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Temporal uncertainty versus coefficient of variation for rational regulation of indoor radon

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Abstract

Significant temporal variations of radon and other air pollutants are always observed in any room, even one with permanently closed windows and doors. Therefore, the following question remains relevant: how can one assess the conformity of a room with a normative and make a reliable decision if the test lasts <1 year (days or months)? The measurement protocol fundamentally differs between Europe with its long-term testing tradition lasting several months, and the US where short-term tests of several days are more common. Neither the European nor the American protocols considers the temporal uncertainty of indoor radon, a factor that usually exceeds the instrumental uncertainty (including in long-term tests) and is 2–3 times higher the coefficient of variation (COV) commonly used to estimate temporal variations. This problem significantly complicates the creation of a rational and harmonized ISO standard. At the same time, strict adhering to the fundamental ISO/IEC rules within such concepts as "measurement uncertainty" and "conformity assessment" allows to control the coverage probability or reliability of decision making. Within ISO/IEC, proposed are a criterion of conformity assessment of a room with a normative for both short- and long-term measurements, as well as a statistical algorithm for determining the temporal uncertainty considering mode and measurements duration.

KEYWORDS

annual monitoring, coefficient of variation, indoor radon, rational regulation, seasonal correction factor, temporal uncertainty

1 | INTRODUCTION

Radon is a dangerous carcinogen among indoor air pollutants: it causes lung cancer, while being odorless and invisible. Reference levels (RL) are established to minimize health hazards due to exposure to indoor radon and other pollutants. According to the recommendations of WHO[1] and the requirements of EU-BSS,[2] the RL for the annual average indoor radon (AAIR) concentration should not exceed 300 Bq m^{-3}. The national RLs vary in different countries due to differences in regional levels of indoor radon and usually range from 100 to 300 Bq m^{-3}. Concentration of indoor radon in the US is limited by 148 Bq m^{-3} (4 pCi/L) through action level,[3,4] that is not a direct analogue of RL.[5]

It is well known that indoor radon concentration (like other indoor air pollutants) is subject to significant temporal variation (hourly, daily, weekly, and seasonal), as seen in Figure 1. In this regard, the following questions have not yet been resolved—how do the results of the measurements shorter than 1 year (days or months) differ quantitatively from the annual average concentrations; how should one compare the results of such measurements with the RL, and, finally, how to arrive at rational decision as to the compliance of a room with a normative.[5,6]

Obviously, the longer lasts the measurement, the lower the temporal uncertainty in the estimate of the AAIR. This said, monitoring for the whole year or even for several months is quite time-consuming, costly, and generally not preferred by residents[7,8] or by many measurement professionals.[9] This contradiction is expressed, for example, in the fundamentally different measurement protocols accepted in the US applying widely short-term tests—from 2 to 7 days[3,4,10–13] and the EU applying long-term tests—from 2 months to 1 year. The latter measurement protocol is accepted by the most European laboratories which follow the standard of the International Organization for Standardization ISO 11665-8:2019 "Measurement of radioactivity in the environment - Air: radon-222 - Part 8: Methodologies for initial and additional investigations in buildings".[14] Such fundamentally different measurement protocols between the US and EU significantly complicate the creation of a harmonized international standard as a basis for the *rational regulation of indoor radon*.

Regulation (or measurement strategy) is indeed rational if all main sources of uncertainty in decision making are being considered according to the ISO/IEC concept,[15] and the decision is based on managing the trade-off between cost and reliability. Such a trade-off is assessed through both: (a) false positive error or "false rejection"[16]—when it is decided that the RL is exceeded but no danger is actually present, and (b) false negative error or "false acceptance"[16]—when it is decided that the RL is not exceeded but danger is actually present. In summary, fundamental concepts and principles within ISO/IEC standards as "Introduction to the expression of uncertainty in measurement"[15] and "Role of measurement uncertainty in conformity assessment"[16] should serve as basis for development of a rational and harmonized regulation of indoor radon and other air pollutants. According to the spirit and rules of ISO/IEC,[15–20] the standards related to measurements, and especially those dealing with conformity assessment, should not only consider and quantify the main uncertainties, but also ensure their management, a fact that guarantees cost-effective and reliable decision making. An additional target of international standardization is to harmonize the traditional measurement protocols accepted in different countries. Despite these important principles, the ISO 11665-8 simply ignores the short-term measurements, the main tests in the US, and instead requires conducting long-term tests only, the result of which should not exceed the RL. Without any rigorous justification, the indoor radon long-term tests are to be carried out for "at least two months", a rather vague period from a standardization perspective. Such a vague measurement and conformity assessment procedure forces the inspectors to use their intuition, instead of rational planning and execution of a strategy (duration) of measurements and decision-making with a given reliability. Moreover, the structure and principle of the aforementioned standard do not correspond to the "Principles and rules for the structure and drafting of ISO and IEC documents",[18] while the temporal (key) uncertainty in the estimate of the AAIR is not mentioned at all.

Practical implications

- In lieu of the traditionally established COV and SCF (seasonal correction factor), a more relevant parameter as the temporal uncertainty with given probability must be used
- The proposed statistical algorithm allows to actually determine the temporal uncertainty considering the test duration and the influence of all anthropogenic and natural factors
- Within the algorithm, verification of the available values of temporal uncertainty by conducting 200–300 of annual continuous indoor monitorings in different countries is needed
- The rational criterion of conformity assessment taking into consideration the main uncertainties allows to control the reliability of decision making (usually 95%) for both short- and long-term tests
- Within the framework of ISO/IEC proposed is an approach that could serve as basis for creating rational and harmonized indoor regulation in different countries.

Thus, the current version of the ISO 11665-8 is practically the same as its previous version published in 2012, while both versions of the standard meet neither the modern challenges of harmonization and rational regulation, nor the fundamental rules of ISO. Therefore, the need for an early revision of ISO 11665-8:2019 is urgent. This recommendation, like the criticism above, also applies to the ISO 16000 series (Indoor air) standards. Similarly, this series of standards do not contain quantitative criteria for comparing the measurement results with the RL, as well as for determining the measurement duration, such as airborne particles (ISO 16000-34: 2018, ISO 16000-37: 2019), VOC (ISO 16000-29: 2014, ISO 16000-6: 2021) and other pollutants, while the standard regulating the IAQ management system (ISO 16000-40: 2019) provides only qualitative guidance for determining risk level and assessing indoor air quality aspects.

The concept of "measurement uncertainty" concerns not only the measurement procedure (for example, of activity concentration of radon in air) itself, but also the assessment of output quantity in a measurement model.[15] In our case, with a focus on radon as an earlier regulated pollutant, the output quantity is the AAIR concentration. Naturally, when estimating AAIR concentration through a measurement that is shorter than 1 year, AAIR temporal uncertainty arises (and grows with shortening of measurement) in addition to AAIR instrumental uncertainty, while the latter is associated only with the concentration measurement procedure, regardless of the nature of radon behavior. Thus, the budget of AAIR uncertainty must include both temporal and instrumental uncertainties if the measurement duration is shorter than 1 year. In most cases, when the test duration is less than half a year, the AAIR temporal uncertainty plays a key role[5] in deciding whether the tested room

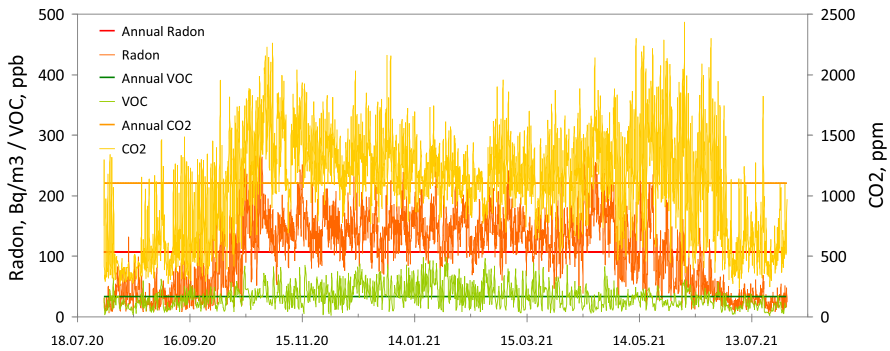

FIGURE 1 Typical example of temporal variability of air pollutants in a naturally ventilated room and their annual average levels (data taken from the current project "SMART_RAD_EN", courtesy of Prof. Alexandra Cucoş [Dinu], Babes-Bolyai University, Romania)

meets radon safety requirements. Without evaluating the temporal uncertainty, it is impossible to compare different measurement strategies to select the most reliable and efficient measurement protocol. Accordingly, it seems impossible to create a harmonized international standard rooted in good standardization practice based on rationality. Therefore, we are convinced that one of the main challenges in the standardization is to make appropriate efforts and reach a consensus on the assessment and management of temporal (key) uncertainty. However, due to the lack of the objective data and absence of criticism and challenges, instead of the temporal uncertainty, the focus has traditionally been put on the instrumental one. The output of the recently completed European metrology project "MetroRADON" (www.metroradon.eu), for instance, confirms this rather sad fact. As a result of prolonged neglect of the importance of deeper understanding of temporal uncertainty for the purpose of standardization, the irrational and inefficient regulation of indoor radon has become quite entrenched over several decades. It has simply become the norm.[5]

2 | TRADITIONAL CHARACTERISTICS OF INDOOR RADON TEMPORAL VARIATIONS

Apparently, the deep rooted conservatism in the regulation of indoor radon is due to the fact that the international standardization principles based on the concepts of "measurement uncertainty" and "conformity assessment" had spread over relatively recently, while the need to study and estimate temporal variations of indoor radon arose much earlier. In fact, temporal variations of indoor radon have been the subject of many studies for the last three decades.[21–39] However, none of these publications discussed the challenges and needs of international standardization of indoor radon measurements. Therefore, instead of well-defined concepts associated with uncertainty within ISO/IEC, Seasonal Correction Factor (SCF) and Coefficient of variation (COV) as the characteristics of indoor radon temporal variations were introduced. Unfortunately, the SCF and COV have since become firmly rooted and continue to be used in current regulation of indoor radon. The recently published guidelines for indoor radon measurements[40] or quality assurance,[41] and many other examples only confirm this unfortunate truth. In this regard, it is necessary to discuss in more detail a possibility of estimating AAIR concentration and its temporal uncertainty through the commonly used SCF and COV for the purpose of standardization.

Indeed, many articles[24,28,29,32,34–39] as well as the ICRU Report[42] studied the SCF. This coefficient is commonly used in radon research for adjusting the measured radon concentration to predict AAIR most accurately. The SCF is indeed of practical importance for better estimation of the average level of radon (among a set of buildings) or the collective risk from radon in a given area, provided there are few tests and/or the measurements are carried out unevenly throughout the year. However, the goal of ISO 11665-8 is not an assessment of the collective or individual risks but the standardization of indoor radon concentration measurements to conformity assessment of a room with a norm at a given (manageable) level of confidence ("coverage probability" in ISO) or reliability of decision-making by quantifying each of the main uncertainties. Usually, the reliability is set to at least 95%, no more than 5% false negative error. To achieve the standardization goal, according to ISO rules, the concepts of "measurement uncertainty" and "conformity assessment" must be applied. According to these concepts, the assessment of the coverage interval (or confidence interval in the statistical concept) of the AAIR concentration, in addition to the expected average, plays an important role. The boundaries of this interval determine the level of confidence or reliability of decision-making in conformity assessment. In other words, the task of the indoor radon inspection is not to predict the AAIR concentration, but rather to compare the upper bound of the coverage interval of the estimated AAIR concentration with the RL at a given reliability. Moreover, it is well known that even within a town or a village, a significant proportion of buildings (far exceeding 5%) exists in which a violation of the seasonal pattern of indoor radon (or even opposite seasonal influence) is always observed.[28–31,43,44] Therefore, SCF cannot be used as a characteristic of temporal uncertainty for conformity assessment of a room with a normative in principle. In this regard, the ongoing resource-consuming efforts to study the SCF,[36,38,39] including those within the current "RadoNORM" project (www.radonorm.eu) under EURATOM Horizon 2020, instead of a more in-depth investigation of the temporal uncertainty of indoor radon (and other air pollutants) concentration seem unjustified.

Another frequently mentioned parameter, especially within quality assurance, is the COV. However, significantly less research has been conducted on this coefficient in relation to indoor radon temporal variations than on the SCF. The relevant values of the COV have been collected in the ICRU Report[42] from the results of only three studies[22,32,34] considering the measurement duration (period). The COV values are shown in Table 1.

The geometric standard deviation (GSD) or standard deviation (SD) are used to express COV. Both parameters, GSD and SD, characterize the dispersion of data, including the boundaries of the confidence interval and the corresponding level of confidence (or probability). Accordingly, the COV has a relationship with "temporal uncertainty". However, this relationship is not direct, because COV and temporal uncertainty are different parameters (see the next section). Therefore, the data presented in Table 1 from the ICRU Report[42] do not express the values of the temporal uncertainty of indoor radon—in contrast to the opinion of the authors of this report. At the same time, the COV can be converted to temporal uncertainty. In addition, we noticed that the study[22] used a different equation for COV (COV=SD/Average), instead of the formula below Table 1. As far as the study[32] is concerned, it does not only lack an algorithm (equation) for calculating COV which is accepted as 25% for 3 months period, but does not even mention the COV anywhere. Finally, the ICRU Report[42] lacks an explanation of how COV = 63% for 1 week period was obtained. The analysis of Table 1 shows that the ICRU Report[42] estimates the COV values quite arbitrarily and also erroneously directy related them to temporal uncertainty using inadequate data for analysis and conclusions in other sections of the report, including the discussion of the measurement strategy.

Thus, the objectives of the study are to convert the COV data in Table 1 into the actual values of temporal uncertainty of indoor radon, and to compare the results of such conversion with the results of our previous studies.[5,6] An additional objective is to present and discuss an updated algorithm for processing our initial data from annual continuous monitorings to estimate the temporal uncertainty of indoor radon considering measurement duration and compare with the data published before.

TABLE 1 Variation of the ratio of short-term to annual average radon activity concentrations for different measurement periods, according to Table 6.1 from the ICRU Report[42]

Measurement period	Coefficient of variation, COV, of period/annual average ratio[a] Minnesota, 75 houses[22]	UK, 91 houses[32]	Finland, 326 houses[34]
Two days: closed	76%		
Four days: closed	70%		
One week		63%[b]	
Monthly: normal	40%		45%
Two months			29%
Three months	25%	25%	22%
Semi annual	17%		18%

[a]COV = 100 (GSD – 1), where GSD is the geometric standard deviation of the period/annual average radon activity concentration ratio.[42]
[b]Derived from the other UK results.[42]

3 | METHODS AND ORIGINAL DATA

3.1 | Methods for determining the temporal uncertainty

Previous attempts to estimate indoor radon temporal variations by other authors have been based on the traditional experimental approach.[22,34] In a sample of n buildings (n = tens…hundreds) usually located in a small area (for example, a city and suburb), measurements of the same duration (less than a year) were simultaneously carried out. In parallel, the AAIR concentration was measured (or calculated from several measurements) in each building from the sample. For example, if measurements (2 days duration each) in each season (total four measurement), or monthly measurements (1 month duration each) are carried out in each such building, then an array of deviations for each measurement period $D(i)_{period} = C(i)_{period}/C(i)_{AAIR}$ (or $D(i)_{period} = C(i)_{AAIR}/C(i)_{period}$, it does not matter) would be accumulated including 4n or 12n values, respectively. Here, $C(i)_{period}$ is the measured concentration over the period, $C(i)_{AAIR}$ is the annual average concentration, and i is the serial number of the building or test room. Then, statistical processing of data arrays (deviations) is carried out to determine the values of COV (through SD or GSD) for each measurement period. The values of COV_{period}, as well as the boundaries of confidence intervals, depend on the nature of the distribution $D(i)_{period}$ and are determined using the following equations:[22,34,42,45,46]

- for the normal distribution (hereinafter, the "period" index is not used, since a certain duration of measurements is always implied):

$$COV = SD / AM, \tag{1}$$

$$\text{the interval } [AM - SD, AM + SD] \text{ contains approximately } 68\,\% \text{ of the probability,} \tag{2}$$

$$\text{and the interval } [AM - 2 \cdot SD, AM + 2 \cdot SD] \text{ contains approximately } 95\,\%; \tag{3}$$

- for the log-normal distribution:[34,42]

$$COV = GSD - 1, \tag{4}$$

the interval [GM/GSD, GM·GSD] contains approximately 68% of the probability, and the interval [GM/GSD^2, $GM \cdot GSD^2$] contains approximately 95%, where AM—arithmetic mean, GM—geometric mean, which are related by the following equation:[45]

$$GM = AM / \exp\left[0.5 \cdot \ln^2(GSD)\right]. \tag{5}$$

According to the expression of the lower limit of the interval for log-normal distribution (GM/GSD^2) and taking into account (5), RL in the test room will not be exceeded with a probability of 95%, if the measurement result C meets the condition:

$$C < C_{RL} / GSD^2 / \exp\left[0.5 \cdot \ln^2(GSD)\right], \quad (6)$$

where C_{RL} – RL concentration, corresponding to AM.

On the contrary, the AAIR concentration determined by the measurement result C will be lower than RL with a probability of 95%, provided that

$$C + \Delta C = C \cdot (1 + \Delta C / C) = C \cdot \left[1 + U(C)\right] < C_{RL}, \quad (7)$$

where ΔC and U(C) are the absolute and relative uncertainties of the AAIR measurement with a coverage factor of 2 providing a 95% level of confidence.

If the duration of the radon test <1 year, the AAIR uncertainty budget includes not only the instrumental (device) uncertainty U_D but also a temporal uncertainty $U_V(t)$ which depends on the measurement duration. It is obvious that the shorter the test, the greater the temporal uncertainty of AAIR (U_V) which is an analogue of K_V—the coefficient of temporal radon variation used in our previous publications.[5,6]

An additional source of the AAIR uncertainty may be associated with spatial variations. However, spatial variations of radon within a room (with a typical area less than 100 m^2 in dwellings) are much lower than their temporal variations, especially if measurements are taken for several days or more at a height from the floor corresponding to the breathing zone (from 0.2 to 1.7 m). For example, the RESET (https://www.reset.build/standard) recommends one measuring point per 500 m^2. Indeed, natural diffusion and convective air flow in different directions due to the temperature differences between the indoor air and the walls, floor, and ceiling occur always even in poorly ventilated rooms (when all windows and doors are hermetically closed).

Since U_V and U_D are the main and independent components of the combined uncertainty U(C), the condition (7) can be presented in more detail as a criterion for conformity assessment of a room with a norm[5,6]:

$$C(t) \cdot \left[1 + \sqrt{U_V(t)^2 + U_D{}^2}\right] < C_{RL}, \text{providing probability of } 95\,\% \quad (8)$$

Assuming $U_D = 0$ in (8), and considering (4), and (6) then for the case of log-normal distribution we obtain equations connecting GSD and COV to the temporal uncertainty of indoor radon:

$$U_V = GSD^2 \cdot \exp\left[0.5 \cdot \ln^2(GSD)\right] - 1, \text{and} \quad (9)$$

$$U_V = (COV + 1)^2 \cdot \exp\left[0.5 \cdot \ln^2(COV + 1)\right] - 1. \quad (10)$$

Obviously, for the normal distribution:

$$U_V = 2 \cdot SD / AM = 2 \cdot COV. \quad (11)$$

Hence, considering (7) and criterion (8), an updated algorithm for determining U_V is obtained, which is based on the following equation:

$$D_V(t) = C_{AAIR} / C(t) - 1, \quad (12)$$

which expresses partial temporal uncertainty as a relative difference (deviation) between the AAIR and the measured radon concentrations over the period of t.

Thus, the temporal uncertainty $U_V(t)$ is defined as maximum of the range of $D_V(t)$ values, which should cover all deviations with period of *t* in a representative sample of buildings (rooms) with a probability of at least 95%, that corresponds to the location of the 95th percentile, regardless of the distribution shape. In each building (room), continuous measurements in 1 year (monitoring) of the indoor radon concentration are carried out (not necessarily at the same time), that provides good statistics for a reliable determination of the 95th percentile for any period of t.

Indeed, 1 year-long monitoring with a registration period of 1 (or 3) hours, allows to register 8760 (or 2920) results of radon activity concentration. The original results can be transformed by the moving (rolling) average method into time series (or arrays of deviations) with any (longer averaging) period (or measurement duration). On each transformation, the amount of transformed data remains the same as in the original monitoring, as shown in Figure 2. Accordingly, the beginning of measurement periods (regardless of their duration) is shifted uniformly within 1 year with a step of 1 (or 3) hours, so the problem of considering the influence of the seasonal factor is eliminated. If the end of the transformed period is outside the time range of the original monitoring, then the protruding segment of this period is filled with the data recorded at the beginning of the monitoring.

Such an original approach for determining the $U_V(t)$ makes it possible to consider the influence of all anthropogenic and natural factors (including seasonal ones) on the behavior of indoor radon in time, if a sample of experimental buildings (rooms) is representative. In addition, the accuracy of statistical analysis is greatly increased. For example, the accumulated data array for each building (room) is 2–3 orders of magnitude larger than that in the traditional approach discussed before.

Our experience shows that modern and inexpensive CRMs (continuous radon monitors), such as Radon Eye Plus type, (www.radonftlab.com), allow to reliably measure indoor radon concentration with a period of 1, 2, or 3 hours for many years. The other features of using CRM:

a. data collected are verified remotely via WiFi and Cloud for the entire monitoring period;
b. precise calibration of CRM is not required due to the definition of the $D_V(t)$ through the ratio: $C_{AAIR}/C(t)$, where both concentrations are measured by the same CRM;
c. high sensitivity of CRM is not required due to sufficiently long interval rolling average of the measured radon concentration (2 days or more);

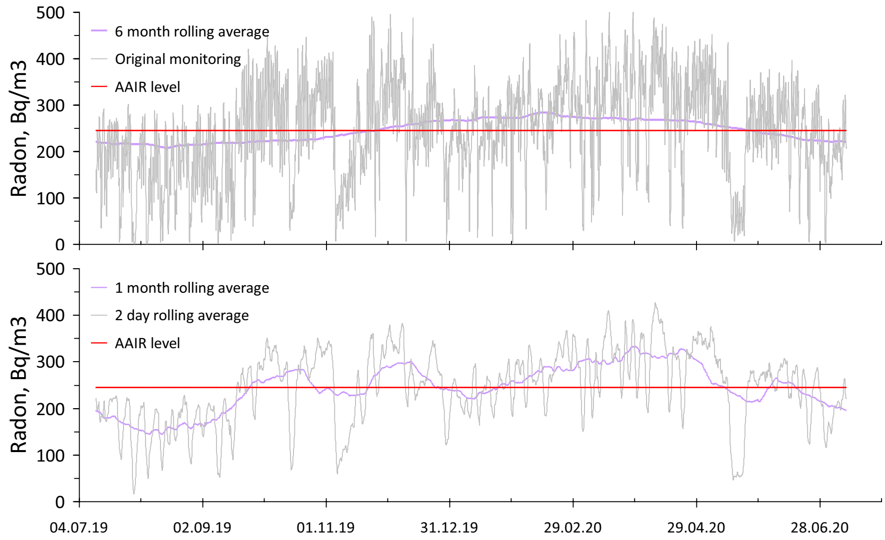

FIGURE 2 Example of transforming the original annual monitoring of indoor radon concentration with a recording period of 3 h into time series with a longer averaging period (2 days, 1 and 6 months)

d. measurement procedure using CRM connected to the electrical network and datalogging is easier than, for example, using SSNTD (Solid State Nuclear Track Detector), which requires preparation of a sampler with a new film and its analysis in the end of passive sampling;
e. approximate cost of one CRM is not more than the cost of 10 SSNTD measurements.

The algorithm for determining $U_V(t)$ proposed by us earlier[5,6] was based on the comparison and generalization of the results of statistical analysis of separate data arrays (deviations) obtained for each experimental room. An updated algorithm proposed in this study is different because the deviation values $D_V(t)$ for all experimental buildings (rooms) with period of t are accumulated in a common array subject to statistical analysis. This algorithm gives a more objective assessment of the $U_V(t)$ values.

3.2 | Original data

The following data sources were used to determine the values of the temporal uncertainty $U_V(t)$ depending on the duration of indoor radon concentration measurements:

a. Publication,[6] including the results of annual monitoring of radon concentrations available to the authors in 6 experimental rooms (ERs 1, 3, 7, 8, 9, and 10) located in 5 buildings in Russia. To clarify, radon concentration was also monitored in ER6, which had very low air exchange (an average of 0.1 h^{-1}), so it was excluded from the analysis;
b. Publication,[5] including the results of the annual monitoring of radon concentrations available to the authors in 12 experimental rooms located in 9 Israeli buildings;
c. Publication,[34] including the data with COV and GSD based on studies in 326 Finnish buildings;
d. Publication,[22] including the data with COV based on studies in 75 buildings located in US (Minnesota).

4 | RESULTS AND DISCUSSION

Based on the algorithm described above, as well as the data from the previous annual monitoring of indoor radon in Russia[6] and Israel,[5] three sets of deviation arrays $D_V(t)$ for Israel and Russia (12 and 6 experimental rooms, respectively), and the combined version (Israel and Russia) have been obtained. Each such set consists of 23 arrays of $D_V(t)$ values differing in the measurement duration: 3 h (spot measurement), and 1, 2, 3, 4, 6, 8, 10, 12, 14, 21 days, and 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 months. The examples of the distribution shape of the deviations among the Israel and Russia arrays, depending on the measurement duration, are shown in Figure 3.

Figure 3 shows that the distributions of the deviations $D_V(t)$ remain log-normal when the measurement duration does not exceed 1 month. For longer durations the second peak appears; this is most pronounced for measurement duration of about 6 months. Moreover, this effect is observed in each set of the deviation arrays, both in Israel and Russia. It means this effect is not related to geological and climatic differences between the territories. Most likely, the violation of the lognormal distribution of the deviations $D_V(t)$ at $t > 1$ month is explained by more significant influence of the winter/summer season variability on the indoor radon behavior compared with other factors. In this case, the use of lognormal distribution patterns (in particular, the GSD parameter) can lead to significant errors in estimating the temporal uncertainty of indoor radon. Apparently, this is one of the reasons for the use of the Equation (1) for statistical analysis of temporal variation in the work by D. Steck,[22] including his later publication.[27] Thus, the most reliable estimate of the temporal uncertainty is achieved using the updated algorithm described in the previous section. This new algorithm, due to good statistics of the initial data, proposes to directly determine the value of the

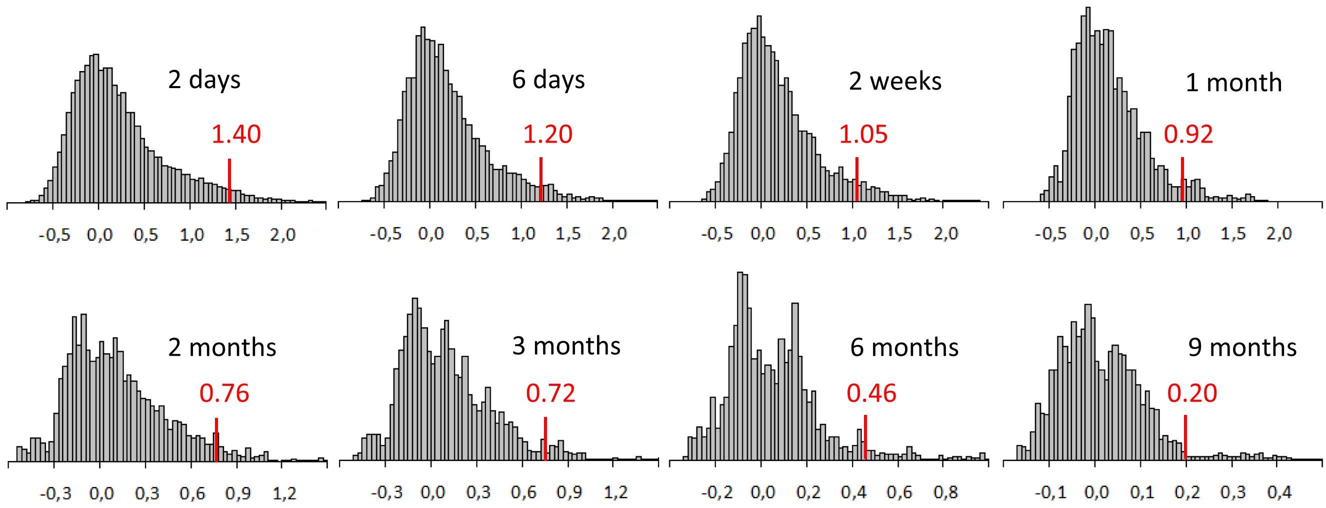

FIGURE 3 Distributions of deviations $D_V(t)$ and location of the 95th percentile depending on the measurement duration (2, 6 days, 2 weeks and 1, 2, 3, 6, 9 months) among the Israel and Russia arrays

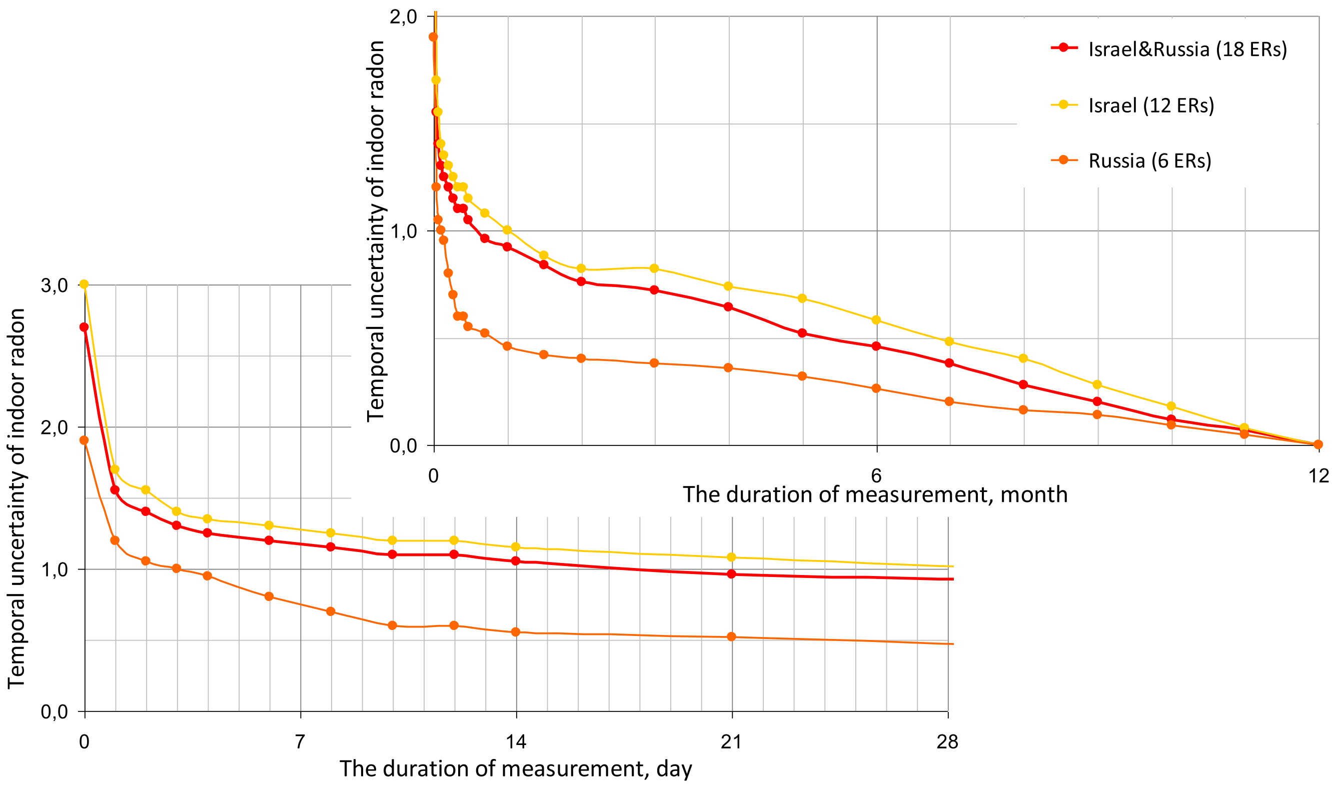

FIGURE 4 Temporal uncertainty of indoor radon depending on the duration of measurements in Israel, Russia, and the combined version (Israel and Russia)

95th percentile (Figure 3), regardless of the shape of the deviation distribution. The same updated algorithm was used to determine $U_V(t)$, the values of which are given in Figure 4 for each of the sets of experimental rooms located in Israel (12 ERs) and Russia (6 ERs), including the combined version (Israel and Russia).

Figure 4 shows that the temporal uncertainty of indoor radon for Israel is 1.5–2 times higher than for Russia, which was also noted in our paper.[5] Firstly, this is due to the fact that when planning the first study,[6] the priority of selecting experimental rooms and buildings in Russia was their higher air tightness and rare occupancy. Consequently, it results in higher radon concentrations and more stable behavior of radon in time, as well as ensures the integrity of monitors and provides reliable data collection. After gaining the experience, the second study was organized later in Israel,[5] in which the authors used more advanced and cost-effective CRMs (Radon Eye Plus2). Moreover, mass indoor radon screening was preliminarily carried out to select the most suitable buildings and rooms for year-long monitoring.[47] This approach made it possible to identify buildings and experimental rooms with an increased concentration of radon, but under normal operating conditions (without any restrictions on natural or mechanical ventilation, it means at the less stable behavior of radon in time). In addition, it has to be noted that the windows in Israeli buildings are less airtight in general. Probably, the difference in geological conditions can serve as an additional explanation. For example, the geology of Israel is characterized by a predominance of fractured and more permeable soil, compared with less permeable sedimentary soil in the sites of Russia. The above qualitative reasons can help in understanding the difference between the $U_V(t)$ values.

Unfortunately, the apparently insufficient number of experimental buildings and rooms in both Russia (6 ERs) and Israel (12 ERs) precludes more definite estimates and conclusions. This said, it is of great interest to compare the data in Figure 4 with the data previously published by the authors in 2018[6] and the data obtained by other authors[22,34] which can be converted to the $U_V(t)$ values by means of the unique equations in Section 3.1.

The paper[34] published by Arvela et al in 2016 reports GSD values of D_{period} according to the starting month (Jan, March, June, and Oct) and duration of measurements (from 1 to 11 months in 1-month increments) that were obtained in 326 Finnish houses. According to Table 2, we previously calculated the arithmetic means, as well as the boundaries of the GSD ranges (as one standard deviation) for each measurement duration. Then, the GSD(t) values from this table were converted to the corresponding $U_V(t)$ values using Equation (9). The converted results are shown in Figure 5.

Figure 5 also shows the $U_V(t)$ values converted from the COV values[22] provided by Steck in 2005 using Equation (11). Indeed, D. Steck specifically lists Equation (1) that he used to determine COV in his paper. Apparently, the distributions of deviations in this study were not identified as lognormal. At the same time, in the ICRU Report,[42] as well as in the paper,[34] for some reason, it is reported that D. Steck used Equation (4) for lognormal distributions to determine COV. Therefore, Figure 5 also shows for comparison sake other results (although they do not look credible) obtained after converting COV through Equation (10), which is marked in the legend by *.

Additionally, Figure 5 shows the $U_V(t)$ values previously published in our paper[6] in 2018, which then seemed quite conservative and were presented as tabulated values, that is, recommended for application in the absence of more reliable data. However, comparing the data in Figure 5 obtained from different sources using appropriate conversions and updated statistical analysis (Section 3.1) confirms the relevance of the tabulated $U_V(t)$ values. Indeed, the earlier tabulated values of indoor radon temporal uncertainty are the most reliable (conservative) generalization among the data shown in Figure 5. At the same time, there may be other opinions, for example, regarding the range from 0.5 to 4 months, where the average values of $U_V(t)$ could look like a smoother (almost linear) function. Comparison of the tabulated values of $U_V(t)$ from Figure 5 (black curve) with the COV(t) values published in the works[22,34] and combined in the ICRU Report[42] (see Table 1) shows a difference of 2–3 times, that indicates a significant underestimation of the role of indoor radon temporal variation in the current indoor radon regulation.

Curiously, the results of monitoring in Russia and Israel, despite a limited number of the experimental buildings and rooms, provided more experimental information about the temporal uncertainty of indoor radon than all main previous studies in this area (Table 1). This statement is fully justified by the data assembled in Table 3. In contrast with numerous studies of spatial variations in indoor radon,[22,27,34,48–56] usually covering a large number of buildings, it would be much cheaper and less laborious to increase the frequency of data recording, that is, to carry out year-long monitoring by means of CRMs, albeit in a much smaller sample of buildings, given the subject of the study is temporal variations. For example, we assume that in Finland, it would be sufficient to conduct annual monitoring in 30–50 buildings, focusing on the data of Table 3. If there exist inhabited territories with sharply different geology within the country, then it is advisable to conduct 20–25 continuous annual measurements in a representative sample of buildings within each territory.

The representativeness of the sample of buildings is provided by the following conditions:

a. in each building, there should be only one monitored room with an increased concentration of radon (on average, at least 70 Bq m^{-3} and exceeding the concentration of outdoor radon by at least five times); the conformity assessment of a room with a normative at low (close to outdoor) concentration is not as demanding as with elevated indoor radon; in addition, the nature of radon temporal variations in buildings with low and elevated concentrations may differ due to the different contribution of outdoor radon to the overall balance of indoor radon;

TABLE 2 Calculated GSD values for Finnish buildings obtained from paper[34] published by Arvela et al in 2016

	Duration of measurement (period), months										
Parameter	1	2	3	4	5	6	7	8	9	10	11
Min GSD	1.40	1.24	1.15	1.16	1.16	1.15	1.11	1.09	1.07	1.04	1.03
Average GSD	1.55	1.39	1.33	1.23	1.19	1.17	1.14	1.11	1.09	1.06	1.04
Max GSD	1.70	1.54	1.50	1.30	1.22	1.19	1.16	1.13	1.10	1.07	1.05

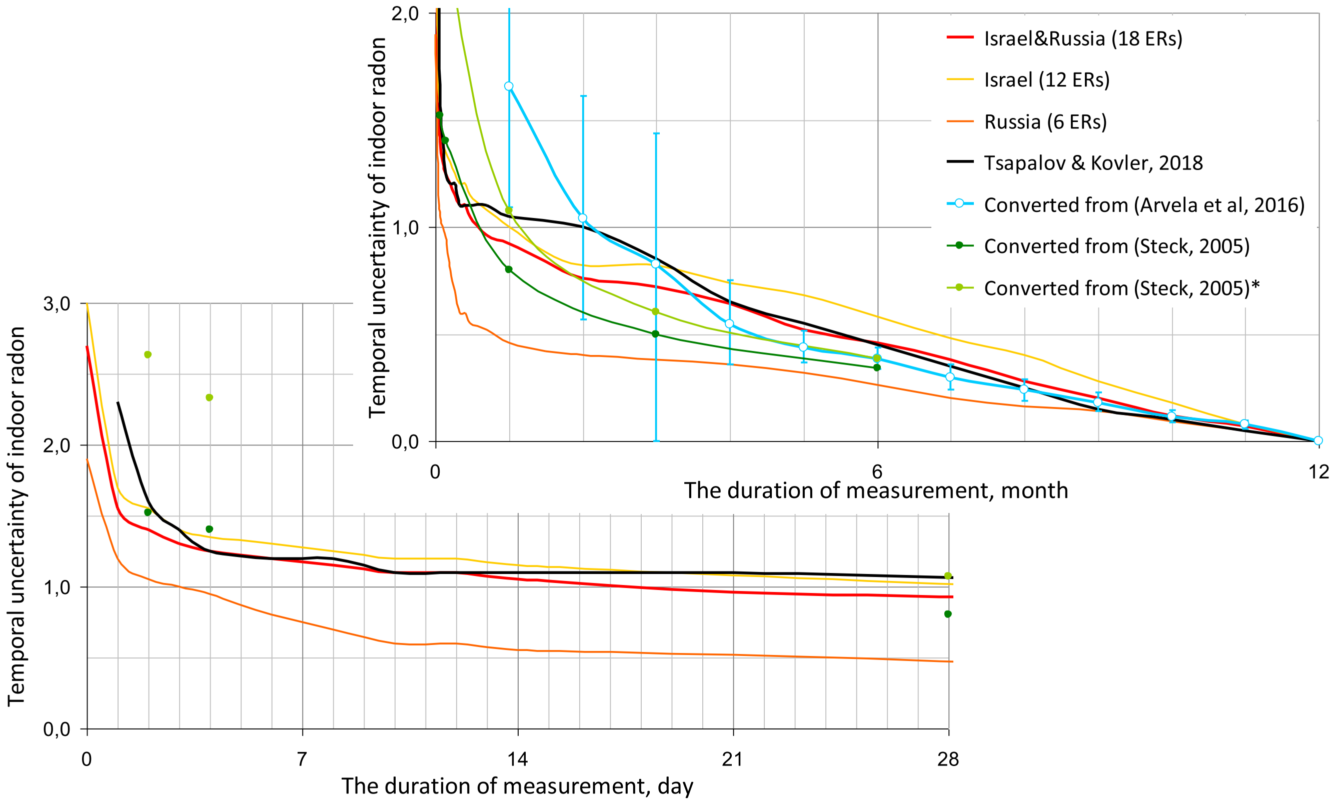

FIGURE 5 Comparison of the temporal uncertainty of indoor radon (considering the measurement duration) obtained from the proposed conversion and the updated statistical analysis of previously published data (*another equation was used to convert the data from this source, as described in more detail in the text)

TABLE 3 Number of sites and measurement results among published data used for statistical analysis and estimation of indoor radon temporal uncertainty

Parameter	Steck, 2005,[22] US	Arvela et al, 2016,[34] Finland	This study, (Israel + Russia)
Number of buildings	75	326	14 (9 + 5)
Number of experimental rooms (ER)	75	326	18[a] (12 + 6)
Number of measurements in each ER (within 1 year)	Max 20	12	2920[b]
Number of intervals with different measurement durations	5	12	23
Number of values (deviations) for each measurement duration	From 80 to 767	3912	52 560
Total number of initial data (deviations)	1202	46 944	1 208 880

[a]Corresponds to the total number of annual monitorings by CRMs.

[b]For Israel, this parameter is equal to 8760, because monitorings were carried out with a registration period of 1 h; however, the original data were transformed into the time series with a period of 3 h, because they are easier to work with and do not affect the accuracy of the statistical analysis.

b. the monitored room should be the longest time occupied (for example, a bedroom or office space, which is occupied for at least 6 h a day);
c. preference is given to residential buildings with natural ventilation (dwellings, as well as small and multi-storey buildings);
d. the monitored room, like the building itself, must be operated in a regular (normal) mode during the entire monitoring period, excluding special effects on natural (or mechanical) ventilation, as well as carrying out repairs in the room or building;
e. the sample should cover about 30–50 (or more) most typical buildings within each country; if the country includes large settlements located in different climatic zones or in territories with sharply differing geology, it is recommended to cover at least 20 buildings in each such zone (territory).

TABLE 4 Indoor radon temporal uncertainty and the corresponding Action Levels depending on the measurement duration and the mode of operation of the room, as well as Reference Levels and Instrumental uncertainty

Measurement duration		Temporal uncertainty of indoor radon $U_V(t)$		Action level in Bq m^{-3} for normal/closed modes				Instrumental uncertainty[a] U_D
		Operating mode		Reference level in Bq m^{-3}				
		Normal	Closed	100	150	200	300	
Day	2	1.60	1.05	38/47	57/71	75/94	113/141	0.40
	3	1.40	1.00	41/48	61/72	81/96	122/144	
	4	1.25	0.95	43/49	65/74	86/98	130/148	
	5	1.20	0.90	44/50	66/76	88/101	132/151	
	6	1.20	0.80	44/53	66/79	88/106	132/158	
	7	1.20	0.75	45/55	67/83	89/111	134/166	0.30
	8	1.20	0.70	45/57	67/85	89/114	134/170	
	10	1.10	0.65	47/60	71/89	94/119	142/179	0.20
	12	1.10	0.60	47/61	71/92	94/123	142/184	
	14	1.10	0.55	47/63	71/95	94/126	142/189	
	20	1.10	0.50	47/65	71/97	94/130	142/195	
Month	1	1.05	0.45	49/68	73/102	97/136	146/203	0.15
	2	1.00	0.40	50/70	75/105	99/140	149/210	
	3	0.85	0.38	54/71	81/106	107/142	161/213	
	4	0.65	0.36	60/72	90/108	120/144	180/216	
	5	0.55	0.32	64/74	96/111	127/148	191/222	
	6	0.45	0.26	68/77	102/115	136/154	203/231	
	7	0.35	0.20	72/80	109/120	145/160	217/240	
	8	0.25	0.16	77/82	116/123	155/164	232/246	
	9	0.17	0.14	82/83	122/124	163/166	245/249	
	10	0.10	0.09	85/85	127/128	169/170	255/255	
	11	0.05	0.05	86/86	130/130	173/173	259/259	
	12	0.00	0.00	87/87	130/130	174/174	261/261	

[a]The most optimal values of U_D are given by the authors as an example.

Due to the absence of another criterion for conformity assessment within measurement standardization at the moment, as well as the data on the temporal uncertainty of indoor radon, we propose to use criterion (8), as well as the tabulated $U_V(t)$ values from our paper[6] given in Table 4 in the "Normal" column. The data in the "Normal" column correspond to normal room (and building) operating conditions without any restrictions or additional conditions that may affect normal natural or mechanical ventilation. The adjacent column "Closed" means unoccupied building (for example, newly built or during a real estate transaction) with limited ventilation (all windows and doors are closed). The data in the "Closed" column correspond to the $U_V(t)$ values obtained in Russia according to Figure 4, because the ventilation conditions in the six experimental rooms[6] almost corresponded to "Closed" mode. In addition, Table 4 shows the values of Action Level termed in our paper[5] as measured radon concentration at which the Reference Level will not be exceeded. The Action Level is calculated by the criterion (8) as the C(t)-values considering the dependence of the Temporal uncertainty ($U_V(t)$) on measurement duration and the operating mode, as well as the Reference Level (C_{RL}) and the Instrumental uncertainty (U_D). The reliability of decision-making based on criterion (8) will be at least 95% if representative (reliable) values of $U_V(t)$ obtained from the results of annual monitoring in a representative sample of buildings are used.

Table 4 shows how to rationally manage instrumental uncertainty U_D using criterion (8). Indeed, U_D values may be higher for shorter tests without reducing the reliability of the conformity assessment. This statement is explained by the fact that the contribution of U_D decreases as the temporal uncertainty increases due to the decrease in measurement duration, as can be seen from Table 4. This important fact is not only addressed to manufacturers of measuring equipment and national metrology institutes, but also opens a possibility and legalizes the participation of non-professionals in the radon tests at the screening stage due to the softer requirements for quality assurance of short-term measurements.

As shown in Table 4, the management of AAIR uncertainty, including $U_V(t)$ and U_D values, allows to select an optimal measurement strategy, covering both short- and long-term tests, which serves as the basis for harmonizing national approaches to indoor radon regulation. Moreover, the knowledge of temporal uncertainty also allows estimation of the share of buildings for which a reliable decision on compliance with a norm will be made in the case of short-term (or any duration) tests through modeling—for example, if RL and the average concentration of radon in buildings in the surveyed area[53] are given.

As discussed above, the difference in $U_V(t)$ values obtained for Israel and Russia (Figure 4) requires more detailed research to determine the real reasons. Also, the tabulated values of $U_V(t)$ from Table 4 need to be verified and clarified—by gaining a statistically representative array of deviations $D_V(t)$. Therefore, about 200–300 continuous annual monitoring of indoor radon in different countries located in Europe and America are needed, if considering the data in Table 3. Previously, it is necessary to create an unified repository to collect the results of annual monitoring, including the following characteristics of a site: (a) average annual values of meteorological parameters, (b) geology and (c) topography, (d) function, (e) shape, (f) dimensions of building, (g) foundation type, (h) HVAC system, and also features of the monitored room including (i) function, (j) duration of occupancy, (k) size, and (l) location. When collecting the results from a large number of annual monitorings (at least 300) conducted under various conditions, ranking the $U_V(t)$ values depending on the above-mentioned factors, similar to the ranking according to the Normal or Closed mode in Table 4, may be possible. Moreover, parallel annual monitoring of the concentrations of other air pollutants in the same sample of buildings will additionally provide the data on temporal uncertainty for each of the indoor air pollutants based on the same statistical algorithm.

5 | CONCLUSIONS

1. Despite the continuing attention to the Seasonal Correction Factor (SCF), this parameter is not related to temporal uncertainty, thus rendering it useless in standardizing measurements within the ISO/IEC.
2. The Coefficient of Variation (COV) is indeed associated with temporal uncertainty of indoor radon, however, the COV values are 2–3 times lower than the tabulated values of temporal uncertainty. This indicates that the role played by indoor radon temporal variations is being dramatically underestimated in the current indoor radon regulation. Therefore, in the standardization within the ISO/IEC, a more adequate parameter from the metrology or standardization viewpoint—the temporal uncertainty of indoor radon with 95% (or more relevant) probability, as is customary for instrumental uncertainty, should be used instead of COV (and SCF).
3. Proposed are a rational criterion (8) for conformity assessment of a room with a normative considering main uncertainties with a probability of 95% for both short- and long-term tests as well as the updated algorithm for determining indoor radon temporal uncertainty depending on the measurement duration. This criterion and the updated algorithm can serve as the basis for creating rational regulation of indoor radon at the international level within ISO, including the harmonization of national measurement protocols and regulatory traditions.
4. At the moment, the tabulated values of the temporal uncertainty presented in Table 4 are the most reliable for practical use. However, they need to be verified and clarified, so the actual solution would be to conduct 200–300 of annual continuous indoor radon (and other air pollutants) monitorings in different countries, for example, in Europe and America.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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