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ORIGINAL ARTICLE

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Short- versus long-term tests of indoor radon for risk assessment by Monte-Carlo method towards effective measurement strategy

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Abstract

There now exists a broad consensus among the European radon community members that long-term measurements are the best practice in managing the risk of indoor radon exposure. This, not with standing the fact that <1% of buildings have been tested in Europe so far. At the same time, US' experience over the years shows more effective regulation has been accomplished through tests that are short-term. This study quantifies the uncertainty of collective risks obtained independently through short- and long-term measurements under the same conditions using the Monte Carlo method that takes into account the number of measurements, as well as the diversity of the spatial distribution of radon concentrations in representative samples of buildings. Simulation results have shown that contrary to the erroneous practice of the European radon community, the accuracy of the assessment of the collective risk due to radon exposure does not in fact depend on the duration of the indoor test at all. The main problem remains ensuring the existance of a representative sample of buildings, especially given limited number of tests. In this regard, recommended is a revision of the regulatory documents of IAEA, ICRP, WHO, and ISO focusing on (i) the principle of the effective measurement strategy based on rational ISO/IEC concepts, (ii) the mass measurements via short-term tests, and (iii) the societal engagement in measurements.

KEYWORDS
indoor radon, measurement strategy, Monte-Carlo method, risk assessment, short- and long-term tests, spatiotemporal variations

1 | INTRODUCTION

Over the past decade, increasing attention has been given to the problem of Indoor Air Quality (IAQ), as people spend more than 80% of their time inside buildings — a fact that may undoubtedly cause health risks for the buildngs inhabitants. National authorities worldwide are establishing national regulatory systems to minimize risks by reducing the concentration of indoor air pollutants in both existing and planned buildings. For example, for such a common pollutant as radon, the WHO[1] recommends and the EU-BSS[2] requires that the Reference Level (RL) for the Annual Average Indoor Radon (AAIR) concentration shall not be higher than 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}.

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However, as of yet no rational measurement protocol exists that allows, with a given reliability, to assess the compliance of a room (as well as the building as a whole) with the normative. This fundamental issue, not only regarding the regulation of radon but also other indoor air pollutants, was discussed in detail in our recently published article.[3] This article also proposed an approach for harmonizing and standardizing indoor measurements based on such fundamental ISO/IEC concepts as "measurement uncertainty"[4] and "conformity assessment."[5] Without the implementation of a rational measurement protocol, the main task of regulation—namely, effective identification of hazardous buildings, according to para. 3.46 in IAEA SSG-32,[6] remains unsolved. That is why a national action plan addressing long-term risks from radon exposures in dwellings, buildings with public access and workplaces which should be developed and implemented by Article 103 in EU-BSS,[2] must first and foremost be based on studying the main components of AAIR uncertainty (within the ISO/IEC concepts)— in particular, the temporal variations as a key uncertainty of indoor radon test.[7] Otherwise, it is rather impossible to manage risks during the regulatory process. In view of this, the main challenge within the IAQ regulation is the lack of attention of the scientific community to the direct study of the temporal uncertainty, instead of other surrogate characteristics of temporal variations of indoor pollutants, such as Seasonal Correction Factors and Coefficient of Variation.[3] In addition, it is necessary to understand and take into account the difference between the concepts, as well as the tools used for risk assessment and for conformity assessment of a room with a normative. For example, it is clear that individual risk assessment of indoor radon requires only long-term measurements. At the same time, it is not at all clear that long-term measurements are an effective tool for assessing collective risk or compliance with a normative. In addition, it is obvious that long-term tests cannot be considered an effective tool for identifying potential hazards among hundreds of millions of buildings.

The defocusing of priorities for the needs of standardization of measurements,[3] as well as regulation in general,[7] observed for many years, contributed to the promotion of long-term tests (lasting at least 2–3 months) in Europe. The preference for long-term tests is only due to subjectively less confidence in short-term tests since these only last a few days. At first glance, prioritizing long-term tests seems reasonable however there is still no rigorous justification or refutation that is the main goal of this article.

The recommendation for long-term measurements in the foundational regulatory documents, such as ICRP Publications 126[8] and IAEA SSG-32,[6] as well as IAEA reports[9,10] and WHO handbook,[11] expresses the consensus that has become established in the European radon community. As a result, short-term measurements are ignored all together in the international standard ISO 11665-8:2019,[12] as well as in its previous (original) version published in 2012. Both versions of the international standard indicate the need for measurements for at least 2 months, while the short-term measurements (from 2 to 7 days) were and remain the main tests in the US.[13–20]

Indeed, the above-mentioned regulatory documents published by ICRP, IAEA, WHO, and ISO do not take into account the radically different experience in regulating indoor radon in the US (but in fact, much more effective and much longer, than the one in Europe). Due to the mass character of the short-term measurements, American population's high level of awareness of the radon risks and its wide involvement, 30–50 times more tests per 1000 people are carried out in the US than in Europe.[7] Accordingly, over 1 240 000 homes in the US have been mitigated,[21] while <1% of buildings have only been tested in Europe, according to the recent IAEA report.[10] In addition, the accumulation of the results off tens of millions of short-term indoor tests[21] distributed throughout the country makes it possible to improve the accuracy of risk assessment and the location of radon priority areas due to a significantly better statistical representativeness of the sample of test objects. As a result, an enormous volume of testing and mitigation activities dramatically reduces the health risks associated with radon exposure in the US, while no national budget is being spent.

At the same time, despite the compelling advances in the US regulation, the American measurement protocol[13–20] cannot be considered rational[3] because it does not quantify the factor of temporal uncertainty which is a key for decision making. The same applies also to the international standard ISO 11665-8:2019,[12] as well as to the European regulation in general. This problem is discussed in detail in our recently published articles.[3,7] Therefore, quality assurance of conformity assessment through short-term measurements based on the US protocol does not to this day have a rigorous scientific justification (for example, according to the ISO/IEC concepts). This fact probably explains the lack of confidence of the European radon community in the measurement protocol accepted in the US. However, this is not a compelling reason for ignoring short-term measurements altogether and promoting only long-term tests. The advantage of the long-term tests is not rigorously proven, and their implementation does not contribute

Practical Implications

- Adequate focusing of priorities for the needs within indoor measurement standardization as conducting a large number of continuous year-long indoor measurements in different countries.
- Detailed analysis of uncertainty sources of collective risk including estimation of geometric standard deviation of activity concentrations due to variation of indoor radon in time.
- The algorithm for assessing uncertainty of indoor radon collective risk using Monte-Carlo method introduced for the first time.
- Legalization and implementation of the short-term tests as a best practice in managing indoor radon risk.
- Harmonizing and improving the effectiveness in national regulation approaches through the rational protocol and the societal engagement in measurements.

to effective risk mitigation, as can be seen by comparing indoor radon regulation outputs between Europe and the US. In this regard the question of the principles of an effective measurement strategy remains relevant. An effective strategy should cover not only the standardization of measurements to conformity assessment of a room with the normative,[3] but also the assessment of the collective health risks, including the delineation of areas that can be used as specific indicators of situations with potentially high exposure to radon.

Thus, the first objective of the current study is to quantify the uncertainty of collective risks obtained independently through short- and long-term measurements under the same conditions, taking into account the number of measurements, as well as the diversity of the spatial distribution of radon concentrations in representative samples of buildings. For achieving this objective, statistical modeling by Monte-Carlo method will be used. The additional objective of the study is to present and discuss the principle of an effective indoor radon measurement strategy considering the results of the statistical simulation.

2 | METHOD AND ORIGINAL DATA

2.1 | Characteristics of collective risk including uncertainty sources

The radon concentration among buildings has a lognormal distribution,[22] which is described in terms of the arithmetic or geometric mean, as well as the geometric standard deviation. Therefore, the main parameters of the radon potential collective risk are:

(i) arithmetic mean (AM) of radon concentration in buildings—"…to estimate the average probability of detrimental health effects" through dose assessment due to radon exposure,[22] and
(ii) geometric standard deviation (GSD), that characterizes dispersion of radon spatiotemporal distribution and allows assessing the part of buildings with high radon concentration above the RL or other target level.[9]

An important condition for a reliable assessment of the AM and GSD is a representative sampling of buildings, including their number.

Main sources of collective risk uncertainty, expressed in terms of AM and GSD within a representative sampling, besides the number of tested buildings (or measurements taken), are:

a. the instrumental (device) uncertainty U_D that is associated only with the concentration measurement procedure, regardless of the nature of indoor radon behavior and also sources of radon,
b. the temporal variations of indoor radon expressed as the GSD(t) that are due to only fluctuations in radon concentration in time, depending on the duration of the measurements; obviously, GSD(t) decreases with increasing measurement duration t, and GSD(t = 1 year) = 1,
c. the spatial variations of indoor radon expressed as the GSD(s) that are due to only fluctuations in radon concentration in space (among buildings), for example, when measurements are taken within 1 year and $U_D = 0$.

It is obvious that GSD(s) ≤ GSD, since the last parameter covers both the dispersions associated with GSD(s) and GSD(t). It is also important to clarify that the GSD(s) yields a more adequate estimate of the share of buildings that may exceed the RL.

In addition to those listed above, a significant source of collective risk uncertainty is the unevenness of measurements over the course of a year, since temporal variations in indoor radon are often seasonal in nature (we emphasize that this source of uncertainty is not related to [b]). Usually, indoor radon concentrations are higher during the cold (heating) season than in the warm season, but this observation is not a strict rule that applies to any building. Moreover, the opposite pattern is observed in a significant share of buildings.[23–28] In this regard, the considered source of uncertainty applies equally to both short-term and long-term tests if the duration of measurements is <8–9 months. However, to strictly ensure the equality of comparison conditions within the first objective, we will assume that any measurements are carried out at a random time, or evenly over 1 year.

Another additional source of risk uncertainty may be year-to-year variations of indoor radon. However, it is not clear which parameter, GSD(s) or GSD(t), may be associated with this uncertainty. In this regard, it is advisable to compare the uncertainty of risks within no more than 1 year in order to exclude the uncertainty of year-to-year variations. It provides equal conditions for comparing the uncertainty of risks through the measurements with different durations.

The effect of U_D on the uncertainty of risk (as well as on the estimate of the annual concentration) is always lower for short-term measurements than for long-term measurements due to the relatively larger contribution of indoor radon temporal uncertainty in the combine uncertainty. Indeed, in contrast to long-term tests, a significantly larger U_D value does not lead to a noticeable increase in the combined uncertainty for decision making by the short-term tests, according to examples in.[3,7] To avoid complicating the analysis, U_D may not be taken into account for both short- and long-term measurements that also provides a level playing field for comparing risk uncertainty through the measurements with different durations.

Thus, our study will consider three main sources of risk uncertainty: (i) the number of measurements (or tested buildings) N in a representative sample, (ii) GSD(s), and (iii) GSD(t).

Within the first objective, it is sufficient to consider the following three values of GSD(t): GSD(t = 2 days) associated with the short-term measurements, and GSD(t = 2 months) and GSD(t = 1 year) - both associated with the long-term measurements. The values of GSD(t = 2 days) and GSD(t = 2 months) can be determined by the results of annual radon monitoring in a representative sample of buildings.[3] The array elements for determining GSD(t) should be the ratio between the concentrations measured over period t and AAIR concentration: $C_{ij}(t)/C_j^{AAIR}$ ($i = 1...M$; $j = 1...L$), where L is the number of buildings (monitored rooms), each of which year-long continuous measurements with a registration period of 1 h (at $M = 8760$) are carried out that provides good statistics for any measurement duration (period t).

A comparative analysis of the risk uncertainty between three GSD(t) values can be done in conjunction with, for example, the following four GSD(s): 1.6, 2.0, 2.4, and 3.0. This will estimate the uncertainties of both AM and GSD using the Monte-Carlo method, given the number of simulated measurements and their duration (2, 60 and 365 days), covering 12 estimated GSD values corresponding to the global range. According to UNSCEAR 2000 and 2006 reports,[29,30] the global range of the GSD values is about 1.8 to 3.2 with an average of 2.3. In addition, the range of the calculated GSD values according to section 3.2 lies well within the range reported by P. Bossew (1.4...3.5) in his critical state-of-the-art review paper.[31]

2.2 | Monte-Carlo method for assessing risk uncertainty

The statistical modeling algorithm based on the Monte-Carlo method needs to generate random numbers that is quite simply implemented in MS Excel. Therefore, some formulas below are expressed through the corresponding MS Excel functions for better understanding and implementation of the algorithm by interested users. The algorithm of uncertainty estimation for both AM and GSD using Monte-Carlo method within a representative sample includes the following four steps.

2.2.1 | Step 1

Setting the following set of input parameters:

(i) number of simulated measurements N (e.g., 100, 300, 1000, 5000, or 10 000),
(ii) GSD(t) value corresponding to the duration of measurements (2 days, 2 months or 1 year); these GSD(t) values are defined in sections 2.1 and 3.1, and
(iii) one of the GSD(s) values among the set: 1.6, 2.0, 2.4, and 3.0.

Thus, $5 \cdot 3 \cdot 4 = 60$ pairs of AM and GSD uncertainty estimates are expected.

2.2.2 | Step 2

Creation of a set of data arrays $\{C_j\}_{j=1...J}$ (where $J = 1000$ or more), each of which includes the same number (N) of radon concentration values C_{jn} generated in accordance with (1) as a multiplication of two independent from each other values of probability functions. According to (1), the first function generates a lognormal distribution of indoor radon concentration in space (s), and the second one generates a lognormal distribution in time (t):

$$C_{jn} = \text{LOGINV}\left(p_n(s), \mu_s, \sigma_s\right) \cdot \text{LOGINV}\left(p_n(t), \mu_t, \sigma_t\right) \text{at} j = 1 \ldots J, n = 1 \ldots N, \quad (1)$$

where $p_n(s)$ and $p_n(t)$ are the pairs of random numbers ranging from 0 to 1 generated independently using the RAND() function,

σ_s and σ_t are the standard deviations of logarithms related to the corresponding GSD(s) and GSD(t) values through the known formulas[9]:

$$\sigma = \text{Ln}\,(\text{GSD}), \quad (2)$$

μ_s and μ_t are the average values of logarithms related to the AM and corresponding GSD(s) and GSD(t) values through the following equation, which is derived from the combination of the well-known expressions[9]:

$$\mu = \text{Ln}\left[\text{AM} / \text{Exp}\left(\text{Ln}^2(\text{GSD}) / 2\right)\right] \quad (3)$$

under condition that AM = 1 for μ_t, then for μ_s the value of AM can be assumed equal to 50 or any integer expressing the expected arithmetic mean among the generated values of C_n.

Figure 1 shows an example of modeling (generating) radon concentration distributions and constructing an approximating function of combined spatiotemporal log-normal distribution which is based on the calculated values of AM_j and GSD_j obtained in accordance with Step 3 as a result of processing the generated radon concentration values. To clarify, this figure shows separately the following simulation results:

(i) only for the spatial distribution, when only the first function in (1) is taken into account (or if GSD(t) = 1.00001), and
(ii) combined spatiotemporal distribution, when both functions in (1) are taken into account.

It can be seen that the dispersion (characterized by GSD) increases in case (ii). Just for the sake of this comparison, as well as for a better understanding of the simulation procedure within (1), case (i) is given, while the simulation results are not taken into account in this case.

2.2.3 | Step 3

Determining the AM_j and GSD_j values of the approximating function for each of generated arrays $\{C_j\}$, using standard functions, as well as equations converted from (2) and (3):

$$\text{GSD}_j = \text{Exp}\left(\sigma_j\right), \quad (4)$$

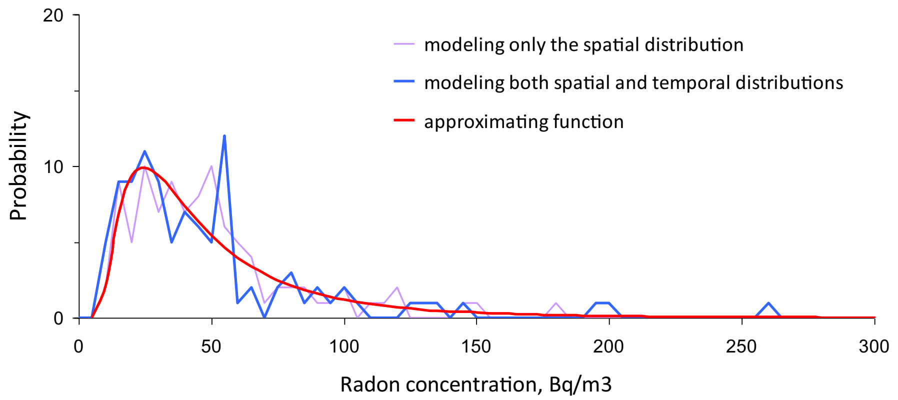

FIGURE 1 An example of modeling radon concentration distributions (at GSD(*s*) = 2.0, GSD(*t*) = 1.58 and *N* = 100, when $AM_s = 50$ and $AM_t = 1$) and constructing an approximating function of combined spatiotemporal log-normal distribution which is described by the following calculated values: AM = 47.34 and GSD = 2.16.

where σ_j is the standard deviation of logarithms of the values of array $\{C_j\}$ which is determined using the following functions:

$$\sigma_j = \text{STDEV}(\text{Ln}(C_{jn}))\,\text{at}\,n = 1 \ldots N,\text{and} \quad (5)$$

$$\text{AM}_j = \text{Exp}(\mu_j + \sigma_j^{\,2}/2), \quad (6)$$

where μ_j is the average of logarithms of the values of array $\{C_j\}$ which is determined using the function:

$$\mu_j = \text{AVERAGE}(\text{Ln}(C_{jn}))\,\text{at}\,n = 1 \ldots N. \quad (7)$$

2.2.4 | Step 4

Calculation of the AM and GSD uncertainties (in percent) that are associated with the original data (Step 1) using the following equations with standard functions:

$$\text{U(AM)} = 100 \cdot k \cdot \text{STDEV}(\text{AM}_j)/\text{AVERAGE}(\text{AM}_j)\,\text{at}\,j = 1 \ldots J, \quad (8)$$

$$\text{U(GSD)} = 100 \cdot k \cdot \text{STDEV}(\text{GSD}_j)/\text{AVERAGE}(\text{GSD}_j)\,\text{at}\,j = 1 \ldots J, \quad (9)$$

where k is the coverage factor equal to 2 (the test showed that both arrays of the AMj and GSDj values have normal distributions).

2.3 | Original data

The following data sources were used to determine the values of GSD(*t*):

a. Publication,[32] including the results of annual monitoring of radon concentrations available to the authors in six experimental rooms (ERs 1, 3, 7, 8, 9, and 10) located in five 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,[7] including the results of the annual monitoring of radon concentrations available to the authors in 12 experimental rooms located in nine Israeli buildings.

3 | RESULTS AND DISCUSSION

3.1 | GSD in temporal variation of indoor radon

The determination of GSD(*t*) taking into account the duration of measurements was carried out using the algorithm described in section 2.1, as well as the data from the previous annual monitoring of indoor radon in Russia[32] and Israel,[7] according to section 2.3. The distribution of $C_{ij}(t)/C_j^{AAIR}$ ratios obtained in aggregate from the results of monitoring in 18 ERs (12 ERs in Israel + 6 ERs in Russia) depending on the different values of t (2, 4, 6, 10, 21, 60, 90, 180, and 270 days) was analyzed. In the end 9 arrays were formed, the elements of which are the concentration ratios. The method of forming similar arrays is described in detail in our publication,[3] in which it is not concentration ratios that are analyzed, but their relative deviations, which does not affect the algorithm for generating indoor radon experimental distributions due to temporal variations.

The results of processing the experimental distributions of indoor radon concentration ratios as a function of GSD(*t*) related to one measurement at any time of the year are shown in Figure 2. In particular, GSD(*t*) is 1.58 for 2 days and 1.36 for 2 months. It seems useful to present also two indicative values of GSD(*t*) associated with two measurements with a start interval of about 6 months and four measurements in different seasons. Both dependencies were obtained in 2018, using the experimental data only from the Russian site.[33]

It must be noted that the temporal variations of indoor radon in Israel are almost twice as high as those in Russia.[3] However, this is still a tentative estimate that needs to be clarified through the accumulation and analysis of additional experimental data. Nonetheless, the predominance of the data from Israel in the total set of experimental data (12 ERs vs. 6 ERs) suggests that the GSD(*t*) values estimated for 2 and 60 days are at least not lower than the global values GSD(*t*) associated with temporal variation of indoor radon.

The relevance of our estimation of GSD(*t*) for 2 months is confirmed by the results of a study in 326 Finnish houses.[34] For example, the Finnish study yields four values of GSD(*t*) at *t* = 2 months: 1.37, 1.29, 1.61 and 1.29. These values are slightly different depending on the starting month of the measurement. The average of these

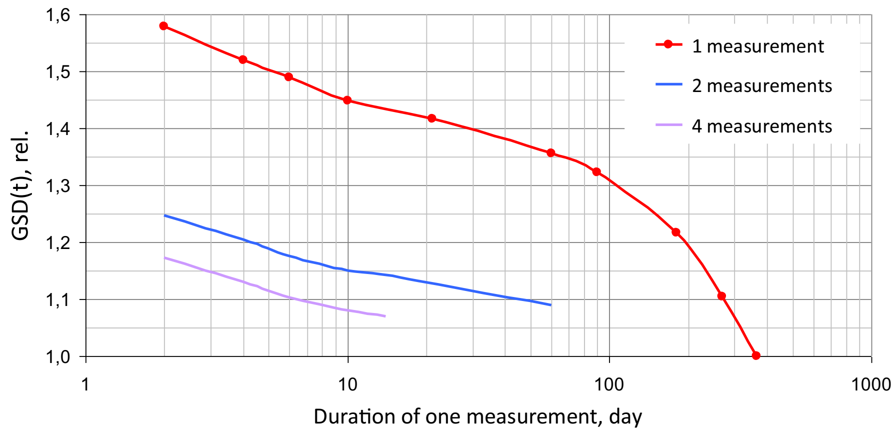

FIGURE 2 GSD(*t*) vs. measurement duration: (i) one measurement at any time of the year, (ii) two measurements with a start interval of about 6 months, and (iii) four measurements in different seasons; the data (ii) and (iii) were presented at the conference in 2018[33]

four values is GSD(*t*) = 1.39, which differs slightly from our estimate (1.36).

Unfortunately, alternative data regarding GSD(*t*) for 2 days are practically absent in the scientific literature, with the exception of the studies conducted by *D.* Steck,[35] the results of which do not inspire much confidence due to the very low statistics of the experiments compared to our data.[3] Probably for this reason, D. Steck uses the statistical equations of normal distributions (instead of lognormal) to describe the temporal variations of indoor radon in his later publications.[36,37] Indeed, the description of the distributions of indoor radon temporal variations requires a special attention. For example, courtesy of the good experimental statistics, our article[3] identified and discussed in detail the problem of violation of the lognormal distribution of deviations of the measured radon concentration from the annual average if the test duration exceeded 1 month. Therefore, GSD(*t*) values for $t > 1$ month should be treated with caution. However, our estimate of GSD(*t*) for $t = 2$ months is the most reliable, at least because of the closure to the estimate for the Finnish houses.[34] Unfortunately, unlike the GSD, the global values of GSD(*t*) have not yet been estimated.

In summary, GSD(*t*) = 1.58 for 2 days and GSD(*t*) = 1.36 for 2 months are the most relevant values for modeling and assessing risk uncertainty.

3.2 | Comparison of risk uncertainties between short- and long-term measurements

Simulation results in terms of calculated AM and GSD uncertainties versus duration and number of measurements spanning the global GSD range are shown in Figures 3 and 4, respectively.

Comparison of the data obtained shows that the difference in the assessment of collective risk using short-term and long-term tests within a representative sample of buildings does not exceed 1%–2%, if the number of measurements is at least 500. For the fewer measurements (100 measurements, for example) and lower GSD, this difference slightly increases—to 5% only. Thus, the problem in collective risk assessment is not duration of measurement but the representativeness of the sample of buildings, including their number (or number of measurements).

The insignificant (or practically non-existent) difference in the assessment of collective risk through short- or long-term tests is explained by the fact that GSD(*t*) is always lower than GSD(*s*), while the difference between these parameters increases with increasing GSD. It also justifies the possibility of combining test results of any duration into a single data array without creating additional uncertainties in the assessment of both the collective dose and the location of Radon Priority Areas (RPA) expressing the potential radon hazard.

In summary, contrary to the erroneous opinion that there is no alternative to long-term measurements rooted in the European radon community (through such authoritative and influential organizations as IAEA, ICRP, WHO, and ISO), in fact the accuracy of the assessment of the collective risk due to radon exposure does not at all depend on the duration of the indoor test that agrees with the experimental data obtained almost 20 years ago.[38,39] Meanwhile ensuring a representative sample of buildings remains a major challenge in collective risk assessment, especially when the number of measurements is limited.

3.3 | Strategy for indoor radon measurements

The unexpected for many professionals (including national regulators) yet quite justified conclusion that measurements of any duration are suitable for collective risk assessment (without sacrificing accuracy) points to the need in revising the ineffective regulation of indoor radon in Europe, as well as around the world. Moreover, there is already a solid ground to create a rational protocol covering both short- and long-term measurements of indoor radon for conformity assessment of a room with a normative within the ISO standardization practice.[3] This solid ground could serve as a basis for choosing an effective strategy for indoor radon measurements in different countries, taking into account national regulatory features. In this regard, the most important considerations in the three subsections below, as a synthesis of scientific achievements and best

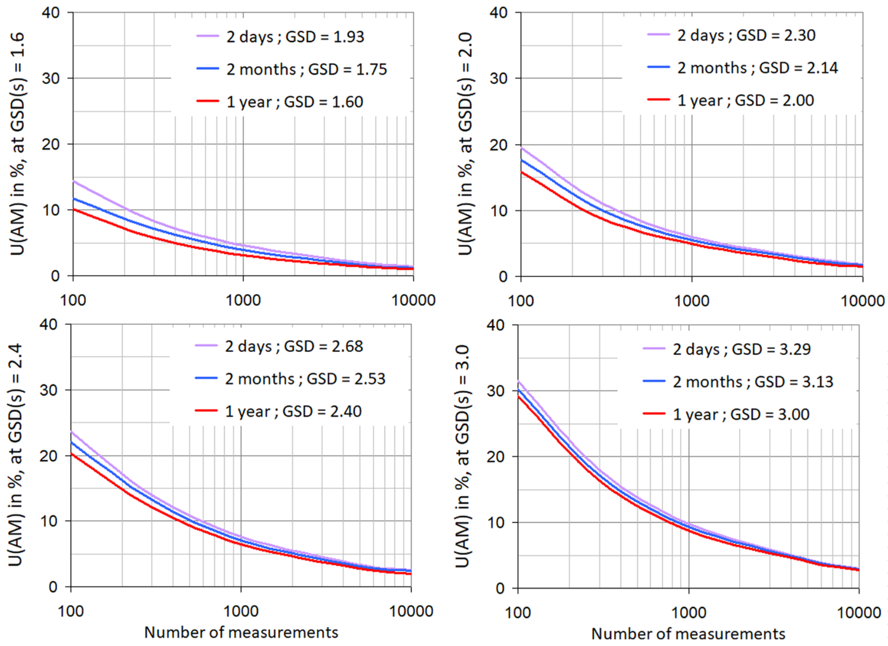

FIGURE 3 AM uncertainty calculated by Monte-Carlo method at k = 2 depending on three parameters: (i) GSD(*s*), (ii) duration of measurements (when GSD(*t*) equals 1.58 for 2 days, 1.36 for 2 months, and 1.00 for 1 year), and (iii) number of measurements.

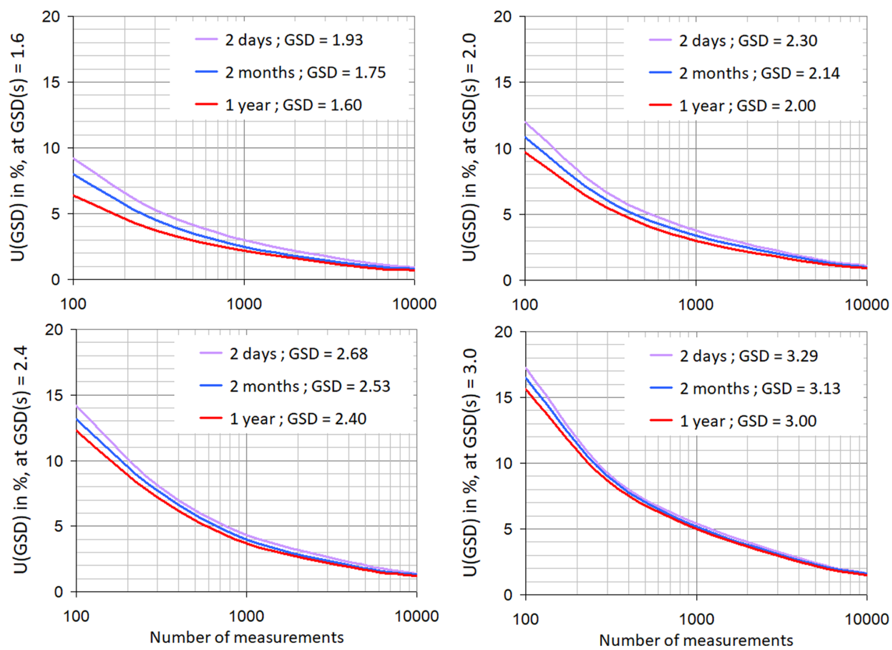

FIGURE 4 GSD uncertainty calculated by Monte-Carlo method at k = 2 depending on three parameters: (i) GSD(*s*), (ii) duration of measurements (when GSD(*t*) equals 1.58 for 2 days, 1.36 for 2 months, and 1.00 for 1 year), and (iii) number of measurements.

practice through the revision of foundational documents of IAEA, ICRP, WHO, and ISO, could contribute to the implementation of rational and harmonious regulation of indoor radon (as well as other pollutants) on the international level.

3.3.1 | Principle of an effective measurement strategy

The most reliable conformity assessment of any room with a normative can be obtained by measurements taken continuously for a period of 1 year. In the same time, the radon concentration in the majority of buildings (or global GM-value) is only about 30 Bq m^{-3}, according to the UNSCEAR reports.[29,30] This value is significantly lower than the RL (see "Introduction"). Under these circumstances, measuring low activity with high accuracy using the long-term tests would be time-consuming and costly. It is true that the shorter the test, the higher the AAIR uncertainty. However, due to the generally low level of radon in buildings, even a high uncertainty of up to 200% (for example, 30 Bq m^{-3} + 60 Bq m^{-3} < RL) would be satisfactory in most cases. Only in relatively rare instances, where the high uncertainty of the short-term test does not allow for a reliable safety assessment, a decision must be taken based on more accurate long-term measurements. Thus, the most effective strategy should include two stages: (i) initial (short-term or screening) measurements, and (ii) additional (long-term) measurements if necessary. Similar measurement strategy with two stages is accepted and effectively implemented in the US for years. It actually provides more effective indoor radon regulation compared with that accepted in EU, where only one stage long-term tests are being promoted. Within the effective strategy, the rational Criterion for Decision Making is based on the assessment of the main uncertainties, such as the temporal $U_V(t)$ and instrumental U_D ones, taking into account the mode and duration of measurements.[3] Indeed, the measurements can be taken at any time and building operation mode, at either normal or limited ventilation. This rational Criterion will allow for the first time to quantify the trade-off between duration (which influences both accuracy and cost) and reliability of the radon test by managing false positive/negative errors in decision making.

Regretably, the full application of the rational Criterion is hampered by insufficient knowledge of the temporal uncertainty of indoor radon (especially for short-term tests) which is explained by defocusing of the priorities for the needs of standardization of measurements and regulation in general, as already mentioned in the Introduction. This problem can be solved quite simply, for example, within the framework of the recently launched "RadoNORM" project (www.radonorm.eu) under EURATOM Horizon 2020 which aimed at managing risk from radon and NORM exposure. Relevant study should be based on the analysis of the results of continuous year-long measurements of the concentration of radon (and other indoor pollutants) in a representative sample of buildings (from several tens to several hundred in each country), guided by certain research method.[3]

For RPA (usually covering not more than 10% of the territory), introducing an additional criterion for choosing the optimal duration of measurements (short-, middle-, or long-term) to start tests would be recommended. Such an additional criterion can be developed on the basis of a more complex simulation using the Monte-Carlo method with the following set of input parameters: average mean (AM) of indoor radon, RL, U_D, and N, as well as GSD and GSD(t) or $U_V(t)$ values.[3] This task only emphasizes the importance of a more detailed study of the $U_V(t)$ and GSD(t).

3.3.2 | Mass character of measurements via short-term tests

The experience with the most effective regulation of indoor radon, such as that implemented in the US[16–20] or Sweden[40] shows that all buildings in all areas, not just RPA, should be tested. Moreover, this statement has recently been rigorously substantiated by analyzing the results of measurements of indoor radon in Germany.[41] Finally, the survey of any area is also promoted in ICRP Publication 126,[8] which is a significant advance in relation to the excessive focus on only RPA in the earlier documents such as ICRP Publication 65[22] and EU-BSS.[2]

Since any existing building (among hundreds of millions of buildings everywhere) has a potential for radon hazard, conditions for large-scale (mass) indoor radon measurements in each country, similarly to what has long been successfully implemented in the US, should be created on the international level. Thanks to the mass measurements based on short-term tests, it will be possible not only to identify hazardous buildings effectively, but also to assess the collective risks due to indoor radon, including developing a more accurately map of Radon Priority Areas. It has to be emphasized that, unlike long-term measurements, the implementation of short-term tests opens a possibility and legalizes the participation of non-professionals in the radon tests at the initial (screening) stage due to softer requirements for quality assurance of short-term measurements.[3,7] Indeed, the rational value of the instrumental uncertainty is about (30–40)% for short-term measurements, while (15–20)% for long-term measurements.[3] Thus, the cost of short-term tests can be markedly lower than long-term tests. To implement such an ambitious goal as global mass indoor measurements, the population must be motivated to actively participate in conducting indoor tests.

3.3.3 | Societal engagement in measurements

Organization and conducting of mass measurements of indoor radon (and further mitigation activities) are impossible without societal engagement. This is firmly supported by statistics, for example, regarding the still underdeveloped radon monitoring industry in Europe where only less than 1% of buildings have been tested so far.[10] Usually, indoor radon monitoring and mitigation activities in Europe are initiated by the authorities and have been carried out for several decades with the support of EU and national budgets (so called "top-down" approach). At the same time, tens of millions of short-term tests have already been carried out in the USA and more than a million buildings have been successfully mitigated[21]—thanks to the funding and participation of residents and property owners themselves, who are well informed about the risks of radon and other indoor air pollutants (so called "bottom-up" approach). Apparently for this reason, the "bottom-up" approach began to be promoted in ICRP Publication 126[8] that can also be considered as a very important step towards significant progress within ICRP.

It should also be taken into account that over 90% of residents prefer short-term tests over long-term measurements, according to a US survey published in 1990.[13,42] It would be interesting to know which tests (short- or long-term) are preferred, for example, by modern Europeans. Unfortunately, this very important question was not included in the survey which was recently conducted within the current "RadoNORM" project already mentioned above. This fact only confirms our statement in section 3.2 that the European community erroneously sees no alternative to long-term measurements, while short-term tests are unfairly ignored.

When the population is well-informed (motivated) and initiates the payment for and conducting of tests, the quality of the measurements is improved, including a decrease in the proportion of irrelevant tests. In addition, due to the random nature of testing through the initiative of the population, the representativeness of the sample of buildings is improved, the measurements in which become more uniform (or random) in time, which ultimately increases the accuracy of the risk assessment.

In summary, the following key actions could improve societal engagement, as well as indoor measurements in general:

a. revision of the foundational documents (IAEA, ICRP, WHO, ISO, and relevant national safety standards) for the regulation of indoor radon (and other air pollutants) taking into account the above considerations regarding (i) the principle of the effective measurement strategy based on fundamental ISO/IEC concepts such as "measurement uncertainty" and "conformity assessment," (ii) the mass measurements via short-term tests, and (iii) the societal engagement in measurements;
b. more in-depth study of the GSD(*t*) and the temporal uncertainty of indoor radon (and other air pollutants), depending on the mode and duration of measurements, as well as other influencing factors, guided by certain research method[3]; in particular, it is necessary to conduct a large number of continuous year-long measurements in a representative sample of buildings, for example, located in different countries;
c. development of various types of devices and methods of not only long-term measurements, but mainly short-term measurements (simple and accessible to the public), providing them with adequate quality assurance and control systems as a part of the implementation of a rational measurement protocol[3] within ISO/IEC concepts;
d. development of on-line services for indoor measurements, such as the "RadonTest" system,[43] covering an extensive network of IAQ laboratories in different countries; this will improve not only the organization and quality of mass measurements through the participation of the population, but also continuous accumulation of test results (including the characteristics of objects and measurement conditions) in a global repository for a more accurate risk assessment, as well as an assessment of the effectiveness of national regulatory systems;
e. transferring the main cost burden associated with testing and mitigation from national budgets onto the residents and building owners, and redirecting the freed-up finances in the national budgets to informing and educating the population as to the health risks of radon and other pollutants;
f. improving public awareness and initiatives through other resources at the disposal of local authorities and other stakeholders and organizations, for example, Citizen Science, Living Labs, etc.

4 | CONCLUSIONS

1. Contrary to the erroneous opinion rooted in the European radon community that there is no alternative to long-term measurements, the accuracy of the assessment of the collective risk due to radon exposure does not depend on the duration of the indoor test; while the main problem in collective risk assessment remains to ensure a representative sample of buildings, especially in the context of a limited number of measurements.
2. In this regard, a revision of the foundational documents of IAEA, ICRP, WHO, and ISO focusing on (i) the principle of the effective measurement strategy within ISO/IEC concepts, (ii) the mass measurements via short-term tests, and (iii) the societal engagement in measurements, could contribute to the rational and harmonious management of indoor radon (as well as other air pollutants) risks at the international level. The main output of such a revision should be the legalization and implementation of short-term tests as a universal tool that allows to effectively identify buildings with elevated radon, as well as accumulate data for collective risk assessment and RPA location through mass indoor measurements with a wide involvement of residents.
3. A deeper study of the GSD(*t*) and the temporal (key) uncertainty of indoor radon (and other air pollutants), depending on the mode and duration of measurements, as well as other influencing factors, is necessary. Such study should be based on the analysis of the results of continuous year-long measurements of the concentration of radon (and other indoor pollutants) in a representative sample of buildings (from several tens to several hundred in each country), guided by certain research method.[3]
4. It is necessary to develop various types of devices and methods of not only long-term, but mainly short-term measurements that are simple and accessible to the public. These will provide adequate quality assurance and control systems as a part of the implementation of a rational measurement protocol[3] with support through on-line services for indoor measurements.

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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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