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RESEARCH ARTICLE

REVISED Temporal uncertainty in rational method: Reassessment of data from the article "Short-term temporal variability of radon in Finnish dwellings and the use of temporal correction factors"

[version 4; peer review: 4 approved with reservations]

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Abstract

Background

This in-depth study is based on the materials presented in the article referenced in the title. The study in Finnish dwellings provides valuable initial experimental data in the form of year-long continuous measurements of radon concentrations across a large number of buildings. However, the data analysis relied on a traditional (outdated and inefficient) approach focusing on the Temporal Correction Factor that raises significant questions regarding the robustness of conclusions and the strength of the underlying assumptions.

Methods

A reassessment of the initial experimental data was performed based on previously published rigorous mathematical algorithms of the Rational Method within the fundamental metrology concepts such as "measurement uncertainty" and "conformity assessment". The uniqueness of this method lies in the fact that it takes into account both temporal (key) and instrumental uncertainties in the conformity assessment of a room (or the entire building) to safety requirements.

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Results

(1) Refinement of limitations for the Rational Method, including guidelines for statistical data collection to enhance the representativeness of indoor radon temporal uncertainty estimates. This is particularly relevant given the issue of relatively low radon concentrations over weeks and months, even in buildings with high annual averages. (2) Clarification of temporal uncertainty values based on the initial experimental data, supporting the justification of previously published uncertainty estimates as potentially universal across countries in the absence of reliable country-specific data. (3) Critical evaluation of the traditional research design and approach to indoor radon testing in Finland, including the statement that short-term radon measurements are not yet recommended.

Conclusions

The results of our previous and current studies demonstrate that short-term radon measurements form the foundation of Rational Method for indoor radon testing, which, for the first time, has full metrological support because it takes into account the main components of uncertainty in decision-making.

Plain Language Summary

Radon is the most significant factor in radiation risk, the contribution of which exceeds the total impact of all other sources of natural and man-made radiation that can be regulated. This intangible carcinogenic gas causes cancer, so regulatory authorities limit the annual average concentration of indoor radon. High radon content, exceeding the reference level, is often found in areas with low average indoor radon levels. Therefore, radon testing should be conducted in every building, and measurement is the only way for a conformity assessment of a room/building with national safety requirement. However, despite the recently completed major European project "RadoNorm", fundamental problems remain: 1) effective and reliable mass testing to identify hazardous buildings through involvement of the population, 2) implementation of advanced technologies to protect buildings from soil radon. This paper contributes to the improvement of the previously published Rational Method, that ensures efficient and reliable indoor radon testing by adapting the basic principles of metrology with verification of the temporal (key) component of uncertainty in decision making, as well as clarifying the testing conditions. This improvement is based on the use of data provided by experts from Finland. A comparative analysis of approaches to processing these data confirms that the traditional European approach to radon regulation is outdated and ineffective. Indeed, unlike Europe, in the US alone tens of millions of indoor radon tests have been conducted and millions of buildings have installed reliable (active) protection against soil radon, that effectively reduces

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radiation risk. Incidentally, the US EPA estimates the annual turnover of the national IAQ industry, funded primarily by householders, to be $18-30 billion, including the turnover of the radon industry, estimated by the author to be $1-3 billion. It seems that the established practice of radon regulation in Europe clearly needs to be rethought and updated.

Keywords
building; IAQ; radiation safety; indoor radon; temporal variability; correction factors; quality assurance; metrology; standardization; measurement uncertainty; temporal uncertainty; conformity assessment; decision-making; Rational Method; IAEA; ISO



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REVISED **Amendments from Version 3**

Although the third reviewer's comments were helpful in continuing the open discussion about the importance of implementing the Rational Method in international radon regulation, the author rejected all of the comments with detailed justification. At the same time, the author found it useful to slightly clarify the wording of the second sentence in the first paragraph of Section 1.1. Additionally, text has been added to "Plain language summary".

Any further responses from the reviewers can be found at the end of the article

1. Introduction

1.1. Problematic aspects of indoor radon testing

Recently, experts from the Radiation and Nuclear Safety Authority (STUK, Finland), published an important article titled "Short-Term Temporal Variability of Radon in Finnish Dwellings and the Use of Temporal Correction Factors".[1] Article 1 addresses a highly relevant issue: the potential for standardizing short-term radon measurements for the purpose of conformity assessment of rooms (buildings) with radiation safety requirements. The urgency of this topic is underscored by the conflict between residents' preference for short (rapid) testing[1] and STUK's requirement to conduct only long-term measurements lasting at least two months,[2,3] in accordance with ISO 11665-8:2019 recommendations.[4] Additionally, STUK mandates that indoor radon testing be carried out only between September 1 and May 31,[2] and that such testing "must comply with the quality criteria specified in national regulatory guidelines".[1]

In this context, it is important to note that short-term measurements (typically lasting from 2 to 7 days) have been used in U.S. regulations—demonstrating high effectiveness—for over 30 years.[5,6] However, the applicability of short-term measurements remains a topic of discussion in Europe and other parts of the world. Over the decades, numerous thematic studies have been conducted at both national and international levels, including within major scientific projects such as *MetroRADON*[7] and *RadoNorm.*[8]

In recent years, however, there has been a noticeable shift away from field studies on the temporal variability of indoor radon— which could have been conducted within a long-proposed rational approach[6,9] —toward the publication of numerous reviews on radon strategies adopted in various countries, including methods for indoor radon testing,[10–18] none of which are supported by adequate metrological foundations.[9] Moreover, the *RadoNorm* project places considerable hope in a questionable hypothesis: the possibility of identifying hazardous buildings (i.e., those exceeding the reference level) without conducting indoor radon measurements.[19,20] It remains unclear what value such reviews and hundreds of related studies offer if they fail to generate the data necessary for harmonization and international standardization of measurements aimed at improving the effectiveness and reliability of indoor radon testing within the framework of modern metrology.

Despite the significant time and financial investments made over the years, there is still no internationally agreed-upon standard with metrological support for the reliable conformity assessment of rooms and buildings with radiation safety requirements.[6,9] The international standard for indoor radon testing, ISO 11665-8:2012[21] —introduced over a decade ago as an application rather than a basic standard in the ISO 11665 series[6] —lacks adequate metrological support.[6,9,22] Its updated version, ISO 11665-8:2019,[4] also fails to address this issue, as it still does not account for the temporal (key) component of uncertainty in decision-making for conformity assessment.[6,9,22] Even with measurement durations of two or three months, temporal uncertainty remains very high—around 100% and 85%, respectively.[6,9] Unfortunately, many national regulators and ISO experts continue to disregard this fact, maintaining a narrow focus on instrumental uncertainty, which rarely exceeds 30%.[6,9,23] Moreover, due to the deeply rooted conservatism within the radon community,[22] there is still no internationally harmonized strategy for rational radon regulation.[6,24]

1.2. Rational approach to studying and measuring indoor radon

Given the current gaps in international radon regulation[6] and the fragmented state of national research efforts, only the study under discussion[1] stands out for its practical utility. This Finnish study, for example, like the Austrian study,[25] are based on results of long-term continuous measurements of radon concentrations in various buildings.

Unfortunately, in study,[25] the maximum measurement duration did not exceed six months, which significantly undermines the reliability of its findings. This is because the temporal uncertainty of indoor radon—unaccounted for in that study—remains high, at approximately 40% even with semi-annual measurements.[6,9] Since the reference level is defined as the **annual average radon concentration**, only measurements lasting a full year should be considered baseline (benchmark) values when the temporal variability of indoor radon is the focus of the research. This requirement

is fundamental for such studies and is readily achievable thanks to the wide availability of reliable and affordable continuous radon monitors.[23]

In this regard, the study discussed in[1]—particularly its experimental data—is especially valuable. The STUK researchers made their field (initial) results publicly available in the "Supplementary Materials" section,[1] including time series data from continuous year-long indoor radon measurements with a 24-hour integration interval. Nearly complete year-long measurements were conducted in 55 dwellings, providing strong statistical power and representativeness of the dataset.

However, both of the aforementioned studies[1,25] continue to rely on the traditional use of "correction factors", which is outdated and ineffective. Indeed, many researchers and regulators believe that applying correction factors improves the accuracy of estimating the annual average radon concentration (AARC) when the measurement duration is less than one year. Yet, it seems increasingly clear that striving for high-accuracy AARC estimates in every tested room is not a rational approach because indoor radon levels in the vast majority of buildings are relatively low, around 30 Bq/m^3,[26] which is significantly below the reference levels with a range typically from 100 to 300 Bq/m³ (the reference level is higher in radon priority areas). Therefore, it is rational to accept high AARC uncertainty (at the level of 100% and even more) during initial (first) testing in short-term mode, but this uncertainty must be known and taken into account when making decision.[6,9]

Within the framework of fundamental ISO/IEC concepts **—**such as **measurement uncertainty**[27] and **conformity assessment**[28] **—**and particularly under the rational approach,[6,9] the principle of conformity assessment (for effective identification of radon hazardous buildings requiring remediation) lies in comparing the reference level with the upper bound of the confidence interval of the estimated AARC. This interval is derived from the measured radon concentration, taking into account the main components of AARC uncertainty—temporal and instrumental—which decrease as the measurement duration increases. Corresponding to this principle, a strategy for rational indoor testing is very briefly but accurately outlined in[6]:

- *"In the vast majority of cases, due to the low level of indoor radon, it is sufficient to conduct inexpensive short-term tests (from 2 to 7 days) within the framework of the rational criterion to ensure the absence of a radon problem. In another, relatively small proportion of cases, additional more accurate and costly long-term tests (from 2 to 12 months) will be required after (or in continuation of) short-term measurements due to the high temporal uncertainty of short tests and the elevated radon levels in some buildings, which will ultimately be reliably identified".*

Thus, from the perspective of modern metrology and rational methodology, it is more effective and straightforward to operate directly with the **temporal uncertainty** of AARC (of indoor radon), rather than relying on correction factors or other traditional concepts such as "false negatives" or "false positives".[1] Temporal uncertainty has a clear definition within the ISO/IEC concepts and is directly incorporated into the conformity assessment criterion (see Section 2.1) within a measurement protocol.[6,9] This rational approach enables the most effective implementation of the primary goal of indoor radon testing — "to assess the need for radon remediation in buildings",[1] while "estimate residents' exposure or assess public exposure"[1] should be considered as a secondary (optional) goal. The issue of priority in the design of indoor radon surveys (testing) is discussed in more detail in the final paragraph 3.4.3(a), as well as in previously published articles.[6,9,24]

It is also important to recognize that the effectiveness of correction factors—or of accounting for various influencing factors such as climate, geology, or architectural style—should likewise be evaluated through the lens of temporal uncertainty. If temporal uncertainty cannot be meaningfully reduced (e.g., by more than 10%), then the use of correction factors or consideration of such influencing variables provides no practical benefit.

Unfortunately, neither the effectiveness of temporal correction factors[1] nor the influence of external factors[25] has been evaluated using a rational, uncertainty-based concepts. Nevertheless, the study[25] is classified as a "novel approach",[1] while the rational approach is neither discussed nor even mentioned in the introductions of either paper.[1,25]

1.3. Excessive focus on seasonal correction factor

In the Finnish study under discussion,[1] the concept of the *Temporal Correction Factor* differs only slightly from that of a *Seasonal Correction Factor*, as evidenced by numerous references cited within the study itself. In this context, it seems important to quote an entire paragraph from[6]:

- *"Regarding the pattern of seasonal variations in indoor radon, it is important to clarify the following sensitive point. An analysis of the accumulating global results of annual and seasonal indoor radon measurements shows that higher radon levels are more likely (with an undetermined probability) to occur in the cold period… However, seasonal variations often follow the opposite trend (higher radon levels in the warm period) or are not expressed at all… This indicates the absence of a strict pattern of temperature (or seasonal) influence that could be universally applied to any rooms and buildings. Therefore, a separate consideration of the seasonal factor does not contribute to improving the quality of conformity assessment of rooms (buildings) to safety requirements. The consideration of the seasonal factor may be useful in refining collective risks but not individual risks within the conformity assessment of rooms/buildings. In this regard, the traditionally increased attention in the IAEA Safety Guides… related to the Seasonal Correction Factor seems not entirely justified, especially when assessing conformity".*

Indeed, the correction factor used in Finland—set at 0.9[2] —introduces only a 10% seasonal adjustment, which indicates that seasonal variation has a relatively minor impact on the results of indoor radon testing. In this context, the prohibition on conducting measurements from June through September (a full three-month period) appears excessively strict and not entirely justified.

These circumstances also indicate that the traditional approach to indoor radon measurements using the *Temporal (or Seasonal) Correction Factor* is outdated and ineffective.

1.4. Objectives of the study

We might also classify the study[25] as a "novel approach",[1] were it not for the fact that the rational concepts of ISO/IEC[27,28] —supported by the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995 with minor corrections)[29] —have already been globally adopted in the field of measurement standardization.

In contrast, we have been advocating for the application of the JCGM 100:2008 rational approach in the context of indoor radon testing for many years.[6,9] Nevertheless, the rational approach is only mentioned at the very end of the article,[1] where it is subjected to a critique that appears to be based on a misinterpretation of methodological assumptions:

- *"The novelty of this study lies in the probabilistic method applied, which allowed for the estimation of the proportion of false negatives in the results, as well as the determination of action levels for different measurement durations using the actual temporal distribution of the results, rather than, for example, an assumed log-normal distribution. In the method presented by Tsapalov and Kovler…, the action level is set based on log-normally distributed temporal variation in such a way that the reference level is not exceeded in 95% of the measurement locations".*

This remark in[1] regarding the limitation of our rational method due to the assumed log-normal distribution appears both puzzling and unsubstantiated. None of our publications[5,6,9,22,23] —including article,[30] which is cited in[1] —suggest that our rational method is constrained by such an assumption. On the contrary, a detailed set of limitations associated with the rational method is clearly outlined, for example, in the "Test Conditions" section of,[6] as well as in the context of collecting statistical data to ensure the representativeness of temporal uncertainty values.[9]

Given the above, the use of the extensive statistical dataset provided by independent experts from STUK in the Supplementary Materials of[1] enables to implement the following objectives (novelty) within the previously published rational approach[6,9]:

1. **Analyze and process the initial data** presented in the Finnish study[1] using mathematical algorithms based on the Rational Method.[6]

2. **Refine the limitations of the Rational Method**, including the rules for collecting statistical data to improve the representativeness of temporal uncertainty estimates.

3. **Verify the values of temporal uncertainty based on data from independent experts**, including checking the hypothesis that:

    - *"Certain characteristics unique to Finland suggest that temporal variations in radon concentration, as quantified in other parts of the world, may not necessarily apply to Finnish conditions".*[1]

4. **Critically examine the traditional research design**[1] and approach to indoor radon testing in Finland, including the controversial conclusion that:

   - *"short-term radon measurements cannot yet be recommended as a replacement for current methods."*

2. Methods and materials

2.1. Rational method for indoor radon measurements

The rational approach enables the integrated consideration of all anthropogenic and natural factors—including seasonal variations—that influence temporal uncertainty. As a result, it eliminates the need for traditional analyses that examine the effect of each factor individually on the temporal behavior of indoor radon.[6,9] This allows buildings to be tested at any convenient time without accounting for seasonal effects, as this does not compromise the reliability of the conformity assessment. Moreover, temporal uncertainty values can be stratified not only by measurement duration but also by the operational mode of the room (e.g., normal or closed conditions).[6,9]

The **Rational Method for indoor radon measurements** —including its principles and limitations —is presented in[6] as a measurement protocol that, for the first time, has full metrological support due to accounting both temporal (key) and instrumental uncertainties of AARC (or indoor radon). In this context, it is useful to recall the **rational conformity assessment criterion**, which covers any methods, devices, and samplers intended for radon concentration measurements, in both short- and long-term modes.

The rational criterion for conformity assessment ensures a **decision reliability of at least 95%**, meaning no more than a 5% false-negative error in determining whether a room complies with safety requirements, provided the following condition is met[6,9]:

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

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

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

$U_V(t)$ is the temporal uncertainty in relative units (with a coverage factor of $k = 2$), the values of which depend on the measurement duration and operation/ventilation mode (see Section 2.2),

U_D is the instrumental (device) uncertainty in relative units ($k = 2$), the algorithm for its determination is provided in ANNEX B.[6]

An additional criterion for identifying hazardous rooms ensures a decision reliability of at least 95% regarding the non-compliance with a safety requirement, provided the following condition is met[6]:

$$\frac{C(t)}{MF(t)}\cdot(1-U_D)>C_{RL}, \tag{2}$$

where $MF(t)$ is the multiplicity factor expressed in relative units; its depend solely on the measurement duration under normal-mode conditions (see Section 2.2).

2.2. Algorithms for determining temporal uncertainty and the multiplicity factor

Temporal uncertainty is a key component of the combined uncertainty in conformity assessment. It is defined as the 95th percentile (i.e., the value or 95% probability) in the distribution of all deviations $D_{ij}(t)$ between the measured concentrations $C_{ij}(t)$ and the measured annual average (AA) concentration C_j^{AA}, where $D_{ij}(t)$ is calculated as:

$$D_{ij}(t)=\frac{C_j^{AA}}{C_{ij}(t)}-1 \text{ for } i=1,\ldots,M; j=1,\ldots,N \tag{3}$$

Here, N is the number of buildings (rooms) in a representative sample from an international or national case study, and M is the number of registration (or integration) periods of measurements in the j-th room for one year.

Year-long continuous measurement (YLCM) of radon concentration conducted in each of the N buildings, with a registration period of 1 or 3 hours (corresponding to $M = 8760$ or $M = 2920$, respectively), provide robust statistics for the deviations $D_{ij}(t)$ for any measurement duration t.[6,9] It is worth noting that the initial registration (or integration) period can be extended to 1 or 2 days ($M = 365$ or $M = 182$, respectively), since the minimum measurement duration is 2 days, as specified in criterion (1). Any reduction in statistical power due to a longer integration period (i.e., smaller M) can be compensated by increasing the number of buildings N included in the study.

According to the original algorithm,[9,30] an initial YLCM can be transformed into multiple new YLCM datasets with the same number of M, but with any measurement duration t greater than the original registration period. This approach enables the generation of, for example, 10–30 additional YLCM datasets from a single initial YLCM (for the same monitored room), each corresponding to a different registration period or measurement duration t. Collectively, these datasets can span the entire target range—from 2 days up to 11 months.

The **multiplicity factor** is used within the additional criterion for identifying hazardous rooms. However, this additional criterion (2)—as well as the multiplicity factor values themselves—does not play as critical a role in conformity assessment as the primary criterion (1), since the likelihood of satisfying condition (2) is relatively low. This is due to the fact that extremely high indoor radon levels are relatively rare.

The multiplicity factor is defined as the 95 th percentile (i.e., 95% probability) in the distribution of all ratios $R_{ij}(t)$ between the measured concentrations $C_{ij}(t)$ and the measured annual average (AA) concentration, where $R_{ij}(t)$ is calculated as:

$$R_{ij}(t) = \frac{C_{ij}(t)}{C_j^{AA}} \text{ for } i = 1, \ldots, M; j = 1, \ldots, N \tag{4}$$

The arrays of values $C_{ij}(t)$ and C_j^{AA} used in this calculation are the same as those employed in determining temporal uncertainty.[6,23]

It is important to clarify that the deviations $D_{ij}(t)$ and ratios $R_{ij}(t)$ typically do not follow a normal distribution. Therefore, a more reliable estimate is obtained by determining the 95th percentile of the processed data arrays, rather than calculating twice the standard deviation. Notably, the algorithm described above for determining **temporal uncertainty** characterizes it as a **Type A uncertainty** within the framework of the **"measurement uncertainty"** concept.[27,29]

The values of **temporal uncertainty** and the **multiplicity factor** are provided in.[6] It is worth emphasizing that although temporal uncertainty has been refined over many years, the same values (for both normal and closed modes) have been consistently reported in earlier publications.[5,9,22,23,30,31]

2.3. Limitations of the Rational Method

The limitations of the Rational Method are described in detail—point by point—in Section 4.5, *"Test Conditions"* of.[6] In addition, several limitations for year-long continuous measurement (YLCM) have been established to ensure the representativeness of temporal uncertainty values for indoor radon,[9] including:

(a) In each building, only one monitored room should be selected, and it must exhibit an elevated radon activity 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 hours 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.

As part of our in-depth study, it is necessary—beyond the limitations already outlined—to also focus on the issue of **low indoor radon concentrations** (approaching outdoor levels) observed over extended periods of time, either continuously or cumulatively throughout the year. Such occurrences can sometimes be found even in rooms with a high annual average radon concentration that exceeds the reference level. In these cases, the results of short-term or long-term measurements—if conducted during intervals that coincide with these prolonged low-radon periods—may lead to misinterpretation in the conformity assessment of a room or building with respect to safety requirements.

In this context, it is necessary to clarify the limitations of the Rational Method, including additional constraints beyond those previously listed, to ensure a more rigorous selection of initial YLCM suitable for evaluating temporal uncertainty, in accordance with the algorithm described in Section 2.2.

These additional limitations for selection of YLCM can be formulated as follows:

(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 also unsuitable for evaluating temporal uncertainty if the daily average ratios $C^{AA}/C_i(t{=}24\ h)$ exceed a threshold value X_R for more than X_D days cumulatively over the year.

Thus, the specific objectives of this study include:

- Determining the values X_D and X_R as part of the selection algorithm in 2.3(f), and
- Evaluating temporal uncertainty based on **relevant YLCMs** obtained in the Finnish dwellings study.[1]

It is particularly valuable to compare the new results of determining temporal uncertainty —derived from initial data collected by other researchers (from STUK)—with previously published findings.[5,6,9,22,23,30,31]

2.4. Materials based on original STUK data

The experimental data from the Finnish dwellings study,[1] kindly provided by our colleagues at STUK as *Supplementary Materials*, include 55 year-long continuous measurements (YLCM) with a registration interval of one day. These datasets serve as the initial data for our computational analysis.

For brevity, the full or partial set of these data will hereafter be referred to as “STUK data.”

3. Results and discussion

3.1. Key results and analysis

At the outset, the STUK data were filtered according to criteria 2.3(a) and 2.3(e). The identifiers of the 38 YLCMs that met these two criteria are listed in Table 1. This step is essential for ensuring clear traceability and identification of the original STUK data used in our in-depth study.

A large set of intermediate results from our analysis has also been compiled as Supplementary Materials, which can be retrieved from the archive in the "Data availability" section. The files in this archive contain the conversion algorithms and the results of processing the original STUK data, along with corresponding graphs and figures. All files are in Microsoft Excel format, and their filenames are linked to the dataset identifiers listed in Table 1.

The analysis of the selected YLCM using the algorithm described in Section 2.2 revealed that the partial values of temporal uncertainty (without using index *j*) for each of the eight YLCM (with codes J, O, V, AA, AL, AP, BA, and BD, highlighted in Table 1) differ significantly not only from previously published data,[5,6,9,22,23,30,31] but also from the results obtained for the remaining thirty YLCM. Figure 1 and Figure 2 illustrate examples of the difference in partial temporal uncertainty values (highlighted in red and yellow) for measurement durations of $t = 2$ days and $t = 2$ months, respectively. The largest discrepancies across the entire range of t values are observed for YLCMs with codes AA, AL, BA, and BD, which are marked in red in Figure 1 and Figure 2.

A visual analysis of the time series for the eight YLCMs (coded J, O, V, AA, AL, AP, BA, and BD) shown in Figure 3 reveals the presence of extended periods with relatively low radon concentrations. The duration of these periods can exceed 2–3 months (codes O and BA), 4 months (codes AA and BD), and even 6–8 months (code AL). These prolonged

Table 1. Designations and characteristics of selected YLCM.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Code	B	C	D	E	F	I	J	K	L	M	N	O	Q	R	S	U	V	W	X
AARC	148	82	96	88	285	211	314	97	75	269	202	66	108	141	154	401	74	126	106
Inclusion	+	+	+	+	+	+	-	+	+	+	+	-	+	+	+	+	-	+	+
No.	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**
Code	Z	AA	AC	AD	AE	AG	AH	AL	AO	AP	AR	AT	AU	AW	AY	BA	BB	BC	BD
AARC	135	298	254	102	61	62	103	131	86	160	52	70	203	109	59	100	98	195	234
Inclusion	+	-	+	+	+	+	+	-	+	-	+	+	+	+	+	-	+	+	-

Note: **No.** – Identifier of the file in our archive containing the YLCM processing results. **Code** – Column number corresponding to the original YLCM data in the Excel file from STUK.[1] **AARC** – Annual Average Radon Concentration, expressed in Bq/m³. **Inclusion** – Indicates whether the YLCM data is included (+) or not included (–) in the dataset used to determine the temporal uncertainty, $U_y(t)$.

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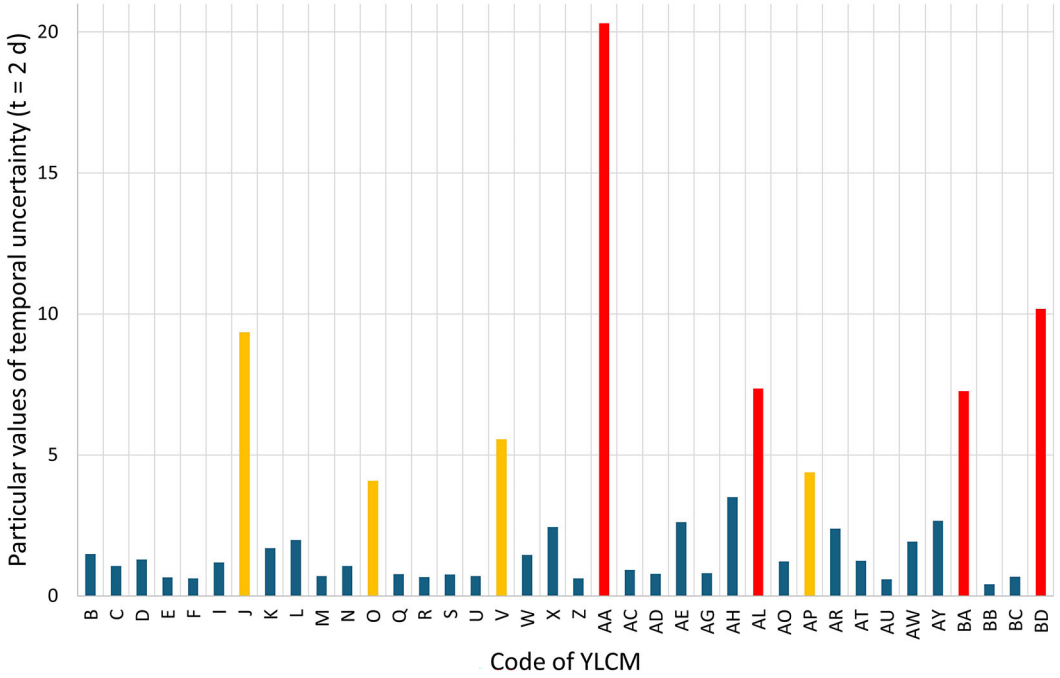

Figure 1. **Partial values of temporal uncertainty for each of the 38 YLCMs, based on STUK data, for a measurement duration of 2 days.**

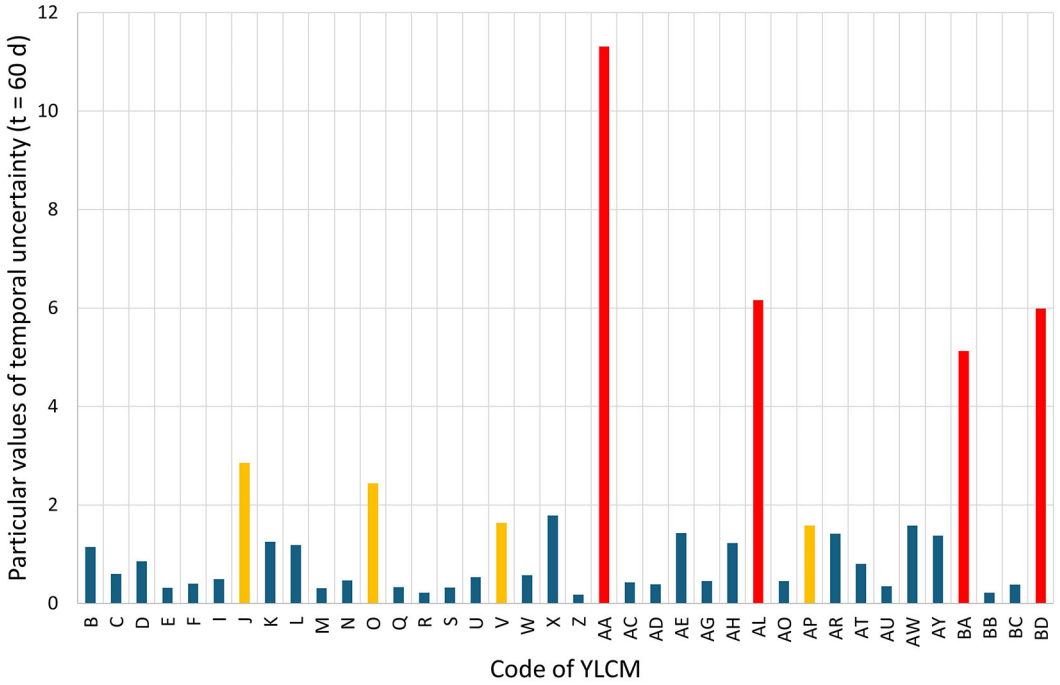

Figure 2. **Partial values of temporal uncertainty for each of the 38 YLCMs, based on STUK data, for a measurement duration of 2 months.**

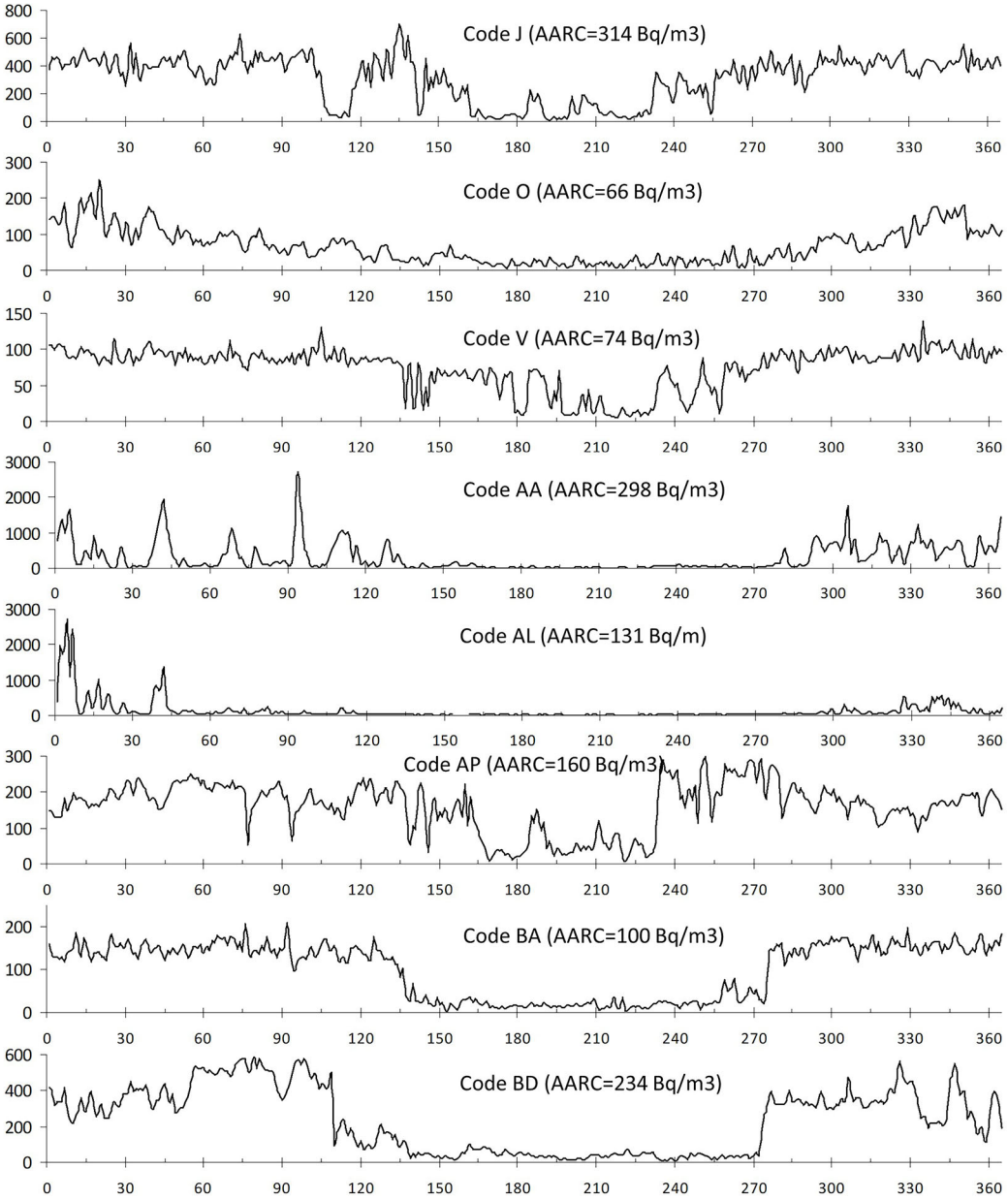

Figure 3. Examples of YLCM (coded J, O, V, AA, AL, AP, BA and BD) characterized by long-time intervals with low indoor radon concentrations in Bq/m ^{3}; the time axis (days) starts from January 1.[1]

low-radon periods contribute to the increased difference between the partial values of temporal uncertainty and previously published data. Notably, such extended intervals of low radon concentration create a conformity assessment problem not only in short-term but also in long-term measurements.

In this context, an effective solution is to exclude the data from at least four YLCMs (codes AA, AL, BA, and BD) from the overall set of deviations $D_{ij}(t)$. Figure 4 presents the generalized temporal uncertainty, calculated from the remaining 34 YLCMs within the STUK dataset, which shows satisfactory agreement with previously published data.[5,6,9,22,23,30,31]

As shown in Figure 5, further improvement in convergence across the measurement duration range of 4 to 120 days is achieved by excluding eight YLCM (coded J, O, V, AA, AL, AP, BA, and BD) from the overall set of deviations. Figure 5 also includes an estimate of $U_V(t)$ derived from the conversion of data[22,30] from earlier Finnish study by Arvela *et al.* (2015), originally reported in.[32]

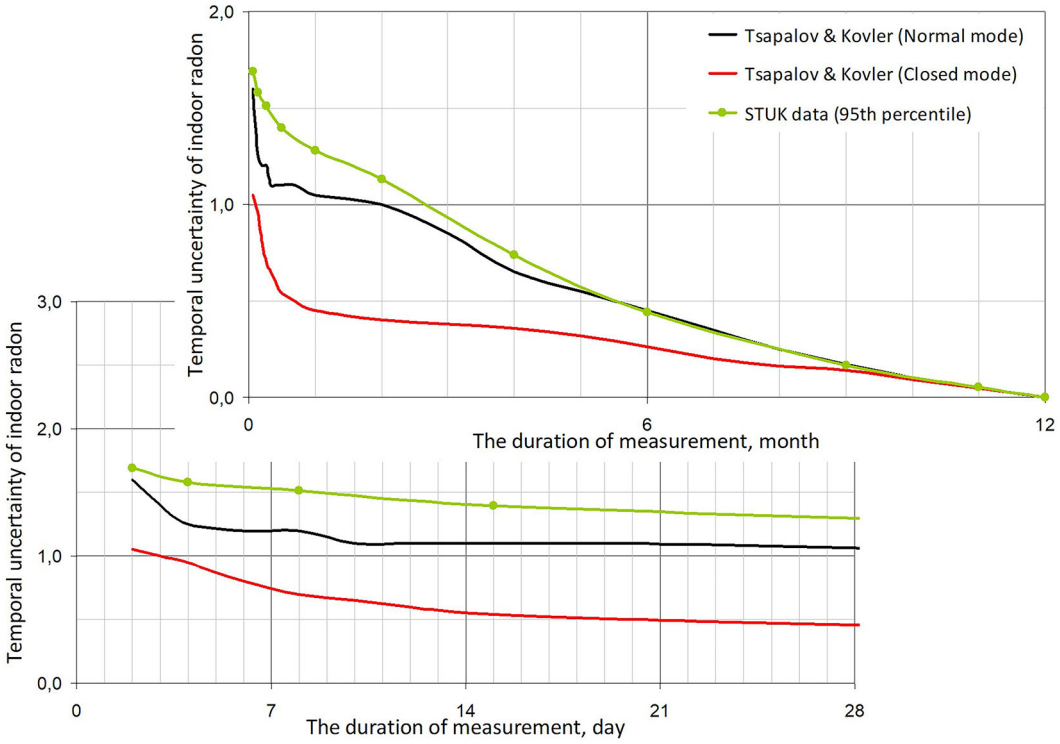

Figure 4. Comparison of the temporal uncertainty obtained from STUK data (excluding 4 YLCM coded AA, AL, BA and BD) with previously published data.[5,6,9,22,23,30,31]

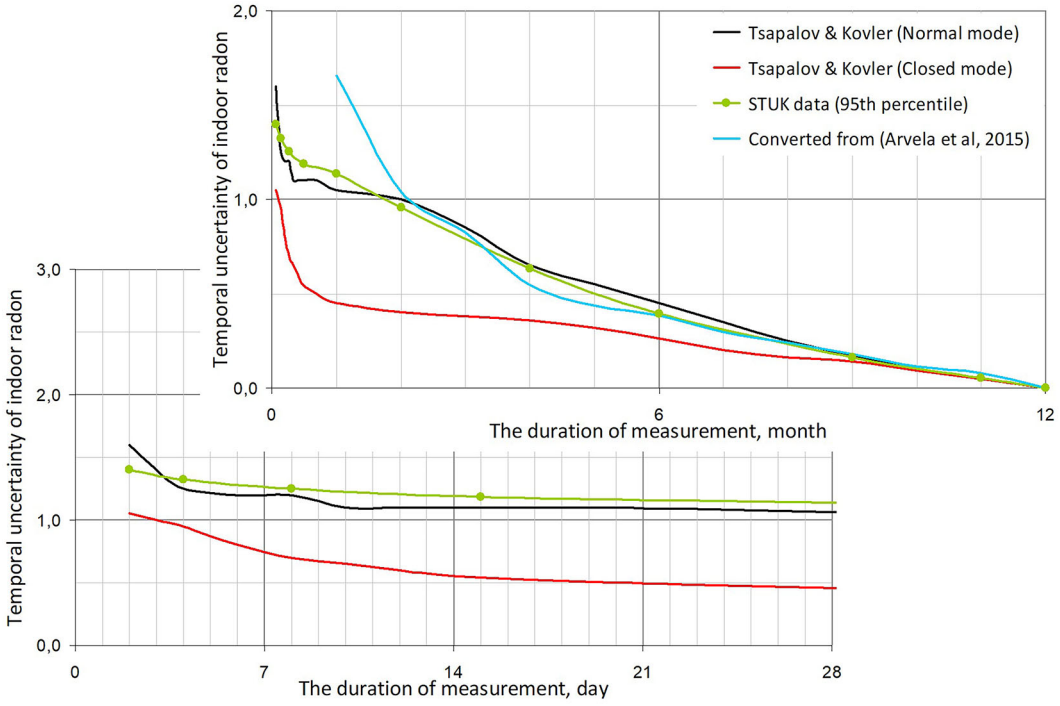

Figure 5. Comparison of the temporal uncertainty obtained from STUK data (excluding 8 YLCM coded J, O, V, AA, AL, AP, BA and BD) with previously published data.[5,6,9,22,23,30,31]

The data presented in Figure 5 demonstrate good agreement between the temporal uncertainty values obtained from the STUK data and those previously published in.[5,6,9,22,23,30,31] This means that the behaviour of indoor radon in Finland is not unique, given that previous studies were conducted under significantly different climatic and geological conditions at Israeli[5] and Russian[30,31] experimental sites. This finding challenges the hypothesis that "certain characteristics unique to Finland suggest that temporal variations in radon concentration, as quantified in other parts of the world, may not necessarily apply to Finnish conditions".[1] Consequently, this strengthens the confidence that previously published values of temporal uncertainty (for example, in[6]) are applicable across different countries and can be used in national regulations in the absence of more reliable country-specific data.

3.2. Additional limitation for determining temporal uncertainty

The exclusion algorithm described above for identifying unsuitable YLCMs from the overall set of deviations $D_{ij}(t)$ is labor-intensive and, moreover, relies on qualitative (subjective) analysis. However, a more straightforward quantitative exclusion criterion was already introduced in Section 2.3(f), formulated as a condition involving two numerical parameters, X_R and X_D, which must be determined.

A mathematical procedure for identifying appropriate values of X_R and X_D, is provided in one of the Excel files included in the archive from the "Data availability" section. The core idea of this algorithm is to select a value of X_R such that the total number of days X_D for each of the eight excluded YLCMs (codes J, O, V, AA, AL, AP, BA, and BD), according to the proposed criterion, exceeds the corresponding X_D value for any of the remaining 30 YLCMs. Based on this approach, it was established that X_D =15 days when X_R =6.

If only four YLCMs (codes AA, AL, BA, and BD) are excluded from the analysis, then X_D =50 days when X_R =6. Nevertheless, considering the strong agreement between the newly derived temporal uncertainty values (based on STUK data) and previously published results—particularly in light of the earlier Finnish survey,[32] as illustrated in Figure 5—the preferred threshold remains X_D =15 days. Regarding the robustness of this threshold, it is also worth noting the 20-day benchmark mentioned in[23]:

- *"…in 5% of cases, or 20 out of 365 days a year, the start of testing may occur at very low radon levels and cause a false-negative decision error. To reduce this error, indoor radon testing must be carried out in the normal mode of room usage, that is, when windows are not constantly open or closed for a long time."*

Therefore, the final formulation of paragraph 2.3(f) should be as follows:

> (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.

This clearly defined condition (f), together with the set of conditions (a)–(e) from Section 2.3, establishes a robust framework for conducting and selecting YLCM to ensure the most reliable assessment of indoor radon temporal uncertainty.

3.3. Additional limitations for indoor radon testing within the Rational Method

As previously noted, the limitations of the Rational Method are discussed in detail in Section 4.5, "Test Conditions".[6] However, in the context of this discussion—and beyond the additional limitations related to determining temporal uncertainty—it is necessary to clarify or introduce further constraints for indoor radon testing. This is particularly relevant in cases where indoor radon concentrations remain relatively low, approaching outdoor levels, over extended periods (either continuously or cumulatively throughout the year). Several examples of such scenarios are illustrated in Figure 3.

It is evident that relatively low indoor radon concentrations—despite elevated annual average radon concentrations (AARC)—can be attributed to two primary factors:

1. **High air exchange rate** due to a strong influx of outdoor air; and/or

2. **A sharp reduction or complete cessation of soil radon transport** into the building.

The influence of the first factor may result from continuous and intensive ventilation, such as when windows in all occupied rooms remain open day and night due to comfortable outdoor temperatures, or when an unregulated central heating system overheats the indoor environment. Wind gusts and sustained high wind speeds, lasting days or even weeks, should also be considered.

The second factor may be linked to a weakening of the stack effect at the soil–building interface, caused by the cessation of heating (and a sharp drop in indoor temperature), or a sudden increase in outdoor temperature. Additionally, a rapid rise in groundwater levels—up to and including flooding of the building's underground parts—following heavy snowmelt or prolonged rainfall, can significantly reduce radon entry. Focusing on understanding the mechanism behind this second factor would be highly beneficial for the radon research community.

All of these circumstances should be taken into account when planning and conducting indoor radon measurements. Doing so will help minimize the risk that short- or long-term measurement periods coincide with intervals of abnormally low indoor radon concentrations. In this context, the following are revised versions of two paragraphs from Section 4.5, "Test Conditions," of the Rational Method[6]:

Updated Content for paragraph 4.5.1(a) in Section "General"

"Measurements in both short-term and long-term modes may be conducted at any time of the year, except when starting measurements during adverse meteorological or geological conditions. In such cases, it is recommended to consult weather forecasts in advance and avoid initiating measurements (especially short-term) under the following conditions:

- *During abnormally high or low temperatures, or during unusually sharp temperature fluctuations in the region;*
- *During periods of high wind speeds and/or strong wind gusts;*
- *During prolonged rainfall and for 1–2 days following its end;*
- *During significant rises in groundwater levels (including flooding of the building's underground parts) caused by heavy snowmelt or rainfall, and for 1–2 months after groundwater levels return to normal."*

Updated Content for paragraph 4.5.2(b) in Section "Ventilation Mode"

"In normal mode, where all rooms and the building are operated in a regular mode without any special restrictions, the measurement duration should be at least 4 days. In this case, no preliminary preparation of the tested rooms is required.

It is important to note that in normal mode, deliberately keeping windows or doors constantly open or closed, as well as intentionally disabling mechanical ventilation (if included in the building's design), can significantly affect the measurement results and reduce the reliability of the testing—particularly for short-term measurements.

Furthermore, measurements should not be conducted when windows remain open day and night due to comfortable outdoor temperatures or excessive indoor heating."

Additionally, it is appropriate to update paragraph 4.6.2(b) under "Performing Measurements" in Section 4.6, "Measurements".[6] Enhancing the reliability of identifying rooms (and buildings) with radon concentrations exceeding the reference level can also be achieved by revising paragraph 4.4.1(i) under "General" in Section 4.4, "Principle of Measurement and Conformity Assessment".[6]

Updated Content for paragraph 4.6.2(b) in Section "Measurements"

"It is recommended to begin indoor radon testing with short-term measurements, in accordance with the conditions outlined in Section 4.5, while initial recording actual weather (temperature/humidity/wind/precipitation), microclimatic conditions, and the operation/ventilation mode (normal or closed). If the conditions specified in Sections 4.5.1(a) or Sections 4.5.2(b) cannot be met, only long-term measurements should be conducted, with a minimum duration of 9 months, covering the entire heating season."

Updated Content for paragraph 4.4.1(i) in Section "Principle of Measurement and Conformity Assessment"

"Renovation or major repairs of a building—including upgrades to engineering systems and underground utilities—can significantly affect the radon environment, especially on lower floors. In such cases, it is advisable

to re-test the building. Additionally, due to the gradual degradation of foundation elements and underground infrastructure, radon migration from the soil into the building may increase over time. Therefore, it is recommended to conduct repeat radon testing every 3–5 years in buildings located in high-radon areas, and every 10 years in low-radon areas. Repeat measurements should be performed in a different season than the previous test."

3.4. Disadvantages of traditional approaches to studying and measuring indoor radon

3.4.1. Introductory considerations

In our view, STUK's approach to indoor radon testing is the most advanced among national regulatory systems across the European Union. Furthermore, the study design adopted in Finland for the purpose of standardization of indoor radon measurement is more effectively compared to those in other European countries.

Nevertheless, it will be beneficial—not only for our colleagues at STUK but also for the broader radon community, including national regulators, metrologists, and researchers—to critically reflect on the traditional approach for studying and measuring indoor radon. This critique, along with the proposed Rational Method,[6] is intended as a constructive contribution to the advancement of indoor radon testing and international standardization efforts.

3.4.2. Comments on the STUK regulation in radon measurements

(a) Radon risk regulation in Finland, according to national regulatory guidelines,[2,3,33,34] covers a broad spectrum of indoor environments—including workplaces, residential buildings, and other premises used by people.

(b) Although one of STUK's documents[3] refers to the concept of "expanded uncertainty of measurement" (defined as the product of the combined measurement uncertainty and a coverage factor), the traditional approach to indoor radon measurements does not account for temporal uncertainty, which is, however, a key component of the combined measurement uncertainty in indoor radon testing. This omission contradicts the recommendations of the *Joint Committee for Guides in Metrology, JCGM 100:2008 (GUM 1995 with minor corrections),*[29] and more importantly, the requirements of *ISO/IEC 17025:2017* for accredited laboratories, as outlined in Section 7.6, "Evaluation of Measurement Uncertainty".[35]

(c) While STUK's regulatory documents[2,3] include requirements and limitations for indoor radon measurements, they do not reference a clearly defined national measurement protocol (such as the Rational Method[6]). Instead, the absence of a national protocol is compensated by referring to the international standard *ISO 11665-8:2019,*[4] which recommends a minimum measurement duration of two months. However, this ISO standard still lacks proper metrological support[6,9,22] —a surprising shortcoming, given that it also fails to account for temporal (key) uncertainty. As noted in the Introduction and seen in Figure 5, this uncertainty can reach 100% for a two-month measurement period.

Unfortunately, many national regulators appear to find it convenient to rely on ISO 11665-8:2019, as it allows them to "justifiably" ignore temporal (key) uncertainty and focus solely on instrumental uncertainty, which rarely exceeds 30%.

3.4.3. Comments on the design and results of the STUK study

(a) As discussed in the Introduction, the traditional approach used in the design of the STUK study on the temporal variability of indoor radon[1] does not comply with the fundamental concepts of ISO/IEC, which have been globally adopted for measurement standardization for several decades and supported by the *Joint Committee for Guides in Metrology (JCGM 100:2008).* Instead of the outdated and ineffective traditional approach, we have been promoting a rational approach to indoor radon testing in line with JCGM 100:2008 for many years. Unfortunately, the radon community continues to overlook the rational approach.[6,9]

The rational approach to radon regulation is thoroughly discussed in our review article, with a focused strategy presented in Section 3.2.1, *"General Strategy of Indoor Radon Surveys"*.[6] The core principle of the Rational Method is outlined in Section 4.4, *"Principle of Measurement and Conformity Assessment"*.[6]

In this context, it is important to emphasize that the primary objective of indoor radon surveys should be the effective identification of hazardous buildings—based on the Rational Method—where the reference level limiting the annual average radon concentration (AARC) is exceeded. Moreover, this prioritization is consistent with the *ratio legis* of Section 19, subsection 1, paragraph 5 of the Finnish *Radiation Act* (859/2018),[33] which establishes the radon concentration register specifically to enable the identification of buildings and workplaces exceeding the reference level. Estimating effective dose of radon exposure is a secondary goal. Notably, the results of short- or long-term measurements from such surveys can also be used to characterize the lognormal distribution of indoor radon concentrations (including AM - arithmetic mean, GM - geometric mean, and GSD - geometric standard deviation), as well as to estimate the collective dose.[6]

Therefore, the foremost aim of indoor radon studies should be to improve the measurement protocol for reliable and cost-effective radon testing, rather than to refine national or regional estimates of AM, GM, and GSD—values that have already been determined with sufficient accuracy in many countries, including Finland. Further refinement of these parameters offers dubious benefit and lacks strong justification within the framework of the rational approach to radon regulation.[6]

(b) Among the reference parameters used to derive the Temporal Correction Factor were AM, GM, and even GSD—an approach that appears questionable. As previously discussed, the main objective of indoor radon testing should be the reliable identification of hazardous buildings, not the enhancement of collective dose estimates.

(c) Time series data (YLCMs) containing extended periods of extremely low indoor radon concentrations were included in the overall dataset for analysis. This decision in[1] appears questionable, especially in light of the findings presented in Section 3.1. The same concern applies to YLCM with AARC below 50 Bq/m³, which meets the exclusion condition outlined in Section 2.3(a).

(d) As discussed in the Introduction, the use of a single seasonal correction factor of 0.9 in Finland reflects the relatively small average difference between indoor radon concentrations in winter and summer. Indeed, a visual analysis of seasonal variations across 38 YLCMs (see "Data availability" section) reveals that in nearly half of the cases, the expected seasonal pattern is reversed (i.e., radon concentrations are higher in summer than in winter), or seasonal variation is not clearly expressed. Therefore, STUK's requirement to conduct indoor radon testing only from the beginning of September to the end of May (excluding the three summer months) seems overly strict—especially in light of the findings in Section 3.3. Comparable concerns may be raised with regard to the regulatory frameworks of other EU Member States, where national guidance continues to recommend limiting indoor radon measurements to the "heating season".[36]

In this context, it is worth examining the results of YLCMs with codes AA, AL, and BD shown in Figure 3. In all three cases, the AARC does not exceed the reference level (300 Bq/m³ in existing buildings in Finland[34]), meaning radon remediation is not formally required. However, these rooms periodically experience very high radon entry—lasting for weeks, months, or even entire seasons. Therefore, to ensure radiation safety, remediation would be justified in these cases based on the ALARA principle.[6]

These two examples illustrate, on the one hand, the excessive rigidity of indoor radon testing requirements, and on the other, their overly formalistic nature. Such issues should be carefully considered when developing or refining a measurement protocol (such as the Rational Method), which—especially in its draft stage—cannot be flawless. For this reason, objective feedback and recommendations from experts in the radon community are of great importance.

(e) STUK experts rightly raise an important issue:

- *"Currently, no established standard defines the acceptable proportion of false negatives when determining an action level. For some individuals, a 5% probability of a false negative may be entirely acceptable, whereas for others—particularly those who work from home or have small children—only the most reliable result is acceptable".*[1]

The reliability of decision-making, or the probability P, that a room complies with safety requirements, is directly related to the false-negative error as $1-P$, or $(100-P)$ %. A high value of P=99% (false-negative error is 1%) seems too stringent a requirement, so such a probability value is not usually used in routine radiation measurements. In addition, applying different P values across countries or institutions may hinder harmonization in radon regulation.

In this context, it is helpful to reference several clear principles adopted in the Russian system of measurement standardization for radiation safety, as outlined in GOST 8.638-2013 (*State system for ensuring the uniformity of measurements. Metrological support for radiation control. General principles*):

- In radiation control, measurement uncertainty is estimated as an interval around the measured value of a quantity, within which the true value of the measured quantity is located with a given probability P=0.95.

- Expanded uncertainty of measurement is the product of the total standard uncertainty of measurements and the coverage factor (k) adopted to take into account the selected coverage probability (in radiation control, for a probability of $P = 0.95$, $k = 2$ is usually adopted).

    - These principles also apply to indoor radon testing and seem to be quite relevant to be adapted at the international level—for example, in relevant IAEA Safety Guides and ISO/IEC or CEN standards.

    - To illustrate the implications of selecting different P values, consider the following examples:

- According to the Rational Method, with P=95% (no more than 5% false-negative error), the action level in Finland (where the reference level is 300 Bq/m³) for a 2–5 day measurement is approximately 110–130 Bq/m³ under normal ventilation mode, and 140–150 Bq/m³ under closed mode.[30] If these thresholds are exceeded, a longer measurement period is required.

- STUK proposes an alternative (when P=99%):

"One of the primary objectives of this study was to determine how the results of short-term radon measurements lasting 2–5 days should be interpreted. Based on the data, a suitable action level could be set at 90–100 Bq/m³, ensuring that only approximately 1% of measurements at this concentration exceed the reference level of 300 Bq/m³".[1]

It is important to note that when P = 99%, the Rational Method enables straightforward recalculation of temporal uncertainty values using the same datasets. However, these uncertainties increase significantly for both short-term and long-term measurements. This, in turn, would require additional effort and considerable expense for the certification and periodic validation of all devices and methods used to measure radon concentrations, in order to ensure that instrumental uncertainty is assessed at P = 99%. Consequently, the overall cost of indoor radon testing could rise substantially.

The choice of P in indoor radon testing is a controversial and highly relevant issue. It would be beneficial to discuss and establish the value of P in the framework of clear, harmonized guidelines—potentially within the RadoNorm project,[8] in which STUK experts are involved.

(f) The article[1] presents a substantial number of descriptive algorithms, accompanied by numerous figures and tables intended to support the outcomes. However, the approach advocated in the article[1] is grounded in conservative decision-making traditions that are outdated and inefficient, which is quite reasonably demonstrated not only in this, but also in our previous publications.[6,9,22,23,30] In contrast, the rational approach requires only one or two illustrations—such as Figure 4 or Figure 5—whose data are directly linked to the conformity assessment criterion (1). This criterion underlies the measurement protocol and ensures compliance with modern metrological requirements, commonly referred to as quality criteria or quality assurance (QA). These observations highlight the excessive complexity—and even the opacity—of traditional (non-rational) approaches, whose results are significantly harder to reproduce and are not clearly tied to specific measurement protocols. This stands in stark contrast to the straightforward algorithm of the Rational Method, which was discussed in detail earlier. Accordingly, the "Data availability" section includes archive with Excel files containing simple algorithms for converting the original STUK data and determining temporal uncertainty within the Rational Method.

(g) The analysis of tabular data in[1] shows that the generic values of the temporal correction factor do not depend on the duration of measurements, and also differ only slightly from 1, except for the values of k_C (regression). At the same time, the data in[1] indicate that applying k_C (regression) actually reduces the reliability of the AARC estimate. The use of other types of temporal correction factors has a negligible effect, therefore the application of correction factors does not provide real benefit. Nevertheless, the article[1] continues to argue for usefulness of temporal correction factors with specific examples based on absolute values of control and reference levels, expressed in Bq/m³, although the results of comparison in relative units are usually more expressive.

(h) All these efforts culminate in the "Conclusion" section of 1, which presents broadly generalized recommendations for applying temporal correction factors. However, it remains unclear how these recommendations could be implemented in a national measurement protocol, which, to date, has not been formally established in Finland. Furthermore, the final part of the "Conclusion" presents a particularly debatable statement:

- *"Based on this study, short-term radon measurements cannot yet be recommended as a replacement for current methods."*

In contrast, most effective radon regulation practices—such as those implemented in the United States—and the results of our long-term studies,[6,9] particularly those refined using STUK data, point toward a different conclusion. Indeed, short-term radon measurements form the core of the Rational Method,[6] which, for the first time, received metrological support by accounting for both temporal and instrumental components of AARC uncertainty.

4. Conclusions

The analysis of the extensive experimental STUK data using Rational Method algorithms has led to the following key outcomes:

a) The limitations of the Rational Method have been refined, enhancing the reliability of identifying hazardous buildings where the annual average radon concentration exceeds the reference level.

b) Additional limitations for statistical data collection have been introduced to improve the reliability and representativeness of temporal uncertainty estimates.

c) The behaviour of indoor radon in Finland is not unique, therefore it can now be more reasonably argued that previously published values of temporal uncertainty—validated using STUK data—are universal across different countries. Therefore, they can be used in national measurement protocols for indoor radon testing in the absence of more reliable country-specific data.

In addition, a critical analysis of STUK's approaches to both regulation and study design revealed several key issues:

d) The traditional approach to indoor radon measurements, adopted not only in Finland (STUK) but also in other countries, fails to account for temporal (key) uncertainty. This neglects the recommendations of the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995) and the requirements of ISO/IEC 17025:2017 for accredited laboratories, rendering the traditional approach outdated and inefficient.

e) Regulatory systems in some countries, including Finland, lack a national indoor radon measurement protocol. This gap is compensated by referencing ISO 11665-8:2019, which still lacks metrological support. As a result, regulators are able to "justifiably" ignore temporal (key) uncertainty in decision-making.

f) The design of the STUK study is also based on traditional approaches, using outdated terminology and focusing on the Temporal Correction Factor and false negative/positive errors, rather than applying the rational concept of "Measurement Uncertainty" (including temporal uncertainty as a key component) within the framework of modern metrology (JCGM 100:2008, GUM 1995).

g) The single seasonal correction factor of 0.9 used in Finland confirms only a minor average difference between indoor radon concentrations in winter and summer. Therefore, STUK's requirement to conduct indoor radon testing from the beginning of September to the end of May (excluding the three summer months) appears overly strict. Moreover, the values of the temporal correction factor do not depend on the duration of measurements, and also differ only slightly from 1, casting doubt on their practical utility.

h) A critical issue remains unresolved—at both the IAEA and ISO levels—regarding the quantitative characterization of decision-making reliability or probability (e.g., $P = 0.95$) regarding the compliance of a room with radon safety requirements.

i) The main conclusion of the STUK study—that "short-term radon measurements cannot yet be recommended as a replacement for current methods"—is insufficiently supported and highly debatable. In contrast, the most

effective radon regulation practices, such as those in the United States, and the results of our long-term studies (especially those refined using STUK data), suggest the opposite. Moreover, short-term radon measurements form the foundation of the Rational Method, which, for the first time, has full metrological support because it takes into account both temporal (key) and instrumental uncertainties in decision-making.

We hope that our critique of the outdated and inefficient traditional approach together with the proposed Rational Method will be regarded as a constructive and valuable contribution by regulators and metrology experts, including those engaged in ISO and IAEA processes. Although still under development, the Rational Method stands to benefit greatly from expert feedback, particularly given the prolonged absence of alternative measurement protocols grounded in modern metrological foundation.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Source data

The initial experimental data was published by experts from the Radiation and Nuclear Safety Authority (STUK, Finland) in[1] as Supplementary Materials with open access:

https://doi.org/10.3390/atmos16050489

Underlying data

Repository: Figshare. Dataset[37]:

https://doi.org/10.6084/m9.figshare.30156709.v1

This project contains the following underlying data:

- Excel file “Original STUK data” (the initial experimental data published by STUK experts),
- Excel file “Selected STUK data_Cond_1 and Figures” (selected STUK data based on conditions 2.3(a) and 2.3 (e) with 38 figures for each of YLCM),
- Excel file “Selected STUK data_Cond_2” (selected STUK data based on conditions 2.3(a), 2.3(e) and 2.3(f) using a special modeling algorithm detailed in Section 3.1 and Section 3.2),
- Folder “Temporal uncertainty_partial values” (the archive of 38 Excel files containing a processing algorithm for determining the partial values of temporal uncertainty for each of the 38 YLCMs),
- Folder “Temporal uncertainty_general values with exclusions” (the archive of 6 Excel files containing a processing algorithm for determining the general values of temporal uncertainty covering all (38) YLCMs, as well as excluding some YLCMs in accordance with Section 3.1 and Section 3.2).

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Extended data

No additional materials were used.

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Publisher Full Text

Open Peer Review

Current Peer Review Status: ? ? ? ?

Version 4

Reviewer Report 31 March 2026

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Mehmet Erhan Emirhan
Istanbul University Faculty of Science, Istanbul, Turkey

This manuscript presents a reanalysis of the supplementary year-long continuous radon monitoring data published by STUK (Finland), with the aim of evaluating indoor radon temporal variability through the authors' previously proposed Rational Method.The manuscript is ambitious and addresses an important topic: the relationship between short-term measurements, temporal variability, and decision-making in radon conformity assessment. The article is also valuable in that it tries to connect radon measurement practice with broader metrological concepts such as uncertainty and conformity assessment. Several key methodological steps are insufficiently justified or appear partly subjective, especially the exclusion of selected year-long continuous measurements and the derivation of additional selection criteria. The manuscript also overstates some conclusions, particularly the universality of temporal uncertainty values across countries and the claim that existing approaches are broadly "outdated and inefficient." To become scientifically sound, the article needs major revision in methodology, tone, structure, and evidential support.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Radon detection, radon-earthquake relations, radiation detectors

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 03 Apr 2026

Andrey Tsapalov

The Author's responses and decisions regarding the comments (from 31 Mar 2026) of the Reviewer - **Mehmet Erhan Emirhan,** Istanbul University Faculty of Science, Istanbul, Turkey.

General comment: This manuscript presents a reanalysis of the supplementary year-long continuous radon monitoring data published by STUK (Finland), with the aim of evaluating indoor radon temporal variability through the authors' previously proposed Rational Method. The manuscript is ambitious and addresses an important topic: the relationship between short-term measurements, temporal variability, and decision-making in radon conformity assessment. The article is also valuable in that it tries to connect radon measurement practice with broader metrological concepts such as uncertainty and conformity assessment.

Author's response to General comment: The author thanks the reviewer for his time and rating the article as valuable and addressing an important topic.

Comment 1: Several key methodological steps are insufficiently justified or appear partly subjective, especially the exclusion of selected year-long continuous measurements and the derivation of additional selection criteria.

Author's response to Comment 1: This comment is not justified because it is not supported by a specific proposal from the reviewer for an alternative estimate of the temporal uncertainty of indoor radon, which, in his opinion, would be more justified and objective. It remains unclear what more justified and objective solution the reviewer could have proposed (or provided a link to an alternative solution), especially instead of "*the exclusion of selected year-long continuous measurements and the derivation of additional selection criteria*". Unfortunately, the reviewer (like all other readers) could not see the Author's response to Comment 2 of the Reviewer 3 (Katerina Navratilova Rovenska), which directly relates to the issue under discussion. For unknown reasons, the author's responses to the comments of Reviewer 3 (Katerina Navratilova Rovenska) have not yet been published (for more than two months now). Therefore, the Author's response to Comment 2 of the Reviewer 3 (Katerina Navratilova Rovenska) is repeated below.

The reviewer, in making such a categorical comment, does not take into account a very important fact. Firstly, as shown in Fig. 3, the duration of abnormally low-concentration periods can reach 3, 6 and even 8 months (however, the reasons for this have not yet been studied or established). The existence of such extended low-concentration periods has a significant impact and reduces the reliability of decision-making, ***including by the results of long-term measurements lasting 2 months (or more)****, the reliability of which the reviewer is mistakenly confident (given her other comments). Secondly, the sequential exclusion of YLCMs presented in Fig. 3 leads to a reduction in temporal uncertainty not only for short-term but also for long-term measurements, as can be seen in Figs. 4 and 5. For example, excluding all eight YLCMs presented in Fig. 3 from the overall analysis allows to reduce the temporal uncertainty to 100% for a two-month measurement period. Otherwise (if unreliable YLCMs are not excluded), the temporal uncertainty for a two-month measurement period increases significantly to 120-150% and higher.* ***It is important to emphasize again that the temporal (key) uncertainty in the case of long-term measurements reaches 100% (if unreliable YLCMs are excluded) and even higher values (if unreliable YLCMs are not excluded).*** *Therefore, in any case, a well-founded procedure for excluding unreliable YLCM with extended low-concentration periods is necessary. The rationale for the quantitative criteria for such exclusion is provided in Sections 2.3, 3.1 and 3.2. Could the reviewer provided specific comments on the proposed YLCM exclusion rules, rather than the exclusion idea? Could you suggest an alternative (based on the results of the recently completed large European project "RadoNorm") that would provide a more representative and reliable estimate of the temporal uncertainty of indoor radon? The author would also like to understand why the causes of abnormally extended low-concentration periods were not investigated in RadoNorm?*

Author's Decision to Comment 1: Rejected.

Comment 2: The manuscript also overstates some conclusions, particularly the universality of temporal uncertainty values across countries and the claim that existing approaches are broadly "outdated and inefficient."

Author's response to Comment 2: In the article, every mention of *"the universality of temporal uncertainty values across countries"* is accompanied by a clear clarification: *"in the absence of reliable country-specific data"*. Ultimately, it is clearly better to use the available universal values of temporal uncertainty in the absence of more reliable country-specific data than to continue to ignore the main component of decision-making uncertainty, which is a sad fact on a global scale. It is useful to recall again that the temporal uncertainty is about 100% for two-month measurements. A more detailed discussion of this issue is provided in the Author's responses to Comments 6 and 2.6 of Reviewer 2 (Miroslaw Janik).

The issue of the claim that existing approaches are "outdated and inefficient" has been discussed in detail previously. Please see the Author's responses to Comments 1, 2.1 and 2.2 of Reviewer 2 (Miroslaw Janik). Reiterating the same comments (to which the author has already given detailed responses, in addition to the abundance of evidence in the article itself) does not contribute to improving the article under review. The author would like to emphasize that so far no one, including all the reviewers of this article, has yet presented a

reasoned (scientifically proven) objection to assessment of the traditional approach as “outdated and ineffective”. It is unlikely that the reviewer will dispute the important role of progress in science and technology over many centuries, when traditional (outdated and ineffective) approaches were improved and periodically updated, sometimes even fundamentally.

Author's Decision to Comment 2: Rejected.

Comment 3: To become scientifically sound, the article needs major revision in methodology, tone, structure, and evidential support.

Author's response to Comment 3: Here it is important to recall the reviewer's answers to six key questions from the ORE editorial board:
Is the work clearly and accurately presented and does it cite the current literature?
Yes.
Is the study design appropriate and does the work have academic merit?
Yes.
Are sufficient details of methods and analysis provided to allow replication by others?
Partly.
If applicable, is the statistical analysis and its interpretation appropriate?
Yes.
Are all the source data underlying the results available to ensure full reproducibility?
Partly.
Are the conclusions drawn adequately supported by the results?
Yes.

Unfortunately, the reviewer did not explain why he answered “Partly” to the two questions above? After all, a huge array, including the source data (underlying the results) and detailed algorithms (within Rational Method) for processing it, was specially placed by the author in the Repository: Figshare. Dataset : https://doi.org/10.6084/m9.figshare.30156709.v1. It therefore remains unclear why the reviewer doubts the availability of all the source data underlying the results via this repository, as well as the possibility of replication by others? For all other questions, the reviewer answered “Yes”, but then it remains unclear why *“the article needs major revision”*? Moreover, the reviewer did not justify his comments. As a result, the comments of the reviewer, which also do not mention the importance of taking into account the temporal (key) uncertainty, do not contribute to improving the article.

Author's Decision to Comment 3: Rejected.

Competing Interests: No competing interests were disclosed.

Version 3

Reviewer Report 28 January 2026

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Katerina Navratilova Rovenska
National Radiation Protection Institute, Prague, Czech Republic

Summary of the manuscript
This study reevaluates Finnish data on radon concentrations in buildings using the Rational Method, which combines the concepts of measurement uncertainty and conformity assessment. The authors criticize the traditional approach using seasonal correction factors, calling it outdated and ineffective because it does not provide a reliable metrological basis for identifying hazardous buildings. An analysis of 38 of the 55 original Finnish year-round measurements confirmed that the time uncertainty values show satisfactory agreement with earlier data from Russia and Israel. According to the authors, this agreement strengthens the argument that the derived parameters of temporal variability are universally applicable even in countries that do not have their own extensive studies focused on long-term continuous radon measurements in buildings. The study concludes, similarly to previous studies and articles by the authors frequently cited in this draft manuscript, that short-term measurements using the Rational Method are a reliable tool for health protection, as they effectively identify objects requiring remediation.

General comments on the Rational method
This reviewer considers the core idea of replacing seasonal correction factors with an uncertainty-based framework to be an interesting exercise.
The algorithm offers a way to integrate seasonal and non-seasonal temporal effects into a single uncertainty metric. At the same time, this reviewer believes that several methodological assumptions underlying the algorithm would benefit from a more explicit discussion, as it seems that some interpretations of the algorithm's output may be stronger than what the methodology alone can strictly support.
In particular, the link between the 95th percentile of temporal deviations and a guaranteed 95% decision reliability appears to rely on additional implicit assumptions about data representativeness and stability.

In addition, the reviewer notes that the exclusion of certain year-long datasets with extended low-concentration periods may unintentionally bias the resulting uncertainty estimates towards more stable temporal patterns. From a statistical perspective, the authors intentionally excluded cases that could also represent realistic and relevant scenarios. Only after removing selected data sets does the emphasised agreement between data sets from Finland, Israel, and Russia become apparent.

The statistical structure of the generated data deserves more careful explanation. Because the algorithm relies on highly overlapping sliding windows, the resulting deviations are not statistically independent. In particular, the use of strongly overlapping sliding windows introduces

substantial autocorrelation among the derived values. While independence is not strictly required for percentile estimation, the effective information content may be lower than suggested by the number of windows. While the assumption of “circular periodicity” may be practically convenient, it is not self-evident from a statistical perspective and could be **stated more explicitly as an approximation.**

This reviewer also notes that the claim of broad or universal applicability of the resulting uncertainty values is currently supported by a limited number of datasets. Although the results are presented as excellent and encouraging, a more cautious formulation would be appropriate, one that better reflects the internal limitations of the method and the limitations arising from the small data set that has been processed and is available.

The authors do not provide any clue how to solve borderline situations.

In summary, this reviewer sees the algorithm as methodologically interesting and practically useful but considers that moderating some claims would improve its scientific credibility.

General comments on the manuscript
- Most of the articles supporting the authors' opinion are by the authors themselves, not by other authors who would also discuss the topic.

- The language of the article is very confrontational.

- The authors emphasise temporal variability while describing year-over-year variability as low, ranging between 15 and 20%. While they strongly criticise other authors' approaches to measurement procedures, they take a completely uncritical approach to this parameter of year-to-year variability.

- The authors refer to the American (US) system. The fact that the system is American and works in America does not mean that it is correct and would work in Europe. The number of measurements in the US is determined by the obligation to measure when buying/selling. This obligation is not established in many EU member states. There are many times more real estate transactions in the US than in Europe, as well as measurements, which is why more measurements are taken there.

- There are many circumstances that can significantly affect the radon activity concentration in a building and may not necessarily occur during a short or very short measurement. These are also reasons for maintaining long-term measurements, especially annual ones.

Comments on specific parts of the text:
- Text: Nearly complete year-long measurements were conducted in 55 dwellings, providing strong statistical power and representativeness of the dataset.
- Comment: This is a misleading statement. The authors of the article state that although the selection of households was designed to correspond as closely as possible to the national housing stock (type of house, year of construction, type of foundation, ventilation, radon levels), which was achieved, but the selection of the buildings themselves was based on voluntary registration and the "first come, first served" principle, which may limit strong statistical representativeness. They further state that some areas are slightly under-represented. Furthermore, data from apartment buildings and buildings with higher radon activity are completely missing.

The authors of the original article themselves point out the limitations caused by the size of the sample.
One more comment on the representativeness – there are 3,124,000 dwellings in Finland, with 47% of dwellings in blocks of flats, according to Stat.fi.

- Text: In the vast majority of cases, due to the low level of indoor radon, it is sufficient to conduct inexpensive short-term tests (from 2 to 7 days) within the framework of the rational criterion to ensure the absence of a radon problem. In another, relatively small proportion of cases, additional more accurate and costly long-term tests (from 2 to 12 months) will be required after (or in continuation of) short-term measurements due to the high temporal uncertainty of short tests and the elevated radon levels in some buildings, which will ultimately be reliably identified"
- Comment: What are the arguments of authors when they claim that a 2- to 7-day measurement is less expensive than a 2- to 12-month measurement?

- Text: Reference 2 deals with measurement in dwellings.
- Comment: Reference 2 deals with measurement at workplaces (practice), not in dwellings.

- Text: C_RL is the reference level (Bq/m3), expressing the limit for the annual average indoor radon concentration.
- Comment: Reference level is not a limit in radiation protection.

- Text: In normal mode, where all rooms and the building are operated in a regular mode without any special restrictions, the measurement duration should be at least 4 days.
- Comment: This adjustment brings the measurement period closer to the one-week measurement (7 days) that some countries have long established as an indicative measurement e.g. for selling/buying purposes.

- Text: (b) Although one of STUK's documents refers to the concept of "expanded uncertainty of measurement" (defined as the product of the combined measurement uncertainty and a coverage factor), the traditional approach to indoor radon measurements does not account for temporal uncertainty, which is, however, a key component of the combined measurement uncertainty in indoor radon testing.
- Comment: Temporal uncertainty is at least partially covered by the requirement on minimal duration of measurement. See https://stuk.fi/en/measuring-radon.

- Text: In contrast, most effective radon regulation practices—such as those implemented in the United States …
- Comment: Please provide a reference supporting the claim that the regulatory practice implemented in the US is the most effective.

- Text: This neglects the recommendations of the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995) and the requirements of ISO/IEC 17025:2017 for accredited laboratories, rendering the traditional approach outdated and inefficient.
- Comment: The authors mix together measurement requirements (ISO 17025) and radiation protection requirements for describing the exposure situation. While measurement concerns a specific measurement location and measurement conditions, radiation protection naturally seeks to obtain sufficient information to describe the exposure situation in sufficient detail.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: radon measurement and building diagnostic, NORM workplaces

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 02 Feb 2026

Andrey Tsapalov

The Author's responses and decisions regarding the comments (from 28 Jan 2026) of the Reviewer - **Katerina Navratilova Rovenska,** National Radiation Protection Institute, Prague, Czech Republic

Summary of the manuscript
This study reevaluates Finnish data on radon concentrations in buildings using the Rational Method, which combines the concepts of measurement uncertainty and conformity assessment. The authors criticize the traditional approach using seasonal correction factors, calling it outdated and ineffective because it does not provide a reliable metrological basis for identifying hazardous buildings. An analysis of 38 of the 55 original Finnish year-round measurements confirmed that the time uncertainty values show satisfactory agreement with earlier data from Russia and Israel. According to the authors, this agreement strengthens the argument that the derived parameters of temporal variability are universally applicable even in countries that do not have their own extensive studies focused on long-term continuous radon measurements in buildings. The study concludes, similarly to previous studies and articles by the authors frequently cited in this draft manuscript, that short-term measurements using the Rational Method are a reliable tool for

health protection, as they effectively identify objects requiring remediation.
Author's response to reviewer's Summary of the manuscript:
The author expresses deep gratitude to the reviewer for reading not only with the article under review, but also with previous publications with the author's participation. Although all comments were rejected by the author with detailed justification, the reviewer's efforts are of value because they contribute to the development of a crucial discussion about the vital need to introduce the Rational Method into the European (international) radon regulation. Unfortunately, the European radon regulation is still dominated by very conservative views that hinder the implementation of progressive (rational) approaches and technologies. The last sentence in the reviewer's Summary misstates the conclusion of the reviewed and the author's earlier studies. According to the principles and specific conditions (criteria) for the application of the Rational Method, **the results of short-term measurements allow for the effective and reliable identification of rooms (and buildings) that do not require remediation**, which are usually the overwhelming majority (on average 80-99% in different regions of the world). In another, relatively small proportion of cases (when the result of a short-term measurement does not allow a reliable decision), an additional more accurate and costly long-term measurement must be carried out (the reviewer quotes the same text in Comment 13). **Thus, the decision on the need for remediation should be made on the basis of long-term measurements, according to the Rational Method**. This is precisely what is reported in Section 1.2 of the article under review, as well as in the detailed description of the Rational Method in article [6]. Only in extremely rare cases, with unusually high indoor radon levels, can a decision on the need for remediation actually be made based on short-term measurements. For example, according to criterion (2) in Section 2.1, the average radon concentration for at least four days should exceed 745 Bq/m3 if the reference level is set at 300 Bq/m3 and the instrumental uncertainty is 30%.

General comments on the Rational method

Comment 1: This reviewer considers the core idea of replacing seasonal correction factors with an uncertainty-based framework to be an interesting exercise.
The algorithm offers a way to integrate seasonal and non-seasonal temporal effects into a single uncertainty metric. At the same time, this reviewer believes that several methodological assumptions underlying the algorithm would benefit from a more explicit discussion, as it seems that some interpretations of the algorithm's output may be stronger than what the methodology alone can strictly support.
In particular, the link between the 95th percentile of temporal deviations and a guaranteed 95% decision reliability appears to rely on additional implicit assumptions about data representativeness and stability.
Author's response to Comment 1: First, the link between the 95th percentile of "temporal" deviations and a guaranteed 95% decision reliability also includes accounting for instrumental uncertainty in relative units (with a coverage factor of k = 2), which is explicitly expressed in formulas (1) and (2) in Section 2.1 "Rational method for indoor radon measurements". Secondly, the reviewer, only hesitantly refers to unclear "additional implicit assumptions about data representativeness and stability."
Author's Decision to Comment 1: Rejected

Comment 2: In addition, the reviewer notes that the exclusion of certain year-long datasets with extended low-concentration periods may unintentionally bias the resulting uncertainty estimates towards more stable temporal patterns. From a statistical perspective, the authors intentionally excluded cases that could also represent realistic and relevant scenarios. Only after removing selected data sets does the emphasised agreement between data sets from Finland, Israel, and Russia become apparent.
Author's response to Comment 2: The reviewer, in making such a categorical comment, does not take into account a very important fact. Firstly, as shown in Fig. 3, the duration of abnormally low-concentration periods can reach 3, 6 and even 8 months (however, the reasons for this have not yet been studied or established). The existence of such extended low-concentration periods has a significant impact and reduces the reliability of decision-making, **including by the results of long-term measurements lasting 2 months (or more)**, the reliability of which the reviewer is mistakenly confident (given her other comments). Secondly, the sequential exclusion of YLCMs presented in Fig. 3 leads to a reduction in temporal uncertainty not only for short-term but also for long-term measurements, as can be seen in Figs. 4 and 5. For example, excluding all eight YLCMs presented in Fig. 3 from the overall analysis allows to reduce the temporal uncertainty to 100% for a two-month measurement period. Otherwise (if unreliable YLCMs are not excluded), the temporal uncertainty for a two-month measurement period increases significantly to 120-150% and higher. **It is important to emphasize again that the temporal (key) uncertainty in the case of long-term measurements reaches 100% (if unreliable YLCMs are excluded) and even higher values (if unreliable YLCMs are not excluded).** Therefore, in any case, a well-founded procedure for excluding unreliable YLCM with extended low-concentration periods is necessary. The rationale for the quantitative criteria for such exclusion is provided in Sections 2.3, 3.1 and 3.2. Could the reviewer provided specific comments on the proposed YLCM exclusion rules, rather than the exclusion idea? Could you suggest an alternative (based on the results of the recently completed large European project “RadoNorm”) that would provide a more representative and reliable estimate of the temporal uncertainty of indoor radon? The author would also like to understand why the causes of abnormally extended low-concentration periods were not investigated in RadoNorm?
Author's Decision to Comment 2: Rejected

Comment 3: The statistical structure of the generated data deserves more careful explanation. Because the algorithm relies on highly overlapping sliding windows, the resulting deviations are not statistically independent. In particular, the use of strongly overlapping sliding windows introduces substantial autocorrelation among the derived values. While independence is not strictly required for percentile estimation, the effective information content may be lower than suggested by the number of windows. While the assumption of “circular periodicity” may be practically convenient, it is not self-evident from a statistical perspective and could **be stated more explicitly as an approximation**.
Author's response to Comment 3: The absence of the overlapping sliding windows problem is discussed in detail in the Author's responses to Comments 5 and 2.5 of the Reviewer 2 (Miroslaw Janik), with which he agreed. The “Data availability” section provides the initial data that allows the reviewer (and any interested colleague) to double-check the author's relevant algorithms and conclusions through mathematical modeling.
Author's Decision to Comment 3: Rejected

Comment 4: This reviewer also notes that the claim of broad or universal applicability of the resulting uncertainty values is currently supported by a limited number of datasets. Although the results are presented as excellent and encouraging, a more cautious formulation would be appropriate, one that better reflects the internal limitations of the method and the limitations arising from the small data set that has been processed and is available.
Author's response to Comment 4: Cautious wording (with the corresponding warning) is used in the reviewed article. The limitations of the Rational Method are discussed in detail in Sections 2.3, 3.1 and 3.2. A more detailed discussion of this reviewer's comment is provided in the Author's responses to Comments 6 and 2.6 of the Reviewer 2 (Miroslaw Janik).
Author's Decision to Comment 4: Rejected

Comment 5: The authors do not provide any clue how to solve borderline situations.
Author's response to Comment 5: Could you specify what “borderline situations” means? The limitations of the Rational Method are discussed in detail in Sections 2.3, 3.1 and 3.2. If the term “borderline situations” refers to the proximity of the measured indoor radon concentration to the reference level, then in any case the assessment of the room’s compliance with radiation safety requirements is performed using clear criteria (mathematical formulas), which are given in Section 2.1 “Rational method for indoor radon measurements”. Both criteria take into account the main components of uncertainty, thus providing for the first time a decision reliability of at least 95% for indoor radon testing. Additional thoughts are provided in the Author's responses to Comments 4 and 2.4 of the Reviewer 2 (Miroslaw Janik). I repeatedly mention to ISO/IEC concepts such as “measurement uncertainty” and “conformity assessment” in detail, which can be found following the links in References:
27. ISO/IEC Guide 98-3: Uncertainty of measurement—Part 3: guide to the expression of uncertainty in measurement (GUM: 1995). International Organization for Standardization and International Electrotechnical Commission: Geneva, Switzerland, 2008.
28. ISO/IEC Guide 98-4: Uncertainty of measurement—Part 4: role of measurement uncertainty in conformity assessment. International Organization for Standardization and International Electrotechnical Commission: Geneva, Switzerland, 2012.
29. JCGM 100: 2008 (GUM 1995 with minor corrections): Evaluation of measurement data—guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology.
Author's Decision to Comment 5: Rejected

Comment 6: In summary, this reviewer sees the algorithm as methodologically interesting and practically useful but considers that moderating some claims would improve its scientific credibility.
Author's response to Comment 6: Unfortunately, all general comments on the Rational Method do not contain any benefit (that contributes to improving the article under review) and were rejected by the author (with justification).
Author's Decision to Comment 6: Rejected

General comments on the manuscript

Comment 7: Most of the articles supporting the authors' opinion are by the authors themselves, not by other authors who would also discuss the topic.
Author's response to Comment 7: Please see the Author's response to Comment 2 of the Reviewer 1 (Joan Frédéric Rey).
Author's Decision to Comment 7: Rejected

Comment 8: The language of the article is very confrontational.
Author's response to Comment 8: An independent, critical analysis of the state of the art, based on rigorous logic and facts, demonstrating serious problems in European radon regulation, would be considered extremely helpful rather than confrontational. A discussion of the entrenched conservatism in the radon community, which perceives criticism as confrontational (and polemical), can be found in the Author's responses to both Comments 8, 9 and 13 of the Reviewer 1 (Joan Frédéric Rey) and Comments 1, 2, 2.1 and 2.2 of the Reviewer 2 (Miroslaw Janik). It is also important to take into account that the author is not involved in any way with the European radiation risk management system and therefore expresses an independent point of view.
Author's Decision to Comment 8: Rejected

Comment 9: The authors emphasise temporal variability while describing year-over-year variability as low, ranging between 15 and 20%. While they strongly criticise other authors' approaches to measurement procedures, they take a completely uncritical approach to this parameter of year-to-year variability.
Author's response to Comment 9: I disagree with reviewer's comment because the problem of year-to-year variability in indoor radon is not discussed at all in the reviewed article. It is important to remember that the reference level is expressed as an annual average (not year-to-year) radon concentration, so the temporal uncertainty is expressed in terms of the relative deviations of measured concentrations from the annual average (not year-to-year) level. However, the problem of accounting for year-to-year variability is discussed (with the participation of the author) in previously published articles [9] and [23], which indeed report that most often year-to-year variability does not exceed 15-20%. These values are obtained by analyzing very long-term studies conducted year-to-year and published by other authors. It is important to note that the Rational Method not only mentions but also takes into account the problem of year-to-year variability in indoor radon. Please see points 4.4.1 (g) and (i) in article [6].
Author's Decision to Comment 9: Rejected

Comment 10: The authors refer to the American (US) system. The fact that the system is American and works in America does not mean that it is correct and would work in Europe. The number of measurements in the US is determined by the obligation to measure when buying/selling. This obligation is not established in many EU member states. There are many times more real estate transactions in the US than in Europe, as well as measurements, which is why more measurements are taken there.
Author's response to Comment 10: The American (US) radon risk regulation system, focusing on short-term measurements, is much more effective than the European one. This is discussed in more detail in the Author's response to Comment 1 of the Reviewer 1 (Joan Frédéric Rey). Indeed, unlike Europe, in the US alone tens of millions of indoor radon tests have been conducted and millions of buildings have installed reliable (active) protection

against soil radon, that effectively reduces radiation risk. Incidentally, the US EPA estimates the annual turnover of the national IAQ industry, funded primarily by householders, to be $18-30 billion, including the turnover of the radon industry, estimated by the author to be $1-3 billion. Despite the recently completed major European project "RadoNorm" with the participation of more than 50 institutes from different EU countries, fundamental problems remain: 1) Effective and reliable mass testing (using the Rational Method) to identify hazardous buildings (in which the reference level is exceeded) through involvement of the population, 2) Development and implementation of advanced technologies (as in the US) to protect buildings from soil radon, 3) Responsibility for indoor radon testing and remediation, 4) Excessive focus on Radon Priority Areas. Please see articles [6] and [24]. It seems that the established practice of radon regulation in Europe clearly needs to be rethought and updated.
Author's Decision to Comment 10: Rejected

Comment 11: There are many circumstances that can significantly affect the radon activity concentration in a building and may not necessarily occur during a short or very short measurement. These are also reasons for maintaining long-term measurements, especially annual ones.
Author's response to Comment 11: These most critical circumstances (which most significantly affect the reliability of the decision) are discussed in Section 3.3 “Additional limitations for indoor radon testing within the Rational Method” with subsequent recommendations to minimize the negative impact on the results of building testing. Moreover, these circumstances significantly influence the reliability of decision-making not only in the case of short-term, but also **long-term measurements**, as is reported in the reviewed article. It is important to emphasize again that temporal uncertainty can reach 100% for a two-month measurement period, even after excluding unreliable YLCM, according to the limitations specified in the article. If unreliable YLCMs are not excluded, the temporal uncertainty for long-term measurements will also increase, as can be seen when comparing Figs. 4 and 5. Therefore, in any case, a reasonable exclusion procedure is necessary as discussed in more detail above within Comment 2.
Author's Decision to Comment 11: Rejected

Comments on specific parts of the text:

Comment 12:
- Text: Nearly complete year-long measurements were conducted in 55 dwellings, providing strong statistical power and representativeness of the dataset.
- Comment: This is a misleading statement. The authors of the article state that although the selection of households was designed to correspond as closely as possible to the national housing stock (type of house, year of construction, type of foundation, ventilation, radon levels), which was achieved, but the selection of the buildings themselves was based on voluntary registration and the "first come, first served" principle, which may limit strong statistical representativeness. They further state that some areas are slightly under-represented. Furthermore, data from apartment buildings and buildings with higher radon activity are completely missing.
The authors of the original article themselves point out the limitations caused by the size of the sample.

One more comment on the representativeness – there are 3,124,000 dwellings in Finland, with 47% of dwellings in blocks of flats, according to Stat.fi. http://stat.fi/
Author's response to Comment 12: The text quoted at the beginning adequately reflects the understanding of the representativeness of the dataset within the Rational Method, especially in relation to such a relatively small country as Finland (moreover, the author of the article under review did not make the statement reported by the reviewer). The fact is that, in addition to concerns about ensuring the representativeness of the data (which the reviewer rightly expresses), in no study of the spatiotemporal behavior of indoor radon has the 100% (or about 100%) representativeness been ensured, usually due to the limited sampling of rooms and buildings. The representativeness of the data in such studies has not been examined quantitatively, so this parameter is usually perceived as qualitative. At the same time, increasing representativeness was always achieved by increasing the statistical power of the target parameter. Within the Rational Method, the target parameter is the relative deviation of the measured indoor radon concentration from the annual average. For example, the article [30] reports that the transformed array of such deviations from the data of an earlier Finnish study covering 326 buildings [32] included 46,944 values, while the latest Finnish study [1] made it possible to obtain 109,500 (365x10x30) deviations from the monitoring results of only 30 buildings (after excluding all unreliable YLCM) within the transformation algorithms in the Rational Method. Based on many years of research and experience in studying the temporal uncertainty of indoor radon in different geological, climatic and architectural conditions, the author can assume with a high degree of confidence that approximately the same values of temporal uncertainty as in Fig. 5 will be reproduced with a random sample (and corresponding aggregate processing), for example, 20 YLCM from a reliable 30 YLCM (which were selected as a result of excluding 25 of 55 YLCM according to the rules defined in the article). At the same time, the author strongly supports conducting as many YLCMs as possible in buildings in different countries on different continents. Incidentally, such vital research could have been carried out without much effort and expense within the framework of the large European project "RadoNorm" (Managing Risk from Radon and NORM towards effective radiation protection based on improved scientific evidence and social considerations, 2020-2025), in which more than 50 institutes from 22 EU countries participated. Unfortunately, this important study wasn't conducted (with the exception of Finland alone).
Author's Decision to Comment 12: Rejected

Comment 13:
- Text: In the vast majority of cases, due to the low level of indoor radon, it is sufficient to conduct inexpensive short-term tests (from 2 to 7 days) within the framework of the rational criterion to ensure the absence of a radon problem. In another, relatively small proportion of cases, additional more accurate and costly long-term tests (from 2 to 12 months) will be required after (or in continuation of) short-term measurements due to the high temporal uncertainty of short tests and the elevated radon levels in some buildings, which will ultimately be reliably identified"
- Comment: What are the arguments of authors when they claim that a 2- to 7-day measurement is less expensive than a 2- to 12-month measurement?
Author's response to Comment 13: The cost of using an active radon monitor (CRM-type)

for 2-7 days will be 30-50 times less than measuring for 2-12 months (proportional to the length of time the monitor is used). For example: Long-term radon test kit is about $45 (https://radonova.com/product/radtrak2-radon-long-term-test/). Short-term radon test kit is about $19 (https://radonova.com/product/st-charcoal-test/). The use of CRM monitors is the cheapest and most reliable tool within the Rational Method.
Author's Decision to Comment 13: Rejected

Comment 14:
- Text: Reference 2 deals with measurement in dwellings.
- Comment: Reference 2 deals with measurement at workplaces (practice), not in dwellings.
Author's response to Comment 14: Thank you for the clarification regarding Reference 2, however, this reference is used correctly throughout the text of the article under review. The reviewer cites the text: “Reference 2 deals with measurement in dwellings,” which is not present in the article under review.
Author's Decision to Comment 14: Rejected

Comment 15:
- Text: C_RL is the reference level (Bq/m3), expressing the limit for the annual average indoor radon concentration.
- Comment: Reference level is not a limit in radiation protection.
Author's response to Comment 15: Indeed, the reference level is not a limit in radiation protection, therefore in the quoted text, instead of “limiting”, the term “expressing the limit for…” is used.
Author's Decision to Comment 15: Rejected

Comment 16:
- Text: In normal mode, where all rooms and the building are operated in a regular mode without any special restrictions, the measurement duration should be at least 4 days.
- Comment: This adjustment brings the measurement period closer to the one-week measurement (7 days) that some countries have long established as an indicative measurement e.g. for selling/buying purposes.
Author's response to Comment 16: Different countries have different measurement durations (from several days to several months). However, what is common to all countries is the ignoring of temporal (key) uncertainty and, accordingly, the lack of a quantitative assessment of the reliability of the decision on the compliance (or non-compliance) of a room (building) with safety requirements. The Rational Method addresses this problem for the first time using both short-term (including 7 days) and long-term measurements.
Author's Decision to Comment 16: Rejected

Comment 17:
- Text: (b) Although one of STUK’s documents refers to the concept of “expanded uncertainty of measurement” (defined as the product of the combined measurement uncertainty and a coverage factor), the traditional approach to indoor radon measurements does not account for temporal uncertainty, which is, however, a key component of the combined measurement uncertainty in indoor radon testing.
- Comment: Temporal uncertainty is at least partially covered by the requirement on minimal duration of measurement. See https://stuk.fi/en/measuring-radon.

Author's response to Comment 17: Unfortunately, the reviewer does not specify how the temporal uncertainty is "partially covered". The next paragraph of the article under review states: "(c) While STUK's regulatory documents2,3 include requirements and limitations for indoor radon measurements, they do not reference a clearly defined national measurement protocol (such as the Rational Method6). Instead, the absence of a national protocol is compensated by referring to the international standard ISO 11665-8:20194, which recommends a minimum measurement duration of two months. However, this ISO standard still lacks proper metrological support6,9,22—a surprising shortcoming, given that it also fails to account for temporal (key) uncertainty. As noted in the Introduction and seen in Figure 5, **this uncertainty can reach 100% for a two-month measurement period**".
Author's Decision to Comment 17: Rejected

Comment 18:
- Text: In contrast, most effective radon regulation practices—such as those implemented in the United States ...
- Comment: Please provide a reference supporting the claim that the regulatory practice implemented in the US is the most effective.
Author's response to Comment 18: Please see the Author's response to Comment 1 of the Reviewer 1 (Joan Frédéric Rey)
Author's Decision to Comment 18: Rejected

Comment 19:
- Text: This neglects the recommendations of the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995) and the requirements of ISO/IEC 17025:2017 for accredited laboratories, rendering the traditional approach outdated and inefficient.
- Comment: The authors mix together measurement requirements (ISO 17025) and radiation protection requirements for describing the exposure situation. While measurement concerns a specific measurement location and measurement conditions, radiation protection naturally seeks to obtain sufficient information to describe the exposure situation in sufficient detail.
Author's response to Comment 19: The author does not describe (or mention) any radiation exposure situations in the article under review. The Conclusion section says: "d) The traditional approach to indoor radon measurements, adopted not only in Finland (STUK) but also in other countries, fails to account for temporal (key) uncertainty. This neglects the recommendations of the Joint Committee for Guides in Metrology (JCGM 100:2008, GUM 1995) and the requirements of ISO/IEC 17025:2017 for accredited laboratories, rendering the traditional approach outdated and inefficient". This focuses on key uncertainty in the context of its importance and promotion (implementation) with the support of such fundamental documents as JCGM 100:2008 (GUM 1995) and ISO/IEC 17025:2017 (please also see 3.4.2(b) in Section 3.4). It is also important to recall here the Author's response to Comment 10 of the Reviewer 1 (Joan Frédéric Rey), the last paragraph of which contains the following text.
However, in this connection it is also useful to draw the reviewer's attention to one of the following fundamental recommendations of the International Commission on Radiological Protection (ICRP Publication 126): "(n) It is the responsibility of the appropriate national authorities, as with other radiation sources, to establish their own national reference levels of dose and derived reference level of concentration, and to apply the process of

optimisation of protection within their country. The objective is both to reduce the overall risk to the general population and, for the sake of equity, the individual risk to the most exposed individuals. **In both cases, the process is implemented mainly through the management of buildings rather than individual exposures**, and should result in radon concentrations in ambient indoor air that are as low as reasonably achievable below the national reference level".
Author's Decision to Comment 19: Rejected

Competing Interests: No competing interests were disclosed.

Version 2

Reviewer Report 30 December 2025

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Miroslaw Janik
National Institutes for Quantum Science and Technology (QST), Chiba, Japan

Response to Author's Reply to Comment 1 (Tone / Polemical Language)
Thank you for your explanation. My concern is not related to the scientific basis of your statements, but to how the wording may be interpreted by readers. Even if a method has clear limitations, expressions such as "outdated and ineffective" can sound too categorical and may reduce acceptance among regulators and practitioners who still use these approaches. Using a more neutral formulation would not weaken your argument. In my opinion, it would make it more persuasive by ensuring that the discussion remains constructive. For this reason, I continue to recommend adjusting the language tone.

Response to Author's Reply to Comment 2 (Utility of Correction Factors)
Thank you for the detailed explanation. I understand your position; however, my intention was not to claim that correction factors are optimal, but to point out that they have had some practical use in certain regulatory and data-limited situations. Describing them as entirely without benefit may be perceived as dismissive by some readers. More balanced wording, e.g. emphasizing their limited usefulness but clear insufficiency for conformity assessment, would make your argument stronger and easier to accept for a wider audience.

Response to Author's Reply to Comment 3 (Novelty of the Study)
Thank you for pointing out Section 1.4. Even though the objectives are listed there, it would help the reader if the manuscript explicitly stated how this study is different from your previous work. As some important arguments (like the role of uncertainty about time and the critique of

correction factors) were presented earlier, a short paragraph would be useful to summarize the specific new things this paper adds (e.g. using Finnish data, improving the YLCM exclusion criteria, checking the uncertainty about time across countries). This would make it clearer what is new and improve the overall clarity of the paper.

Response to Author's Reply to Comment 4 (Handling Borderline Cases)
Thank you for the reference to article [6]. However, for completeness, the current manuscript should briefly summarize how the Rational Method deals with borderline cases near the reference level. This information is essential for regulators and practitioners, and it is more convenient if it appears directly in the manuscript instead of **requiring readers to consult another publication**. A concise explanation would significantly improve the usefulness and accessibility of the paper.

Response to Author's Reply to Comment 5 (Overlapping Windows / Autocorrelation)
Thank you for the clarification. The agreement between overlapping and non-overlapping windows is reassuring. However, the issue of autocorrelation is a known methodological point, and acknowledging it briefly would improve transparency. A short note explaining why the effect is expected to be small in your analysis would strengthen the methodological section without changing your conclusions.

Response to Author's Reply to Comment 6 (Universality of Temporal Uncertainty Values)
Thank you for the detailed answer. I understand your argument that universal values may be practical in the absence of country-specific data. At the same time, the current evidence is based on only three countries. Therefore, statements about universality should be phrased carefully. It would be scientifically stronger to say that the available results suggest broad applicability, but that additional validation in other climates and building types would be useful. This approach maintains your core message while reducing the risk of overgeneralization.

Response to Author's Reply to Comment 7 (Limitations Section)
Thank you for the explanation. Nevertheless, I believe the manuscript would benefit from a short, self-contained section summarizing the main limitations, including data representativeness, regulatory acceptance challenges, and practical requirements for implementing the Rational Method. Presenting these points directly in the manuscript will improve clarity for readers and increase transparency, especially for stakeholders who may consider applying the method in practice.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My core areas of research involve radon studies, encompassing measurement and monitoring techniques, statistical and data analysis as well as regulatory frameworks.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 06 Jan 2026

Andrey Tsapalov

The Author's responses and decisions regarding the comments (from 30 Dec 2025 in second round) of the Reviewer - **Miroslaw Janik,** National Institutes for Quantum Science and Technology (QST), Chiba, Japan

Author's General comment in second (2) round: The author would like to express many thanks to the reviewer for continuing an interesting and very useful discussion that contributes to a deeper understanding of the Rational Method, as well as the author's critical position on the current practice of radon regulation in Europe, which clearly needs to be rethought and updated.

Comment 2.1: Response to Author's Reply to Comment 1 (Tone / Polemical Language) Thank you for your explanation. My concern is not related to the scientific basis of your statements, but to how the wording may be interpreted by readers. Even if a method has clear limitations, expressions such as "outdated and ineffective" can sound too categorical and may reduce acceptance among regulators and practitioners who still use these approaches. Using a more neutral formulation would not weaken your argument. In my opinion, it would make it more persuasive by ensuring that the discussion remains constructive. For this reason, I continue to recommend adjusting the language tone.

Author's response to Comment 2.1: First of all, it is important to emphasize that the reviewer's concern is not related to the scientific basis of the author's statements. As for the concern about the use of expressions such as "outdated and ineffective", this is a very subjective feeling of the reviewer, which does not coincide with the feeling of the author. In this regard, it is important to recall that, for example, the term "outdated" (in the same context of criticism of the traditional approach) is used 6 times in our recent article "IAEA Safety Guides..." [6], which the author frequently refers to in the reviewed article. Moreover, the tone and level of criticism in [6] appear significantly harsher than in the article under review. However, the use of such terminology (Tone / Polemical Language) was accepted by all six co-authors (from different institutions and countries) and did not raise any comments from either the editor or any of the three reviewers during the review process of the Article [6]. Moreover, Article [6], published by MDPI, has already received more than 2200 views in less than a year, and the dynamics of views even increases over time (https://www.mdpi.com/2073-4433/16/3/253#metrics). Unfortunately, this is not the case for two other articles [9] and [23], which were previously published in MDPI (with the author's participation), but they did not use terms such as "outdated and ineffective". It is very sad that the reviewer suggests not highlighting (and in fact hiding) a problem that is, moreover, fundamental. If a problem is hidden (i.e. absent), then there is no reason for constructive discussion and scientific search for an optimal solution to the fundamental problem.

Author's Decision to Comment 2.1: Rejected

Comment 2.2: Response to Author's Reply to Comment 2 (Utility of Correction Factors) Thank you for the detailed explanation. I understand your position; however, my intention was not to claim that correction factors are optimal, but to point out that they have had some practical use in certain regulatory and data-limited situations. Describing them as entirely without benefit may be perceived as dismissive by some readers. More balanced wording, e.g. emphasizing their limited usefulness but clear insufficiency for conformity

assessment, would make your argument stronger and easier to accept for a wider audience.

Author's response to Comment 2.2: Indeed, the author believes that the use of Correction Factors is useless and even harmful (a dead end) in radon regulation. In the context of an impartial and rigorous analysis, the use of Correction Factors does not have even limited usefulness; on the contrary, it leads to an uncertain (unreliable) conformity assessment of a room (building) to radon safety requirements. However, it is important to clarify here that the author does not use terms such as “entirely without benefit” or “useless” or “harmful” in the reviewed article, preferring softer expressions such as “outdated and ineffective”, which most accurately reflect the real situation in regulation that has arisen since the publication of the Rational Method (approach). Unfortunately, the radon community traditionally continues to use the uncertain (unreliable and outdated) Correction Factors approach, which has become so deeply rooted in radon regulation practice over three decades that the Rational Method (approach) is not even accepted (discussed) in the radon community (among researchers and regulators). For example, a Review Article (https://doi.org/10.1155/ina/2486546) was recently published covering data on Seasonal Correction Factors for 30 countries. In this Review Article, the following facts raise fundamental questions and comments: (A) The Review Article reports: “*Five different methods for estimating annual averages using seasonal correction factors (SCFs) are critically reviewed. Due to the number and complexity of human-induced and environmental influences,* ***seasonal fluctuations in 222Rn activity may be unpredictable and nonsinusoidal****. The typical pattern observed in the Northern Hemisphere—elevated indoor 222Rn concentrations during autumn and winter—****does not universally apply****. Accordingly, SCFs should be locally derived and interpreted within the regional climatic and hydrogeological context*”. Apparently, the statements (conclusions) highlighted in bold required about 30 years of research, although these conclusions became clear to me (the author of the reviewed article) within 2-3 years after the start of systematic research (through year-long continuous measurements of radon concentration in different rooms and buildings). It is important to recall here that, unlike the SCF approach, the Rational Method (approach) enables the integrated consideration of all anthropogenic and natural factors—including seasonal variations—that influence temporal (key) uncertainty. As a result, it eliminates the need for traditional analysis that examine the effect of each factor individually on the temporal behavior of indoor radon. This allows buildings to be tested at any convenient time without accounting for seasonal effects, as this does not compromise the reliability of the conformity assessment. (B) The variety of SCF methods mentioned in the Review Article indicates the lack of a unified approach (standard) in organizing studies of temporal variations of indoor radon, despite 30 years of efforts in one direction among many countries. (C) The representativeness of national SCF values (presented in the Review Article for comparative analysis) is highly questionable, especially in cases where the sum of the four SCFs divided by 4 differs significantly from 1. After all, SCF values should express the weights of seasonal contributions when assessing the annual average (arithmetic mean) concentration of indoor radon. (D) The problem of the duration of measurements is not discussed at all, although it is obvious that the reliability of the conformity assessment increases with the increase in the duration of measurements. (E) In addition to the various national SCF values (which are not credible), the Review Article provides a Flowchart (Figure 4) for “*SCF application for aboveground structures in practice if 222Rn mean annual activity concentration is not available*”.

This Flowchart appears to be the current culmination of 30 years of efforts by different countries, while the issue of the reliability of conformity assessment based on such a Flowchart is not (traditionally) discussed at all in the Review Article. (F) **The most amazing fact.** The References list in the Review Article includes our recent article "IAEA Safety Guides..." [6], in which the Rational Method is proposed as a detailed guideline (measurement protocol). The Rational Method has full metrological support and can serve as a basis for international standardization of indoor radon testing, ensuring the decision-making reliability of at least 95% in accordance with fundamental ISO rules. **However, the Rational Method is not even mentioned in the Review Article**. It is very sad that experts from the radon community prefer to endlessly discuss and examine the SCF without system, instead of simply paying attention to the Rational Method (protocol), in which no expert (including the reviewer) has identified any shortcomings. Another argument of the reviewer that Correction Factors "have had some practical use in certain regulatory and data-limited situations" is not entirely relevant, since data-limited situations often arise due to: 1) the unjustified mistrust of the radon community in the results of short-term measurements, which are deliberately discarded (please see Section 2.5 in Article [6]), and 2) the unwillingness (or inability) of European regulators to involve the population in the radon regulation industry, although this has long been implemented in the US. Moreover, efforts by European national regulators to improve the accuracy of collective dose (radon risk) assessments or the location of RPA boundaries (especially using questionable SCF values) have no clear practical benefit. After all, the collective dose (radon risk) and RPA boundaries have already been defined with good accuracy in European countries. Furthermore, it is known that a much larger number of hazardous buildings are usually located outside the RPA, so it is necessary to implement mass measurements of indoor radon throughout the country via active participation and funding from the population (as in the US) and not just test buildings inside the RPA. For example, in Germany a detailed Radon Map has been created and collective doses (radiation risks) have been well assessed, but this does not contribute to reducing the collective dose (risk). Indeed, fundamental challenges still remain unresolved: 1) effective and reliable mass testing to identify hazardous buildings in which the reference level is exceeded; 2) the development and implementation of advanced technologies (as in the US) to protect buildings from soil radon. Although the large European five-year project RadoNorm, coordinated by the German Metrology Institute (BfS) with the participation of more than 50 institutes from different countries, was recently completed. Thus, the traditional application of SCF for 30 years clearly demonstrates a dead-end path that has no development and also replaces and hinders the implementation of the Rational Method (approach) in both international and national radon regulation.

Author's Decision to Comment 2.2: Rejected

Comment 2.3: Response to Author's Reply to Comment 3 (Novelty of the Study) Thank you for pointing out Section 1.4. Even though the objectives are listed there, it would help the reader if the manuscript explicitly stated how this study is different from your previous work. As some important arguments (like the role of uncertainty about time and the critique of correction factors) were presented earlier, a short paragraph would be useful to summarize the specific new things this paper adds (e.g. using Finnish data, improving the YLCM exclusion criteria, checking the uncertainty about time across countries). This would make it clearer what is new and improve the overall clarity of the paper.

Author's response to Comment 2.3: Thank you for this comment. The corresponding adjustments have been made to Section 1.4, which emphasize the novelty of the study by clarifying the wording of objectives 1 and 3 (without changing their original meaning). It is also useful to recall that the “specific new things” noted by the reviewer – such as (1) “using Finnish data”, (2) “improving the YLCM exclusion criteria”, and (3) “checking the uncertainty about time across countries” – were previously expressed in the wording of Objectives 1, 2 and 3, respectively. To understand the objectives (novelty) of the research under discussion, it seems obvious that a reader (as well as a reviewer) should first study the previously published Rational Method (approach) [6,9], as well as other articles [5, 22, 23, 30, 31], if the reader (reviewer) has questions. It is also useful to clarify that it is not the manuscript that is subject to review, but the already published article.

Author's Decision to Comment 2.3: Accepted

Comment 2.4: Response to Author’s Reply to Comment 4 (Handling Borderline Cases)
Thank you for the reference to article [6]. However, for completeness, the current manuscript should briefly summarize how the Rational Method deals with borderline cases near the reference level. This information is essential for regulators and practitioners, and it is more convenient if it appears directly in the manuscript instead of requiring readers to consult another publication. A concise explanation would significantly improve the usefulness and accessibility of the paper.

Author's response to Comment 2.4: Judging by the very general wording of the question, containing specific terminology (“borderline cases near the reference level”), it seems that the reviewer has not yet fully studied the Rational Method based on the concept of uncertainty that provides a reliable conformity assessment (with a probability of a true decision of at least 95%), which is radically different from the traditional SCF approach (with an unknown reliability of conformity assessment of a room/building with radon safety requirements). The principle of conformity assessment is given in Section 1.2 (in the context of comparison with the traditional approach), and Section 2.1 provides a quantitative (rational) criterion for conformity assessment ensures a decision reliability of at least 95%, meaning no more than a 5% false-negative error in determining whether a room complies with safety requirements (reference level). Additionally, Section 2.2 provides algorithms for determining temporal uncertainty and the multiplicity factor. If this extensive information is not sufficient to answer the reviewer's question, then it is necessary to refer to Article [6], which presents in detail the Rational Method in the form of a clear measurement protocol for indoor radon testing, which can be used as a draft of an international or any national standard, which is indeed essential for regulators and practitioners. Moreover, given the opinion of the first reviewer (Joan Frédéric Rey): “that it becomes illusory to identify a single standard”, the author is confident that no additional information added to the reviewed article will in any way help those who do not wish to delve deeply into the Rational Method. In this regard, the reviewer should formulate not a general question, but a specific question addressed to a specific fragment of text from the article under review, or a specific paragraph from Section 4 in Article [6], where the Rational Method is presented in detail.

Author's Decision to Comment 2.4: Rejected

Comment 2.5: Response to Author's Reply to Comment 5 (Overlapping Windows / Autocorrelation) Thank you for the clarification. The agreement between overlapping and non-overlapping windows is reassuring. However, the issue of autocorrelation is a known methodological point, and acknowledging it briefly would improve transparency. A short note explaining why the effect is expected to be small in your analysis would strengthen the methodological section without changing your conclusions. **Author's response to Comment 2.5:** The author does not see the benefit of discussing (or mentioning) irrelevant issues in the article under review. If, besides the reviewer, someone else has a similar question (Overlapping Windows / Autocorrelation), then the answer to this question can be obtained independently by studying the relevant articles from the list of references, or by appropriately processing the original data arrays from the "Underlying data" section. Furthermore, the results of this discussion between the reviewer and the author will always be publicly available as an integral part of the peer-reviewed article on the ORE platform.

Author's Decision to Comment 2.5: Rejected

Comment 2.6: Response to Author's Reply to Comment 6 (Universality of Temporal Uncertainty Values) Thank you for the detailed answer. I understand your argument that universal values may be practical in the absence of country-specific data. At the same time, the current evidence is based on only three countries. Therefore, statements about universality should be phrased carefully. It would be scientifically stronger to say that the available results suggest broad applicability, but that additional validation in other climates and building types would be useful. This approach maintains your core message while reducing the risk of overgeneralization.

Author's response to Comment 2.6: The experimental (statistical) material accumulated over many years shows that the initially determined values of temporal uncertainty (several buildings in Russia), published back in 2018 [31], were confirmed on a more extensive statistical material (a larger number and variety of buildings in Israel) in 2021 [5], as well as in 2022 [30] and 2023 [22]. Now the original values of temporal uncertainty have been confirmed again on the basis of a more extensive statistical array, which was obtained by independent (other) researchers from STUK (Finland). Thus, based on long-term and systematic research experience, the author believes with a high degree of confidence that the existing values of temporal uncertainty (in normal mode), previously considered conservative [22,30,31], will change insignificantly as the statistical data array, covering more and more countries on different continents, continues to accumulate. At the same time, the author does not exclude the possibility of adjusting the values of temporal uncertainty, therefore, in paragraph (b) of ANNEX A (Temporal Uncertainty Component in Conformity Assessment) in Article [6] the following is reported. "*(b) Reducing temporal uncertainty $U_V(t)$ can likely be achieved by significant increasing the array of statistical data through the accumulation and processing of continuous year-long measurements of radon concentration (with a registration period of 1 or 3 h) in several hundred buildings (with elevated radon content) of different types located in one or multiple countries under different climatic and geological conditions.... **National values of temporal uncertainty may vary due to the influence of geology, climate, architectural design, and household traditions**. Additionally, a statistically significant correlation between $U_V(t)$ and characteristics such as building type, floor*

level, etc., may be discovered, allowing for the ranking of measurement conditions and further reduction in temporal uncertainty".

Author's Decision to Comment 2.6: Rejected

Comment 2.7: Response to Author's Reply to Comment 7 (Limitations Section) Thank you for the explanation. Nevertheless, I believe the manuscript would benefit from a short, self-contained section summarizing the main limitations, including data representativeness, regulatory acceptance challenges, and practical requirements for implementing the Rational Method. Presenting these points directly in the manuscript will improve clarity for readers and increase transparency, especially for stakeholders who may consider applying the method in practice.

Author's response to Comment 2.7: The main limitations of the Rational Method are discussed in detail in Sections 4.4 ("Principle of Measurement and Conformity Assessment") and 4.5 ("Test Conditions", which were clarified in the reviewed article) of Article [6]. Limitations regarding collecting statistical data to improve the representativeness of temporal uncertainty estimates are given as a list from (a) to (f) in Section 2.3 of the article under review, and Section 3.2 is devoted entirely to clarifying only limitation (f). In this regard, unfortunately, it is not possible to briefly formulate in a self-contained section (Limitations Section) of the article under review the main limitations of the Rational Method. Therefore, it would be appropriate to publish an updated (regulatory-agreed) Rational Method as an international and/or national standard, including: i) appropriate clarifications in Sections 4.4 and 4.5, ii) an additional paragraph in ANNEX A listing limitations on collecting statistical data to improve the representativeness of temporal uncertainty estimates, iii) relevant additional literature (including the reviewed article) in the reference list.

Author's Decision to Comment 2.7: Rejected

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 22 November 2025

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Miroslaw Janik

National Institutes for Quantum Science and Technology (QST), Chiba, Japan

The manuscript raises important points and reflects the authors' strong commitment to improving radon regulation. However, several aspects require further explanation and clarification, as outlined in the comments below:

- The manuscript's language is at times overly polemical (e.g., "irrational," "outdated"), which may reduce its persuasive power. A more neutral and collaborative tone would better engage regulators and readers.
- Statements dismissing correction factors as "ineffective" overlook their partial utility in population-level risk mapping and data-limited contexts. Reframing them as incomplete rather than invalid would improve balance.
- Several core arguments (e.g., dominance of temporal uncertainty, critique of correction factors, ISO/IEC framing) have appeared in earlier publications. The authors should clearly identify what is new in this manuscript and how it extends prior to work.
- The manuscript should clarify how the Rational Method handles cases where measured radon concentrations are close to the reference level e.g., through extended measurements, repeated tests, confidence intervals or the others.
- Temporal uncertainty is estimated using overlapping windows, which are highly correlated. Without correcting autocorrelation, the effective sample size is inflated, and uncertainty estimates may be biased.
- The assertion that temporal uncertainty values are globally applicable is based on a limited number of datasets (Russia, Israel, Finland). Broader validation across diverse climates and building types is needed to support this claim.
- The authors briefly mention some constraints (e.g., The RM requires access to high-quality, year-long datasets for its uncertainty estimation process; exclusion of incomplete series), but a more systematic discussion of limitations such as including data representativeness, regulatory acceptance, and practical deployment, would strengthen the manuscript.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My core areas of research involve radon studies, encompassing measurement and monitoring techniques, statistical and data analysis as well as regulatory frameworks.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 25 Nov 2025

Andrey Tsapalov

The Author's responses and decisions regarding the comments of the Reviewer - **Miroslaw Janik,** National Institutes for Quantum Science and Technology (QST), Chiba, Japan

General comment: The manuscript raises important points and reflects the authors' strong commitment to improving radon regulation. However, several aspects require further explanation and clarification, as outlined in the comments below:
Author's response to General comment: The author thanks the reviewer for understanding the importance of the article and for the overall high rating. At the same time, almost all seven of the reviewer's comments were rejected by the author based on the evidence for each comment. Unfortunately, it remained unclear which specific points (from "a" to "i") in the Conclusion Section the reviewer had in mind when he selected "Partly" in answer to the question: "Are the conclusions drawn adequately supported by the results?"

Comment 1: The manuscript's language is at times overly polemical (e.g., "irrational," "outdated"), which may reduce its persuasive power. A more neutral and collaborative tone would better engage regulators and readers.
Author's response to Comment 1: Thank you for this comment. Indeed, both terms appear repeatedly in the published article (not the manuscript), but not in the context of polemical, but as the author's statement that a traditional approach focusing on the Temporal Correction Factor is outdated and inefficient. This statement occurs several times in the Introduction in the context of a fairly simple logical justification. Then, this statement is repeatedly found in the final sections of the article in the context of the comparative analysis and generalization of the results within the Rational Method with the results of colleagues from Finland. It should be recognized, however, that the verb "seems" cannot be used in the context of the statement, so the author has slightly corrected the first sentence in the fourth paragraph in Section 1.2, which will be clarified in the updated version of the article: "However, both of the aforementioned studies1,24 continue to rely on the traditional use of "correction factors", which is outdated and ineffective." Here "is" is used instead of "seems". Contrary to the reviewer's opinion, the author is convinced that a scientifically proven fact (not only on the basis of elementary logic, but also on the basis of data, including the results of the comparative analysis), expressed in the form of the statement that "a traditional approach is outdated and inefficient", cannot reduce the persuasive power of the article.
Author's Decision to Comment 1: Accepted partly

Comment 2: Statements dismissing correction factors as "ineffective" overlook their partial utility in population-level risk mapping and data-limited contexts. Reframing them as incomplete rather than invalid would improve balance.
Author's response to Comment 2: First, there is a provision regarding the partial usefulness of the correction factors in Section 1.3: *"Therefore, a separate consideration of the seasonal factor does not contribute to improving the quality of conformity assessment of rooms (buildings) to safety requirements. The consideration of the seasonal factor may be useful in refining collective risks but not individual risks within the conformity assessment of rooms/buildings"*. Secondly, despite the cited provision, the author does not see any tangible benefit from using correction factors in general for the following reasons: 1. Given that Finnish data are highly statistically representative (compared to data from other countries), especially given the significant temperature difference between winter and summer, the correction factor used in Finland (set at 0.9) introduces only a 10% seasonal adjustment, which indicates that seasonal variation has a relatively minor impact. 2. The traditional use of correction factors replaces and hinders the implementation of a rational approach, within which population-level risk mapping could be much more effective through large-scale (mass) indoor radon testing (as in the US), rather than the traditional European focus on only Radon Priority Areas. This is discussed in more detail in Section 2.2, "Excessive Focus on Radon Priority Areas," in [6].
Author's Decision to Comment 2: Rejected

Comment 3: Several core arguments (e.g., dominance of temporal uncertainty, critique of correction factors, ISO/IEC framing) have appeared in earlier publications. The authors should clearly identify what is new in this manuscript and how it extends prior to work.
Author's response to Comment 3: The relevance (novelty) of the published article (not the manuscript) is clearly expressed in the four objectives that are given at the very end of the Introduction in section 1.4 "Objectives of the study". The rationale for the relevance of these particular study objectives is provided in four sections of the Introduction. Regarding " *ISO/IEC framing*", the author (as a member of the working group ISO/TC85/SC2/WG17 "radioactivity measurements" until 2023) was very surprised by the reluctance of other ISO experts to develop (and even discuss) constructive proposals regarding the implementation of the Rational Method, which is intended for efficient and reliable testing of indoor radon. At the same time, no one (including the reviewer) has yet identified any serious shortcomings in the Rational Method. Moreover, some colleagues from the expert community (such as another reviewer, Joan Frédéric Rey) are conservative and poorly informed to such an extent that they still believe "*that it becomes illusory to identify a single standard*".
Author's Decision to Comment 3: Rejected

Comment 4: The manuscript should clarify how the Rational Method handles cases where measured radon concentrations are close to the reference level e.g., through extended measurements, repeated tests, confidence intervals or the others.
Author's response to Comment 4: The clarification required by the reviewer is provided in the article [6], the second part of which presents in detail the Rational Method in the form of a clear measurement protocol for indoor radon testing, which can be used as a draft of an international or any national standard. It is a pity that the reviewer did not try to study the

Rational Method in detail and missed the article [6], which is referenced about 50 times in the article under review.
Author's Decision to Comment 4: Rejected

Comment 5: Temporal uncertainty is estimated using overlapping windows, which are highly correlated. Without correcting autocorrelation, the effective sample size is inflated, and uncertainty estimates may be biased.
Author's response to Comment 5: Thank you for this important comment. The reviewer rightly points out the potential problem. In this regard, it is important to note that in previously published studies [5,31], the temporal uncertainty was estimated using windows (intervals) of experimental data that did not overlap. However, the temporal uncertainty values are the same as in later studies [22,30], in which the experimental data windows do overlap (as in the study under discussion). Furthermore, it is also important to note that Figure 5 includes an estimate of temporal uncertainty derived from the conversion of data [22,30] from earlier Finnish study by Arvela et al (2015), originally reported in [32]. As can be seen from this figure, the temporal uncertainty is in good agreement over the 2 to 12-month interval, while the original data in Arvela et al (2015) were processed without overlapping windows. Thus, it can be concluded that the estimate of the temporal uncertainty does not depend on the degree of overlap of the windows (intervals) that include the time series of measured indoor radon concentrations.
Author's Decision to Comment 5: Rejected

Comment 6: The assertion that temporal uncertainty values are globally applicable is based on a limited number of datasets (Russia, Israel, Finland). Broader validation across diverse climates and building types is needed to support this claim.
Author's response to Comment 6: In connection with this remark, it is important to draw the reviewer's attention to the relevant clarification that appears repeatedly in the article under review. For example, the Abstract states: "*(2) Clarification of temporal uncertainty values based on the initial experimental data, supporting the justification of previously published uncertainty estimates as potentially universal across countries* ***in the absence of reliable country-specific data***". At the very end of Section 3.1 it is stated: "*This means that the behaviour of indoor radon in Finland is not unique, given that previous studies were conducted under significantly different climatic and geological conditions at Israeli [5] and Russian [30,31] experimental sites. This finding challenges the hypothesis that "certain characteristics unique to Finland suggest that temporal variations in radon concentration, as quantified in other parts of the world, may not necessarily apply to Finnish conditions" [1]. Consequently, this strengthens the confidence that previously published values of temporal uncertainty (for example, in [6]) are applicable across different countries and can be used in national regulations* ***in the absence of more reliable country-specific data***". Finally, the Conclusion Section reports: "*c) The behaviour of indoor radon in Finland is not unique, therefore it can now be more reasonably argued that previously published values of temporal uncertainty—validated using STUK data—are universal across different countries. Therefore, they can be used in national measurement protocols for indoor radon testing* ***in the absence of more reliable country-specific data***". Clearly, it is better to use the available universal values of temporal uncertainty in the absence of more reliable country-specific data than to continue to ignore the main component of decision-making uncertainty, which is a sad fact on a global scale. The author (and his associates) have been calling on colleagues in the radon community to

conduct as many YLCMs as possible in their countries for over **eight years** [9], which is also a concern of the reviewer, judging by his call. However, for example, of the more than 50 EU organizations participating in RadoNorm, only colleagues from STUK (Finland) conducted YLCMs in a representative sample of buildings. Perhaps the reviewer could explain what is stopping him and other colleagues (regulators) from different countries from organizing and conducting not particularly expensive [9], but vitally necessary YLCMs, instead of a multitude of funded radon studies, the value of which is significantly lower or even questionable, as follows from Section 1.1. "*In recent years, however, there has been a noticeable shift away from field studies on the temporal variability of indoor radon— which could have been conducted within a long-proposed rational approach [6,9]—toward the publication of numerous reviews on radon strategies adopted in various countries, including methods for indoor radon testing [10–18], none of which are supported by adequate metrological foundations [9]. Moreover, the RadoNorm project places considerable hope in a questionable hypothesis: the possibility of identifying hazardous buildings (i.e., those exceeding the reference level) without conducting indoor radon measurements [19,20]. It remains unclear what value such reviews and hundreds of related studies offer if they fail to generate the data necessary for harmonization and international standardization of measurements aimed at improving the effectiveness and reliability of indoor radon testing within the framework of modern metrology*".
Author's Decision to Comment 6: Rejected

Comment 7: The authors briefly mention some constraints (e.g., The RM requires access to high-quality, year-long datasets for its uncertainty estimation process; exclusion of incomplete series), but a more systematic discussion of limitations such as including data representativeness, regulatory acceptance, and practical deployment, would strengthen the manuscript.
Author's response to Comment 7: The issue of data representativeness is discussed in the Author's response to Comment 6. The reviewer's other concerns (regulatory acceptance and practical deployment) are discussed in detail in [6], which the reviewer unfortunately missed and is reported in more detail in Author's response to Comment 4.
Author's Decision to Comment 7: Rejected

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 November 2025

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Joan Frédéric Rey
HES-SO University of Applied Sciences and Arts Western Switzerland, Fribourg, Switzerland

General comment: The present study reports the results of a reanalysis of continuous indoor

radon data conducted in Finland using an algorithm referred to as the rational method. Although the findings are interesting and the methodology demonstrates reproducibility, the work lacks impartiality. The discourse adopted in the paper appears biased and does not fully meet academic standards. Furthermore, the literature review focuses on only one aspect of the issue of the annual representativeness of short-term radon measurements, while neglecting other relevant perspectives. Before indexing, the study must address the comments outlined below and adopt a more scientific and rigorous stance, rather than defending a predetermined position at all costs.

Comment 1: "*In this context, it is important to note that short-term measurements (typically lasting from 2 to 7 days) have been used in U.S. regulations—demonstrating high effectiveness—for over 30 years*". Can the author support this affirmation by other studies, carried out by other researchers than himself, in the US and Canada for instance?

Comment 2: The literature is not sufficient to provide a food overview to the reader. Among the 37 references, 9 were co-written by the Author, 14 are related to regulations, 2 websites and only the rest other studies. Here the Author must expand the literature review by including more peer-reviewed studies assessing the yearlong representativeness of radon short-term measurements, the challenges it raises in Europe, and what is the consensus in Europe nowadays.

Comment 3: I can't agree with the following affirmation : "*none of which are supported by adequate metrological foundations*". Studies carried out in MetroRadon and RadoNorm were explicitely carried out in the metrological frameworks at both national, and continental levels. The author should (again) add references here and look at how they're included and in-line within national regulations.

Comment 4: This sentence "*Moreover, the RadoNorm project places considerable hope in a questionable hypothesis: the possibility of identifying hazardous buildings (i.e., those exceeding the reference level) without conducting indoor radon measurements*[19,20]" relates more to the Author opinion than a real scientific position. Please rephrase this sentence.

Comment 5: I agree with the following sentence "*Despite the significant time and financial investments made over the years, there is still no internationally agreed-upon standard with metrological support for the reliable conformity assessment of rooms and buildings with radiation safety requirements*[6,9].". However, this is for a good reason: buildings characteristics and environmental features are too different across countries that it becomes illusory to identify a single standard. Can the Author investigate more this field, or at least, present this major issue in the present paper ?

Comment 6: "*Even with measurement durations of two or three months, temporal uncertainty remains very high—around 100% and 85%, respectively*[6,9]." Again, if the Author had looked deeper in the literature (not only his references), and this in recent studies, this sentence is absolutely false. Such a sentence presents only a side of the issue, the one that deserve Author's purposes. Therefore, the author should remove this sentence, or complement it with other studies.

Comment 7: " Unfortunately, many national regulators and ISO experts continue to disregard this fact, maintaining a narrow focus on instrumental uncertainty, which rarely exceeds 30%[6,9,22]." I request the Author to look (again) at other studies than his own. Recent studies (>2020) have been

carried out in Europe, and Canada and depict performance above 30% related to the device used. Although devices type does not fully contribute to the uncertainty, this issue should not be disreguarded as the Author suggest. Please add reference, and adapt the sentence relatively to the references found.

Comment 8: "Moreover, due to the deeply rooted conservatism within the radon community, there is still no internationally harmonized strategy for rational radon regulation[6,23]." This is not a the reason. Please change this.

Comment 9: "which seems outdated and ineffective". This sentence does not belong to a scientific paper. Please remove.

Comment 10: "*This rational approach enables the most effective implementation of the primary goal of indoor radon testing — "to assess the need for radon remediation in buildings"[1], while "estimate residents' exposure or assess public exposure"[1] should be considered as a secondary (optional) goal*" I do not agree with this sentence. Indoor radon measurements are recommended by public health authorities, which first and main aim is to estimate residents exposure, to develop public health politics. The Author should rephrase this sentence.

Comment 11: Results are well structured, presenting successively the results of the analysis. I would suggest the Author to move sections 3.2, 3.3, and 3.4 in a new discussion section. These sections are not results in themselves, however they more a interpretation of them.

Comment 12: Section 3.4 is excessively long. The author must here considering to shorten this section by keeping only the necessary.

Comment 13: "We hope that our critique of the outdated and inefficient traditional approach together with the proposed Rational Method will be regarded as a constructive and valuable contribution by regulators and metrology experts, including those engaged in ISO and IAEA processes." These sentences does not fit an academic standard.

Is the work clearly and accurately presented and does it cite the current literature?
No

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I work in radon field since 2019 and published different papers tackling related-issues.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 09 Nov 2025

Andrey Tsapalov

The Author's responses and decisions regarding the comments of the Reviewer - **Joan Frédéric Rey,** HES-SO University of Applied Sciences and Arts Western Switzerland, Fribourg, Switzerland
General comment: The present study reports the results of a reanalysis of continuous indoor radon data conducted in Finland using an algorithm referred to as the rational method. Although the findings are interesting and the methodology demonstrates reproducibility, the work lacks impartiality. The discourse adopted in the paper appears biased and does not fully meet academic standards. Furthermore, the literature review focuses on only one aspect of the issue of the annual representativeness of short-term radon measurements, while neglecting other relevant perspectives. Before indexing, the study must address the comments outlined below and adopt a more scientific and rigorous stance, rather than defending a predetermined position at all costs.
Author's response to General comment: The author thanks the reviewer for taking the time, but his review cannot be considered impartial and useful, meeting the requirements of ORE (academic standards). None of the reviewer's comments were supported by references to specific alternative data or specific literature sources. 10 of the 13 comments relate to the first two sections of the Introduction. The other two comments concern the structure of the article. As a result, 11 of the 13 reviewer comments were reasonably rejected by author (with references to specific data and literature sources). Only two remaining comments were accepted partly only formally, although they are more in line with the “rejected” status. It is important to note that the reviewer made no comments on the vast majority of the article, including the Rational Method, the results and their discussion (not including two comments on structure), and all points in the Conclusion Section. Consequently, the Article Sections: Method, Results and Discussion, and Conclusion, - completely satisfy the reviewer. Nevertheless, the reviewer makes a rather stern remark to the author: “adopt a more scientific and rigorous stance”. In this regard, it is advisable to redirect to the reviewer himself his conclusion on “defending a predetermined position at all costs”.

Comment 1: "In this context, it is important to note that short-term measurements (typically lasting from 2 to 7 days) have been used in U.S. regulations—demonstrating high effectiveness—for over 30 years". Can the author support this affirmation by other studies, carried out by other researchers than himself, in the US and Canada for instance?

Author's response to Comment 1: For some reason, the reviewer missed the references to Articles 5 and 6 at the end of this quote. While these articles provide the relevant analysis and evidence requested by the reviewer (but it is unclear why the reviewer also mention Canada). For example, Article 5 contains the following text: “Statistical data proves that radon regulation in the US (further called “The American approach”) is in general more efficient than the one implemented within the EU. For instance, about 1,155,000 measurements (**Cinelli et al., 2019**) or about only 2 tests per 1000 people were conducted in the EU (Fig. 1). This number covers less than 1% of buildings in Europe (**IAEA, 2019**), although with the support of national governments measurements have been taken for over two to three decades. Thereafter, only 26,000 European dwellings have undergone remediation (**Holmgren et al., 2013**). In contrast, more than 23,000,000 short-term (about 98%) and about 500,000 long-term (only 2%) measurements (**George, 2015**), i.e. about 70 tests per 1000 people, have been taken in the US. As a result, over 1,240,000 homes in the US have been successfully mitigated (**George, 2015**), thanks to the initiative and funding of occupants and property owners themselves as well as due to the low cost and the relative simplicity of short-term tests. Such a huge volume of testing and mitigation dramatically reduces the health risks associated with radon exposure in the US. One of the main reasons for this achievement is obviously the popularity and priority setting of screening (short-term tests) in the US, given that only 9% of the population agrees to conduct long-term tests (**Johnson, 1990; US EPA, 1992**). However, this important fact has not been taken into account by European regulators, including ISO experts (ISO 11665-8, 2019).” Article 6 contains the following text: “It is also important to note that the effective US approach to reducing radon risk [15], based on short-term measurements (2–7 days) [16,17], fundamentally differs from the European approach based on long-term measurements [14,18]. Radon tests (and mitigation measures) in the US have been conducted due to funding by the population in tens of millions [15,19] (and several million [20]) of buildings, which is 10–100 times greater than in the EU [15], where building testing is mainly funded from administrative (national or municipal) budgets [18].” [19] George, A. The history, development and the present status of the radon measurements programme in the United States of America. Radiat. Prot. Dosim. 2015, 167, 8–14. [20] The US National Radon Action Plan 2021–2025. Available online: http://www.radonleaders.org/sites/default/files/2022-01/NRAP-2021-2025-Action-Plan-508.pdf Unfortunately, none of European experts have conducted a similar comparative analysis of the effectiveness of national radon regulation systems, apparently due to the very low effectiveness of radon regulation in the European system.

Author's Decision to Comment 1: Rejected

Comment 2: The literature is not sufficient to provide a food overview to the reader. Among the 37 references, 9 were co-written by the Author, 14 are related to regulations, 2 websites and only the rest other studies. Here the Author must expand the literature review by including more peer-reviewed studies assessing the yearlong representativeness of radon short-term measurements, the challenges it raises in Europe, and what is the consensus in Europe nowadays.

Author's response to Comment 2: The article under discussion is devoted to the problem of estimating the temporal uncertainty of indoor radon (and not the representativeness of radon short-term measurements), which is used in the Rational Method. Unfortunately, until now no one except the author (and his co-authors from previous publications) has

attempted to estimate the temporal uncertainty of indoor radon, especially within the framework of a rational approach (where the temporal uncertainty was clearly defined). Therefore, there are no other published studies that specifically address the assessment of temporal uncertainty. This fact explains the need to include 9 articles (co-written by the author) in the References list. Furthermore, the author does not see the benefit or necessity of including additional articles (by other authors) in the References list for the reason given in section 1.1: “It remains unclear what value such reviews and hundreds of related studies offer if they fail to generate the data necessary for harmonization and international standardization of measurements aimed at improving the effectiveness and reliability of indoor radon testing within the framework of modern metrology.” In the context of the article under review (titled "Temporal Uncertainty in the Rational Method: Reassessment of Data from the Article 'Short-Term Temporal Variability of Radon in Finnish Dwellings and the Use of Temporal Correction Factors'"), a detailed comparative analysis of the results using the Rational Method with the results of colleagues from Finland seems entirely sufficient. This comparative analysis does not require additional references to studies by other authors, although other authors are also mentioned in the article. While the Finnish colleagues published valuable initial experimental data, they used an outdated and ineffective traditional approach to process it, which, overall, reflects a deeply ingrained conservatism in radon regulation, that the reviewer assesses as "the current consensus in Europe". This sounds very sad.
Author's Decision to Comment 2: Rejected

Comment 3: I can't agree with the following affirmation : "none of which are supported by adequate metrological foundations". Studies carried out in MetroRadon and RadoNorm were explicitely carried out in the metrological frameworks at both national, and continental levels. The author should (again) add references here and look at how they're included and in-line within national regulations.
Author's response to Comment 3: The reviewer disagrees with the author, but does not provide references to research within the MetroRadon or RadoNorm, or articles published by other authors, which would specifically study the temporary (key) uncertainty, and not various surrogates such as Correction Factors, etc., the use of which does not allow one to determine the reliability of the conformity assessment of a room (building) with safety requirements. According to the fundamental concepts of modern metrology in the context of indoor radon testing, temporal uncertainty is a key component of the uncertainty in conformity assessment, since it is not just the measured concentration that is subject to metrological assurance, but the **annual average** concentration of indoor radon, which is limited by a reference level. The reference level is expressed in units of **annual average** radon concentration. However, the temporal (key) uncertainty in the assessment of the **annual average** indoor radon concentration is still not taken into account, so the affirmation: "none of which are supported by adequate metrological foundations" expresses the actual situation in radon regulation.
Author's Decision to Comment 3: Rejected

Comment 4: This sentence "Moreover, the RadoNorm project places considerable hope in a questionable hypothesis: the possibility of identifying hazardous buildings (i.e., those exceeding the reference level) without conducting indoor radon measurements19,20" relates more to the Author opinion than a real scientific position. Please rephrase this

sentence.
Author's response to Comment 4: The reviewer (who is the first author of 20) again does not provide specific examples (evidence) to support his comment. It is unclear what "a real scientific position" means. It is important to remember that Article 20 is titled "Systematic review of statistical methods for the identification of buildings and areas with high radon levels." However, Article 20 does not mention at all indoor radon measurement protocols for conformity assessment (reliable identification) of a rooms (buildings) with safety requirements. The problem of reliability of conformity assessment is mentioned in 20 only occasionally and only at a qualitative level, as is the description of identification algorithms. No quantitative criteria for conformity assessment (reliable identification) are given at all. At the same time, only the Rational Method is capable of ensuring high efficiency and the specified reliability of identifying hazardous buildings, while its algorithm for determining temporal uncertainty is based on a statistical method, but the long-proposed rational approach is not mentioned at all in 20. Moreover, the title of article 20 does not fully correspond to the objectives, methods and results of the study presented in 20, since the problem of identifying buildings with high radon levels is replaced by the problem of identifying areas with high radon levels, which is not the same thing. Thus, the title of article 20 (as well as its abstract), prepared within the RadoNorm project, is misleading to the scientific community and interested readers. The most appropriate title would be: “Systematic review of statistical methods for the identification of areas with high indoor radon levels.” Unfortunately, such substitutions of “a real scientific position” significantly complicate the implementation of a rational approach to radon regulation. It would also be advisable for the reviewer to carefully read Section 2.2 titled “Excessive Focus on Radon Priority Areas” in Article 6.
Author's Decision to Comment 4: Rejected

Comment 5: I agree with the following sentence "Despite the significant time and financial investments made over the years, there is still no internationally agreed-upon standard with metrological support for the reliable conformity assessment of rooms and buildings with radiation safety requirements6,9.". However, this is for a good reason: buildings characteristics and environmental features are too different across countries that it becomes illusory to identify a single standard. Can the Author investigate more this field, or at least, present this major issue in the present paper?
Author's response to Comment 5: The reviewer again makes a questionable comment, demonstrating their insufficient knowledge of the Rational Method, as well as the article under review as a whole. For example, section 2.1 states the following: “The rational approach enables the integrated consideration of all anthropogenic and natural factors—including seasonal variations—that influence temporal uncertainty. As a result, it eliminates the need for traditional analyses that examine the effect of each factor individually on the temporal behavior of indoor radon6,9.” This unique advantage of the Rational Method is achieved due to the representativeness of the data of the statistical method for determining temporal uncertainty, the description of which is given in the same section 2.1. In relation to the question of data representativeness, it is useful to quote the entire paragraph that appears at the end of section 3.1: “The data presented in Figure 5 demonstrate good agreement between the temporal uncertainty values obtained from the STUK data and those previously published in 5,6,9,22,25,30,31. This means that the behaviour of indoor radon in Finland is not unique, given that previous studies were

conducted under significantly different climatic and geological conditions at Israeli5 and Russian30,31 experimental sites. This finding challenges the hypothesis that “certain characteristics unique to Finland suggest that temporal variations in radon concentration, as quantified in other parts of the world, may not necessarily apply to Finnish conditions”1. Consequently, this strengthens the confidence that previously published values of temporal uncertainty (for example, in 6) are applicable across different countries and can be used in national regulations in the absence of more reliable country-specific data.” It is a pity that the reviewer did not pay attention to these important fragments of the text. Moreover, the reviewer had the opportunity to make specific comments regarding the Rational Method (which is framed as a draft international standard in Article 6), but for some reason he did not take advantage of this opportunity, preferring to remain captive to the conservative belief that “it becomes illusory to identify a single standard”. Unfortunately, such a deeply ingrained conservatism in the judgments of the reviewer (and his colleagues in the RadoNorm project) significantly complicates the implementation of a rational approach to radon regulation.
Author's Decision to Comment 5: Rejected

Comment 6: "Even with measurement durations of two or three months, temporal uncertainty remains very high—around 100% and 85%, respectively6,9." Again, if the Author had looked deeper in the literature (not only his references), and this in recent studies, this sentence is absolutely false. Such a sentence presents only a side of the issue, the one that deserve Author's purposes. Therefore, the author should remove this sentence, or complement it with other studies.
Author's response to Comment 6: The reviewer again makes an unfounded comment (that “this sentence is absolutely false”) because he does not provide references to specific data from specific literary sources to support his harsh conclusion. If the reviewer had read the entire reviewed article carefully, he could have seen that the “absolutely false” (according to the reviewer) values of temporal uncertainty (100% and 85%) are reproduced in Fig. 5 (based on data from STUK experts), and they are even greater in Fig. 4. It is a great pity that the reviewer focused his attention only on the first two sections of the Introduction and missed a lot of interesting things in the remaining (much larger) part of the article under review. As discussed above, even in such a large international project as RadoNorm (in which the reviewer took an active part), the temporal (key) component of the uncertainty in conformity assessment, unfortunately, for some reason was not investigated, as in all other previously conducted studies both at the national and international level. In this regard, it is useful to recall that the author warned the RadoNorm coordinators about the need for a systematic study of indoor radon temporal variations, but this proposal was rejected, as mentioned in section 2.4 “The Standardization of Indoor Radon Measurements” in article 6. Among the more than 50 organizations participating in RadoNorm, only STUK experts conducted YLCM in a relatively large number of buildings in Finland (but used an inefficient data processing algorithm). Unfortunately, instead of vitally needed large-scale systematic field studies, the reviewer and his colleagues participating in RadoNorm have chosen to publish unhelpful (and even misleading) review articles such as 20.
Author's Decision to Comment 6: Rejected

Comment 7: "Unfortunately, many national regulators and ISO experts continue to disregard this fact, maintaining a narrow focus on instrumental uncertainty, which rarely

exceeds 30%6,9,22." I request the Author to look (again) at other studies than his own. Recent studies (>2020) have been carried out in Europe, and Canada and depict performance above 30% related to the device used. Although devices type does not fully contribute to the uncertainty, this issue should not be disreguarded as the Author suggest. Please add reference, and adapt the sentence relatively to the references found**.**
Author's response to Comment 7: Thank you for this comment. This fragment of text will be clarified in the updated version of the article: "Unfortunately, many national regulators and ISO experts continue to disregard this fact, maintaining a narrow focus on instrumental uncertainty, which rarely exceeds 30%6,9,22,25." As you can see, the updated fragment includes only additional link to Article 25, which presents the results of testing the most popular low-cost active radon monitors (CRM-type), which are actively purchased by the public, so their sales have already exceeded millions. Although the author is a co-author, Article 25 discusses and summarizes the checking results of low-cost monitor conducted by experts from Europe and Canada after 2020 (according to the reviewer' criterion). It is important to note that all these monitors are not subject to individual metrological checking after production. However, even in this case, exceeding 30% is rare, according to data from Article 25. Regarding the quality of measurements based on the popular SSNTD and charcoal methods, it can be confidently stated that the instrumental uncertainty does not exceed 30%, because such measurements are carried out by professionals in accredited laboratories. Thus, estimating the proportion of measurements with instrumental uncertainty greater than 30% among millions of indoor radon concentration measurements worldwide, one can state that such a proportion does not exceed 5%, and most likely it is lower than 1-3%. Such an insignificant proportion is quite acceptable within the framework of radiation (including radon) control (please see point (e) in paragraph 3.4.3). Apparently, a lack of understanding of the rational principles of radiation risk regulation explains the desire of the reviewer (and his colleagues at RadoNorm) to achieve an even greater reduction in the proportion of measurements (with instrumental uncertainty greater than 30%), which, however, leads to a significant increase in the cost of regulation without tangible benefits. Moreover, the reviewer and his colleagues at RadoNorm ignore the fact that the temporal (key) uncertainty is usually several times larger than the instrumental uncertainty, yet they continue to focus only on controlling and reducing the instrumental uncertainty, which is highly irrational and is discussed in detail in Articles 6, 22 and 25. It is also important to clarify (and reassure the reviewer) that the author never called for disregarding instrumental uncertainty in any of his articles, including the one under review. Indeed, instrumental uncertainty is taken into account in criterion (1) of section 2.1, and its definition is entirely devoted to Annex B in Article 6.
Author's Decision to Comment 7: Accepted partly

Comment 8: "Moreover, due to the deeply rooted conservatism within the radon community, there is still no internationally harmonized strategy for rational radon regulation6,23." This is not a the reason. Please change this.
Author's response to Comment 8: The author categorically does not share this opinion of the reviewer, especially considering not only the arguments in Articles 6 and 23, but also the fundamental controversy that arose during the review process. Indeed, the reviewer focused all of his criticism (10 out of 13 comments) on the first two sections of the Introduction. However, there were no comments from the reviewer regarding either the Rational Method or the results obtained and their discussion, including all points in the

Conclusion section. Perhaps the reviewer is so confident in his conservative position that he does not even try to understand and discuss the Rational Method and the results obtained. These circumstances are once again convincingly proving the fact that the traditional approach (which the reviewer passionately defends) is outdated and ineffective compared to the Rational Method. Defending the traditional (outdated and ineffective) approach at any cost (without references to specific data and specific literary sources), instead of discussing scientific achievements and their implementation in regulatory practice, is a manifestation of conservatism, to put it mildly. It is this circumstance that is the main reason preventing the implementation of a rational approach to radon regulation.
Author's Decision to Comment 8: Rejected

Comment 9: "which seems outdated and ineffective". This sentence does not belong to a scientific paper. Please remove.
Author's response to Comment 9: Thank you for this comment. This fragment of text will be clarified in the updated version of the article: "which is outdated and ineffective". The reviewer is right that the original text looks like an evaluative (unconfident) opinion, which is not entirely appropriate for scientific paper. Therefore, instead of an evaluative opinion, it is appropriate to use an affirmative expression here. It is also important to clarify that this statement has been used repeatedly and with good reason previously in Review Article 6. In the article under review, this statement occurs several times in the Introduction in the context of a fairly simple logical justification. Then, this same assertion that the traditional approach is outdated and ineffective is repeatedly found in the final sections of the article in the context of the comparative analysis and generalization of the results within the Rational Method with the results of colleagues from Finland using the traditional approach.
Author's Decision to Comment 9: Accepted partly

Comment 10: "This rational approach enables the most effective implementation of the primary goal of indoor radon testing — “to assess the need for radon remediation in buildings”1, while ”estimate residents’ exposure or assess public exposure”1 should be considered as a secondary (optional) goal" I do not agree with this sentence. Indoor radon measurements are recommended by public health authorities, which first and main aim is to estimate residents exposure, to develop public health politics. The Author should rephrase this sentence.
Author's response to Comment 10: Unfortunately, the reviewer did not take into account the text that immediately follows the quoted text, so it is useful to recall it as well: “The issue of priority in the design of indoor radon surveys (testing) is discussed in more detail in the final paragraph 3.4.3(a), as well as in previously published articles6,9,23”. The author does not consider it necessary to reproduce here the text from paragraph 3.4.3(a) or articles6,9,23 as a response to the reviewer who might read it in the process of writing the review. However, in this connection it is also useful to draw the reviewer's (and his colleagues at RadoNorm) attention to one of the following fundamental recommendations of the International Commission on Radiological Protection (ICRP Publication 126): “(n) It is the responsibility of the appropriate national authorities, as with other radiation sources, to establish their own national reference levels of dose and derived reference level of concentration, and to apply the process of optimisation of protection within their country. The objective is both to reduce the overall risk to the general population and, for the sake of equity, the individual risk to the most exposed individuals. **In both cases, the process is**

implemented mainly through the management of buildings rather than individual exposures and should result in radon concentrations in ambient indoor air that are as low as reasonably achievable below the national reference level".
Author's Decision to Comment 10: Rejected

Comment 11: Results are well structured, presenting successively the results of the analysis. I would suggest the Author to move sections 3.2, 3.3, and 3.4 in a new discussion section. These sections are not results in themselves, however they more a interpretation of them.
Author's response to Comment 11: If the reviewer believes that "Results are well structured, successfully presenting the results of the analysis" then his suggestion to change the structure of the article is unclear. The main results of the study have been placed in a repository (due to their large volume) and are attached to the article as Underlying data. For this reason, section 3.1 "Key results and analysis" closely intertwines key results with their analysis. The same applies to section 3.2. For this reason, dividing Section 3 "Results and Discussion" into two separate sections "Results" and "Discussion" seems inappropriate, or rather even harmful.
Author's Decision to Comment 11: Rejected

Comment 12: Section 3.4 is excessively long. The author must here considering to shorten this section by keeping only the necessary.
Author's response to Comment 12: The content of Section 3.4 is fully consistent with the implementation of Objective 4 entitled "Critically examine the traditional research design1 and approach to indoor radon testing in Finland, including..." (see Section 1.4). It is particularly important here that the problem of "Disadvantages of traditional approaches to studying and measuring indoor radon" is discussed in the context of a comparative analysis of the results of our study with the practice of indoor radon testing and the results of research by a specific European organization (STUK), which is a member of Euratom and also a participant in the RadoNorm project. Therefore, the author is confident that the reader will be interested in the entire section 3.4, especially since the reviewer did not specify the criteria for "necessary".
Author's Decision to Comment 12: Rejected

Comment 13: "We hope that our critique of the outdated and inefficient traditional approach together with the proposed Rational Method will be regarded as a constructive and valuable contribution by regulators and metrology experts, including those engaged in ISO and IAEA processes." These sentences does not fit an academic standard.
Author's response to Comment 13: The author does not share this opinion of the reviewer. In this contentious matter, the author relies more heavily on the opinion of the ORE editor, who has not raised such a concern. However, if the ORE editor changes his (her) mind on this matter, this text will be removed.
Author's Decision to Comment 13: Rejected

Competing Interests: No competing interests were disclosed.