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Deliverable 5.5

Proficiency testing program for continuous radon monitors utilized for control of active mitigation systems

Work Package 5 - Mitigation

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Disclaimer

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Executive Summary

This document forms a solid technical foundation for a proficiency testing program design for continuous radon monitors (CRM) intended and utilised to control ventilation systems operated as radon preventive or remedial mitigation systems, emphasising some of the practical and metrological requirements. The document itself is not structured to be perfectly aligned and comply with specific requirements of the ISO/IEC 17043 standard. It is rather targeted at specific technical and metrological aspects relevant to unique purposes of use of tested sensors. Special attention was paid to the relevance of the practical use of CRM, and in the case of sensor performance testing, the role of detection efficiency, sensitivity and response delay was highlighted as key technical parameters affecting the CRM's performance according to the intended application. Stable reference atmosphere and stability under varying environmental conditions are pointed out as the critical criteria for PT programs design. The report is focused on the metrological aspects of quality assurance of radon concentration measurements using currently available continuous radon monitors (sensors) with regard to their use for controlling ventilation systems, where knowledge of the metrological characteristic of the monitors is considered as a key factor.

The first part of the report (Part A) includes information on the system for preparation of a stable radon atmosphere necessary for testing of monitors at low radon activity concentration. The used system is based on a 150-L radon chamber connected to flow through radon source, both operating in the flow-through mode. The air for radon atmosphere preparation passing through the source and chamber was taken from radon free air generator and the flow rate was set using two gas mass flow controllers. This arrangement allowed for the radon sensors to be tested for a sufficiently long time even for low radon concentrations of tens or hundreds of Bq/m^3. The functionality of the system was demonstrated by measuring the stability of radon concentration in the prepared atmosphere. An analysis of variability of the measured results confirmed that if the atmosphere is prepared at a constant temperature, only instability caused by changes in atmospheric air pressure can be expected. Another advantage of this system, besides its simplicity, is the traceability of the radon activity concentration in the prepared atmosphere to the radium 226 primary standard.

In the second part of the report (Part B) test results of three types of sensors (declared by producers for air handling units and exhaust air fans) with different detection efficiency and different detection methods are presented. Testing was focused on the ability of radon monitors, primarily their use as radon sensors of indoor air quality for direct ventilation regulation to achieve at least the recommended radon reference level of 300 Bq/m^3. From tested sensors, only the Radon Eye sensor manufactured by FTLab, Korea (after temperature dependence correction) provides data suitable for direct ventilation control.

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1. Part A - System for monitor testing at radon atmosphere

1.1 Introduction

SÚRO has a long tradition in testing and calibration of radon devices. For this purpose, SÚRO has the appropriate equipment, which includes two radon chambers. The first one is a large radon chamber with a volume of 45 m^3, with temperature, humidity, ventilation and aerosol concentration control systems. For calibration of radon measurement instruments in this chamber, AlphaGuard monitors [3] as the reference monitors are used. The second one is a small radon chamber with a volume of 150 L, which is in most cases more suitable for tests where better accuracy and stability is required. This chamber was used for most of the tests that were part of this study.

For radon atmosphere generation SÚRO has about 15 radon sources produced by the Czech Metrology Institute (CMI) [1]. These sources with radium activity from 5 Bq to 2 MBq have certificated values of activity and emanation power, so they can also be used as a reference for radon activity concentrations in prepared atmospheres.

SURO has also a new generator for preparation of radon free air with typical activity lower than 20 mBq/m^3. Nominal air flow from this generator is about 2 m^3/h.

1.2 System for radon atmosphere preparation with activity in the 300 Bq/m^3 range

For the needs of this project, the reference atmosphere was prepared in a SÚRO small radon chamber (150 dm^3) operating in flow-through mode (Figures 1 and 2). Tested devices/sensors were placed inside the small radon chamber. Reference atmosphere was sampled to the external box with the device for monitoring the stability of the prepared atmosphere.

The reference atmosphere was prepared from radon free air from the local compressed air distribution net, which enabled to do of **long-term tests (longer than 14 day)**, at low level radon activity concentration. Radon was generated by means of a flow-through radon source (product of CMI [1]), from which radon is released at a constant rate.

Two **mass flow controllers** [2] (Bronkhorst, FG-201CVP Pressure Insensitive Mass Flow Controller) for adjusting the air flow were used. These controllers have **repeatability better than 0.2%** and therefore should not contribute to any instability of the system.

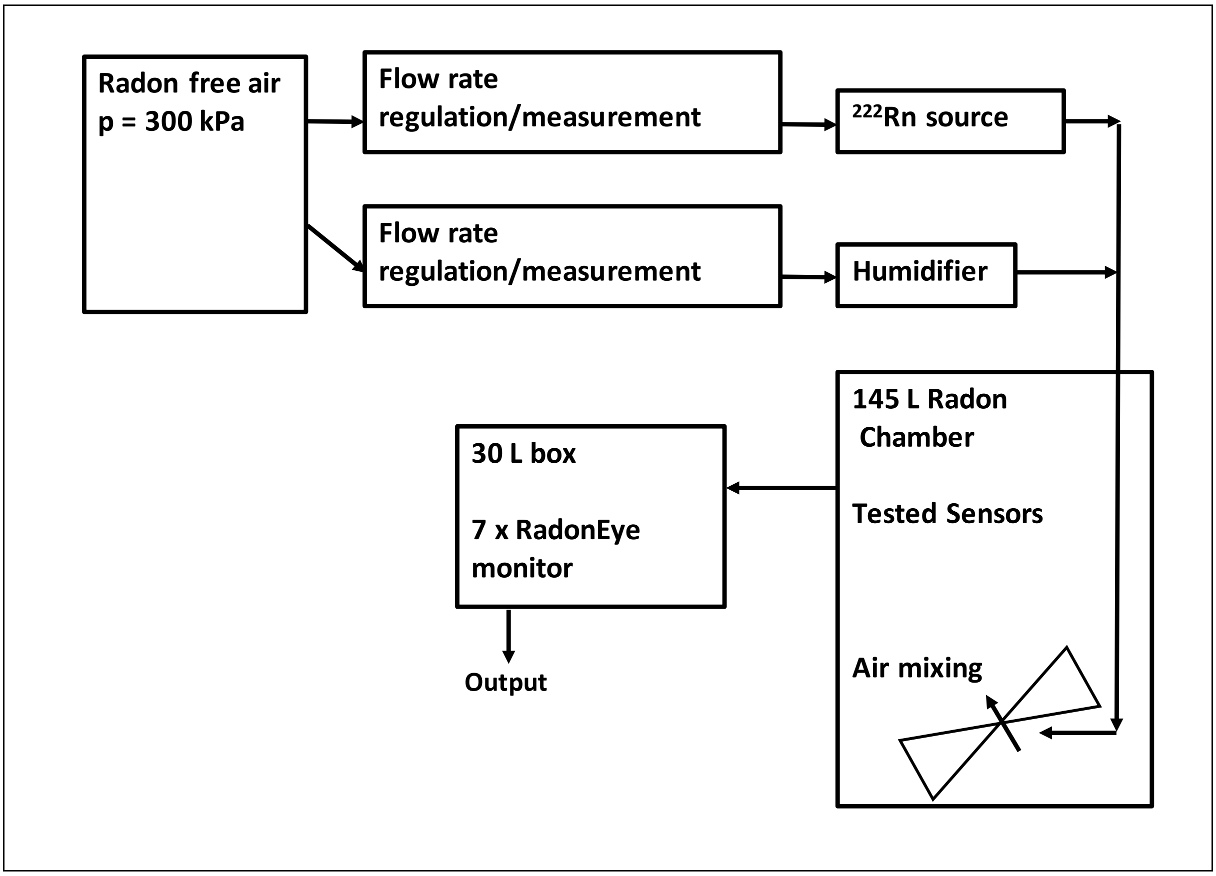

Figure 1 – Simplified scheme of "new" SÚRO system for generation of radon reference atmosphere

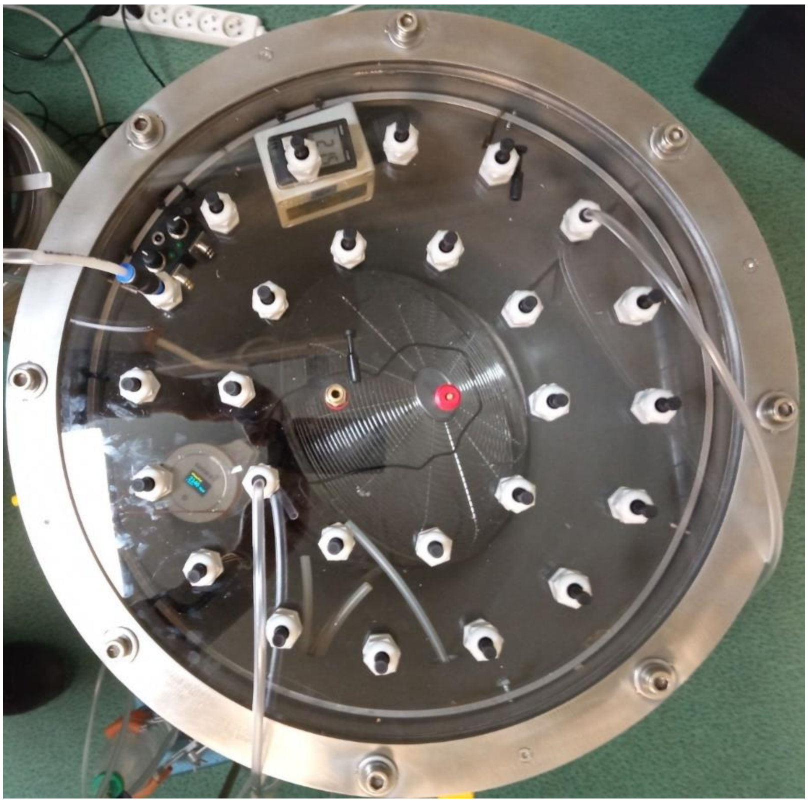

Figure 2 – 150 L radon chamber

The main characteristics of a flow-through system for generating a radon atmosphere are the stability of the radon concentration in the atmosphere, a simple formula for calculating the steady-state radon concentration and direct traceability (of radon concentration) to the primary radium 226 standard.

The radon activity concentration was calculated according to the formula for steady state, $A_v = A_{(226Ra)} \cdot \varepsilon / (V+Q/\lambda)$, from the activity of ^{226}Ra in the radon source ($A_{(226Ra)}$), its emanation power (ε = 0.99), free chamber volume (V) and flow rate (Q) defined by setting of (Bronkhorst FG-201CVP [2]) mass flow controller. The result was corrected to temperature and pressure difference between the conditions under which the flow regulator was calibrated and the real test conditions.

The uncertainty of radon activity concentration in prepared atmosphere (in steady state) depends mainly on certified values of radium activity and emanation power (typically, u < 2% (k=1)), and uncertainty of air flow rate (0.5%). Besides that, an uncertainty component less than 0.5% due to correction for the temperature, pressure and humidity should be applied. If the reference atmosphere is prepared at a constant temperature and humidity, practically, only instability derived from changes in atmospheric pressure was expected.

1.3 Stability of radon concentration in prepared reference atmosphere

Radon activity concentration in the prepared atmosphere was monitored by the AlphaGuard radon monitor [3], firstly at kBq radon activity range (Figure 3). The measured concentration was stable, only instability derived from atmospheric pressure variation was expected. Then the system was tested in the 300 Bq/m^3 radon activity range (Figure 4). The test was carried out at Av(^{222}Rn) = 304 Bq/m^3 (calculated value from flow rate) using monitor with low internal contamination that corresponded to about 4 Bq/m^3 of radon concentration.

To demonstrate the functionality of the system (at the 300 Bq/m³ range), fluctuations in measured data were evaluated with the aim of estimating the monitor detection efficiency, assuming that only the component related to the small number of monitoring records contributes to the overall instability. The detection efficiency estimate derived from the variance of the measured results corresponded to 1.2 CPH per 1 Bq/m³ at 300 Bq/m³. The estimate does not include correlations arising as a result of the possible detection of a single radon decay as an alpha particle from radon, ^{218}Po or ^{214}Po. This effect can reduce the estimate. Since the monitor manufacturer only provides values of detection efficiency at lower activity [3], it was not possible to correctly compare the estimate at 300 Bq/m³ with the declared value at 100 Bq/m³.

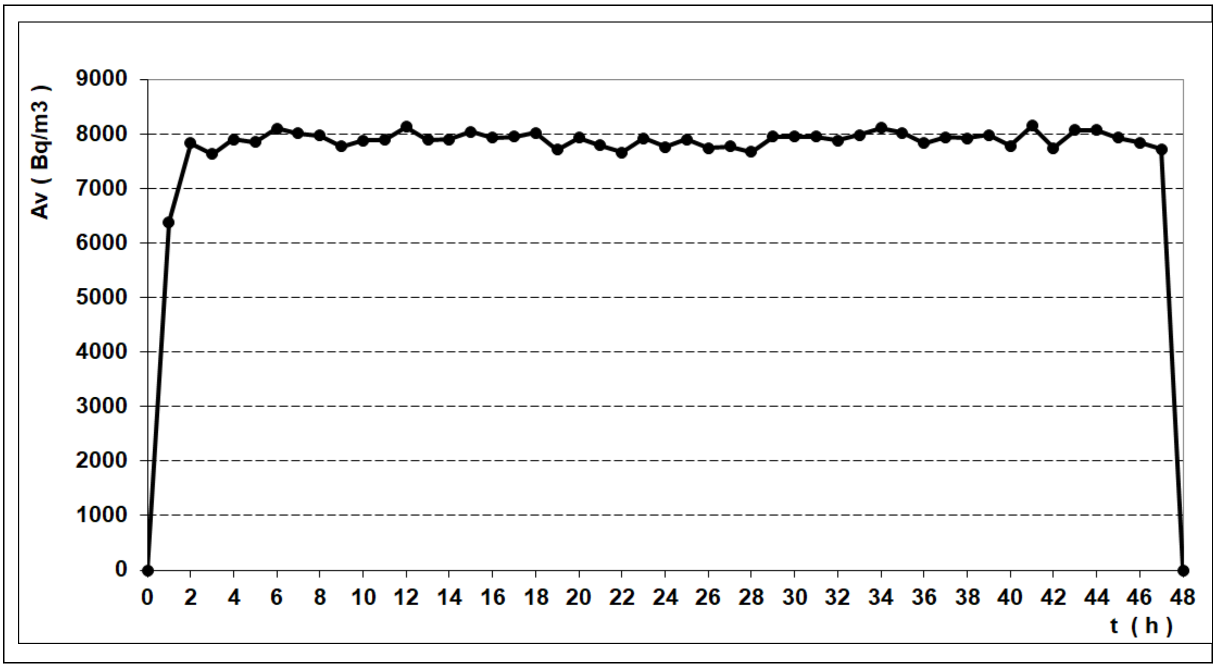

Figure 3 – Stability of radon volume concentration in the radon chamber for kBq/m³ range

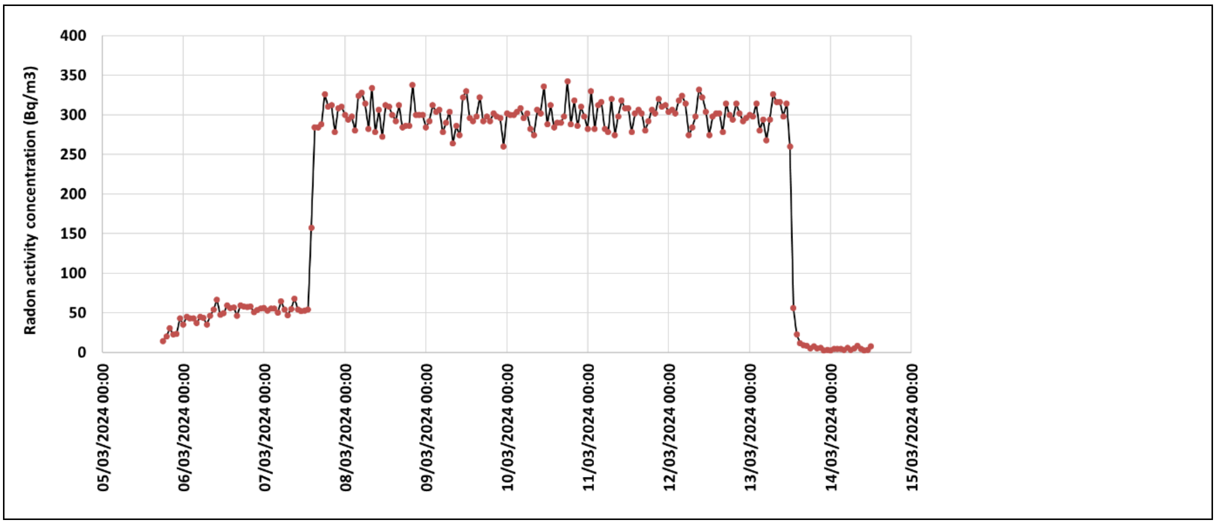

Figure 4 – Stability of radon volume activity concentration in the radon chamber at 300 Bq/m³ range

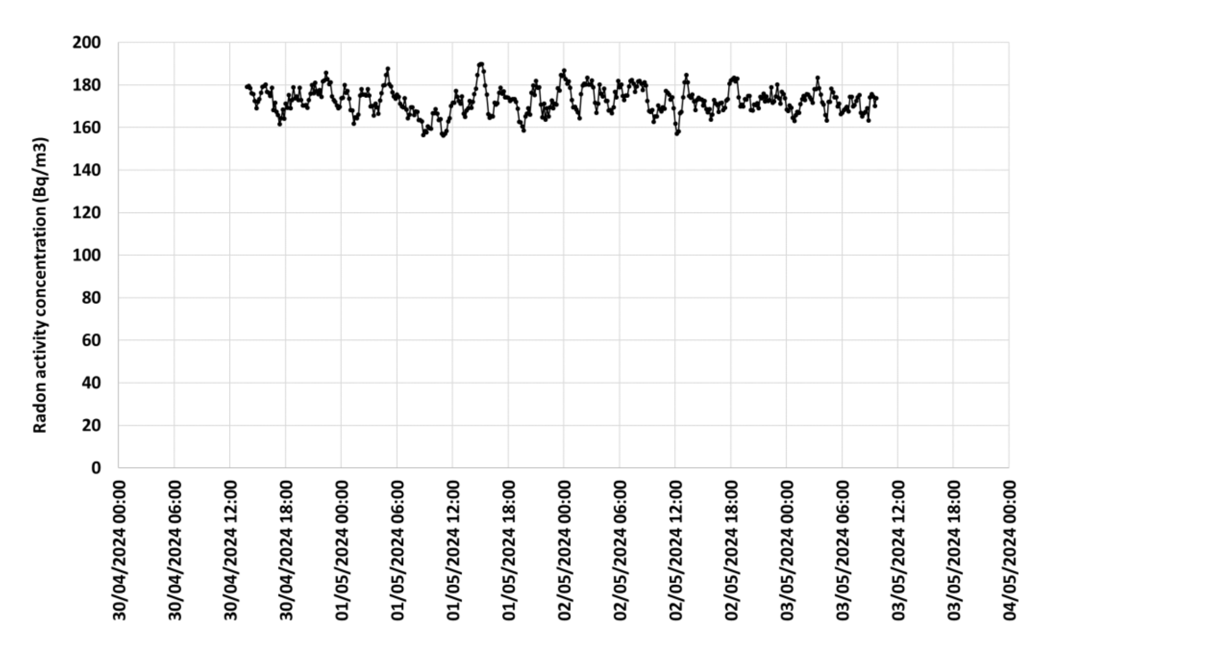

Figure 5 – Measurement of stability of radon activity concentration in the radon chamber using seven RadonEye monitors

The situation was better in the case of stability measurement of radon volume activity concentration using a set of 7 FTLab RadonEye monitors [4] (Figure 5). RadonEye is low-cost monitor, which has a high sensitivity pulsed ion chamber. The detection efficiency (of 7 monitor set) estimated from the variance of the measured results corresponded to 4.2 CPH per 1 Bq/m^3, which is about 75% of the declared value by the manufacturer. This result is considered as a good agreement and a demonstration of the stability of the system. In addition, the result showed that the set of 7 RadonEye monitors can be used in some tests as the reference at lower radon activity concentrations. However, the disadvantage of these cheap monitors is the high temperature dependence of their response, which was proven by comparative measurements with the AlphaGuard monitor (Figure 6). Therefore, RadonEye monitors can be used as a reference only at constant temperature (after monitor calibration). As an example of its use, there could be measurement of the increase and decrease in radon concentration, where the 10-minute data readings were used. This was possible thanks to the open communication data protocol on the original FTLab monitors (Figure 7).

1.4 Conclusion

The SÚRO system for reference atmosphere preparation based on flow-through method has been modified for use in the 300 Bq/m^3 radon activity range. The functionality of the system was proved by measuring the stability of the radon concentration in prepared atmosphere. Systems using the flow-through method of radon atmosphere preparation is particularly suitable for long-term tests, where the stability of radon concentration is an important criterion. If the reference atmosphere is prepared at a constant temperature and humidity, practically, only instability derived from changes in atmospheric pressure can be expected.

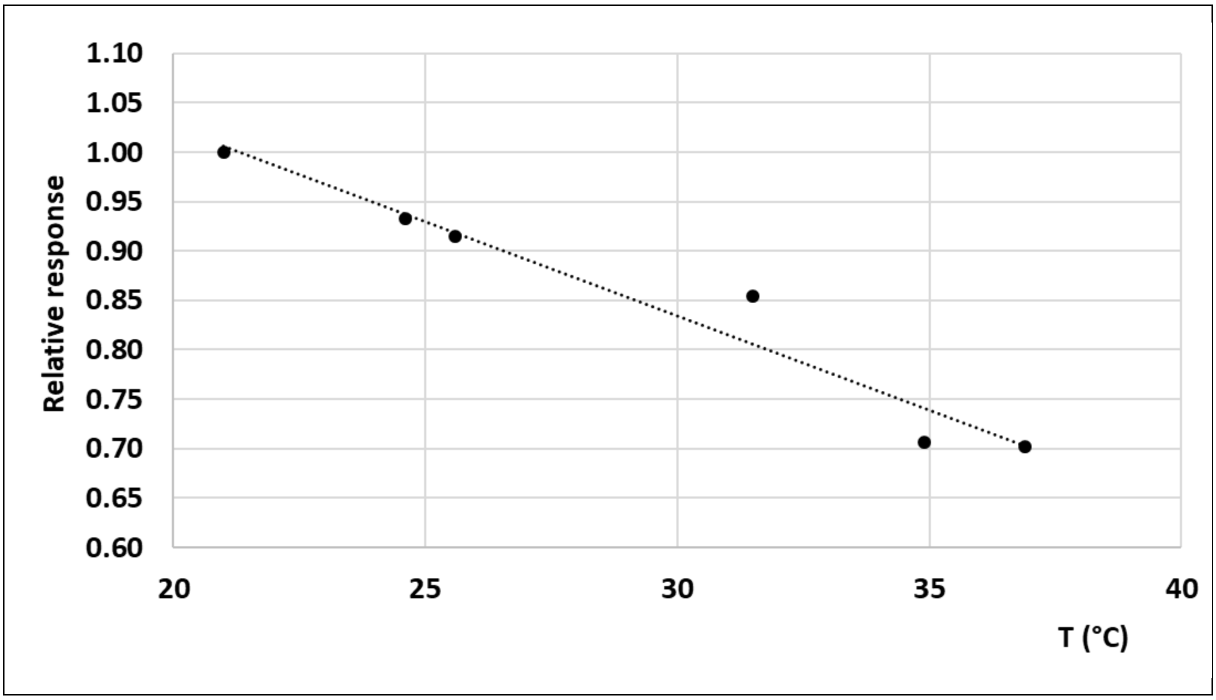

Figure 6 – Response of RadonEye sensors depends on temperature

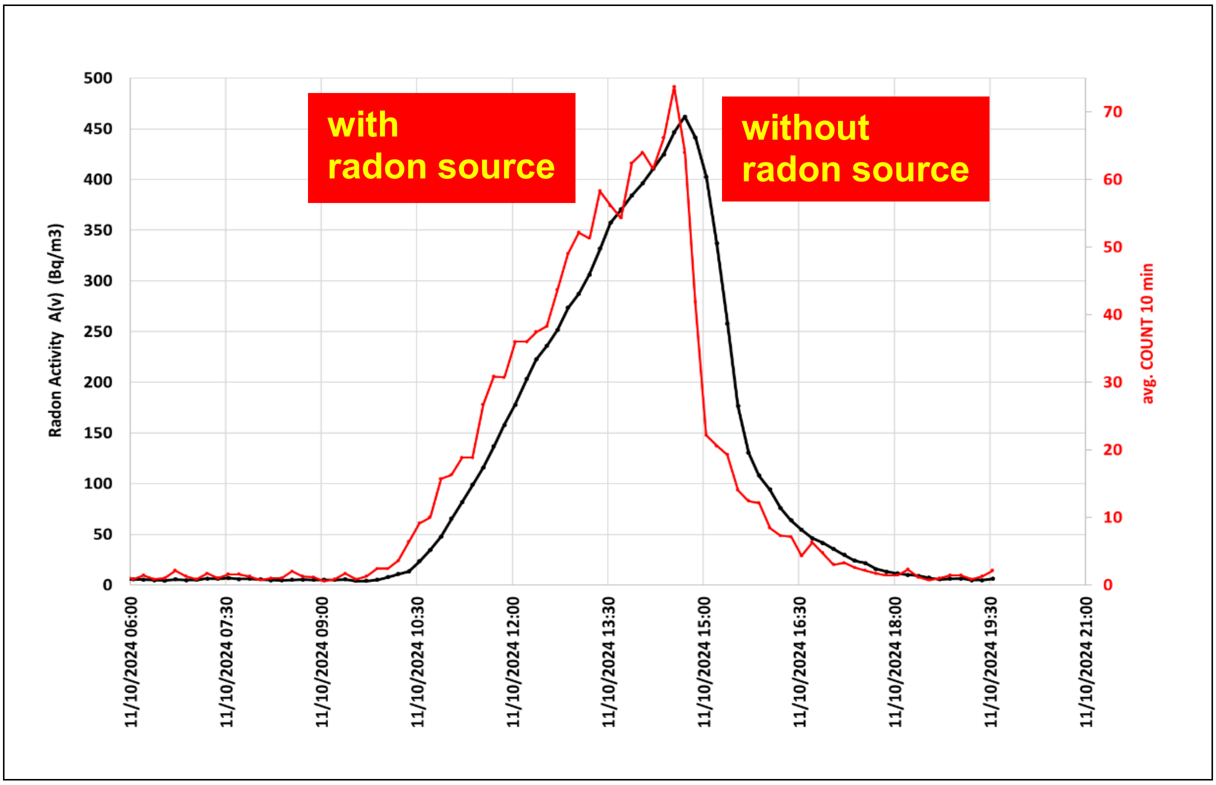

Figure 7 – Response of 7 RadonEye monitors to increases and decreases in radon concentration

2. Part B – Sensor tests

2.1 Introduction

This part of presented study is focused on testing the ability of radon monitors, primarily their use as radon sensors of indoor air quality for direct ventilation regulation to achieve the recommended radon reference level of 300 Bq/m^3. The ventilation of indoor air can be used as an alternative radon risk reduction measure, for example, when other radon protection technology has failed or it can be used in low-risk radon areas.

Three types of sensors (declared by producers for air handling units and exhaust air fans) with different detection efficiency and different detection methods were tested to determine their parameters in a reference radon atmosphere. Some parameters, such as time constants of data delay for tested monitors were estimated from the model, because the direct tests in a radon atmosphere provide less reliable results.

2.2 Tested monitors

For this study the RadonEye monitor [4] (FTLab, Korea), Tesla probe [5] (Tesla, Czech Republic) and Robin sensor [6] (Radonova, Sweden) were selected. The first has a pulse ion chamber, the other two are based on the principle, where the activity of 218 and 214 polonium ions electrostatically collected on the detector is measured. All three sensors work in diffusion mode. Their sensitivity (given by the manufacturer) is summarized in Table 1. Their detailed parameters can be found on the websites [4], [5] and [6].

The original RadonEye monitors and original Tesla sensors were commercially available at the time of the project launch, but are currently unavailable.

2.3 Key sensor parameters for radon measurements in 300 Bq/m^3 activity range

Considering, sensors to be applied for direct ventilation control should be able correctly and quickly measure 300 Bq/m^3, the sensor key parameters are their sensitivity, data delay constant and stability of these parameters for a long time and under variable temperature and humidity conditions.

The sensor sensitivity is usually declared by the manufacturer (Table 1), but it is often only given at one level of radon activity, even though it is not constant over the entire range. Table 1 illustrates how important the overall sensitivity is for the measurement time to achieve a 10% uncertainty when measuring a radon activity concentration of 300 Bq/m^3. Time was calculated only from sensor detection efficiency given by the manufacturer.

Detection efficiency can be estimated from tests in a stable radon atmosphere but the end user usually does not have this option; the situation is even worse in the case of other technical parameters.

Table 1 – Minimum counting time to achieve 10% uncertainty (estimation for tested sensors)

Sensor type	**Sensitivity (CPH per 1 Bq/m^3)**	**Time (min) needed to reach 100 counts at Av = 300 Bq/m^3 ***
Radon Eye RD200	0.8	25
TESLA probe	0.25	80
ROBIN sensor	0.027	740

If the device is to be used as a radon sensor of indoor air quality for direct ventilation control, then its time to achieve 10% results uncertainty should be much shorter than 740 min. Therefore, due to low sensitivity, the ROBIN sensor is suitable only for very long-time radon measurement or indirect ventilation switching.

2.4 Monitor response delay

The second key parameter of radon sensors for direct ventilation regulation is **the time constant of response delay.** The manufacturer does not usually give its value. In certain cases, we can estimate it based on a well-established detection principle. The delay constant has two main components. The first one corresponds to delay related to decay of detected radionuclides, the second relates to integration times. For example, it is 30 minutes for a 60-minute moving average. In addition, further delays may be caused by slow radon diffusion to the measurement chamber or by software data processing algorithms.

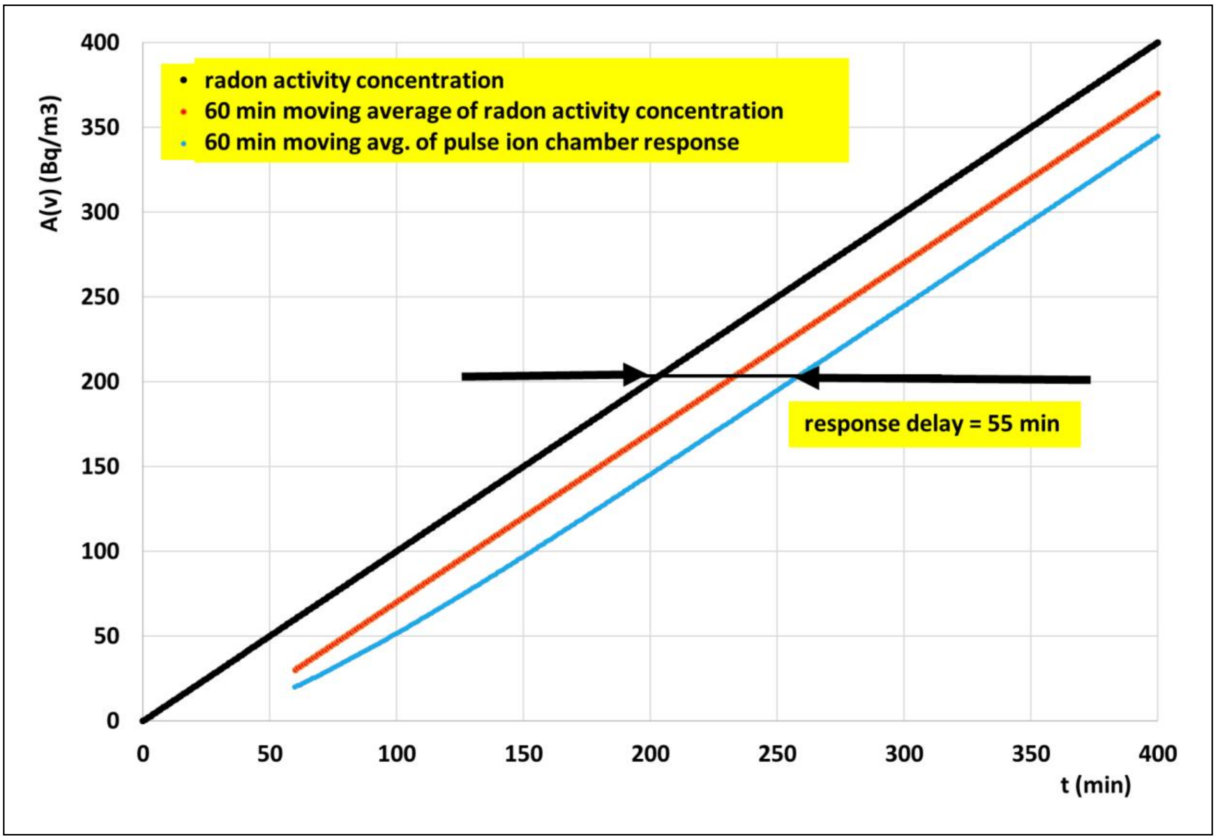

Figure 8 – An estimate of the data delay constant for the RadonEye monitor

An estimate of the data delay constant for the RadonEye monitor, assuming that the overall detection efficiency of the monitor is the sum of equal fractions (1/3) for detecting radon, ^{218}Po, and ^{214}Po, is shown in Figure 8, where it is taken into account that the standard RadonEye monitor output is a 60-minute moving average. The estimated value is 55 minutes, which means that the delay from reaching a certain radon concentration to its display (by the monitor) is on average 55 minutes. For sensors similar to the Tesla probe, where ^{218}Po and ^{214}Po nuclides are detected with same efficiency, the response delay (of 60 minutes moving average) is 68 minutes. The smaller delay constant has a 10 min moving average, it is about 30 min as shown in the picture (Figure 7 - red line).

Delay related to radon diffusion to the measurement chamber was estimated from RadonEye monitor testing in stable thoron (^{220}Rn) atmosphere (Figure 9), where it was found that RadonEye monitor detection efficiency for thoron is about ½ of detection efficiency for radon. This implies that the delay associated with radon diffusion into the chamber is approximately 1 minute.

2.5 Stability of monitor response

Another parameter tested was the **sensor's stability in air with varying temperature and humidity.** The dependence of the RadonEye monitor response for temperatures in the interval 21 to 37°C is shown in Figure 6. Tesla probe and Robin sensor response were affected by air humidity (Figures 10 and 11). This phenomenon is typical for sensors with the same detection method as Tesla or Robin sensors.

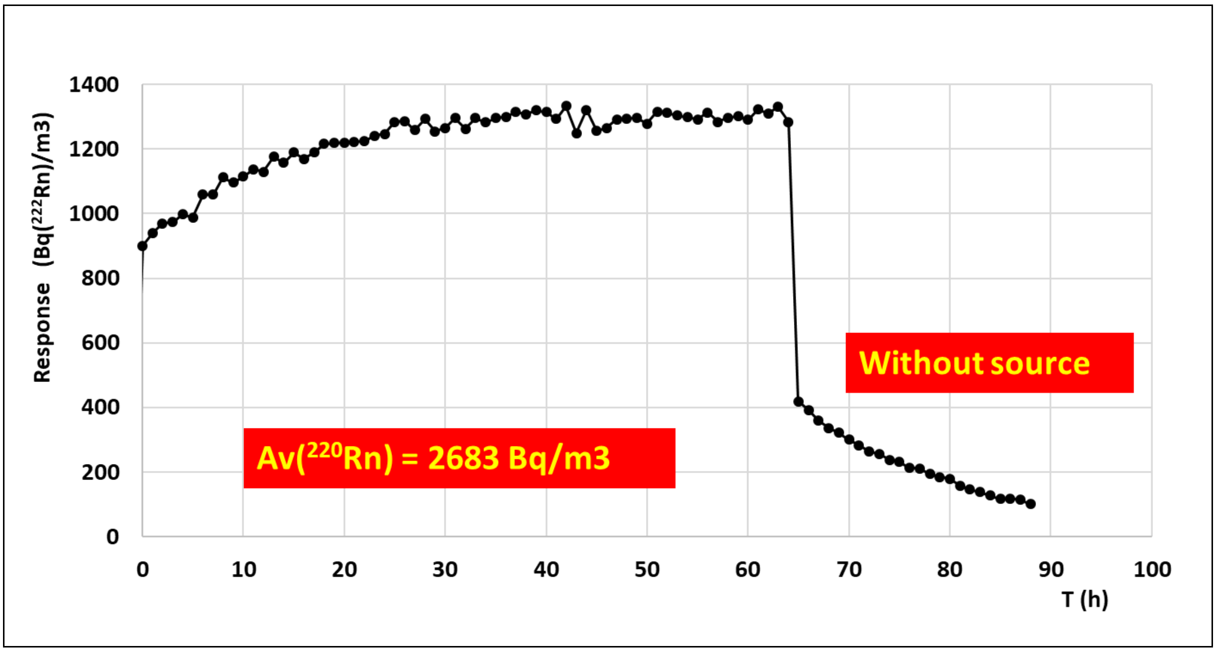

Figure 9 – Test of RadonEye monitor in thoron atmosphere

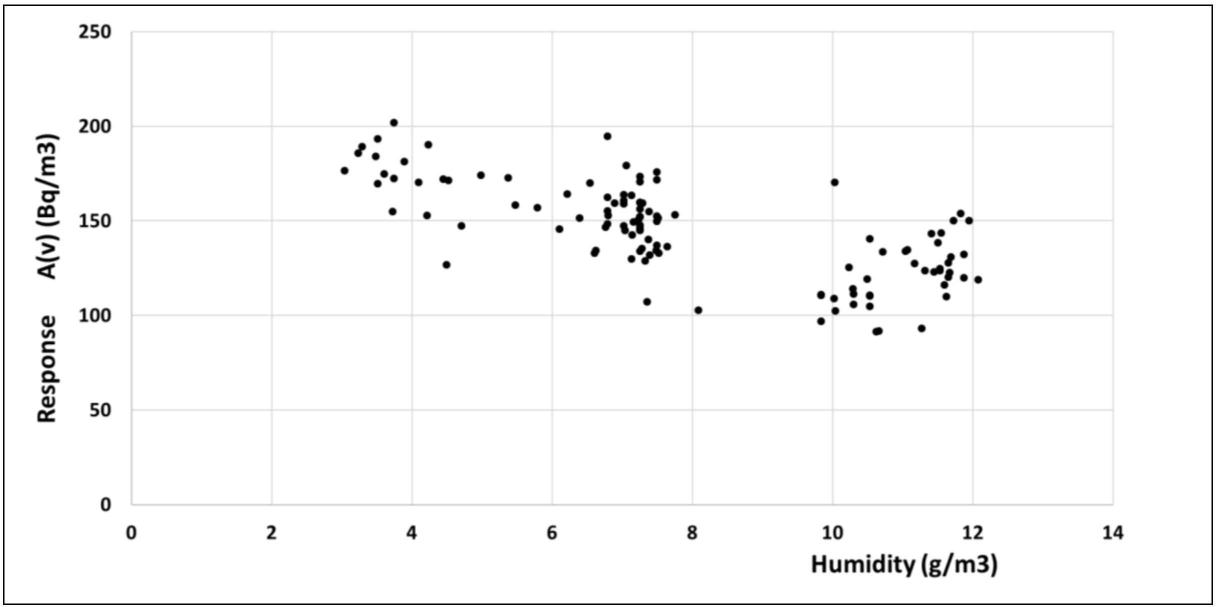

Figure 10 – Humidity dependence results of two tested Tesla sensors at 250 Bq/m³

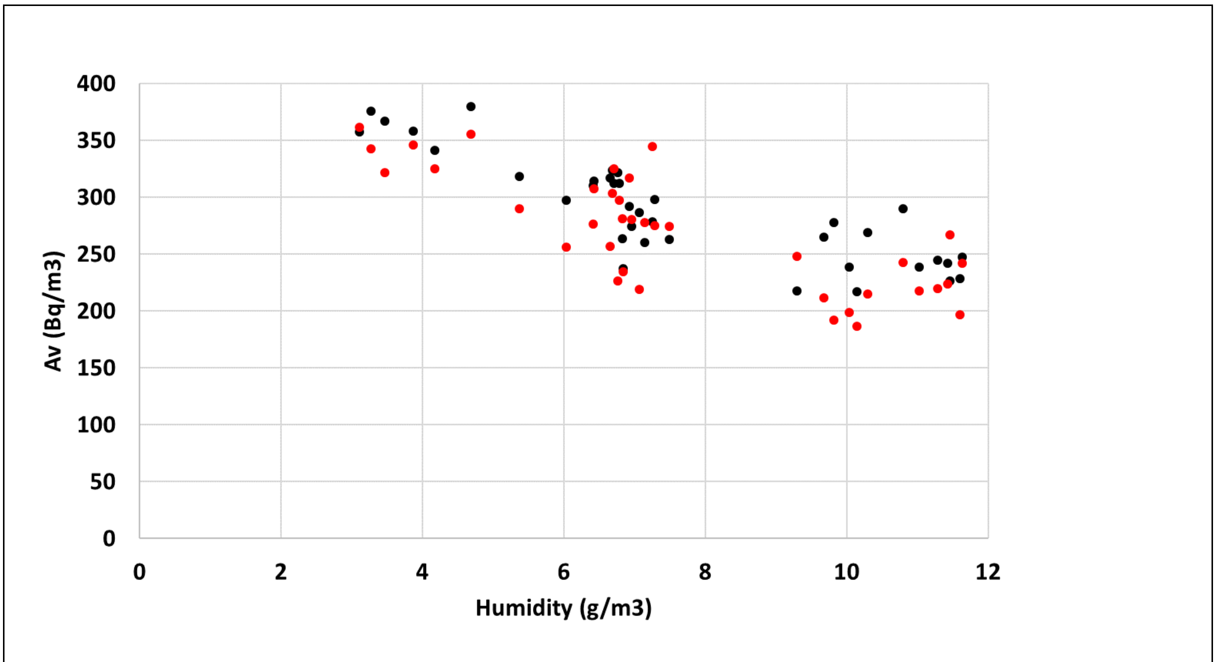

Figure 11 – Humidity test results of two Robin sensors at 250 Bq/m³ radon activity concentration

2.6 The simulation of the monitors responses, when used to control ventilation

The behaviour of the monitor during ventilation was estimated from a simulation based on the simplest possible (two-phase) ventilation strategy with a target radon activity concentration of 300 Bq/m³. The first phase consists of a linear increase in the radon activity concentration to the ventilation switching-on level of 400 Bq/m³. The second phase is a decrease in radon concentration to the ventilation switch-off level of 200 Bq/m^3 (Figure 12 – black line). This ventilation strategy with a 220-minute cycle duration operates with a 50% air exchange rate in one ventilation cycle.

The rate of increase in radon concentration for the ventilation model examples was 60 Bq/m^3 per 1 hour. The radon concentration decrease rate was estimated from CO_2 concentration measurement (Figure 13), where CO_2 concentration dropped from 2300 to 700 ppm during 5 minutes of ventilation, so that 85% of the indoor air (and radon) was ventilated. If we compare radon sensors with CO_2 sensors, radon measuring sensors have a very slow response to switching off the ventilation, compared to, for example, conventional CO_2 sensors, which can handle this aspect of ventilation much better.

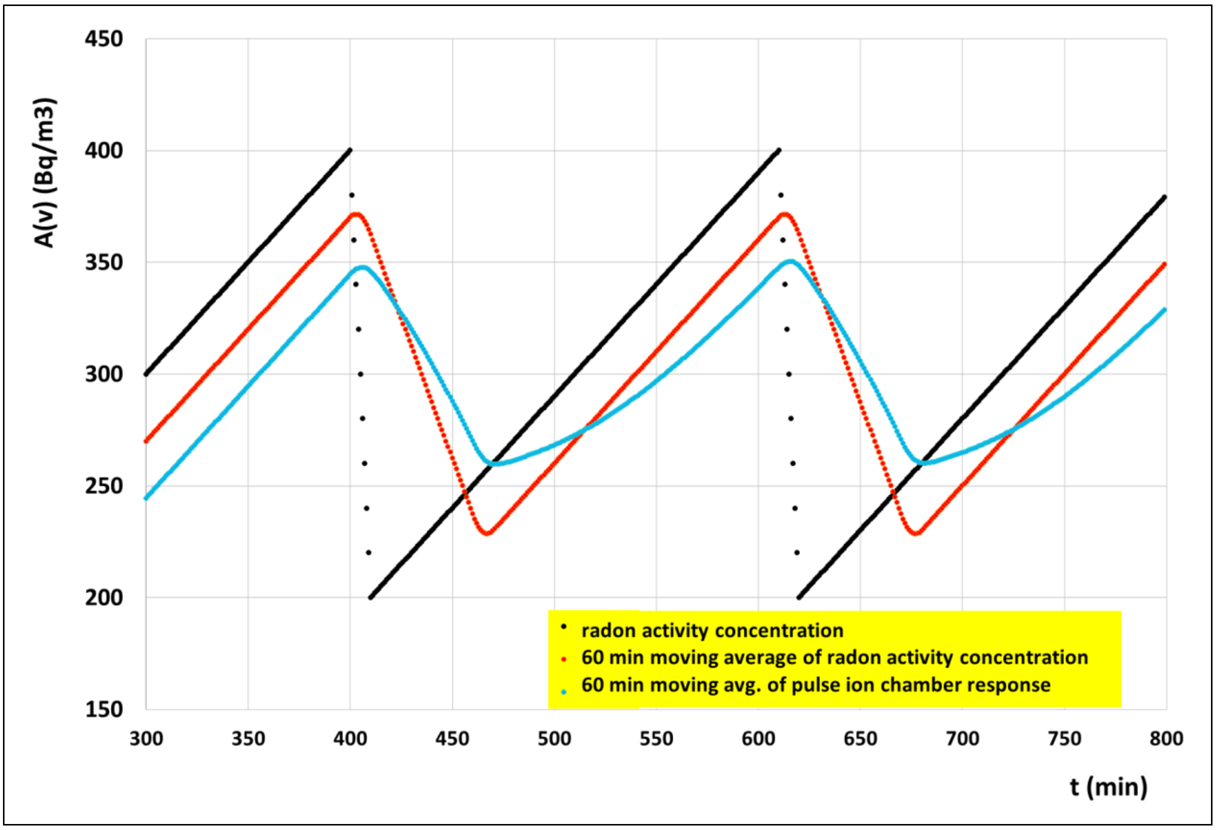

Figure 12 – Simulation of the monitor response during ventilation

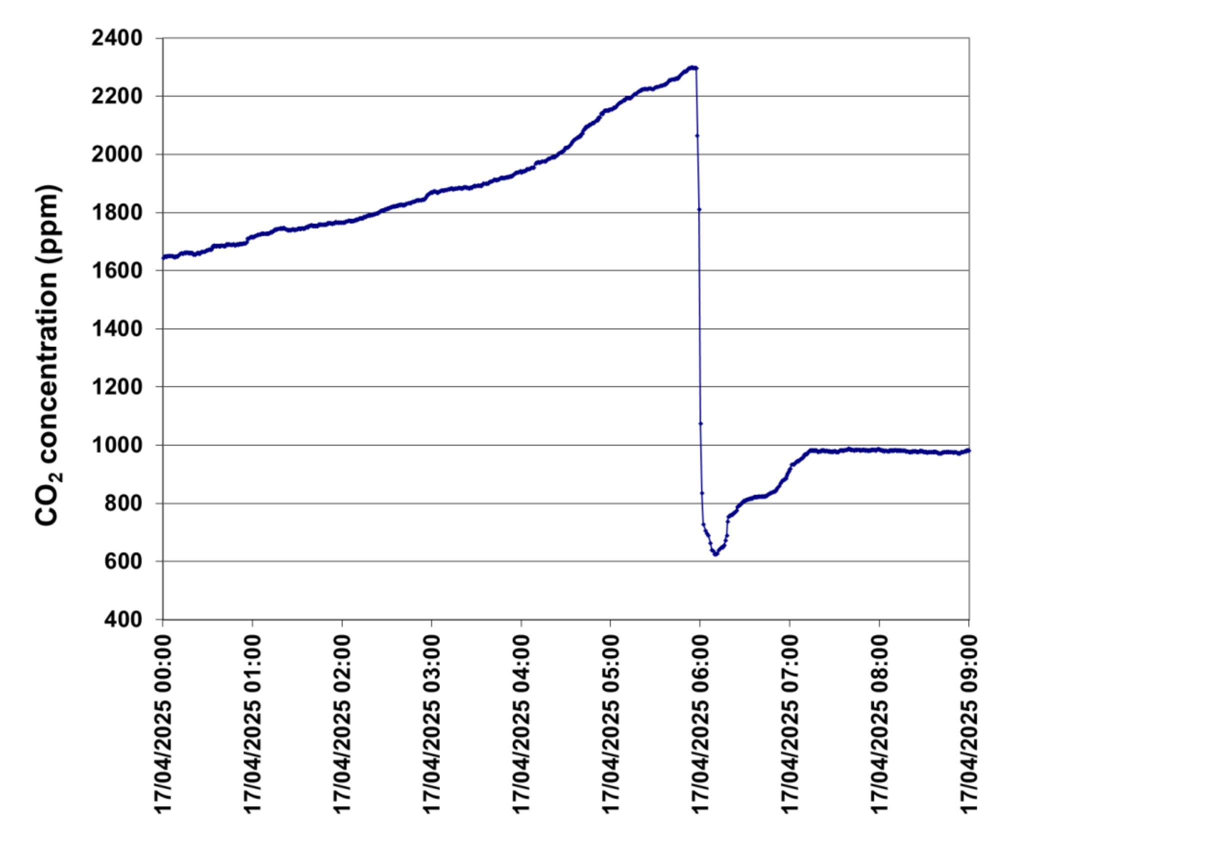

Figure 13 – Decrease in CO_2 concentration during ventilation

An example of a simulation of the response of a monitor based on a pulsed ion chamber (similar to the RadonEye monitor) is shown in Figure 12 (blue line); here it is assumed that sensors with high detection efficiency have been used, so that the response is not affected by fluctuations due to the registration of a small number of pulses. In this example, the monitor response variation (blue curve) is only in the range from 260 to 350 Bq/m^3, while the actual radon concentration values range from 200 to 400 Bq/m^3. This small difference in response means that only devices with sufficient sensitivity can be used to control the switching.

An even worse situation occurs in the case of a sensor based on detection of ^{218}Po and ^{214}Po (similar to a Tesla probe), where the simulated response range is even smaller, only from 272 to 341 Bq/m^3. This means that detectors operating on the same principle as the Tesla probe should have greater sensitivity compared to a detector based on a pulsed ion chamber, if the same switching error rate is required.

Figure 14 (blue points) shows the possible response of the RadonEye monitor in the case of actual detection efficiency (0.8 CPH per 1 Bq/m^3) during ventilation. Further simulations of ventilation switching using both sensors (RadonEye and Tesla) showed that the RadonEye sensor gives better results than the TESLA TSR4 probe, which often switches on ahead of right time. The results of this simulation for the RadonEye sensor are shown in Figure 15, where *td* means the difference between the time of the switch on ventilation caused by tested device and exact time of 400 Bq/m^3 activity level.

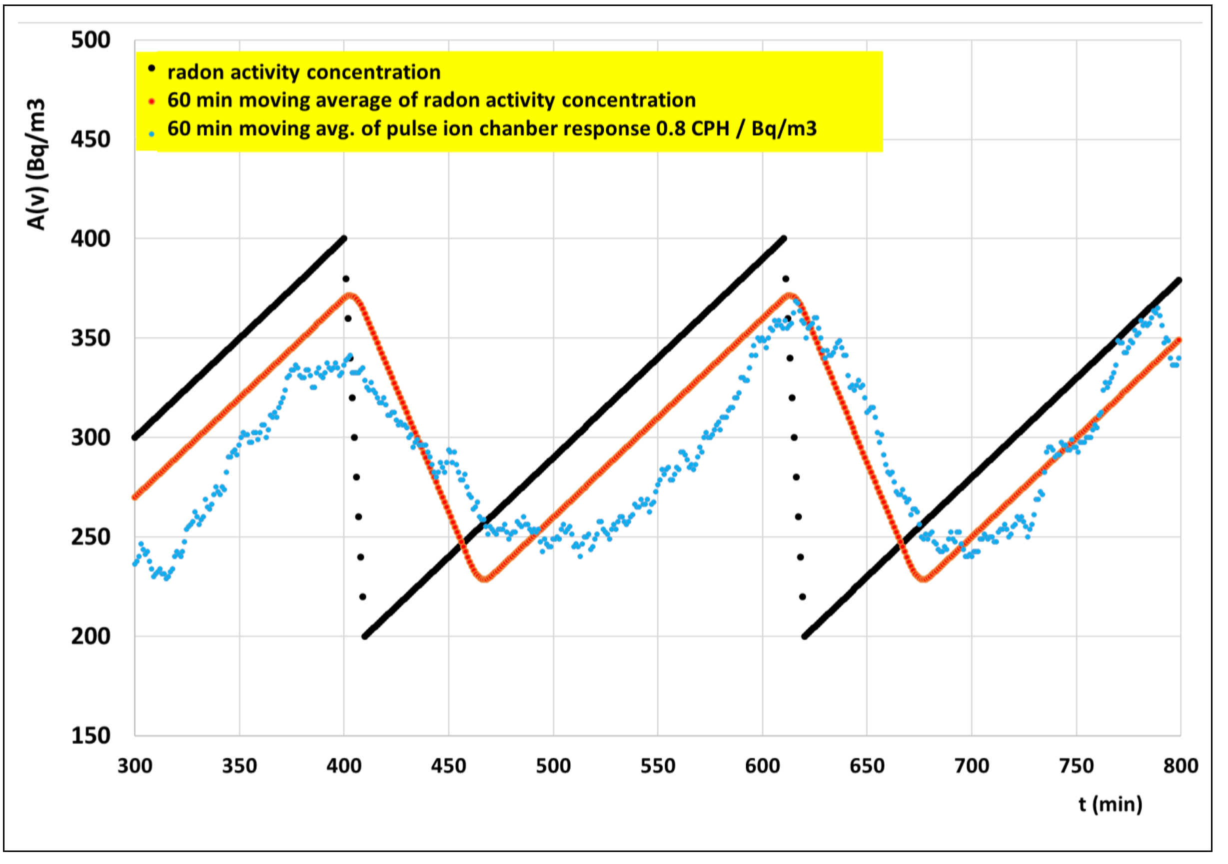

Figure 14 – Simulation of the possible response of the RadonEye monitor

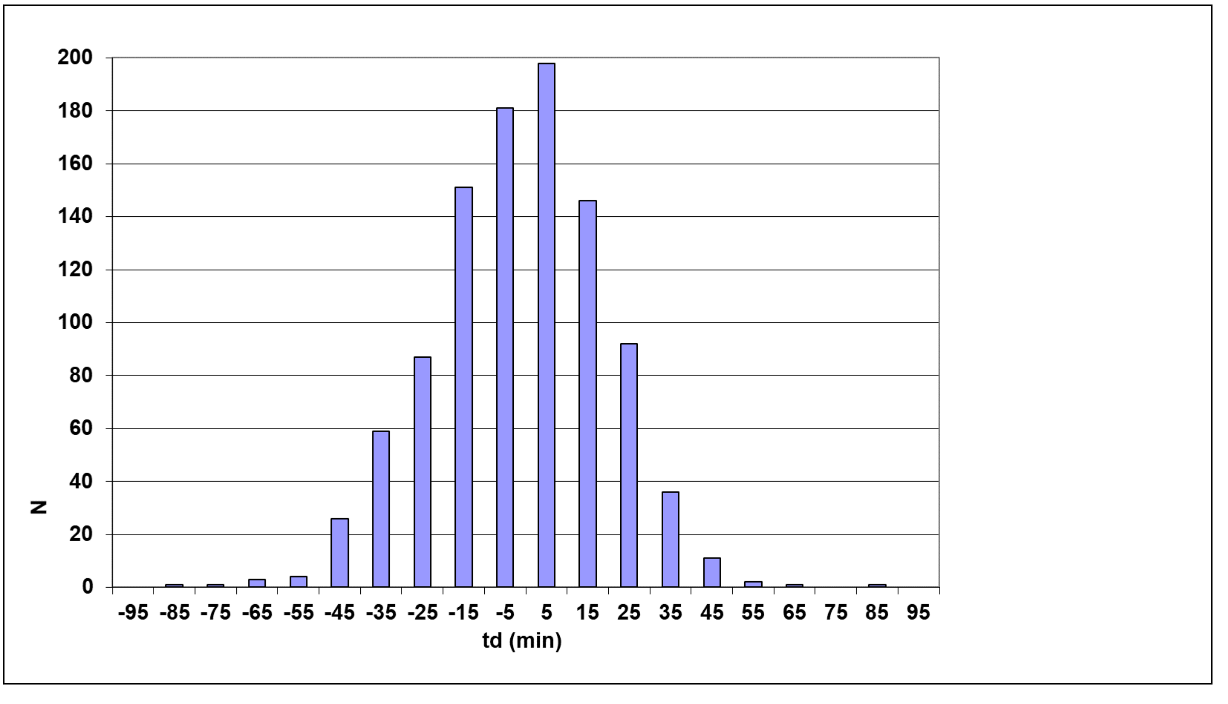

Figure 15 – Simulation of ventilation switching using RadonEye sensor

2.7 Conclusion

Detailed tests, including detection efficiency and temperature/humidity tests, of three types of radon sensors for ventilation switching were carried out in a radon atmosphere. Tested sensors have some additional uncertainty components due to temperature/humidity instability. Time constants of data delay for tested monitors were estimated from the model, because the direct tests in a radon atmosphere provide less reliable results.

From the tested sensors, only the Radon Eye sensor (**after temperature correction** applied) provides data suitable for **direct control of ventilation** in building interiors. The other types of tested sensors are more suitable for **indirect control of ventilation** units.

Another conclusion of the sensor tests is that the sensitivity of sensors for direct switching of ventilation in order to achieve a radon volumetric activity of 300 Bq/m^3 should be at least 0.8 CPH per 1 Bq/m^3 in the case of a detector operating on the principle of pulsed ion chamber and at least 1 CPH per 1 Bq/m^3 in the case of detectors detecting ^{218}Po and ^{214}Po. Considering the significant dependence of the detection efficiency on the humidity of the measured air in the second type of sensors, it is necessary that the value of the detection efficiency should be derived from the humidity of the actually measured air sample.

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