and Beta 0.5 m) recovered by the multiplication by the calculated correction coefficients, as well as temperature on the earth surface.

Recovery of β-series at 0.5 m by a simple multiplication by the correction coefficient failed. As the result, the correction coefficients for the conversion of measurement data from pulse/s into radon VA units (Bk/m^3) were determined for α- and β-detectors by different ways. A more complicated scheme was required with the recovery of β-series to determine the correction coefficient K_β. The pulse counting rate values for β-detector (N_β) were divided into 2 parts: a) the constant one ($N_{\beta s}$), determined by soil radionuclide not referring to radon component and b) the variable one ($N_{\beta Rn}$), determined by β-radiating radionuclide of radon decay chain which are contained in the borehole air and the 5 cm soil layer in the bottom open borehole basis.

Thus, the total rate of pulse counting was determined as $N_\beta = N_{\beta s} + N_{\beta Rn}$, and radon VA was estimated by the expression

$$VA_{Rn}(i) = \left(N_\beta(i) - N_{\beta s}\right) \cdot K_\beta.$$

The constant component $N_{\beta s}$, which value was 47% from the average pulse counting rate for the borehole under the study depend on physical-geological characteristics of the area under investigation, distance from the detector to the earth surface and borehole diameter.

Analysis of calibration results for the borehole 0.5 m deep with α-detector showed that temporal changes of radon VA and α- and β-radiation fluxes measured at one depth of 0.5 m but in different boreholes are almost synchronous, they have almost a saw-tooth form. Amplitude of α-radiation FD variations changes in time according to radon field. Dynamics of β-radiation FD at the same depth almost coincide with α-field radon dynamics for the period under consideration.

Time variations of radon VA, FD of α- and β-radiations at the depth of 0.5 m correlate well with the dynamics of the earth surface temperature.

To estimate how the system of air pumping during the calibration affects the behavior of α- and β-fields, Fig. 3 illustrates a longer period of about 2 days before and after the calibration. When the system of air pumping was connected via the radon radiometer, the average α-background decreased by 20% at the depth of 0.5 m. Variation amplitude did not significantly change. Such a reaction of the α-background is associated with the partial removal of thoron and α-radiating decay products of radon and thoron from the air in the borehole. When the air pumping was stopped, α-background in the borehole quickly recovered.

The system of air pumping affected the β-background more significantly. On June 10, the system of air pumping with RTM 2200 radiometer was connected to the borehole 0.5 m deep with a mounted β-detector inside. Variation amplitude decreased by almost two times (Fig. 4).

The calibration results for β-detector in the borehole 0.5 m deep are shown in Fig. 5. The upper diagram illustrates the series of radon VA in the borehole 0.5 m deep (Rn 0.5 m) measured by the radiometer and the series of radon VA measured β-radiation and recovered by multiplication by the correction coefficient (Beta 0.5 m). For comparison, the lower diagram of Fig. 5 shows the series of radon VA measured α-radiation and recovered by multiplication by the correction coefficient (Alpha 0.5 m).

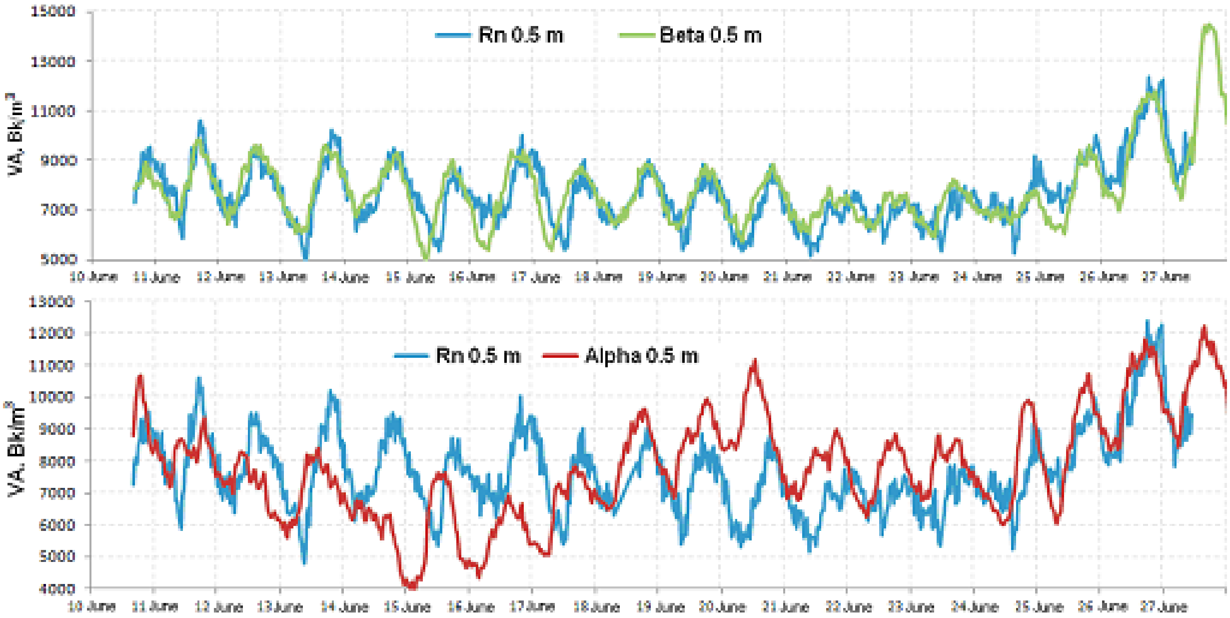

Fig. 5. Results of calibration of β-detector in the borehole of 0.5 m

It was obtained that the dynamics of β-radiation FD at the depth of 0.5 repeats well the radon dynamics at the same depth in contrast to α-radiation FD measured in the neighboring borehole at the distance of only 1.5 m.

It was also obtained in this calibration experiment that α-radiation FD at the depth of 0.5 m does not quite correctly reflect the soil radon dynamics, both the diurnal variation and the variation amplitude. During some periods, radon diurnal variation advance up to asynchronous is observed (from June 14 to 17, 2011).

The last calibration procedure of the summer season was that of β-detector in a borehole 1 m deep. During the calibration, anomalous increase of radon VA at the depth of 1 m was observed (Fig. 6) from July 13 to 15 which, as analysis showed, was caused by intensive precipitation (47 mm). At the same time almost synchronous anomalous increases of α-radiation flux density at the depths of 0.5 and 1 m and that of β-radiation at the depth of 1 m were registered.

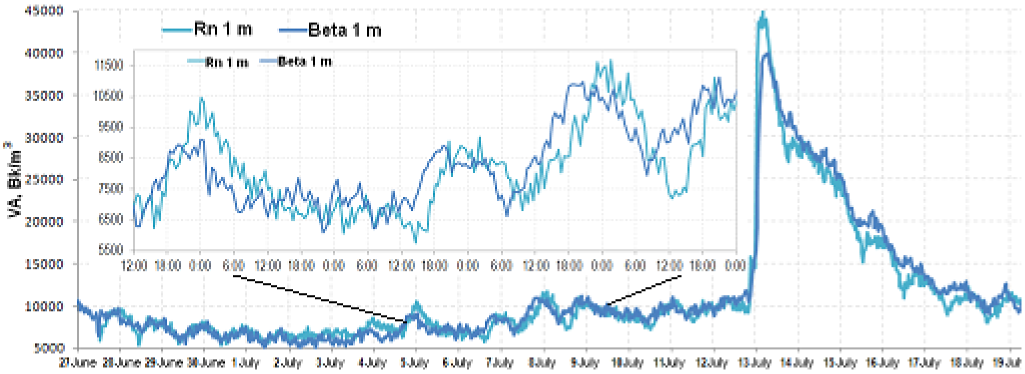

Fig. 6. Results of calibration of β-detector in the borehole 1 m deep

Recovery of radon VA series according to β-detector data at the depth of 1 m was carried out by the same scheme as it was described above. Good agreement with the values measured by radon radiometer was obtained. Nevertheless, during some periods, the advance of β-background diurnal variation at the depth of 1 m in comparison to radon VA by about 2-3 hours was observed. Diurnal variation of α-radiation FD at the depth of 1 m was not determined during the calibration, thought radon VA at the same depth showed clear diurnal variations. Thus, we may conclude that α-field at the depth of 1 m does not reflect diurnal variations of radon VA, thought it reacts on strong external effects but with less sensitivity. The diurnal variations of α- and β-radiation FD at the depth of 0.5 m showed almost 6-hour delay in the maxima in comparison to radon VA variation at the depth of 1 m.

Analysis of calibration results showed that temperature diurnal variation for the observation period may be described by the function $T(t) = T_0 + T_1 \cos(w(t - tm))$, where T_0=18.9 ^{0}C is the average temperature, T_1=4.78 ^{0}C is the maximum deviation from the average value w=0.261799 is the frequency, tm the time of maximum which was 17:00. The radon field is well described by a similar function with 2 hour delay of the maximum, i.e. t_m=19 h. Temperature variation within a day were about 25%, and radon VA was 18%. If we suppose that temperature change is the only source of radon field variations, increase in temperature by 1 ^{0}C would cause radon VA increase (at the depth of 0.5 m) by 300 Bk/m^3, and vice-versa respectively.

The procedure of detector calibration was partially repeated in autumn 2011. Special consideration was given to the questions of borehole pumping effect since due to the big sizes of “etalon” radon radiometers, calibration of soil detectors of ionizing radiations may only be realized by the method of air pumping out from a borehole for the following analysis.

The obtained during the autumn calibration experiment series of radon VA measured by a radiometer in a borehole 1 m deep (Rn 1 m) and the series of radon VA of α- and β-radiations at the depth of 1 m recovered by the multiplication by the correction coefficients are shown in Fib. 7. α-radiation FD dynamics at the depth of 1 m repeats well the dynamics of radon VA at the same depth in contrast to β-radiation FD. However, strong effect of the process of cyclic air pumping through the borehole and the radiometer on the value and the dynamics of α-radiation flux density in the calibrated borehole was discovered.

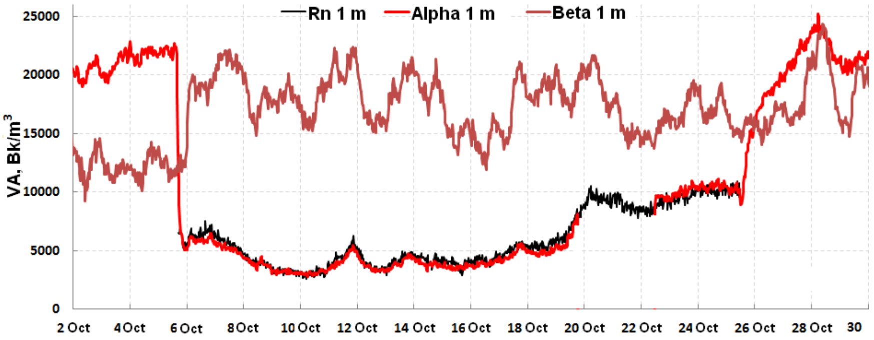

Fig. 7. Radon VA dynamics at measured by the radiometer at the depth of 1 m and the recovered series of radon VA at the depth of 1 m according to β- and α-radiations

The counting rate of pulses from α-radiation in the borehole decreased by almost 4 times after the connection to the scheme of cyclic blowing. At that, standard deviation significantly increased. Though when the borehole pumping was over, α-background (in radon VA units) increase and equaled to β-background.

Strong effect of the pumping system during the autumn calibration experiment in contrast to the summer experiment, when after the connection of the pumping system the average α-background in the borehole of 0.5 m deep decreased by only 20%, may be explained by seal failure at the points of connection of tubes with the plastic pipe casing the borehole due to larger temperature differences.

Analysis of the calibration experiments showed the following. Some correction coefficients, determined for one detector in repeated experiments had strong deviations. For the β-background it may be explained by the fact that when the air pumping system was connected, the detector was moved to another distance from the surface which caused the change of $N_{\beta}s$ value changing from 2.1 to 3.1 pulse/s (from 47% to 65% from the total counting rate of pulses). Thus, the change of β-detector mounting height in the borehole significantly affects both the correction coefficient for the conversion of the counting rate into the volumetric activity and the constant ($N_{\beta s}$) component of counting rate determined by β-radiating soil radionuclide not referring to DDP of radon and thoron.

It was also obtained that during the calculation of the correction coefficients for the conversion of the measured value into radon VA values, we should consider the fact for the soil air that forced air pumping out of a borehole decreases the flux of β- and α-radiations. The range of diurnal variations reduces significantly in this case. Analysis of real and recovered series of radon VA showed the following.

α-radiation FD at the depth of 1 m reflect inadequately the real change of radon VA in the borehole, there are no diurnal variations. Agreement of radon VA and α-radiation FD at the depth of 1 m was registered only in autumn. Mainly, α-radiations reflect only the changes of averaged over 1-2 days values of radon VA with the error of 30%. However, during anomalous emissions of radon, α-radiation FD at the depth of 1 m evidently reacts which makes this parameter acceptable to predict hazard phenomena, for example, the change of the stress-deformation state of the Earth crust but with some limitations.

α-radiation FD at the depth of 0.5 m shows time delay of the moments of maxima in radon VA in comparison to the depth of 1 m. The delay may reach 8 hours. According to the time delay, radon motion velocity in the soil was estimated to be 17×10^{-4} cm/s, that is almost 3 times higher than radon motion velocity only via molecular diffusion, 6×10^{-4} cm/s.

β-radiation FD at the depths of 0.5 and 1 m quite well reflects the soil radon dynamics. When air temperature is positive and it is not raining, diurnal variation is clearly observed. However, β-field diurnal variation has a shift during some periods in comparison to the diurnal variation of radon field, i.e. there are advances/delays by several hours in the time of maxima of β-field dynamics during various time periods.

γ-radiation FD at the depth of 1 m does not reflect the radon VA at the same depth. According to the results of calibration, recommendations for the procedure of soil detector calibration were developed.

Recommendations for calibration of IR detectors to control soil radon

Recommendations for the conditions and the procedure of calibration of ionizing radiation detectors mounted in boreholes and applied to control soil radon dynamics in monitoring regime may be formulated as follows.

- Applying the method of air pumping from a borehole during the calibration procedure, application of a borehole with already mounted detectors is not recommended. Another borehole with analogous characteristics (depth, diameter) should be drilled at the distance not less than 70 cm and not more than 3 m. Thus, the conditions of natural air exchange between the soil and the atmosphere will not be violated.
- If in the result of maintenance of boreholes with detectors the IR detectors were moved, removed or exchanged, calibration should be repeated and new calibration coefficients should be determined. β-scintillation detectors are very sensitive to movements.
- If calibration was carried out in boreholes with IR detectors mounted inside, besides the detection of the correction coefficient, it is also necessary to detect the correction for diurnal variation range decrease after air pumping out of a borehole. To do that, the data from IR detector should be registered several days before and after the calibration procedure.
- IR detectors should not be taken out of a borehole or moved during the calibration, since it results in data time series distortion.
- Boreholes with IR detectors mounted inside should not be opened during calibration, i.e. the tubes for air pumping from a borehole which are cyclically connected to radon radiometer should be mounted at least one day before the experiment which is enough to recover the radon equilibrium activity in a borehole.

Conclusions

Analysis of the results of calibration experiments showed that it is better to apply β-radiation detectors which can be mounted at the depth of 0.5-1 m to monitor soil radon. α-radiation detectors may be used to monitor radon only when mounted at the depth of about 0.5 m. γ-radiation detectors are not good for soil radon monitoring. According to calibration results, recommendations to the conditions and the procedure of calibration of soil IR detectors were developed.If radon monitoring is aimed at earthquake forecast or investigation of hazard natural phenomenon, the change of the parameter of radon VA measurement by β-radiation FD is quite reasonable and by α-radiation FD may cause great difficulties in interpretation of monitoring data, however, it may be applied with some limitations and assumptions.

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