

Measurement Duration for Reliable Indoor Radon Testing

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Abstract

Although radon measurements have been carried out in most countries for several decades, a rigorous methodology for assessing the reliability (as well as the effectiveness) of indoor radon testing between short-term and long-term measurements has not yet been established at either the national or international level. National regulators, lacking scientific justification, arbitrarily set the duration of indoor radon testing (from a few minutes to several months) preferring long-term measurements simply because it “seems more reliable”. To solve this fundamental regulation problem, an original (innovative) methodology is proposed based on the algorithms of the previously published Rational Method for indoor radon testing, which ensures 95% decision-making reliability within modern metrological concepts. A comparison of the reliability (and effectiveness) between short-term and long-term measurements can be made by taking into account the radon situation at both national and global levels. The obtained dependence of the mean (among 26 countries) percentage of definite (reliable) decisions vs. the duration of measurements indicates: (i) the greater effectiveness of using short-term measurements compared to long-term ones, as well as (ii) the excessive focus of national and international regulators only on instrumental uncertainty within QA/QC to the detriment of temporal (key) uncertainty in decision-making. Key conclusion: The established practice of radon regulation on both global and national levels contains a number of underlying myths, and therefore clearly needs to be rethought and updated within a rational (scientific) strategy. A vital necessity are specific experimental (field) studies to verify (clarify) the national values of the temporal (key) uncertainty of indoor radon (and thoron EEC), as well as the creation of simple and effective (inexpensive but reliable) IoT tools for large-scale measurements of indoor radon through the involvement (and at the expense) of the population.

Keywords: indoor radon; thoron; measurement duration; testing; reliability; standardization; metrology; measurement uncertainty; temporal uncertainty; conformity assessment; decision-making; building; IAQ; radiation safety; Rational Method

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1. Introduction

1.1. Indoor Radon: Global Risk and Regulation

Radon, a naturally occurring radioactive gas, is a well-established human carcinogen and represents a major source of radiation exposure indoors—both in homes and workplaces—where people typically spend 80–90% of their lives. The 2024 UNSCEAR report [1] revised the global average health risk from indoor radon exposure upward by 38%,

increasing the estimated annual effective dose from 1.3 to 1.8 mSv. As a result, the risk contribution due to radon now accounts for approximately 60% of the total dose from all natural radiation sources (3.0 mSv/year), or up to 75% among natural sources that can be mitigated through regulation.

In 2009, the World Health Organization (WHO) and the International Commission on Radiological Protection (ICRP), drawing on extensive epidemiological evidence from different countries, doubled the estimated health risk associated with radon exposure. Based on these findings, the WHO [2] and ICRP [3] issued updated recommendations, while the International Atomic Energy Agency (IAEA) [4] and the European Basic Safety Standards (EU-BSS) [5] established regulatory requirements through reference levels (RLs) for the annual average indoor radon concentration that shall not be higher than 300 Bq/m³. National RLs vary depending on regional radon situations and usually range from 100 to 400 Bq/m³ [6].

1.2. Challenging a Reliable Measurement Duration

It is important to reiterate and emphasize that the reference level (RL) is defined as the annual average indoor radon concentration. This implies that radon measurements should ideally be conducted over an entire year to ensure the most reliable determination of whether a tested room complies with safety requirements, based on a comparison of the result of such a direct measurement with the RL. It is clear that the shorter the measurement duration, the lower the reliability of indoor radon testing, because the temporal component of decision-making uncertainty increases. After all, indoor radon concentration varies substantially over time (during the day, weeks, and months) even in continuously closed rooms [7,8]. Nevertheless, direct year-long measurements are extremely rarely performed, because in the vast majority of buildings radon levels are significantly (several times or almost an order of magnitude) below the RL [1,9], and the cost of direct and long-term measurements is significantly higher than short-term measurements. For this reason, long-term measurements of low radon concentrations over several months or a full year in every room of a building are not an efficient strategy. Moreover, the dominant temporal component of decision-making uncertainty is neither quantified nor considered in any national radon regulatory practice [10].

This leads to a fundamental question: What should be the duration of an indirect measurement (shorter than one year) of the annual average radon concentration to ensure reliable testing of rooms and the entire building?

Unfortunately, a scientifically grounded answer to this question is still lacking—not only from national bodies of metrology and measurement standardization, but also from international organizations such as the IAEA, ISO, or WHO [10]. This gap persists despite the recent completion of the five-year European project RadoNorm [11], which followed the two-year MetroRADON project [12]. Measurement durations established in national regulatory systems vary dramatically (from several minutes, hours, and days to several weeks and months) [13,14], and are completely unsupported by a rigorous assessment of indoor radon testing reliability within a such fundamental concepts as “measurement uncertainty” [15] and “conformity assessment” [16]. These ISO/IEC metrological concepts, supported by the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995 with minor corrections [17]), are already globally adopted in measurement standardization. However, the introduction of metrological science has so far had very little impact on the radon community as a whole, which is still unwilling to notice and take into account such a key component in decision-making as the temporal uncertainty of indoor radon [10].

It is useful to recall that, for example, U.S. national standards (ANSI/AARST MAN, MA-MFLB, and MS-QA) [18] set short-term measurements, lasting 2–7 days. However,

the temporal (key) uncertainty, as well as the reliability of decision-making, is not taken into account quantitatively and is not even discussed [10]. Otherwise (if reliability or temporal uncertainty were taken into account quantitatively), it is unlikely that the persistent distrust of short-term tests among European regulators and ISO experts would have developed [19]. This skepticism is reflected in the international standard ISO 11665-8:2019 [20], which recommends only long-term measurements, but with a very vague (for the standard) duration of “at least two months”. However, in this international standard, as in the previous ISO 11665-8:2012 [21], neither the temporal (key) uncertainty nor the reliability of decision-making has been established [10,22]. At the same time, the unaccounted temporal uncertainty is about 100% or 85% for a measurement duration of 2 or 3 months, respectively [7,8,10,19,22,23].

It is reasonable to think that long-term measurements are more reliable than short-term ones, but it is equally important to understand how much more reliable, especially when considering the cost of indoor radon testing. To date, no national or international regulator has provided a rigorous scientific comparison of the efficiency (as a combination of reliability and cost) between short-term and long-term measurements within the modern metrological concepts [15–17]. Such a comparative analysis is precisely what is needed to answer the fundamental question of the required duration of indirect measurements for reliable indoor radon testing.

In the absence of this essential guidance, national regulators—lacking scientific justification from standardization bodies and authoritative international organizations such as the IAEA, ICRP, or WHO—continue to set measurement durations arbitrarily, without accounting the temporal (key) uncertainty or decision-making reliability, preferring long-term measurements simply because it “seems more reliable” [10].

1.3. Reliability and Cost: Focus on Rational Method Algorithms

Improving any measurement method (or protocol) has tangible benefits only if it reduces financial or time costs while maintaining—or even increasing—the method’s reliability, which must, of course, be quantified. The relative or absolute time-related costs can be illustrated using active radon monitors, given information about the device’s price (P) and service life (SL). The shorter the measurement duration (t), the lower the cost of measurement, which is simply $P \times t/SL$. Notably, the cost of short-term measurements using the charcoal method is also lower than the cost of long-term measurements using the SSNTD method [24]. Moreover, time itself—like any material resource—has a certain value, not only in industrial or other processes but also in the private life of each person.

A clear quantitative relationship between indoor radon measurement duration and the reliability of decision-making must ultimately be established on the basis of modern metrological science. Such a relationship, grounded in fundamental ISO/IEC concepts [15,16], has already been explicitly formulated in the algorithms of the Rational Method for indoor radon measurements [10]. No alternative algorithms have been proposed to date, making it reasonable for our study to focus on the Rational Method.

Indeed, the main criterion of the Rational Method explicitly expresses the quantitative link between the duration of indirect measurement and the combined uncertainty of the annual average radon concentration (see criterion (1) in Section 2.1), at a confidence level (decision reliability) of 95% [10]. A defining element of the Rational Method is the experimentally established dependence of temporal uncertainty on measurement duration. According to this dependence, the temporal uncertainty for a measurement duration of 5–7 days (120%) and 2 months (100%) differs by only 20% (insignificantly) under normal operation/ventilation mode [10,22,23].

1.4. Objectives of the Study

From the standpoint of optimizing regulatory indoor testing practices, comparing the effectiveness and reliability of short-term and long-term indoor radon measurements is most clear when presented as a relationship between the percentage of definite (reliable) decision-making and the measurement duration, while also accounting for the influence of additional factors:

- Variability in the characteristics (specific parameters) of lognormal indoor radon concentration distributions across different countries;
- Differences in national RL values;
- Instrumental uncertainty of indoor radon concentration measurements.

The results of such a study would allow an objective (scientifically grounded) verification of the relevance of current priorities: (i) the preference for long-term over short-term measurements, and (ii) the emphasis placed on instrumental uncertainty, as well as discussing other relevant issues:

- Limitations and representativeness of temporal uncertainty;
- Reference level and other aspects of radon regulation;
- Measurement duration for reliable indoor thoron testing;
- Priorities for radon and thoron studies and indoor testing technologies.

2. Methods and Materials

2.1. Algorithms of Rational Method

The main rational criterion ensures a decision reliability of at least 95% (no more than 5% false-negative error) regarding the compliance of a room with a safety requirement, if the following condition is met [10]:

$$C(t) \cdot \left[1 + \sqrt{U_V(t)^2 + U_D^2} \right] < C_{RL}, \quad (1)$$

where $C(t)$ is the measured (mean) radon concentration (Bq/m^3) over the measurement period of t , the duration of which should be at least two days under closed mode and at least four days under normal mode;

C_{RL} is the reference level for the annual average indoor radon concentration, Bq/m^3 ;

$U_V(t)$ is the temporal uncertainty in relative units (with coverage factor $k = 2$), the values of which depend on the measurement duration and are presented in Table 1 for the normal mode (closed mode is not considered here because in such conditions the rooms are usually not used for long periods of time as weeks and months);

U_D is the instrumental (device) uncertainty in relative units ($k = 2$) [10].

Table 1. The values of the temporal uncertainty and multiplicity factor, depending on the measurement duration for normal operation/ventilation modes [10,22,23].

Day	1	2	3	4	5	6	7	8	10	12	14	20
$U_V(t)$	2.30	1.60	1.40	1.25	1.20	1.20	1.20	1.20	1.10	1.10	1.10	1.10
$MF(t)$	-	-	-	1.74	1.72	1.70	1.69	1.68	1.67	1.66	1.65	1.61
Month	1	2	3	4	5	6	7	8	9	10	11	12
$U_V(t)$	1.05	1.00	0.85	0.65	0.55	0.45	0.35	0.25	0.17	0.10	0.05	0.00
$MF(t)$	1.56	1.48	1.44	1.42	1.37	1.31	1.24	1.20	1.14	1.09	1.05	1.00

The additional criterion for identifying hazardous rooms ensures a decision reliability of at least 95% regarding the non-compliance of a room with a safety requirement, if the following condition is met [10]:

$$\frac{C(t)}{MF(t)} \cdot [1 - U_D] > C_{RL} \quad (2)$$

where $MF(t)$ is the multiplicity factor in relative units, the values of which depend on the measurement duration and are presented in Table 1.

2.2. General Methodological Approach Within Rational Method

Within the framework of the Rational Method, the result of testing a room leads to one of three possible decisions:

- (a) The room complies with safety requirements (remediation measures are not required) if the RL is not exceeded according to criterion (1).
- (b) The room does not comply with safety requirements (remediation measures are required) if the RL is exceeded according to criterion (2).
- (c) The measurement must be continued (or a repeat measurement lasting 10–12 months must be performed) if the RL is exceeded according to criterion (1), but the measurement duration was shorter than 10 months.

Decisions (a) and (b) are definite, whereas decision (c) is indefinite. In this terminology, and in line with the objective of our study, it is important to determine the percentage of definite (reliable) decisions as a function of measurement duration, taking into account the instrumental uncertainty (U_D) and the following national characteristics of the radon situation:

- The parameters of the lognormal distribution of indoor radon concentrations in a country, such as the arithmetic mean (AM), geometric mean (GM) and geometric standard deviation (GSD);
- The national RL value.

Generating lognormal distributions of indoor radon concentrations using specified AM and GSD values is straightforward—for example, in MS Excel using the function LOGINV. The procedure for generating such datasets $\{C_n\}$, including $n = 1, \dots, N$ values, was described in detail in our previous publication [25], and a corresponding example is provided in the “Supplementary Materials”. In this case:

$$C_n = \text{LOGINV}(p_n, \mu, \sigma), \quad (3)$$

where p_n is random numbers ranging from 0 to 1, generated using the RAND() function, and the remaining parameters are determined using well-known formulas [26]:

$$\mu = \text{Ln}(GM), \quad (4)$$

$$\sigma = \text{Ln}(GSD), \quad (5)$$

$$GM = \frac{AM}{\text{Exp}(\text{Ln}^2(GSD)/2)}. \quad (6)$$

A generated lognormal distribution represents the absolute number or percentage of cases as a function of indoor radon concentration. Another MS Excel function, PERCENTRANK, calculates the percentage of all radon concentration values in the dataset that are below a specified value (see Supplementary Materials). Within our objectives, this specified value is the action level (AL), defined as the maximum radon concentration $C^{(1)}_{AL}(t)$ below which criterion (1) is met, **that ensures the confidence of the decision according to point (a)**. Accordingly, $C^{(1)}_{AL}(t)$ can be obtained from criterion (1):

$$C^{(1)}_{AL}(t) = \frac{C_{RL}}{1 + \sqrt{U_V(t)^2 + U_D^2}} \quad (7)$$

$C^{(1)}_{AL}(t)$ depends on the measurement duration: as the duration increases, $C^{(1)}_{AL}(t)$ also increases, as follows from the data in Table 1.

In the case of criterion (2), the action level (AL) represents the minimum radon concentration $C^{(2)}_{AL}(t)$ above which this criterion is met, **that ensures the confidence of the decision according to point (b)**. Accordingly, $C^{(2)}_{AL}(t)$ can be obtained from criterion (2):

$$C^{(2)}_{AL}(t) = \frac{MF(t) \cdot C_{RL}}{1 - U_D} \quad (8)$$

$C^{(2)}_{AL}(t)$ also depends on the measurement duration; however, in contrast to $C^{(1)}_{AL}(t)$, increasing the duration reduces the value of $C^{(2)}_{AL}(t)$, as follows from the data in Table 1. Furthermore, in the case of criterion (2) it is important to calculate the percentage of all radon concentration values in the dataset that are greater than the specified value $C^{(2)}_{AL}(t)$. This requires a simple arithmetic adjustment: subtracting the value returned by the MS Excel function PERCENTRANK from 1 (see Supplementary Materials).

The methodological approach described above makes it possible, for each country (with its specific RL, AM, and GSD values), to determine the percentage of definite (reliable) decisions as a function of measurement duration. In other words, it allows a quantitative (objective) comparison of the overall reliability of short-term versus long-term indoor radon measurements. The term “overall reliability” in this context, in addition to making a decision with a confidence level (reliability) of 95%, also takes into account the efficiency of indoor radon testing when a definite decision of type (a) or (b) is reached without requiring additional measurements. In the case of indefinite decisions of type (c), the proportion of rooms that remain indefinite after testing is calculated as the difference: 100%—percentage of definite (reliable) decisions.

Furthermore, it is useful to examine the dependence of the mean percentage of definite decisions on measurement duration using the combined dataset of calculated values from different countries, each with its own RL, AM, and GSD, while also accounting for the influence of instrumental uncertainty (U_D).

2.3. Methodological Limitations

As noted earlier, the defining element of the Rational Method is the experimentally established dependence of the temporal uncertainty $U_V(t)$ on measurement duration. The multiplicity factor $MF(t)$ is used within the additional criterion (2); however, neither criterion (2) nor the $MF(t)$ values themselves play a role as critical in conformity assessment as the main criterion (1) [23].

The algorithms for determining $U_V(t)$ and $MF(t)$ are presented in the description of the Rational Method [10] and discussed in greater detail—considering updated limitations—in a recently published article on the Open Research Europe platform [23], including detailed algorithms with examples of processing datasets in MS Excel. To ensure the representativeness of $U_V(t)$ and $MF(t)$, several year-long continuous measurement (YLCM) limitations have been established, including [23]:

- (a) In each building, only one monitored room should be selected, and it must exhibit an elevated radon concentration—on average, at least 50–70 Bq/m³, which is at least five times higher than the typical outdoor radon level. Conformity assessment in rooms with low (near-outdoor) concentrations is less demanding than in those with elevated indoor radon. Additionally, differences in the temporal variation patterns of indoor radon concentrations between low- and high-radon buildings may arise from the varying contribution of outdoor radon to the overall indoor radon balance.
- (b) The monitored room should be the one most frequently occupied—typically a bedroom or office—used for at least 6 h per day.

- (c) Preference should be given to both low-rise and high-rise dwellings with natural ventilation, as such buildings are significantly more common than those with mechanical or forced ventilation systems.
- (d) The monitored room, as well as the building as a whole, must operate under normal-mode conditions throughout the entire monitoring period. This excludes any special ventilation effects (natural or mechanical) and any room subjected to building renovations or repairs.
- (e) YLCM is considered unsuitable for evaluating temporal uncertainty if the duration of data registration gaps exceeds 10 consecutive days or 15 cumulative days within a year.
- (f) YLCM is unsuitable for evaluating temporal uncertainty if its annual average radon concentration exceeds six times (and more) its daily average concentration for more than 15 days in total over the course of a year.

A matter of concern is the occurrence of low indoor radon concentrations (approaching outdoor levels) over extended periods of time, either continuously or cumulatively throughout the year. Such situations may arise even in rooms with a high annual average radon concentration that exceeds the reference level. This issue remains poorly studied and is discussed in more detail in [23], as well as in Sections 4.3 and 4.6 below, in the context of the question of the representativeness of the applied $U_v(t)$ values and the necessary research on their verification (clarification).

2.4. Initial Data

The UNSCEAR Report has already been mentioned above, which also provides AM, GM, and GSD for countries on different continents [1]. However, the set of initial data available for our study is limited to a relatively short list of countries for which an RL has been officially established, according to the WHO website [6]. Table 2 presents the initial data required for our study, covering 26 countries from different continents.

Table 2. National data on indoor radon concentration [1] and reference level [6].

Country	Reference Level (RL), Bq/m ³	Parameters of the Lognormal Distribution of Radon Concentration			Proportion of Cases Exceeding RL **, %
		AM, Bq/m ³	GM, Bq/m ³	GSD	
Netherlands	100	16	12 (13)	1.9	0.10
Denmark		59	37 (35)	2.8	15.6
Norway		89	55 (54)	2.7	27.6
United States of America	148				5.8
	300	46	25 (24)	3.1	1.4
	400				0.8
United Kingdom	200	22	15 (16)	2.2	0.1
Israel		65 *	35 *	3.0 *	6.0
Italy		72	50 (53)	2.2	4.8
Latvia		74	54 (54)	2.2	5.1
Canada		82	55 (54)	2.5	8.1
Sweden		90	63 (64)	2.3	8.9
Ireland	300	98	80 (80)	1.9	8.0
Argentina		46	37 (37)	1.9	0.1
Slovakia		48	41 (35)	2.2	0.4
Spain		53	25 (25)	3.4	2.2
China		55	40 (37)	2.4	1.0

Germany		63	41	2.5 **	1.6
Portugal		66	37 (35)	3.1	3.0
Belgium		69	49	2.3 **	1.6
Slovenia		87	60 (64)	2.2	2.6
France		90	53 (59)	2.5	4.0
Finland		96	62 (63)	2.5	4.6
Austria		112	79 (71)	2.6	6.9
Czechia		119	94 (97)	1.9	4.1
Poland		165	133 (134)	1.9	11.0
Türkiye	400	81	57 (57)	2.3	1.1
Serbia		105	60 (57)	3.0	4.0

* Data taken from another source. ** The parameter obtained by calculation based on the table data. The data highlighted in four table cells, are discussed in Section 4.4.

The data presented in Table 2 require several clarifications:

- The values reported for Israel in the 2024 UNSCEAR Report (AM = 31 Bq/m³, GM = 28 Bq/m³, and GSD = 1.6) [1] appear highly questionable, as their use of calculations shows that exceeding the RL (200 Bq/m³) is virtually impossible; even the proportion of cases exceeding 100 Bq/m³ is only 0.3%, which is clearly unrealistically low. For this reason, more reliable data for Israel [27] are used in the table.
- The values reported for Germany (GSD = 2.0) and Belgium (GSD = 1.6) in the 2024 UNSCEAR Report [1] also raise concerns. Calculations based on well-known relationships [26] (also see Section 2.2 and Supplementary Materials) and the corresponding AM and GM values in the report yield substantially different GSD values. Therefore, the corrected values—Germany (GSD = 2.5) and Belgium (GSD = 2.3)—are presented in the table.
- In the “GM, Bq/m³” column, the values shown in parentheses represent the recalculated GM values obtained using the calculation referenced in point (b). As can be seen, some of the original and recalculated values differ significantly for reasons unknown to us. It is possible that the substantial discrepancies observed in some countries are related to underestimated GSD values.
- The three RL values for the United States of America, as well as the data highlighted in four table cells, are discussed in Section 4.4.

3. Results

3.1. Calculation of Action Levels

According to the general methodology described in Section 2.2, the action levels $C^{(1)}_{AL}(t)$ and $C^{(2)}_{AL}(t)$ for each country were calculated using Equations (7) and (8), taking into account the corresponding RL values. Calculations were performed for the following set of measurement durations (t): 1, 2, 4, 7, 14 days and 1, 2, 3, 4, 6, 8, 10, and 12 months.

The country-specific values of $C^{(1)}_{AL}(t)$ and $C^{(2)}_{AL}(t)$, each dependent on measurement duration, are provided in four MS Excel files in the Supplementary Materials. These files differ only in the specified values of instrumental uncertainty U_D : 0.2 (20%), 0.3 (30%), 0.4 (40%), and 0.5 (50%). Using $U_D < 0.2$ is not advisable due to year-to-year variations in indoor radon. Indeed, accumulated data over many years indicate that year-to-year variations usually do not exceed 15–20% [28], which can serve as a benchmark for the maximum achievable accuracy within the criterion (1) [10].

3.2. Calculation of Percentage of Definite Decisions and Exceeding Reference Level

According to the general methodology described in Section 2.2, generating an array of $N = 30,000$ radon concentration values in MS Excel using the LOGINV function, based on the AM and GSD values from Table 2, made it possible—through the use of the PERCENTRANK function—to calculate, for each country, the following parameters:

- The percentage of definite decisions, taking into account the previously obtained action levels $C^{(1)}_{AL}(t)$ and $C^{(2)}_{AL}(t)$, each dependent on measurement duration;
- The proportion of cases exceeding the RL, which is also presented in Table 2.

The country-specific values of the percentage of definite decisions as a function of measurement duration are provided in the same four MS Excel files in the section “Supplementary Materials”. This section also includes an additional MS Excel file containing a template for generating data arrays and calculating both parameters (a) and (b).

3.3. Mean Percentage of Definite Decision

According to the general methodology described in Section 2.2, the country-specific values of the percentage of definite decisions obtained in the previous paragraph were combined across all countries into separate datasets, differing measurement durations taking into account criteria (1) and (2). Thus, the arithmetic average of each dataset represents the mean percentage of definite decisions for a representative set of 26 countries listed in Table 2.

Figure 1 shows the dependence of the mean percentage of definite decisions on measurement duration, taking into account both criteria (1) and (2) when $U_D = 0.2$. The figure also displays the boundaries of the confidence intervals that cover 90% of the values in each dataset. The lower and upper boundaries correspond to the 5th and 95th percentiles, respectively (see Supplementary Materials).

Figure 2 presents the dependence of the mean percentage of definite decisions within criterion (1) on measurement duration, illustrating the influence of instrumental uncertainty: increasing U_D leads to a slight decrease in the percentage of definite decisions.

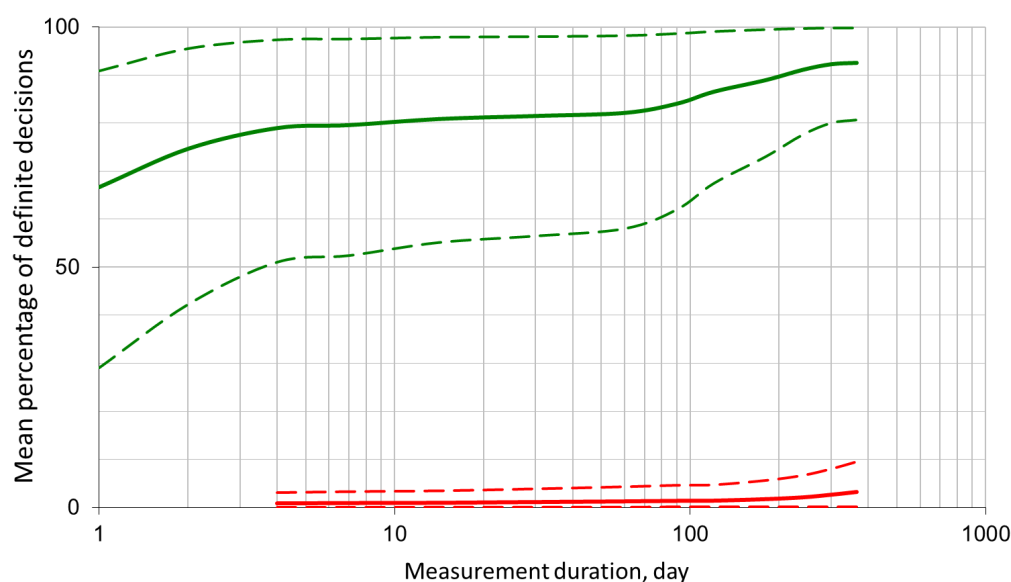


Figure 1. Mean (among 26 countries) percentage of definite decisions with confidence intervals (dashed lines) vs. the duration of measurements, taking into account criteria (1) and (2), which are identified in green and red, respectively.

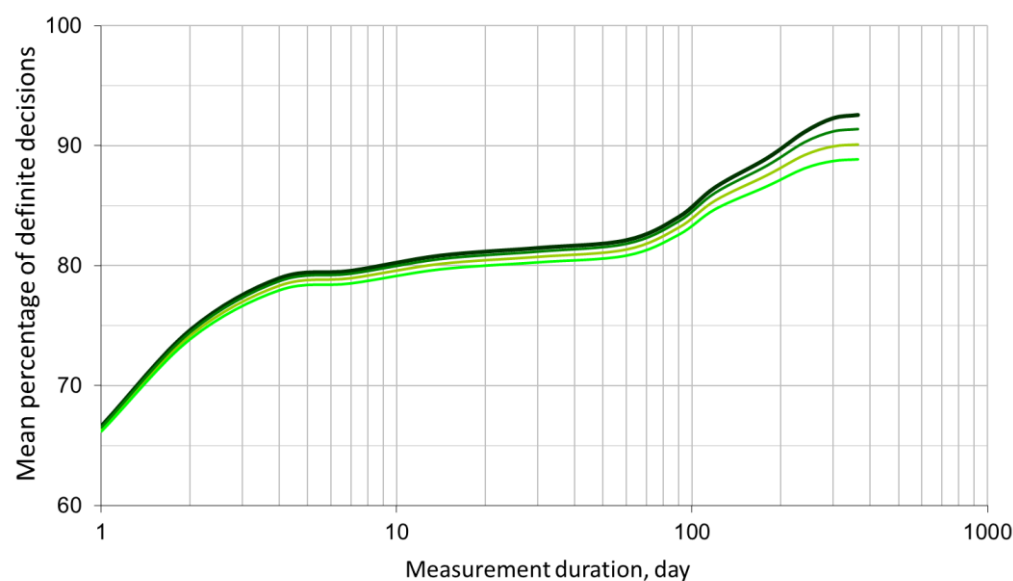


Figure 2. Mean (among 26 countries) percentage of definite decisions within criterion (1) vs. the duration of measurements, taking into account the influence of instrumental uncertainty (20%, 30%, 40%, and 50%), an increase in which leads to a decrease in the percentage of definite decisions (the higher the instrumental uncertainty, the lighter the green line).

4. Discussion

4.1. Excessive Priority on Long-Term Measurements

Figure 1 shows that the mean percentage of definite decisions within criterion (1) differs by only a few percentage points across the measurement duration range from 4 days to 2 months, with an absolute value of approximately 80%. At the global level, this indicates that in roughly 80% of cases, a short-term measurement of 4–6 days (or a long-term measurement of 2–3 months) is sufficient to ensure confidence that no radon problem exists in the tested room.

Even under the most unfavorable combination of RL, AM, and GSD (the lower green dashed line), the percentage of definite decisions increases only modestly—from 51% (4 days) to 58% (2 months), a difference of just 7%. It is also important to note that the maximum achievable mean percentage of definite decisions is about 93% (for year-long measurements), which is not much more than 80% achieved by short-term or typical long-term measurements.

The difference in the mean percentage of definite decisions within criterion (2) is practically negligible across the same 4-day to 2-month interval, with absolute values of around 1%, and a maximum of only 3% for year-long measurements.

Considering the arguments presented in Section 1.3, the cost of indoor radon testing decreases by more than an order of magnitude when the measurement duration is 4–6 days instead of 2–3 months. At the same time, the percentage of definite decisions changes only slightly. Therefore, this combined quantitative analysis of cost and reliability clearly favors short-term measurements.

Taken together, these findings demonstrate the higher efficiency and clear priority of short-term measurements (4–6 days) compared with long-term measurements (2–3 months). This scientifically grounded conclusion directly contradicts the long-standing—and widely accepted—myth, particularly among European and international regulators, that long-term measurements for indoor radon testing should be preferred.

Another (second) widespread myth is the belief that typical long-term measurements lasting 2 or 3 months differ only slightly from the annual average indoor radon level, and

therefore decision-making is considered sufficiently reliable. However, in this case, the temporal uncertainty is 100% or 85%, respectively, according to the data in Table 1.

4.2. Excessive Priority on Instrumental Uncertainty

Figure 2 shows that the mean percentage of definite decisions within criterion (1) decreases by only 1% (or 2%) for measurement durations of 4 days (or 4 months), while instrumental uncertainty increases significantly from 20% to 50%. This reduction becomes only slightly more noticeable (3.7%) for year-long measurements.

Thus, the reliability of indoor radon testing is only weakly dependent on instrumental uncertainty. This scientifically grounded conclusion contradicts another (the third) long-standing global myth about the metrological priority of instrumental uncertainty in indoor radon testing. Meanwhile, the temporal (key) component of decision-making uncertainty is not considered or even discussed in international scientific projects (MetroRADON and RadoNorm), at conferences, or in articles by other authors.

Indeed, the attention of national and international regulators—including metrology institutes and ISO experts—has remained focused exclusively on instrumental uncertainty while neglecting the temporal (key) uncertainty, as repeatedly noted in our earlier publications [8,10,19,22,24,29]. At the same time, our statement above does not imply abandoning the control of instrumental uncertainty. Within QA/QC frameworks, a reasonable (rational) balance must be established between managing temporal and instrumental uncertainties, with a necessary shift in attention (and resources) toward the temporal (key) uncertainty (see Section 4.6).

4.3. Limitations and Representativeness of Temporal Uncertainty

As noted repeatedly above, the defining element of the Rational Method—and of the representativeness of our study—is the experimentally established function of the temporal uncertainty $U_v(t)$, the values of which are presented in Table 1, taking into account the duration of measurements. These values were first published in 2018, based on year-long continuous measurements (YLCM) of radon-gas concentration (and equilibrium equivalent concentration—EEC) at 6 (and 5) locations in Russia [7]. Two years later, the same values were experimentally confirmed and published in 2021, based on YLCM of radon concentrations at 12 locations in Israel [8,22], despite substantial differences in geology, climate, and building architecture. Most recently, these same temporal-uncertainty values were again experimentally confirmed in a 2025 publication [23], in which YLCM data from 55 dwellings in Finland were processed using the algorithms (and limitations) of the Rational Method. The temporal uncertainty was calculated, not for 55 dwellings, but for 30 dwellings, following the selection/exclusion criteria (a), (e), and (f) described in Section 2.3 “Methodological Limitations”.

Thus, the initial data underlying the calculation of the temporal-uncertainty values in Table 1 cover approximately 50 buildings located in Finland, Israel, and Russia. At first glance, these temporal-uncertainty values may appear insufficiently representative of application in other countries. However, it is important to emphasize that the temporal-uncertainty values originally established in 2018 [7] have been confirmed multiple times in countries with markedly different geological, climatic, and architectural conditions. Moreover, the experimental datasets containing deviations of measured radon concentrations from the annual averages (partial temporal deviations in indoor radon) include tens and hundreds of thousands of daily, weekly, and monthly measurements, or more than several million values in total [10,22,23]. At the same time, any alternative data on experimental values of temporal uncertainty are simply absent because the coordinators of the major five-year RadoNorm project declined to conduct corresponding systematic studies across European countries [10], with the exception of Finland alone [23,30]. Under these

circumstances, it is far more reasonable to use the available data than to continue to ignore in national protocols the temporal (key) uncertainty, which is about 100% for a measurement duration of 2 months. Therefore, given the current state of knowledge, the published temporal-uncertainty values (Table 1) can be considered applicable across countries and suitable for use in national regulations, as done in our study, in the absence of more reliable, country-specific data.

As noted in the Introduction, national regulators (including researchers and metrologists) establish different measurement durations without quantifying their relationship to decision-making reliability that cannot be evaluated without accounting for the temporal (key) components of uncertainty. For example, in a recent review—despite its title: “Systematic review of statistical methods for the identification of buildings and areas with high radon levels” [31]—neither quantitative nor even descriptive algorithms for identifying high-radon buildings are presented, and the reliability of indoor radon testing is not discussed at all. Another review article [32] actually shows a lack of measurement unity (harmony) among 30 countries that traditionally use Seasonal Correction Factor (SCF) methods. The representativeness of national SCF values is highly questionable, yet this issue is not addressed by the authors [32]. The reliability of SCF methods for indoor radon testing, as well as the question of measurement duration, is likewise not mentioned in the review [32]. These gaps and inconsistencies were discussed in detail publicly between the author of [23] and the reviewers on the Open Research Europe platform (the full text of the discussion with four reviewers is provided in the Supplementary Materials). In this context, it is important to note that, in addition to numerous other comments, the reviewers strongly criticized the representativeness (universality) of the study output [23], as well as the exclusion criterion (f) mentioned above. However, to date, no one—including the reviewers—has proposed any alternative values or any alternative method for determining the temporal (key) uncertainty of indoor radon.

Unfortunately, instead of adopting the Rational Method for reliable and cost-effective indoor radon testing, the radon community continues to focus on the SCF approach or other less useful statistical methods (including machine learning protocols) that significantly hinder the rational development of radon regulation at both the international and national levels. At the same time, the measurement protocol based on the Rational Method has no alternative, so it is advisable to recommend it to IAEA, ISO, and other international regulatory bodies for use as an international standard for effective and harmonious indoor radon testing in different countries of the world. Indeed, the Rational Method covers any measurement durations traditionally adapted in different countries, while ensuring control of the main components of uncertainty or a specified reliability (95%) of decision-making.

4.4. Reference Level and Other Aspects of Radon Regulation

A well-justified national RL contributes to effective (rational) radon regulation within a country. As noted earlier, the RL limits the annual average radon concentration in buildings and ranges from 100 to 400 Bq/m³, according to Table 2.

Unlike other countries, the United States is represented in Table 2 by three RL values (148, 300, and 400 Bq/m³), although the WHO website [6] lists only one value (148 Bq/m³). The reason is that U.S. regulation uses an action level (AL = 4 pCi/L = 148 Bq/m³) rather than a reference level, adapted in all other countries of the world. According to the methodology in Section 2.2, AL and RL are different parameters [8,10,19,29], linked by Equation (7). However, U.S. standards (clause 7.1 in ANSI/AARST MAH-2023 and MA-MFLB-2023) [18] compare AL and RL directly and mistakenly assume that they are equivalent parameters [29]. Indeed, according to Equation (7), if AL = 148 Bq/m³, then:

- RL $\approx$ 300 Bq/m³ for a measurement duration of about 2 months; or

- $RL \approx 400 \text{ Bq/m}^3$ for a measurement duration of about 2 days.

Thus, U.S. regulation actually applies an RL between 300 and 400 Bq/m^3 , depending on measurement duration—a fact reported more than five years ago [8]. However, neither U.S. nor international regulators (for example, WHO) have addressed this clear terminological inconsistency. Therefore, the actual regulatory requirements in the U.S. have remained relatively soft. In practice, non-exceedance of the annual average concentration is ensured at 400 Bq/m^3 , not at 150 Bq/m^3 , as is mistakenly assumed. This is another example of conservative traditions [10,19,22–25,29] that prevent national regulators from implementing rational (more effective) approaches.

In Table 2, four cells are highlighted where RL values are either too soft (underestimated), as in the Netherlands, United Kingdom, and Argentina, where proportion of cases exceeding RL is only 0.1%, or too strict (overestimated), as in Norway, where the proportion is 27.6%. Among the 26 countries, the mean proportion of cases exceeding RL is about 5%. It may therefore be reasonable to reduce Norway's proportion to 10% (achieved at $RL = 200 \text{ Bq/m}^3$), and to increase the proportions in the Netherlands, United Kingdom, and Argentina to 1.9% ($RL = 50 \text{ Bq/m}^3$), 1.2% ($RL = 100 \text{ Bq/m}^3$), and 0.5% ($RL = 200 \text{ Bq/m}^3$), respectively.

Returning to the issue of representativeness (see the previous section), it is important to note that the reliability of estimating the proportion of cases exceeding RL—as well as collective doses of population exposure due to radon or the delineation of RPAs—remains poorly understood due to the lack of more extensive (representative) statistical data on the basis of which the AM (or GM) and GSD values (Table 2) were determined. Due to the limited statistical data (indoor radon measurements), the main problem in assessing AM and GSD is the reliability of the ratio of the number of radon-exposed occupants between low-rise and high-rise buildings. Especially in high-rise buildings, the floor-averaged radon concentration may differ substantially. The taller the building, the lower the average radon concentration and the lower the collective dose per occupant, because the primary radon source is the soil under the building, while building materials contribute far less per occupant.

These circumstances may explain why regulators in Israel, Belgium, and Germany (see Section 2.4), as well as in other countries with noticeably inconsistent original and recalculated GM values in Table 2, may attempt to present the national radon situation as either more benign or more realistic, given the poorly controlled ratio of occupant radon exposure between low-rise and high-rise buildings. The desire of national regulators to improve the representativeness (reliability) of data on the radon situation in the country without organizing and conducting large-scale measurements based on the Rational Method (with the involvement and at the expense of the population) is not an effective regulatory strategy.

The primary goal of radon regulation is the efficient identification of buildings with excessive radon levels (above RL) across the entire country—not only within RPAs—followed by effective mitigation [10], rather than endlessly clarifying the radon situation in the country, that does nothing to reduce the risk of radon exposure. Large-scale indoor radon testing based on short-term measurements is the best way to clarify the radon situation in a country, as is demonstrated, for example, in the US [8,10,19,25]. It is very important to remind here that the accuracy of estimating AM (or GM) and GSD values based on short-term measurements is only slightly inferior to long-term measurements, because spatial variations are significantly greater than temporal variations in indoor radon [10,25]. This previously grounded conclusion contradicts the fourth globally long-standing myth about the priority of long-term measurements for the assessment of AM (or GM) and GSD.

4.5. Measurement Duration for Reliable Indoor Thoron Testing

As noted in the Introduction, the 2024 UNSCEAR Report increased the global average risk from indoor radon exposure by 38% (from 1.3 to 1.8 mSv/year) [1]. The risk associated with exposure to the decay products (progeny) of Rn-222 (commonly referred to simply as “radon,” as in all previous sections) increased by a factor of 1.2 (from 1.15 to 1.40 mSv/year), whereas the risk associated with exposure to the progeny of Rn-220 (commonly referred to as “thoron”) increased by **a factor of 3.6 (from 0.10 to 0.36 mSv/year)**. This means the need to introduce an RL to limit the exposure risk due to thoron progeny, which will require additional funding for radon regulation.

A previous publication [10] had already raised concerns about the lack of metrological support (measurement standardization) for the passive method used to measure the equilibrium equivalent concentration (EEC) of thoron. This method is based on the deposition of thoron progeny on SSNTDs by diffusion, the rate of which depends on many factors and is not controlled [10,33–36]. Nevertheless, the passive method has become widespread because it enables long-term measurements. In addition, a relatively large number of such thoron EEC measurements in various countries [1,37–40] appear to have influenced UNSCEAR’s decision to substantially increase the estimated risk due to thoron, despite the clear metrological shortcomings of the passive method [10].

At the same time, a reliable (metrologically supported) method exists for measuring thoron EEC, based on the forced deposition of thoron progeny on filter with spectrometry silicon detector or SSNTD [41]. However, this reliable method has not been widely adopted in thoron survey practice, apparently due to the need for a pump and additional electronics that produces noise and consumes electricity [10].

Unfortunately, a scientifically grounded response to the same fundamental question raised in Section 1.2—now applied to indoor thoron testing—is still lacking from both international organizations and national metrology and standardization committees. The fundamental question, with a slight modification, is:

What should be the measurement duration for thoron EEC (not thoron gas) to ensure reliable testing of rooms and entire buildings?

A key difference between indoor radon and thoron testing strategies is that, thanks to many years of systematic research [7,8,22,23], extensive experimental datasets (in the form of YLCM in various buildings and conditions) have been accumulated exclusively for indoor radon. These datasets enabled the evaluation of temporal (key) uncertainty for indoor radon and the development of the Rational Method as a measurement standard that ensures conformity assessment (decision-making) with a specified reliability using both short-term and long-term measurements [10]. Unfortunately, no such systematic studies have ever been conducted to rationalize indoor thoron testing, although the five-year European project RadoNorm [11] was completed recently, following the two-year MetroRADON project [12].

In the case of thoron, national regulators and researchers—also lacking scientific justification from metrological institutes or authoritative international organizations—arbitrarily set the duration of thoron EEC measurements, again favoring long-term measurements simply because they “seem more reliable.” The myth of long-term measurement priority is so deeply entrenched (see Section 4.1) that, instead of adopting the reliable forced-deposition method, preference is given to the unreliable passive method for national-scale thoron EEC measurements solely because of the long-term mode—despite the fact that the need for long-term thoron EEC measurements has never been established.

At the same time, given the proven above priority of short-term measurements for indoor radon testing, high efficiency with controlled reliability of indoor thoron EEC testing will most likely also be achieved through short-term (or even shorter) measurements. Therefore, the next section also includes a discussion of the priorities for thoron studies.

4.6. Priorities for Radon and Thoron Studies and Indoor Testing Technologies

Taking into account previously published field studies and analytical materials [7,8,10,19,22–25,29,42], as well as critical assessments and conclusions presented in the sections above, the established practice of radon regulation on both the global and national levels contains a number of underlying myths, and therefore clearly needs to be rethought and updated within a rational (scientific) strategy. Despite the recently completed major European projects (MetroRADON and RadoNorm), fundamental challenges within radon regulation practices remain [10,42]:

- (1) Effective and reliable mass radon testing within the Rational Method to identify hazardous buildings through involvement of the population;
- (2) Implementation of advanced technologies (as in the US) to protect buildings from soil radon.

Both fundamental problems can be addressed through an objective analysis of the current global situation [10] and the proper formulation of a radon regulation roadmap [42], with a focus on the following priorities for radon and thoron studies and indoor testing technologies:

- (a) Development and implementation of simple and effective (inexpensive, but reliable) IoT tools based on a web platform for large-scale measurements of indoor radon (and other air pollutants), involving motivated (well-informed) citizens and professionals, as well as the organization of radon-mitigation and indoor-air-quality improvement activities with the support of national regulators.

The web platform is an international or national resource with extensive informational, methodological, and technical functionality. It includes sets of instructions, forms (interfaces), modules (algorithms), and databases for organizing and conducting rational indoor radon (and thoron) testing using various measurement devices; visualizing results on web-based maps; making reliable decisions; generating conclusions and recommendations; and providing services for designing and implementing radon-mitigation and indoor-air-quality improvement measures.

- (b) The main priority for radon studies is the implementation of year-long continuous measurements (YLCM) of radon concentration in different buildings (conditions), with registration (integration) periods of 1, 3, or 24 h, taking into account the limitations described in Section 2.3, while simultaneously studying the causes of low radon concentrations observed over extended periods in high average radon rooms. The number of relevant YLCM (meeting all limitations and suitable for combined analysis) should be from 20 to 50 (or more) depending on the size of the country. Conducting such a national study would allow verification (and refinement) of the existing values of temporal (key) uncertainty for indoor radon. Importantly, this does not require substantial research effort or financial resources [10,19]. More detailed information is provided in Tsapalov A et al. [10,19,23,29].
- (c) Another priority for radon studies is investigating the causes of low indoor radon concentrations (approaching outdoor levels) observed over extended periods (weeks, months, or seasons), even in rooms with a high annual average radon concentration that exceeds the reference level. Two primary factors can be identified:
 - High air exchange rate due to a strong influx of outdoor air; and/or
 - A sharp reduction or complete cessation of soil radon transport into the building.

More detailed information is provided in Tsapalov A et al. [10,23].

- (d) A priority for thoron studies is the implementation of YLCM of thoron EEC in different buildings (conditions), where the average thoron EEC is at least 5 Bq/m³ (the

higher, the better). If conducting YLCM is technically difficult, then it is necessary to perform 1–2 (or more) daily spot measurements of thoron EEC for at least one year. This is a labor-intensive procedure; therefore, an initial study may reasonably be limited to 6–10 locations with elevated thoron EEC. Indeed, for example, the first experimental datasets used to estimate temporal uncertainty for indoor radon were obtained from only a small number of monitored rooms [7], yet subsequent studies confirmed those initial results.

The results of such year-long monitoring of thoron EEC at multiple locations will make it possible to evaluate the temporal uncertainty of indoor thoron EEC, which is essential for developing a reliable and cost-effective (rational) method for indoor thoron testing with an optimal (efficient) measurement duration.

In each monitored location (room), it is also advisable to measure the specific activity of Th-232 in the room's wall materials using a portable gamma spectrometer, in order to investigate the expected relationship between Th-232 content and the annual average thoron EEC.

5. Conclusions

The output of our study, based on the original (innovative) methodology within the Rational Method, allowed us to strictly (from a scientific standpoint) substantiate the following key statements:

- (a) Short-term measurements (4–6 days) for both indoor radon testing and assessment of the national (or global) radon situation (via AM, GM and GSD, including delineation RPA) are more effective than long-term measurements (2–3 months).
- (b) Another deeply rooted misconception in the radon community is that typical long-term measurements lasting 2 or 3 months differ only slightly from the annual average indoor radon level, and therefore decision-making is considered sufficiently reliable. However, the temporal uncertainty in this case is 100% or 85%, respectively.
- (c) The overall reliability of indoor radon testing depends only slightly on instrumental uncertainty; therefore, within QA/QC, a reasonable (rational) balance must be established between managing temporal and instrumental uncertainties, with a necessary shift in attention (and resources) toward the temporal (key) uncertainty.
- (d) The Rational Method, which includes the available values of temporal (key) uncertainty, is the most reliable and cost-effective measurement protocol for indoor radon testing compared to the traditional protocol based on the SCF approach, as well as other relatively new statistical methods, including machine learning protocols. Thus, the measurement protocol based on the Rational Method has no alternative, so it is advisable to recommend it to IAEA, ISO, and other international regulatory bodies for use as an international standard for effective and harmonious indoor radon testing in different countries of the world. Indeed, the Rational Method covers any measurement durations traditionally adapted in different countries, while ensuring control of the main components of uncertainty or a specified reliability (95%) of decision-making.
- (e) The measurement duration for effective and reliable indoor thoron testing has not yet been established or even studied, despite the beginning of large-scale national thoron EEC measurements based on the passive method, which does not have metrological support.

The key conclusions are as follows:

- (f) The established practice of radon regulation on both global and national levels contains a number of underlying myths, and therefore clearly needs to be rethought and updated within a rational (scientific) strategy.

- (g) It is vital to conduct experimental (field) studies to verify (clarify) national values of the temporal (key) uncertainty of indoor radon (and thoron EEC), instead of endlessly clarifying the national radon situation.
- (h) There is a vital need to develop simple and effective (inexpensive but reliable) IoT-based tools for: (i) large-scale measurements of indoor radon (and other air pollutants) involving motivated (well-informed) citizens and professionals, and (ii) organization of radon-mitigation and indoor-air-quality improvement activities with the support of national regulators.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17070706/s1>. Data used for the analysis can be found in the MS Excel files: i) the algorithms and calculation results, according to Section 3.1, are given in four files with similar names, ii) the calculation algorithm, as a template for generating data arrays, according to Section 3.2, is given in a separate file. Additionally, a DOCX file titled “Open Research Europe _Discussion with reviewers” is included.

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