

Review

Not peer-reviewed version

IAEA Safety Guides vs. Actual Challenges for Design and Conduct of Indoor Radon Surveys

Andrey Tsapalov , [Konstantin Kovler](#) ^{*} , [Sergey Kiselev](#) , [Iliya Yarmoshenko](#) , [Robert Bobkier](#) , [Petr Miklyaev](#)

Posted Date: 10 January 2025

doi: 10.20944/preprints202501.0718.v1

Keywords: indoor radon; thoron; surveys; metrology; standardization; measurement uncertainty; temporal uncertainty; calibration; conformity assessment; decision-making; QA/QC; IAEA safety guides; legislation; responsibility; awareness; radon priority areas; building protection; mitigation



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Review

IAEA Safety Guides vs. Actual Challenges for Design and Conduct of Indoor Radon Surveys

Andrey Tsapalov ¹, Konstantin Kovler ^{1,*}, Sergey Kiselev ², Ilya Yarmoshenko ³, Robert Bobkier ⁴ and Peter Miklyaev ⁵

¹ National Building Research Institute, Faculty of Civil and Environmental Engineering, Technion, Israel
Institute of Technology, Haifa, Israel

² State Research Center – A. Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency of Russia, Moscow, Russia

³ Institute of Industrial Ecology, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia

⁴ Effective Radon Solutions Ltd., Poole, UK, and Abraham & Ben Hadar Law and Audit, Poole, UK

⁵ Sergeev Institute of Environmental Geoscience Russian Academy of Sciences, Moscow, Russia

* Correspondence: cvrkost@technion.ac.il

Abstract: An analysis of the international radon regulatory framework identified actual challenges for design and conduct of indoor radon surveys, though there is little discussion on this issue in the radon community. The main challenges hindering the development of radon regulation on an international scale, particularly in indoor radon surveys include: (i) Responsibility for indoor radon testing and mitigation, (ii) Excessive focus on Radon Priority Areas, (iii) Role of temporal uncertainty in indoor radon testing, (iv) Standardization of indoor radon measurements, and (v) Standardization of thoron EEC measurements and indoor testing. To address these gaps and inconsistencies, actual needs for design and conduct of indoor radon surveys are proposed, covering the aforementioned challenges. The needs statement, including a discussion of solutions, addresses the following key aspects of radon regulation: (1) Legislation, (2) Radon measurements, (3) Awareness, (4) Building protection. The focus remains on the radon measurement aspect, detailing the strategy and tools for conducting indoor radon surveys within a rational approach. This includes the main research activities necessary for the sustainable development of global radon regulation. The final part of the article presents a rational method (protocol) of indoor radon measurements serving as a detail guideline for standardizing indoor radon testing at the international level. This ensures decision-making reliability of at least 95% and harmonizes relevant national approaches considering traditional measurement protocols using both short-term and long-term measurements. The proposed solutions aim to achieve the goal of modern design and conduct of indoor radon surveys, which consists in the large-scale (mass) testing and effectively identify hazardous buildings. These solutions are based on a rational approach with convenient tools and active voluntary participation of the population, to be implemented within the framework of national radon regulation.

Keywords: indoor radon; thoron; surveys; metrology; standardization; measurement uncertainty; temporal uncertainty; calibration; conformity assessment; decision-making; QA/QC; IAEA safety guides; legislation; responsibility; awareness; radon priority areas; building protection; mitigation

1. Introduction

1.1. Indoor Radon: Risk and IAEA Safety Guides

The last decade has seen a clear increase in the focus on indoor air quality, given the fact that we spend over 80-90% of our time indoors, where certain health risks are present. Indoor radon is the main source of radiation risk for the population. The global contribution of radon to this risk is 50% among natural sources and 40% among all known sources of ionizing radiation, including man-made ones [1]. At the same time, the global contribution from diagnostic procedures in medicine is no more than 20%, and the contributions from pollution caused, for example, by the Chernobyl accident or the production of nuclear energy (including uranium mining) do not exceed 0.1% and 0.01%, respectively [1]. Therefore, contrary to the widespread opinion about the dangers of nuclear power facilities and medical procedures, the main factor of radiation risk is dwellings and workplaces, where the radon content is always higher than in the atmospheric air.

Unlike other natural sources, such as cosmic or terrestrial radiation, radon exposure can be managed to reduce risk. Therefore, the World Health Organization (WHO) [2] and the International Commission on Radiological Protection (ICRP) [3] recommend, while the International Atomic Energy Agency (IAEA) [4] and the European Basic Safety Standards (EU-BSS) [5] require the implementation of a national reference level (RL) of 300 Bq/m³, limiting the annual average radon concentration in buildings. RLs vary due to differences in regional radon levels and usually range from 100 to 300 Bq/m³ [6].

The main legislator in international regulation of radiation risk is the IAEA, which, in partnership with WHO and other international organizations, develops Safety Standards (Fundamentals, Requirements and Guides), including an international radon strategy aimed at reducing the harmful effects of radon on the population. In this regard, the "National and Regional Surveys of Radon Concentration in Dwellings: Review of Methodology and Measurement Techniques" (2013) [7] was first developed, and then the international radon strategy was first proposed, expressed in IAEA SSG-32 "Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation" (2015) [8]. The radon strategy should be implemented with account of legal requirements and the prevailing social and economic circumstances by developing and implementing a National Radon Action Plan, which covers four main aspects [9]:

- Regulation / Legislation,
- Radon measurement and other relevant data,
- Communication / Awareness,
- Building protection.

Recently, the IAEA safety report "Design and Conduct of Indoor Radon Surveys" (2019) [10] was published, followed by the very useful IAEA TECDOC "Protection against Exposure due to Radon Indoors and Gamma Radiation from Construction Materials: Methods of Prevention and Mitigation" (2021) [11], which provide current and complementary recommendations in the development of the international radon strategy. At the end of this year, IAEA SSG-91 "Protection of Workers Against Exposure Due to Radon" (2024) was published [12].

1.2. Gaps and Inconsistencies in Radon Regulation

It is simply impossible to discuss in detail and, moreover, to propose rational improvements for each of the four main aspects of National Radon Action Plans listed above within the framework of the IAEA Safety Guides in one article. While discussing important aspects of indoor radon regulation at the international level, we will focus particularly on "Indoor Radon Measurements".

One of the IAEA presentations (2014) [13] in the section "Inhibitors to Action" stated that "We know how to measure radon" (obviously referring to indoor radon). Indeed, this statement reflects the opinion of many colleagues in the radon community. However, we do not share this opinion at all. On the contrary, such an important aspect of regulation as "Indoor Radon Measurements" has not

had rational development for many years within the framework of the International BSS, which negatively affects the development of other aspects of radon regulation mentioned above.

For example, the effective US approach to reducing radon risk [14], based on short-term measurements (2–7 days) [15,16], fundamentally differs from the European approach based on long-term measurements (at least 2 months) [17], making it difficult to create a harmonious measurement protocol agreed upon at the international level. Radon tests (and mitigation measures) in the US (funded by the population) have been conducted in tens of millions [14,18] (and several million [19]) of buildings, that is 10-100 times greater than in the EU [14], where building testing is mainly funded from administrative (national or municipal) budgets [17].

Despite the lower efficiency of radon regulation in EU countries compared to US regulation, the aforementioned IAEA Safety Guides [7,8,10–12] still recommend conducting long-term measurements, avoiding the analysis of effective US practice using short-term measurements. In our opinion, the radon community's distrust of the US measurement protocol stems from the low reliability of decision-making based on short-term tests [20,21]. However, this issue of reliability is not confined to the US; it remains unestablished globally [21]. This is primarily because such a key component of conformity assessment as temporal uncertainty is not considered [21]. For the same reason, QA/QC in indoor radon measurements based on outdated approaches that were implemented 20-30 years ago are not rational and do not meet the requirements of metrology based on the fundamental concepts of ISO/IEC [21,22]. Moreover, it turns out that none of the many analytical laboratories in the world accredited in the field of indoor radon measurements meets the requirements of the international standard ISO/IEC 17025:2017 [23] (see para. 2.3).

Technological advancements over the past decade, especially in IoT technologies, have significantly improved the quality and variety of radon measurement instruments while substantially reducing the cost of tools (such as low-cost active monitors) [22], which the public has actively started purchasing for self-conducted indoor testing. Thanks to increased awareness and voluntary participation of the public in testing their homes, including paying for indoor radon tests (and mitigation if necessary), the number of radon measurements has sharply increased in recent years, far exceeding previous testing volumes funded by the budget. Our estimate suggests that about 1 million low-cost active radon monitors have already been sold, and this number continues to grow rapidly [22]. However, this rapid growth in indoor testing by the public occurs outside the scope of national radon regulation, which clearly needs a substantial revision of the principles of the international radon strategy, including a fundamental review of the National Radon Action Plans. In this regard, it should also be noted that the traditional design and conduct of indoor radon surveys with an excessive focus on Radon Priority Areas is becoming outdated and even hinders uniform testing of buildings across the populated territory of the country.

At the national level of radon regulation, clear determining the circumstances of responsibility for indoor radon testing and mitigation, as well as promoting the development of competitive testing and mitigation services on a commercial basis are needed.

Given the above, it is useful to discuss in more detail the following actual challenges in indoor radon regulation, with particular attention to the "Radon measurement" aspects, namely:

- responsibility for indoor radon testing and mitigation,
- excessive focus on Radon Priority Areas,
- role of temporal uncertainty in indoor radon testing,
- standardization of indoor radon measurements,
- standardization of thoron EEC measurements and indoor testing.

Analyzing these challenges is necessary for the objective and accurate formulation of actual needs for the design and conduct of indoor radon surveys. The final part of the article presents a rational method (protocol) of indoor radon measurements based on a rational criterion of conformity assessment of a tested room/building with a radiation safety requirement (reference level).

2. Actual Challenges in Indoor Radon Regulation

2.1. Responsibility for Indoor Radon Testing and Mitigation

The crucial issue of *responsibility* for conducting radon control (including testing and mitigation) was taken into account in IAEA GSR Part 3 (Requirement 50: Public exposure due to radon indoors, Article 5.21) [4]. In particular, Article 5.21a) requires that the government shall assign responsibility for “Establishing and implementing the action plan for controlling public exposure due to ^{222}Rn indoors”.

It is worth noting that the effectiveness of the National Radon Action Plans (NRAPs) is significantly limited by their legal nature and lack of binding force under generally applicable law. While NRAPs serve as a valuable framework for addressing radon-related issues, their classification as “soft law” inherently diminishes their enforceability and practical impact. Only through legislative integration and enforcement can NRAPs effectively contribute to reducing radon-related health hazards and achieving the objectives, both of the GSR Part 3 [4] and the EU-BSS [5].

Moreover, discussing responsibility is not possible without addressing extremely important aspects related to the funding sources behind the effective implementation of NRAPs.

An analysis of the IAEA's International BSS system in the field of indoor radon regulation shows that the funding for indoor testing (Conduct of Indoor Radon Surveys) was initially expected to come mainly from administrative (national or municipal) budgets.

IAEA GSR Part 3, Introduction to Requirement 50 clearly says: “The government shall provide information on levels of radon indoors” [4]. In this regard, the task of ranking and delineating Radon Priority Areas with the highest accuracy is quite justified to use the administrative budget most effectively. However, it was clear from the beginning that, regardless of the level of the national budget, it is completely unrealistic to administratively fund tens or hundreds of millions of tests to identify hazardous buildings, including mitigation measures (of which about 8 million have already been conducted in the US only [19]).

Article 5.21b) [4] says: “The government shall assign responsibility for determining the circumstances under which actions are to be mandatory or are to be voluntary, with account taken of legal requirements and of the prevailing social and economic circumstances.” Although this IAEA requirement does not specify particular circumstances, the experience of implementing radon regulation systems in different countries shows that the actual solution to the issue of responsibility for conducting indoor radon control significantly differs from the initially assumed funding mainly from the administrative budget. The most striking example in this regard is radon regulation in the US, which represents a powerful commercial industry (competitive and licensed) for indoor radon testing and mitigation services. A similar but less developed industry for indoor radon control exists, for example, in Canada, the United Kingdom, Sweden and Ireland. In other European countries (and continents), such an industry is only emerging naturally as both public awareness and testing and mitigation services develop. It is important to note that in almost all countries (including those mentioned above) where a national reference (or action) level limiting indoor radon concentration is established, a similar ranking of buildings and corresponding determination of responsibility for indoor radon control naturally emerges:

- residential (non-commercial) buildings, where testing and mitigation are conducted voluntarily at the expense of the residents (owners) or management companies,
- commercial (industrial, office, hotel, retail, store, etc.) buildings, where testing and mitigation are mandatory at the expense of the landlords, with appropriate fines in place,
- public (non-commercial kindergartens, schools, etc.), buildings where testing and mitigation are mandatory at the expense of the administrative (national or municipal) budgets.

It is worth emphasizing about the public buildings—this aspect has not yet been highlighted in the literature—that the specificity of radon occurrence in public buildings, combined with the legal and organizational structure of public finance sectors, generally results in these expenses not burdening “wealthy” central budgets (e.g., the budgets of the State Treasury) but rather the budgets of local government units (municipalities, counties). The latter budgets are limited and undergo

annual planning. From the perspective of Economic Analysis of Law, this allocation of financial responsibility may represent a key factor in the failure to implement effective radon policies across Europe.

A definition of responsibility for indoor radon control that is naturally derived will reduce administrative expenses to a level that is acceptable within the given context. It should be noted that the percentage of non-commercial public buildings controlled by the administrative budget is small (the activity of authorities in this direction serves as a good example and motivation for both voluntary and mandatory testing of buildings). This harmonious definition of responsibility for indoor radon control seems to satisfy all participants in indoor radon testing and mitigation. Accordingly, this principle of responsibility is advisable to recommend for implementation in national legislation *regardless of the prevailing social and economic circumstances* (otherwise, radon regulation turns into an imitation of useful activity), and also to consider in the IAEA Safety Guides to improve radon regulation at the international level.

2.2. Excessive Focus on Radon Priority Areas

Following the IAEA Safety Guides [8,10,12], as well as the EU-BSS Directive in Articles 54(2a), 103(3), and Annex XVIII [5], for example, European national regulators focused their main efforts on identifying Radon Priority Areas instead of organizing mass (large-scale) indoor radon measurements and implementing mitigation measures. Meanwhile, EU-BSS Article 74(2) states [5]: *“Member States shall promote action to identify dwellings with radon concentrations (as an annual average) exceeding the reference level and encourage, where appropriate by technical or other means, radon concentration-reducing measures in these dwellings.”*

It seems obvious that the development of the international radon strategy should take into account the significant evolution in the approach to organizing indoor radon surveys. Initially, it was believed that conducting measurements (and mitigation) exclusively in Radon Priority Areas was the most effective approach to radon regulation, according to ICRP Publication 65 (1993) [24]. However, the results of recent computational studies in Germany [25] and international practical experience in the US [15,16] and Sweden [26] have shown that buildings in all areas, not just Radon Priority Areas, should be tested. Finally, the indoor radon survey of any area is also promoted in ICRP Publication 126 (2014), which mentions that *“...even in areas not classified as radon-prone areas, buildings with high radon concentrations can be found...”* [3]. Indeed, due to the lognormal distribution of indoor radon concentration [24], hazardous buildings can be located outside Radon Priority Areas. Although the proportion of such buildings is significantly smaller, the total number of buildings with elevated radon levels across the country is much higher than in Radon Priority Areas, as shown by the study in Germany [25].

The regulatory experience in the US shows that voluntary and large-scale indoor radon testing (across the entire country, not just in Radon Priority Areas) using short-term measurements allows for the creation of a more detailed (extensive and accurate) national database and radon map of the US [27] compared to the Radon Atlas of Europe [28]. It should be noted that the creation of the European Radon Atlas has involved a variety of approaches, including extensive collection and analysis of soil radon, geological, and other data, with relatively few direct indoor radon measurements [29]. While EU-BSS Article 103(3) clearly expresses the method of assessing Radon Priority Areas (based on direct measurements of indoor radon concentration): *“Member States shall identify areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level [5].”*

Alternative methods for identifying Radon Priority Areas based on soil radon measurements and other geological data do not allow for the identification of buildings with high radon levels [21,30]. In contrast, direct short-term (or long-term) measurements within indoor radon testing allow for the identification of both hazardous buildings and Radon Priority Areas, including the assessment of collective risks. Despite more effective regulation of indoor radon in the US, European national regulators, instead of updating national Radon Action Plans to implement best practices, continue to

focus their main efforts on identifying Radon Priority Areas using alternative methods [30–35]. This is clearly detrimental to the organization of mass indoor radon measurements and implementation of mitigation measures. The outdated approach focusing on Radon Priority Areas lacks rational justification, especially since Radon Priority Areas have already been identified with satisfactory accuracy in almost every EU country. In this context, the goal of further increasing the accuracy of Radon Priority Area identification (by alternative methods) is unclear, especially given the fact that the burden of regulation costs is shifted to the population (property owners and landlords). In this case, there is no need to optimize the administrative budget, as the share of non-commercial public buildings (kindergartens, schools, hospitals, etc.) is very small, and each such building should be surveyed regardless of the radon hazard status of the territory.

Rather than relying solely on the identification of Radon Priority Areas, *policies should emphasize individual radon measurements in all buildings, regardless of their location*. This building-specific approach would ensure that mitigation measures are implemented where they are genuinely needed, without arbitrary exclusions based on administrative boundaries.

The above clearly indicates that international regulations should shift their focus from identifying Radon Priority Areas to creating conditions for mass and reliable testing of buildings. This can be achieved by legalizing public participation through the implementation of a rational conformity assessment criterion [21], which allow for the quantitative consideration of the main components of decision-making, such as temporal and instrumental uncertainties of measurement.

2.3. Role of Temporal Uncertainty in Indoor Radon Testing

First of all, it is important to note again that the reference level is expressed as an annual average value. This means, from a metrological perspective, that the measured parameter is not just the radon activity concentration, but actually the annual average radon activity concentration. However, measurements within one year are practically not carried out. If the measurement duration is less than one year, then the measurement of the annual average radon concentration is not direct. In this case, besides instrumental uncertainty, it is also necessary to consider temporal uncertainty, which increases as the measurement duration decreases. This seems obvious. However, despite this obvious fact, and the fact that temporal uncertainty is usually significantly higher than instrumental uncertainty [21,22], temporal uncertainty is still not considered in either international or national indoor radon regulations. As a result, the reliability of the decision on the conformity (or non-conformity) of the tested room (building) with safety requirement remains unestablished, while excessive attention and costs are devoted to assessing and managing only instrumental uncertainty [17,21], which usually does not exceed 30%.

Instrumental uncertainty combines all sources of uncertainty (mainly random/statistical and systematic/calibration components) associated with the measured radon concentration regardless of the nature of radon origin and behavior of radon in time and space [17,21]. The definition of temporal uncertainty is given below

National regulators, lacking scientific justification from metrological institutes and authoritative international organizations such as the IAEA, ICRP, or WHO, arbitrarily set the duration of indoor radon testing (without considering temporal uncertainty), preferring long-term measurements [7,8,10–12] simply because it "seems more reliable." For example, the minimum measurement duration in Poland is 1 month, in Sweden – 2 months, and in Spain – 3 months, although even in these cases, temporal uncertainty remains quite high and is estimated to be 105%, 100%, and 85%, respectively [36,37]. In the case of short-term measurements from 2 to 7 days, adapted in the US, temporal uncertainty is estimated to be from 160% (105%) to 120% (75%), respectively (values for closed mode are given in parentheses) [36,37]. A survey of IAEA Member States shows a wide variety of national radon measurement protocols [38], according to which the measurement duration varies from a few minutes to 6 months, which, according to our estimates, corresponds to a range of temporal uncertainty from 300-360% to 45%, respectively [36,37]. Such high values and variability of temporal uncertainty, which are not considered in global indoor radon testing, indicate a complete

lack of proper metrological support in indoor radon measurements at the international level, despite increased attention to QA/QC issues in the IAEA Safety Guides [7,10,12].

Furthermore, the radon community's disregard for the consideration of temporal uncertainty has led to the fact that no laboratory in the world accredited in the field of indoor radon measurements actually complies with the international standard ISO/IEC 17025:2017 in terms of meeting the following requirements [23]:

“7.6 Evaluation of measurement uncertainty

7.6.1 Laboratories shall identify the contributions to measurement uncertainty. When evaluating measurement uncertainty, all contributions that are of significance, including those arising from sampling, shall be taken into account using appropriate methods of analysis.

...

7.6.3 A laboratory performing testing shall evaluate measurement uncertainty. Where the test method precludes rigorous evaluation of measurement uncertainty, an estimation shall be made based on an understanding of the theoretical principles or practical experience of the performance of the method.

NOTE 1 In those cases where a well-recognized test method specifies limits to the values of the major sources of measurement uncertainty and specifies the form of presentation of the calculated results, the laboratory is considered to have satisfied 7.6.3 by following the test method and reporting instructions.”

The rational conformity assessment criterion, which includes an algorithm for determining temporal uncertainty (initially called "the coefficient of temporal radon variation"), was introduced at the Final Symposium of the COST NETWORK "NORM4Building" in Rome (6–8 June 2017). Shortly thereafter, support was obtained through the European Commission Grant of H2020: Marie Skłodowska-Curie Individual Fellowship # 792789 "RadonACCURACY" (2018-2020). Thanks to this support, the algorithm has been developed and refined over the following years, and the experimental statistical material has been expanded. The periodically published values of temporal uncertainty, depending on the measurement duration, have remained practically unchanged over these years [14,22,36,37].

Temporal uncertainty defined as the value of the 95th percentile (or 95% probability) in the distribution of all deviations between the measured concentrations $C_{ij}(t)$ and the measured annual average (AA) concentration: $D_{ij}(t) = C_j^{AA}/C_{ij}(t) - 1$ ($i = 1 \dots M; j = 1 \dots N$), in a representative sample of N buildings (rooms) within an international or national case study [21,22]. Year-long continuous measurements of radon concentration carried out in each of N buildings (rooms) with a registration period of 1 or 3 h (at $M = 8760$ or 2920 , respectively), provide robust statistics of deviations $D_{ij}(t)$ for any measurement duration t [21,22].

Existing values of temporal uncertainty were obtained in a sample of buildings covering 1.2 million values of $D_{ij}(t)$ [37]. The sample included buildings located in areas with different geologies and climates. This approach allows for the simultaneous consideration of all anthropogenic and natural factors (including seasonal variations) affecting temporal uncertainty, making the traditional investigation of the influence of each factor separately on the temporal behavior of indoor radon unnecessary [22]. Within this approach, buildings can be tested at any time of the year without separately accounting for the seasonal factor, which does not affect the reliability of the conformity assessment. At the same time, the values of temporal uncertainty can be ranked not only depending on the measurement duration but also considering the normal or closed mode of operation of a room [21,37]. Moreover, the rational conformity assessment criterion covers any methods, devices, and samplers intended for radon measurements, both in short-term and long-term modes.

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 [39–44]. However, seasonal variations often follow the opposite trend (higher radon levels in the warm period) or are not expressed at all [14,36,45–51]. This indicates the absence of a strict pattern of temperature (or seasonal) influence that could be universally applied to any rooms and buildings. Therefore, separate consideration of the seasonal

factor does not contribute to improving the quality of conformity assessment of rooms (buildings) to safety requirement. 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 [7,8,10,12] related to the Seasonal Correction Factor seems not entirely justified, especially when assessing conformity [12].

It is also important to remind that the rational conformity assessment criterion, which includes an algorithm for determining temporal uncertainty values, ensures within ISO/IEC concepts the reliability of decision-making (at least 95%, it means no more than 5% false-negative error) for both short- and long-term measurements [21]. Although arrays of deviations including 1.2 million values of $D_{ij}(t)$ seem statistically powerful, existing values of temporal uncertainty were obtained from limited monitored rooms and buildings [21,37]. However, better values of temporal uncertainty as well as an alternative approach to their definition do not exist. Therefore, to verify and clarify the values of temporal uncertainty, it is necessary to conduct year-long continuous measurements of radon concentrations in a large number of diverse buildings (at least 300) located in different countries with different climates and geologies. This is one of the most urgent tasks in modern radon metrology, without solving which it is not possible to improve QA/QC in indoor radon measurements [21,22].

2.4. Standardization of Indoor Radon Measurements

As mentioned above, the rational conformity assessment criterion was introduced in 2017 in the presence of leaders of the European radon community. However, the assessment of temporal (key) uncertainty in indoor radon measurements was somehow neither resolved nor even discussed within the framework of the European project “MetroRADON” (Metrology for radon monitoring, 2017-2020, metroradon.eu) [52], which was coordinated by metrological institutes. Then, the European metrological community “EURAMET”, instead of focusing on the assessment of temporal uncertainty, considered the project “traceRadon” (Radon metrology for use in climate change observation and radiation protection at the environmental level, 2020-2023, traceradon-empir.eu) [53] more relevant, although the reference level (see para 1.1) is related to indoor radon activity concentration, not outdoor (atmospheric) or soil radon. At the same time, EURAMET is actively introducing the concepts of uncertainty and conformity assessment into measurement practice at the European level [54].

The ongoing “RadoNorm” project in Europe (Managing Risk from Radon and NORM, Towards effective radiation protection based on improved scientific evidence and social considerations – focus on Radon and NORM, 2020-2025, radonorm.eu) [55] is also coordinated by metrological institutes. However, the relevance of implementing the rational conformity assessment criterion in indoor radon testing, as well as the issue of more accurately assessing temporal uncertainty, are neither being discussed nor resolved in this project. Moreover, in November 2022, two authors of this paper sent the RadoNorm coordinators independent analysis of the planned activities of the project, as well as specific proposals for correcting some activities, which did not require significant costs [21], and is usually a necessary condition within the framework of risk management of scientific projects. In the conclusion of this analysis, for example, it was stated:

“5.1. Analysis of the compliance of the planned activity within the RadoNORM project with actually needs of measurement standardization showed the need for a significant correction of the planned WP2 activity to study the spatiotemporal variations of indoor radon. A large number of planned (specific) measures have no justification and no practical benefit, so it is recommended to cancel them. At the same time, the rest of the planned activity covers only about 10% of the actual needs for measurement standardization.

5.2. Specific corrective actions are proposed and justified to fully cover the actual needs of measurement standardization within the target approach based on a systematic study of indoor radon temporal variations.”

Unfortunately, the proposal of the authors was completely rejected. We assume that the best European scientists in the field of radon are participating in the RadoNorm project. Nevertheless, instead of a scientific justification for rejecting the proposal (and developing an interesting scientific

discussion), only a formal response was given, a fragment of which is worth quoting: *“RadoNorm’s research has a strong basis in the strategic research agendas of all European radiation protection platforms, from which it has defined its own objectives. Throughout the course of RadoNorm, members of its advisory board, which is comprised of institutions such as ICRP and IAEA, provide guidance on its implementation, and regular internal reviews ensure we are on the right track.”* We are not sure that advisory board members from ICRP and IAEA were familiar with this proposal.

At the level of countries and national institutions in Europe and other continents, hundreds of studies on radon are being conducted, judging by the large number of published articles, especially over the past decade. Additionally, there are well-known large European projects such as MetroRADON, traceRadon, and RadoNorm. However, despite such grand expenditures (tens of millions of Euro) and research efforts in the field of radon, as well as special attention from metrological institutes, both European (ISO 11665-8:2019 [56]) and US (ANSI/AARST MAN, MA-MFLB and MS-QA) [57] standards for Indoor Radon Testing still rely on traditional and outdated approach lacking metrological support as clear uncertainty budget considering key components, mathematical algorithms (criteria), and QA/QC procedures aligned with fundamental ISO/IEC concepts like 'measurement uncertainty' (ISO/IEC Guide 98-3) [58] and 'conformity assessment' (ISO/IEC Guide 98-4) [59]. These concepts, established over 20 years ago, have been adopted globally in measurement standardization with the support of the Joint Committee for Guides in Metrology (JCGM 100:2008) [60]. However, so far, both AARST and ISO leaders in radon measurement standardization have not embraced these rational concepts, including modern terminology, despite a proposal over 7-8 years ago for a rational criterion within the ISO/IEC concept specifically for indoor radon measurements [21].

Ignoring the temporal uncertainty and rational ISO/IEC concepts in recent updates to ANSI/AARST standards, coupled with misinterpretation of Action Level (which is mistakenly considered equivalent to RL) [14,21,22], underscores the absence of Science-Based Decision Making [61] in US indoor radon testing and emphasizes the significance of focusing on the actual needs of modern metrology for standardizing indoor radon measurements. Unfortunately, AARST leaders in standardizing radon measurements did not respond to the proposal to implement a rational approach during the public revision of radon standards in spring 2024, and the editorial proposal of the Radon Reporter journal to publish a critical article was canceled.

The updated ISO 11665-8:2019 [56] is practically no different from the original ISO 11665-8:2012 [62]. Both standards do not consider the temporal (key) uncertainty [17]. Therefore, they do not comply with the rational ISO/IEC concepts, even though the MetroRADON metrological project (2017-2020) was being implemented during the update period of this standard. The need for the next revision of the international standard ISO 11665-8:2019 arose within 1-2 years. Consequently, a Focus Group in charge of the revision was created as part of ISO/TC85/SC2/WG17 'radioactivity measurements' in 2021 [17]. Towards the end of 2021, two co-authors of this paper made a presentation *“HOW TO ASSESS THE UNCERTAINTY OF TEMPORAL VARIATIONS OF INDOOR RADON?”*. However, the leaders of the Focus Group refused to implement the temporal (key) uncertainty of indoor radon measurements in ISO 11665-8, despite the complete absence of any alternative proposals [17]. Instead of developing the discussion that had begun, these leaders conducted a vote among the 14 members of the Focus Group, which resulted in near consensus, with only two votes against, to reject the rational approach. This outcome essentially reflects the unwillingness of ISO members to implement fundamental ISO/IEC concepts in indoor radon measurements, as incredible and sad as it may seem. In this regard, it is useful to quote in full one of the paragraphs of the international standard of the Joint Committee for Guides in Metrology, JCGM 100:2008(GUM 1995) [60]:

“3.4.8 Although this Guide provides a framework for assessing uncertainty, it cannot substitute for critical thinking, intellectual honesty and professional skill. The evaluation of uncertainty is neither a routine task nor a purely mathematical one; it depends on detailed knowledge of the nature of the measurand and of the measurement. The quality and utility of the uncertainty quoted for the result of a measurement therefore

ultimately depend on the understanding, critical analysis, and integrity of those who contribute to the assignment of its value."

Currently, the revision of ISO 11665-8:2019 is still ongoing, but apart from the rejected rational approach, no other ideas for revision have been received so far. Apparently, the third version of ISO 11665-8 will be approved in the coming year without any significant improvements. Instead of the necessary adequate revision of ISO 11665-8, WG17 decided to develop three additional standards to improve QA/QC by focusing on the management of instrumental uncertainty in radon measurements, which, in our opinion, makes no sense without considering the temporal (key) uncertainty. Let us remind once again that the Reference Level is expressed as the annual average indoor radon concentration, the measurement procedure for which (including conformity assessment) is governed by ISO 11665-8. Moreover, given the absence of RL for soil or outdoor radon, ISO 11665-8 is a high-level standard in the ISO 11665 series, not an application, as shown in ISO 11665-1 [63]. In fact, applications are low-level standards, such as ISO 11665-4 [64], ISO 11665-5 [65], and ISO 11665-6 [66].

Instead of the necessary improvement of the high-level ISO 11665-8 standard based on rational ISO/IEC concepts, the focus of WG17's activities has shifted to creating more and more low-level standards and technical specifications, of which there are already more than ten in the structure of the ISO 11665 series [63], related to radon activity concentration measurements. Perhaps this is why the International Radon Measurement Association (IRMA) has recently emerged, while, for example, no such Associations have emerged for temperature measurements, although the need for temperature measurements is incomparably higher than for radon measurements. The question arises: why are ISO standards periodically updated and why are radon studies conducted under the supervision by metrology institutes if new scientific data that contribute to the implementation of rational ISO/IEC concepts and the adoption of reliable solutions in radon regulation practice are not accepted by either ISO members or the radon community? At the same time, many additional national and international guidelines and even a special IRMA are being created with the aim of improving QA/QC in indoor radon measurements. However, how can this improve QA/QC without taking into account such a key component of conformity assessment as temporal uncertainty?

In summary, such prolonged and persistent ignoring of temporal (key) uncertainty in international indoor radon testing seems very strange. Some readers may find expressions such as "persistent ignoring", "very strange" or "incredible and sad" overly emotional, and the article itself somewhat subjective. The criticism of ISO working group and radon projects is presented as opinion rather than being supported by comparative scientific analysis or objective data, which detracts from the scientific nature of the article. However, what else can the authors do when the criticized parties (scientific organizations and their members) refuse to engage in scientific discussion, ignore questions and rational suggestions, or provide formal responses like those from RadoNorm? The story of the revision of ISO 11665-8 is particularly telling, as it was forced to be discussed in terms of ethical behavior rather than scientific arguments, which have been sorely lacking in the field of radon regulation in recent years.

This is why there is a serious concern about the deep conservatism and lack of critical analysis observed, which has led to a shift in priorities within the scientific and regulatory community regarding the research and regulation of indoor radon. It is essential to refocus the community's attention on the current challenges and actual needs in developing and implementing harmonized international standard for indoor radon measurements within rational ISO/IEC concept. In this regard, we seek rational opinions from the leaders of the radon community (European Radon Association, AARST, EURADOS, RadoNorm), as well as from responsible individuals (including members of IAEA, ICRP, WHO, ISO) making decisions at the highest international level on radon regulation issues.

2.5. Standardization of Thoron EEC Measurements and Indoor Testing

Over the past decade, the practice of measuring activity concentrations of thoron (^{220}Rn) gas and Equilibrium Equivalent Concentration (EEC) of thoron progeny in buildings in Europe and Southeast Asia has been rapidly developing. It is important to clarify that the source of internal exposure is the thoron EEC and not the concentration of thoron gas. There are occasional reports of very high thoron gas concentrations, for example, in the range of 1000–2000 Bq/m³ [67], but thoron EEC levels remain insignificant, since there is no relationship between these parameters [68], in contrast to the well-defined relationship between radon gas and radon EEC. Nevertheless, in many cases, thoron gas concentrations are still measured. At the same time, the practice of measuring thoron EEC is developing and is already widespread in the world [69–72], but the method of passive (diffusion) deposition of thoron progeny on SSNTD, which underlies this practice, cannot be considered reliable.

Indeed, the passive method of measuring thoron EEC lacks metrological support. The problem is that the deposition velocity of thoron progeny under indoor conditions can vary hundreds [73] and thousands [74] of times due to influence of many parameters such as temperature, humidity, electrostatic properties of surfaces in the room, ventilation rate, turbulence, unattached fraction and aerosol size distribution, as well as their concentration [75,76]. These make the passive type of thoron decay product monitor site specific, i.e., for each location the decay product deposition velocities must be determined before deployment [75]. However, even under control conditions (in a calibration chamber or laboratory room), the combined (instrumental) uncertainty of the passive method of measuring thoron EEC is about 80%, according to the data in Figure 7 from [74], that does not meet the requirements for ensuring the quality of measurements. Therefore, it cannot be standardized for measurements in buildings.

At the same time, there are reliable methods for measuring thoron EEC based on the forced deposition of thoron progeny, which allows to control the volume of air pumped through the filter, providing a combined uncertainty of the measurement method of no more than 30% in a variety of indoor conditions. The methods based on the forced deposition of thoron progeny differ in the way they register the alpha radiation of the filter either by spectrometry silicon detector or by SSNTD [77]. However, none of the reliable methods have yet been widely implemented in indoor thoron EEC testing practice, apparently due to the need to use a pump and possible additional electronic devices (silicon detectors) that produce noise and consume more electricity.

The results of the study [78] appear quite unusual. Indeed, this study attempted to conduct parallel (comparative) measurements of thoron EEC in indoor conditions using passive and forced methods of thoron progeny deposition. However, the results were not relevant due to the differing duration of the measurements. This raises the question: what prevented the same duration of parallel measurements in the study [78], and why have comparative measurements of thoron EEC between the passive and forced methods not yet been carried out?

Furthermore, why has the critical issue of metrological support for indoor thoron EEC measurements not been discussed and studied, for example, within the framework of recently completed MetroRADON or the current project RadoNorm? If such studies have been conducted, why is there still no separate ISO standard for thoron EEC measurements based on a reliable forced deposition method, including QA/QC?

Incidentally, the passive method of measuring thoron EEC, implemented in many countries [69–72], was created and promoted by some members of the same ISO/TC85/SC2/WG17, despite its lack of metrological support and the fact that it cannot be standardized, as discussed in detail above. The demand for the passive method is explained by the simplicity and low cost of thoron EEC measurements with SSNTD in long-term mode, despite the indefinite measurement uncertainty. At the same time, thoron EEC measurements in long-term mode using forced method are more difficult to perform. This raises the question again about the importance of understanding the quantitative relationship between the duration of measurements and the reliability of a practical (or research) decision. What is the quantitative difference in reliability if the duration of thoron EEC measurements is, for example, 2 months, 2 days or 2 minutes? Could it be that two minutes of thoron EEC

measurements by the forced method would be sufficient, given the purpose of the measurements in an indoor survey?

In the context of thoron EEC measurements and indoor testing, it is important to continue the discussion started in Section 2.3 about replacing the scientific approach with the entrenched traditional opinion (consensus) in the radon community regarding the determination of measurement duration for indoor testing. IAEA Safety Guides [7,8,10–12] recommend using long-term indoor measurements for radon (and thoron EEC) simply because it "seems more reliable." There is no scientific justification for such a recommendation, which should obviously be based on a certain quantitative dependence of the reliability (or uncertainty) of a practical (or research) decision on the measurement duration, in any official document related to radon regulation at the international or national levels.

It is known that the radon concentration in buildings has a lognormal distribution, which is described in terms of the geometric or arithmetic mean (AM), as well as the geometric standard deviation (GSD). The dependence of uncertainty, for example, of such parameters as AM and GSD, on the duration (as well as the number) of measurements was first quantified and presented in Figures 3 and 4 in [20]. According to these data, the duration of measurements has a weak effect on the assessment of AM and GSD, because the spatial variations in indoor radon are significantly larger than the temporal variations. For example, the systematic difference in the GSD estimate between identical samples with a measurement duration of 1 year and, for example, 2 days (or 2 months) is about 15% (or about 7%), while the random difference does not exceed 1% if the number of measurements is at least 500 [20]. At the same time, the systematic difference (7% or 15%) can be taken into account to refine the GSD if the temporal uncertainty is known [20]. Incidentally, this fact further highlights the importance of assessing the temporal uncertainty. In addition, it should be taken into account that the main component (factor) of the GSD uncertainty is the problem of ensuring the representativeness of the sample of served buildings [20], therefore the combined uncertainty of the GSD really depends weakly on the duration of the measurements. Therefore, the results of indoor radon testing of any duration, both short-term and long-term measurements, can be used to assess the GSD.

The temporal variations of thoron EEC in buildings have hardly been studied, but preliminary data show that the temporal variations of thoron EEC are lower (at least not higher) than those of radon isotopes (gases). Therefore, the conclusion about the minor influence of measurement duration on the accuracy of the assessment of both AM and GSD applies not only to indoor radon measurements but also to thoron EEC measurements.

Thus, there is no need to apply only long-term measurements within the Design and Conduct of Indoor Radon (or thoron EEC) Surveys, which significantly complicates (and increases the cost of) the strategy for assessing radiation risks due to indoor radon (and thoron), as well as the creation of national radon maps. In this regard, it is useful to provide an example of unusual assessing AM and GSD of the lognormal distribution of radon in buildings in Russia. This assessment is based on approximately 90% of express (spot) measurement results (about 800 thousand) with a duration of only a few minutes [79]. Nevertheless, the values of AM and GSD obtained in Russia are quite accepted by UNSCEAR [68]. It should be noted that the negative practice of express measurements for indoor radon testing (for the purpose of conformity assessment) is likely to be canceled in Russia in the coming years. At the same time, the results of express measurements can be used to assess the parameters of the lognormal distribution of radon concentration in buildings.

In conclusion, of the discussion on the problem of standardization in thoron EEC measurements and indoor testing, it is worth paying attention to a very interesting article [80], which presents a linear dependence of the annual average indoor thoron EEC on the specific activity concentration of ^{232}Th in materials of building envelopes. The ^{232}Th content was measured using a portable scintillation gamma spectrometer with a NaI(Tl) detector (63 mm). The annual average indoor thoron EEC was determined using an original method that combined forced deposition of thoron progeny in the filter for 3-5 days with long-term measurements of radon. The theoretically estimated uncertainty of the

method at the level of 60% ($k=2$) is quite high and requires clarification (possibly, the accuracy of the method is better), since direct measurements of the annual average thoron EEC were not conducted in any of the 10 experimental rooms (apartments) [80]. Incidentally, year-long continuous periodic measurements of thoron EEC in buildings (at least a few spot measurements per day), necessary for studying temporal variations of indoor thoron EEC, have never been conducted in any country.

The special value of the study [80] lies in the fact that scaling up such a study will likely provide representative experimental data necessary for developing an inexpensive and easy-to-implement standard method for promptly identifying hazardous buildings with elevated levels of thoron EEC using a portable gamma spectrometer. Scaling implies conducting similar studies in a large number of diverse rooms and buildings (several hundred) with elevated levels of thoron EEC and external exposure to gamma radiation emitted by building materials due to elevated ^{232}Th content.

3. Actual Needs for Design and Conduct of Indoor Radon Surveys

3.1. The Goal of Modern Design and Conduct of Indoor Radon Surveys

The discussion of actual challenges in indoor radon regulation shows that it is impossible to limit the correction to only certain sections and paragraphs of the IAEA Safety Guides, since there is a need to revise and update international radon regulation approaches. This section continues with a more extensive analysis of gaps and inconsistencies in radon regulation, allowing for a better understanding of the principles for solving identified problems and then formulating the goal, as well as the actual needs for the design and conduct of indoor radon surveys within a defined structure.

The goal of modern design and conduct of indoor radon surveys is the mass testing of buildings to assess compliance (and effectively identify hazardous buildings) based on a rational approach and active voluntary participation of the population, which should be carried out within the framework of national radon regulation. Proposals to achieve this goal are systematized considering the following main aspects of radon regulation mentioned in the introduction:

- Legislation,
- Radon measurements,
- Awareness,
- Building protection.

The focus remains on the radon measurement aspect, within which the strategy and tools for the conduct of indoor radon surveys within a rational approach are discussed in detail. The final part discusses the main research activity necessary for the sustainable development of radon regulation at both international and national levels.

3.2. Radon Measurement Aspect

3.2.1. General Strategy of Indoor Radon Surveys

High indoor radon levels can also occur in areas not labelled as Radon Priority Areas due to the high spatial variability in radon concentration in buildings. This means that any existing building is a potential risk object and should, therefore, be tested.

Given the millions of buildings in different countries, it is necessary to create conditions for large-scale surveys and the effective identification of hazardous buildings (with mean radon concentrations above the reference level). Such conditions should ensure not only satisfactory accuracy in radon concentration measurements but also the high reliability of decisions regarding the compliance of the tested rooms (and the entire building) with the normative (reference) level. However, to date, a harmonious measurement protocol for reliable decision making based on a rational conformity assessment criterion, coordinated at the international level, is still lacking. Clearly, this protocol must be based on a rational approach supported by scientific evidence, not on

popular opinion that it "seems more reliable" (even if that opinion represents a conservative consensus in the radon community).

In over 90% of buildings, radon concentrations are significantly lower than the reference level (in countries with elevated indoor radon, the RL is also usually higher). Therefore, it is waste of time and other resources to measure low annual average radon concentrations with high accuracy using only long-term measurements in every building. Given the generally low level of radon in buildings about 30 Bq/m³ [68], even a high combined (temporal and instrumental) uncertainty of up to 100-200 % would be satisfactory in most cases for reliable conformity assessment based on short-term tests. Only in relatively rare instances, where the high uncertainty of the short-term test does not allow for a reliable safety assessment, should a decision be based on more accurate long-term measurements.

Thus, the most effective testing strategy should include two stages: (i) initial short-term measurements, and (ii) additional long-term measurements if necessary. A similar two-stage measurement strategy is accepted and effectively implemented in the US for years. It actually provides more effective indoor radon regulation compared to the EU, where only one-stage long-term tests are being promoted. We previously assumed that the radon community's distrust of the US measurement protocol was due to the low reliability of decision making based on short-term tests. However, the reliability of decision-making remains unestablished not only in the US but also globally because a key component of conformity assessment, temporal uncertainty, is not taken into account.

The data from both voluntary and mandatory building testing, based on a two-stage measurement strategy regardless of the duration of measurements, can be used for the continuous refinement of both collective doses (risks) and the detailing of the national radon map, including the location of Radon Priority Areas, as well as for monitoring the effectiveness of the national radon regulation strategy. Therefore, it is advisable for authorities to focus efforts on creating favorable conditions (including reallocating funding) for the development of a competitive market for indoor testing (and mitigation) services, and to more actively inform the public about radon risk, instead of continuing the traditions of outdated and less effective indoor radon survey designs funded by the administrative budget.

3.2.2. The Rational Criterion of Conformity Assessment

Given the previous discussions, there is a need to implement a rational conformity assessment criterion [21], considering both temporal and instrumental uncertainties, in the IAEA Safety Guides, including national protocols for indoor radon measurements. This will significantly optimize the design and improve the effectiveness of conducting indoor radon surveys.

Besides temporal and instrumental uncertainties, an additional source of uncertainty in conformity assessment may arise from year-to-year variations in indoor radon, driven by long-term climate variations, occupant behavior, and the degradation or restoration of building structures, including underground utilities. However, accumulated data over many years indicate that, in most cases, year-to-year variations in indoor radon are insignificant, typically not exceeding 15–20% [21,81], which can serve as a benchmark for the maximum achievable accuracy within the rational criterion. Nevertheless, it is beneficial to include in the conformity assessment procedure a recommendation for indoor radon re-testing, such as every 3–10 years, depending on the Radon Priority Area ranking. The higher the rank of the Radon Priority Area, the more frequently the repeated indoor tests should be carried out.

Rational conformity assessment of a room with safety requirement through measurements covering all rooms with long-term occupancy allows for the identification of hazardous building as a whole and facilitates decisions regarding the need for mitigation activities. The same testing procedure within the rational criterion can be used to verify the effectiveness of mitigation using the short-term measurements. It is important to emphasize that if the problem of conformity assessment of a room, as an elemental component of a building, remains unresolved, then the more

comprehensive task of conformity assessment for an entire building based solely on patterns of spatial radon behavior, evidently cannot have an effective solution.

Standardizing indoor radon measurements based on the rational criterion of conformity assessment will ensure decision-making reliability within the ISO/IEC concept of no less than 95% for both short-term and long-term measurements [21]. Incidentally, this approach has been supported and promoted by the leading radon experts in the Russian Federation [79].

3.2.3. Temporal vs. Instrumental Uncertainty within Indoor Radon Measurements

Temporal (key) uncertainty in indoor radon measurements for conformity assessment, as well as the specifics of its determination, were discussed in detail in section 2.3. The values of temporal uncertainty are provided in [22,37]. Underestimating or even neglecting the contribution (key role) of temporal uncertainty, besides leading to loss of control over the reliability of decision-making, results in unreasonably high requirements and complications of metrology within QA/QC [21,22]. It also hinders the development of a rational strategy for indoor radon measurements.

Instrumental uncertainty is the second important component of combined uncertainty in conformity assessment, but its values usually do not exceed 30%, which is significantly lower than the values of temporal uncertainty, even for measurement durations of 6 months [22]. Nevertheless, instead of focusing on temporal (key) uncertainty, the radon community's attention is somehow concentrated only on instrumental uncertainty, which is much better studied, as its values are a mandatory characteristic of a specific device that must be periodically checked by the National Metrology Institutes [17,21].

On one hand, technological advancements over the past decade have significantly improved the quality of radon measurement instruments, resulting in more reliable performance, including calibration factor stability. On the other hand, the variety of radon measurement instruments has greatly increased, particularly with the introduction of active (electronic) monitors for continuous radon measurements (CRM). The public has started actively purchasing low-cost active monitors for voluntary indoor testing, leading to widespread indoor radon measurements [22]. However, this rapid growth in indoor testing, driven by public awareness and active involvement, is occurring outside the scope of national radon regulation.

There are three most popular methods for measuring the activity concentration of radon in international indoor testing practice:

1. Short-term measurements using passive radon adsorption with activated charcoal, followed by measuring its activity (charcoal method).
2. Long-term measurements using Solid State Nuclear Track Detectors (SSNTD) like CR-39 or LR-115, followed by etching and track counting (SSNTD method).
3. Measurements of any duration using active (electronic) radon monitors for continuous radon measurements (CRM method).

Radon measurement instruments based on the charcoal and SSNTD methods are produced by a relatively small number of manufacturers, and the measurements are conducted by professionals in laboratory conditions after exposing charcoal or SSNTD in the tested buildings. In this case, managing instrumental uncertainty is not very difficult. Meanwhile, a large number of manufacturers from different countries produce various models of CRM monitors, which are mainly used by the public, significantly complicating the management of instrumental uncertainty.

However, in any case, modern metrological requirements are still lacking in international regulatory practice [21]. These requirements should ensure the uniformity of indoor radon measurements within the ISO/IEC concept, including QA/QC, and should be applicable to any methods and devices intended for indoor radon measurements to ensure reliable (at least 95%) conformity assessment, considering both temporal and instrumental uncertainties. Therefore, a fundamental revision of outdated approaches to managing not only instrumental uncertainty but also overall QA/QC in indoor radon measurements within the ISO/IEC concept is necessary, taking

into account the key role of temporal uncertainty and the active participation of the public in housing testing. Solving this problem is one of the most urgent tasks in modern indoor radon metrology.

3.2.4. Rational Method of Indoor Radon Measurements

Given the discussion above, it seems vital to publish and widely discuss the Rational Method of Indoor Radon Measurements, which is detailed in section 4.

The Rational Method incorporates rational ideas and addresses the gaps in indoor radon regulation discussed earlier. The essence of the method is outlined in its dedicated section 4.4 “Principle of Measurement and Conformity Assessment,” which is useful not only for professionals but also for informing the public. All quantitative data and statements are supported by references to scientific literature. The quality of measurements and the reliability of decision-making are ensured through the control and management of the main components of conformity assessment uncertainty, which are covered in two annexes titled “Temporal Uncertainty Component in Conformity Assessment” and “Instrumental Uncertainty Component in Conformity Assessment.”

It is important to emphasize that, thanks to the relevant formulation of the objectives and tasks of our systematic scientific research, we have, for the first time, achieved strict metrological support for radiation control of such a highly variable parameter as the activity concentration of indoor radon. Thus, the Rational Method covers both temporal and instrumental uncertainties based on the rational criterion of conformity assessment within the ISO/IEC concept, ensuring decision-making reliability of no less than 95% for both short-term and long-term measurements.

3.2.5. National Measurement Platform

Mass testing of buildings for conformity assessment (and effectively identify hazardous buildings), based on a rational approach and active voluntary participation of the population, should be carried out within the framework of national radon regulation. This is the main goal of modern design and conduct of indoor radon surveys.

To achieve this goal within the radon measurement aspect, it is necessary also to develop and implement a national internet platform that integrates and applies the Rational Method of Indoor Radon Measurements in practice. This platform, interacting with the platforms of instrument and service providers for indoor radon measurements, could manage mass indoor testing using various methods and devices, ensuring the collection of test results (in a national database) and quality control of measurements, as well as providing technical and informational support for professionals and the public. The collection of radon measurement results is an important national regulatory task that allows for the refinement of collective risk assessments and the delineation of Radon Priority Areas. An additional motivation for using the platform could be a convenient service for indoor testing and mitigation. For example, the pilot 'RadonTest' online system, which allows even schoolchildren to test their homes using the charcoal method, can serve as an excellent prototype for such a platform [82]. This platform can also support SSNTD and CRM methods.

The introduction of the national platform will legalize and enable the public to independently conduct indoor testing using low-cost radon monitors or inexpensive charcoal and SSNTD samplers with higher efficiency and reliability (using the Rational Method presented below) compared to existing professional testing practices where the temporal (key) uncertainty in decision-making is not taken into account. This approach will increase radon tests by providing convenient online tools and reducing costs, particularly crucial in low-income areas where there are fewer measurements in consideration of the experience demonstrated by the US. To increase radon testing in low-income areas, it would be advisable for national authorities to enter into commercial agreements with sellers of radon measurement services or the instruments themselves on price discounts for buyers from low-income areas (the loss of revenue due to the discounts would be offset by the authorities). Additionally, the rational strategy will enhance the efficiency and reliability of indoor testing in real estate transactions and assessing mitigation effectiveness.

3.2.6. Thoron EEC Measurements and Indoor Surveys

A current task is the standardization of methods for thoron EEC measurements based on the forced deposition of thoron progeny, including QA/QC. It is important that instruments for thoron EEC measurements can provide results with an accuracy to two decimal places (due to the very low indoor thoron EEC levels). Additionally, it is crucial to assess measurement uncertainty, even if it is at the level of 100% or higher, instead of reporting that the measurement result is below the minimum detectable activity (or measurement range).

Indoor thoron EEC testing is not meaningful because there are neither reference levels for indoor thoron EEC nor standardized methods for determining the annual average indoor thoron EEC. Therefore, also considering paragraph 2.5, the design and conduct of indoor thoron EEC surveys can be based on spot measurements without significant loss of accuracy in AM and GSD, provided the measurements are conducted by professionals in public buildings under normal ventilation conditions. Among public buildings, it is better to choose kindergartens, schools, and hospitals, as the share (density) of such buildings is usually proportional to the population density. Additionally, measurements should be conducted in sufficient quantities and evenly throughout the year [20].

3.3. Legislation Aspect

3.3.1. Circumstances Determining Responsibility for Indoor Radon Testing and Mitigation

The following specific circumstances determining the principle of responsibility are recommended for inclusion in national legislation, *regardless of prevailing social and economic conditions*, and should also be considered in the IAEA Safety Guides to improve radon regulation at the international level regarding the following types of buildings:

- residential (non-commercial) buildings, where testing and mitigation are conducted voluntarily at the expense of the residents (owners) or management companies,
- commercial (industrial, office, hotel, retail, store, etc.) buildings, where testing and mitigation are mandatory at the expense of the landlords, with appropriate fines in place,
- public (non-commercial kindergartens, schools, etc.) buildings where testing and mitigation are mandatory at the expense of the administrative (national or municipal) budgets.

3.3.2. Canceling Excessive Focus on Radon Priority Areas

Excessive focus on Radon Priority Areas should be cancelled. Among other things discussed above (see Section 2.2), such excessive focus contradicts the ALARA principle and hinders the uniform testing of buildings across the entire populated area of the country.

It is important to clarify that considering Radon Priority Areas is an important component in radon regulation, for example, in tasks such as land allocation and the construction of new buildings, where construction conditions, including the radiation environment, must be taken into account. At the same time, within populated areas, information about Radon Priority Areas can be accumulated and refined based on the results of both voluntary and mandatory indoor testing, according to paragraph 3.2.1. Therefore, there is no need to make special efforts to identify Radon Priority Areas by other means, especially at the expense of the administrative budgets.

3.3.3. Additional Recommendations

Improving the IAEA Safety Guides (and EU-BSS) on the National Radon Action Plan (NRAP) development, in addition to the above proposals, should also consider the following recommendations:

- increased focus and efforts with government support on developing the building testing and mitigation service industry, which allows for managing the building rather than the exposure, in accordance with the ICRP recommendation [3]: “(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."

- promoting the implementation of the Rational Method of Indoor Radon Measurements at both international and national levels,

- government support for the development and implementation of a national measurement platform, according to paragraph 3.2.5, to ensure that, at a minimum, the administration has the ability to manage the national radon database, which will be continuously and automatically updated,

- if a country lacks (or has an underdeveloped) indoor testing and mitigation service, and an Indoor Radon Survey has never been conducted, then the design and conduct of Indoor Radon Surveys can include both short-term and long-term measurements (which has little effect on accuracy of AM and GSD assessments) [20], which should be conducted (at the expense of the administrative budget) in public buildings under normal ventilation conditions, simultaneously identifying hazardous buildings. Among public buildings, it is better to choose kindergartens, schools, and hospitals, as the proportion of such buildings is usually proportional to the population density. Additionally, measurements should be conducted in sufficient quantities and evenly throughout the year [20], and it is also useful to combine this Indoor Radon Survey with spot measurements of thoron EEC, according to the recommendations of paragraph 3.2.6.

3.4. Awareness Aspect

Awareness of radon risk among the population and authorities is a crucial aspect of national radon regulation. Equally important is the population's awareness of the national service for building testing and mitigation. This service should be well-developed and accessible to the public, which is the responsibility of the national authorities.

At the same time, the reliable, simple, and user-friendly Rational Method of Indoor Radon Measurements, with a detailed description of its principle (see Section 4.4), also contributes to raising public awareness. An additional tool for informing and communicating with the public, as well as motivating voluntary home testing, can be a national measurement platform that provides testing and mitigation services, as discussed in the previous paragraph. Data collection through this platform allows for the continuous enhancement of the online National Radon Map, which is also an important tool for informing both the public and authorities at various levels.

However, traditional radon mapping using 10x10 km squares with three or more colors (depending on the average indoor concentration within the square) does not reflect abnormally high levels outside Radon Priority Areas. As a result, based on the US and Swedish experience, the population conducts significantly fewer tests outside Radon Priority Areas, although the number of buildings with elevated radon levels in the "safe" areas of the map is usually much greater than in Radon Priority Areas (see Section 2.2). Thus, traditional Radon Maps do not accurately represent the actual (individual + collective) radon risk, so it is necessary to improve the method of constructing Radon Maps to clearly display spatial anomalies of indoor radon. For example, the design of the map by the RadonTest Group [83] offers a detailed and understandable representation of the spatial distribution of measured indoor radon concentrations for the public while maintaining the confidentiality of personal data. At the same time, test participants can easily locate their measurement results on the map.

3.5. Building Protection Aspect

Building protection is the most crucial aspect of radon regulation. However, the problem of mitigation in existing buildings with high radon levels has been resolved in only a few countries (US, Canada, UK, Sweden, Ireland).

In this context, the recently released IAEA TECDOC “Protection against exposure due to radon indoors and gamma radiation from construction materials: methods of prevention and mitigation” (2021) [11] is very useful. However, in the mitigation industry, practical experience in effectively protecting a wide variety of buildings with different foundation structures (or underground parts) plays a more significant role than theoretical knowledge. Therefore, creating favorable conditions (including necessary funding) for gaining mitigation experience is the responsibility of national authorities. Initially, gaining mitigation experience is most productive with one or several teams of specialists (starting with small buildings), and then spreading this experience across the country, especially in Radon Priority Areas, on a commercial basis to develop a competitive market for certified mitigation services.

It is also useful to pay attention to the Rational Method of Indoor Radon Measurements presented below, which allows for the rapid assessment of compliance and the effective identification of rooms with the highest radon levels, which is important for planning and implementing measures to protect buildings from soil radon.

3.6. Main Research Activity

3.6.1. Deep Study of Temporal Uncertainty of Indoor Radon

Already reported earlier that the available values of temporal uncertainty can be verified and refined by conducting year-long continuous measurements (with a recording period of 1 or 3 hours) of indoor radon concentrations in a large number of diverse buildings (at least 300) located in different countries with different climates and geologies. For example, the cost of such a study in Ireland was less than 1% of the RadoNorm budget [21]. Therefore, conducting such studies at a national level is not particularly problematic, especially given the large number of studies in the field of radon that do not benefit the development of measurement standards, including indoor radon testing, as reported in paragraph 2.4. It is possible that national values of temporal uncertainty may differ due to the influence of geology, climate, architectural design, and household traditions.

Reducing temporal uncertainty can likely be achieved by significantly increasing the amount of statistical data through year-long continuous measurements in an even larger number of buildings under controlled diverse conditions. Additionally, a statistically significant correlation between temporal uncertainty and characteristics such as building type and floor level may be discovered, allowing for the ranking of measurement conditions and further reducing temporal uncertainty.

Simultaneously with the study of temporal uncertainty, research on the behavior of other indoor air pollutants over time can be conducted, as well as the collection of data on external exposure to gamma radiation emitted by building materials. According to EU-BSS Article 75(1) [5]: “*The reference level applying to indoor external exposure to gamma radiation emitted by building materials, in addition to outdoor external exposure, shall be 1 mSv per year.*” Despite the existence of this reference level, a corresponding measurement standard is still lacking at the international level.

3.6.2. Study of Temporal Variation of Indoor Thoron EEC

To study the temporal variations of indoor thoron EEC, it is necessary to conduct year-long periodic measurements of thoron EEC (at least several spot measurements per day) under various conditions, starting with public and industrial buildings.

It is also very useful to scale up the previously mentioned study [80], which involves determining both the annual average indoor thoron EEC and the specific activity concentration of ^{232}Th in the materials of building envelopes using a portable gamma spectrometer in a large number of diverse buildings and rooms with elevated levels of indoor thoron EEC. The results of such a study will provide the necessary statistical data to standardize the method for the rapid assessment of the annual average indoor thoron EEC using a portable gamma spectrometer.

The method for studying spatial variations of thoron EEC (among buildings) was discussed in detail in paragraph 3.2.6.

4. Rational Method of Indoor Radon Measurements

The structure of the Rational Method is presented in Figure 1.

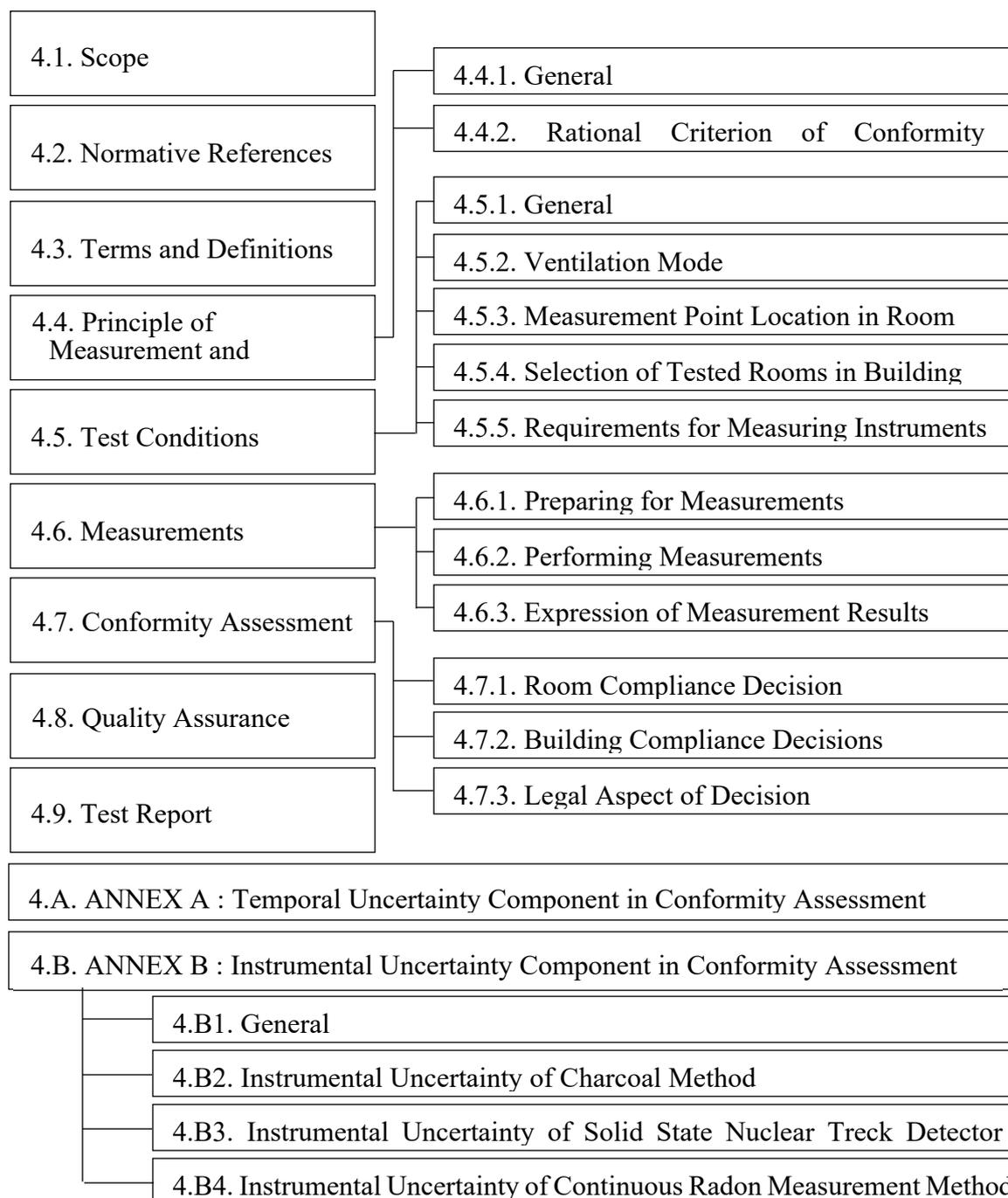


Figure 1. Structure of the Rational Method of Indoor Radon Measurements.

4.1. Scope

The Rational Method establishes the procedure for measuring radon (^{222}Rn) concentration and the criteria for conformity assessment of all sizes and types of buildings (residential, public, and industrial/commercial) with a safety requirement as national reference level limiting the annual average indoor radon concentration.

The rational principle of measurement and conformity assessment, thanks to taking into account main components such as temporal and instrumental uncertainties, ensures decision reliability of at

least 95%, covering any methods and instruments used for both long-term and short-term radon measurements.

The Rational Method provides high efficiency and reliability of indoor testing in both occupied and unoccupied (new) buildings, as well as in real estate transactions and assessing mitigation effectiveness.

The Rational Method, along with its reliability, is distinguished by its simplicity of application, so it can be used not only by authorized inspectors but also by any interested person from the general population, using both professional and low-cost instruments for indoor radon measurements.

4.2. Normative References

IAEA Safety Standards Series No. GSR Part 3. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards.

ISO/IEC Guide 98-3. Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995).

ISO/IEC Guide 98-4. Uncertainty of Measurement—Part 4: Role of Measurement Uncertainty in Conformity Assessment.

ISO/IEC 17025:2017. General Requirements for the Competence of Testing and Calibration Laboratories.

4.3. Terms and Definitions

Building: A building is the result of construction, representing a volumetric above-ground structure that includes rooms intended for living and/or human activities, production placement, product storage, or animal housing, as well as networks and systems for engineering and technical support.

Room: A part of the space inside a building, having a specific functional purpose and enclosed on all sides by building structures: walls (with windows and doors), ceiling, and floor.

Concentration of Radon: Radon activity concentration (Bq/m^3) expresses the number of ^{222}Rn nuclei decays per second (Bq) in one cubic meter of air.

Long-term Measurement: Continuous measurement (including recording of integral data with a period of 1, 3, 6, 12 or 24 hours) or sampling (with subsequent analysis), when the measurement (sampling) durations from 2 to 12 months.

Short-term Measurement: Continuous measurement (including recording of integral data with a period of 1, 3, 6, 12 or 24 hours) or sampling (with subsequent analysis), when the measurement (sampling) durations from 2 to 7 days.

NOTE: measurements/sampling lasting from several weeks to two months are also allowed.

Indoor Testing: A control procedure that includes conducting short-term or long-term measurements, as well as data collection/analysis and conformity assessment of a room/building with a safety requirement.

Natural Ventilation: An organized or unorganized process of removing air from a room and replacing it with outdoor air due to gravity (warmer air rises), as well as solar and wind pressures.

Forced Ventilation: An organized process (system) of removing air from a room and replacing it with outdoor air due to the pressure difference inside the room and outside the building, created by the continuous operation of one or more fans.

Normal Mode (of operation/ventilation): A building operation mode, when all rooms and the building as a whole, including natural or forced ventilation and other engineering systems, operate in a regular mode without any restrictions. The frequency of ventilation (by opening windows and/or doors) depends on the preferences of the occupants (residents or workers) of the building.

Closed Mode (of operation/ventilation): A building operation mode, when an apartment (including several rooms) or the building as a whole is maintained with constantly closed windows and doors, and forced ventilation is turned off (if provided by the design). This operation/ventilation

mode occurs in new unoccupied buildings, as well as in occupied buildings, for example, during weekends when production processes are halted, and no people are present.

Temporal uncertainty: This is a component of the combined uncertainty of conformity assessment determined as the 95th percentile (or 95% probability) in the distribution of all deviations between the measured concentrations $C_{ij}(t)$ and the measured annual average (AA) concentration: $D_{ij}(t) = [C_j^{AA}/C_{ij}(t)] - 1$ ($i = 1 \dots M; j = 1 \dots N$), in a representative sample of N buildings (rooms) within an international or national case study. Year-long continuous measurements of radon concentration carried out in each of N buildings (rooms) with a registration period of 1 or 3 h (at $M = 8760$ or 2920 , respectively), provide good statistics of deviations $D_{ij}(t)$ for any measurement duration t [21] (ANNEX A).

Instrumental uncertainty: This component of the combined uncertainty in conformity assessment accounts for all sources of uncertainty (mainly random/statistical and systematic/calibration components) associated with the measured radon concentration regardless of the nature of radon origin and its behavior over time and space (ANNEX B).

Multiplicity factor: This factor is used as the additional criterion for identifying hazardous rooms. It is defined as the 95th percentile (or 95% probability) in the distribution of all ratios between the measured concentrations $C_{ij}(t)$ and the measured annual average (AA) concentration: $R_{ij}(t) = C_{ij}(t)/C_j^{AA}$ ($i = 1 \dots M; j = 1 \dots N$) [22]. The arrays of values $C_{ij}(t)$ and C_j^{AA} are the same as those used to determine the temporal uncertainty.

ALARA (As Low As Reasonably Achievable): This principle expresses one of the main criteria of radiation protection, aiming to minimize the harmful effects of ionizing radiation. It involves maintaining both individual and collective radiation doses at the lowest possible and achievable levels, considering social and economic factors (see IAEA GSR Part 3 [4], p. 406; EU-BSS [5], Article 5(b)).

4.4. Principle of Measurement and Conformity Assessment

4.4.1. General

4.4.1.1. High radon levels in individual buildings, exceeding the reference level, are often found even in areas with low average indoor radon levels in the region. This fact is explained by the lognormal distribution of radon concentration in buildings [24]. Therefore, radon testing should be conducted in every building, and measurement is the only way for conformity assessment of a room/building with a safety requirement.

4.4.1.2. Conducting large-scale (mass) radon measurements covering every building, regardless of the radon level in the region, contributes to achieving the main goal of radon regulation, which is to reduce both the overall (collective) risk to the entire population and 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. The radon protection strategy should include both preventive measures in new buildings and corrective (radon protection) measures to reduce exposure in existing buildings [3].

4.4.1.3. In the framework of achieving the goal and strategy of radon regulation, the World Health Organization (WHO) [2] and the International Commission on Radiological Protection (ICRP) [3] recommend, while the International Atomic Energy Agency (IAEA) [4] and the European Basic Safety Standards (EU-BSS) [5] require the implementation of a national reference level (RL) of 300 Bq/m^3 , *limiting the annual average radon concentration in buildings*. National reference levels vary due to differences in regional radon levels and usually range from 100 to 300 Bq/m^3 [6].

4.4.1.4. Radon concentration can vary significantly (by multiples) over the course of days, weeks, and seasons, even in continuously closed rooms and buildings [14,36,37]. Therefore, the most reliable decision on the compliance (or non-compliance) of a tested room with a safety requirement (as reference levels) is achieved through year-long measurement. At the same time, in most buildings,

radon levels are significantly below the reference level, so it is impractical to determine the annual average concentration in each room with high accuracy through year-long measurements. However, reducing the measurement duration obviously decreases the reliability of the conformity assessment.

In this regard, the essence of the rational conformity assessment criterion (1) lies in comparing the reference level with the upper bound of the confidence interval of the estimated annual average value, which is determined based on the measurement result of radon concentration, taking into account the possibility of controlling the main components (temporal and instrumental) of uncertainty, which decreases with increasing measurement duration [21]. 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 (1) 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.

The above principle of measurement and conformity assessment (1), by controlling the main components of uncertainty, ensures the reliability of decisions with a probability of at least 95%, regardless of the methods and instruments used in both long-term and short-term measurements [21].

4.4.1.5. Considering international experience [15,16], as well as a rational approach in indoor radon testing [21], the measurement duration should be at least 2 days under closed operation mode, and at least 4 days under normal mode.

4.4.1.6. ANNEX A provides values of temporal uncertainty depending on the measurement duration and operation mode (normal and closed). These values were obtained through statistical analysis of the arrays of differences (deviations $D_{ij}(t)$) between annual average and measured radon concentrations of different durations in a sample of buildings located in areas with varying geology and climate. This approach allows for the consideration of the combined influence of all natural and anthropogenic factors (including operation/ventilation mode and temperature/seasonal influence) on the behavior of indoor radon over time [21].

It is evident that with an increase in measurement duration, temporal uncertainty decreases and equals zero if the measurement duration is one year.

In closed mode with limited ventilation, when all windows and doors in the building are constantly closed, the amplitude of radon concentration fluctuations decreases, so temporal uncertainty is approximately 1.5 to 2 times lower compared to normal mode, when all rooms and the building as a whole are operated in a regular mode without any restrictions [21,36].

It is important to note that accumulated results of annual and seasonal indoor radon measurements show that there is no strict pattern of temperature (or seasonal) influence that can be applied to any rooms and buildings, although reports (publications) more often indicate higher radon levels in the cold season.

4.4.1.7. ANNEX B provides mathematical algorithms, as well as guidelines and recommendations for ensuring measurement quality by controlling instrumental uncertainty.

Comparison of the contributions of temporal and instrumental components to the overall uncertainty budget of the estimated annual indoor radon concentration shows that for measurement durations of up to two months, the contribution of the instrumental component is insignificant, even if the instrumental uncertainty is 40% [21,22]. In long-term measurement mode, it is advisable to use more accurate methods and measurement instruments that provide lower instrumental uncertainty, which, however, is impractical to reduce below 20% due to the existence of year-to-year variations in indoor radon [21,81].

Thus, metrological requirements for ensuring quality in short-term measurements should be more lenient compared to the requirements for long-term measurements [21,22,37]. This allows for the legalization of the use of inexpensive (non-professional) radon measurement instruments [21,22], as well as the participation of the general population in large-scale building testing.

4.4.1.8. Motivating the population to independently test their homes and offices by informing them about radon risks, as well as introducing inexpensive and convenient measurement tools within the framework of a rational conformity assessment criterion, allows for the commercialization of the radon regulation industry to conduct mass testing of buildings nationwide. However, with voluntary testing, it is difficult to achieve the minimum necessary volume of measurements in each building (see section 4.5.4). Therefore, if only 2-3 measurements are conducted in the entire building (simultaneously in different rooms), it is important to specify the conditions for selecting rooms in order of testing priority, depending on the type and location of the room.

High priority is given to testing rooms with prolonged occupancy, such as bedrooms, children's playrooms, home offices, and other rooms where people usually spend at least 6 hours a day. If the rooms are on different floors, then attention is focused on rooms of this type, which are located on the lower floors down to the basements, even though people usually do not live in basements and do not spend much time there.

Low priority is given to testing rooms where people spend little time and, moreover, rarely visit, regardless of their location (floor).

Typically, radon levels are higher in basement because the soil is the main source or supplier of radon into buildings (additional less significant sources include building materials of mineral origin, such as those made of natural stone, ceramics, concrete, bricks, etc., and in rare cases, water supply sources). However, with a limited number of measurements, testing rooms in the basement is impractical if these rooms are rarely visited.

4.4.1.9. Renovation or major repairs of a building, including the modernization of engineering systems and underground utilities, can affect the radon situation in the building, especially on the lower floors. In this case, it is advisable to re-examine the building. Additionally, due to the gradual degradation of foundation elements and underground engineering systems, radon migration from the soil into the building may increase. Therefore, it is recommended to conduct repeat radon tests every 3-5 and 10 years, not only in areas with high radon levels but also in areas with low radon levels in buildings, respectively.

4.4.1.10. Collecting and accumulating the results of indoor radon tests, including the characteristics of rooms and buildings, allows for better assessment of collective risks from radon exposure in different regions of the country, as well as more accurate identification of Radon Priority Areas on a scale from regions to municipalities, while ensuring the confidentiality of voluntary test participants.

4.4.2. Rational Criterion of Conformity Assessment

4.4.2.1. The rational criterion ensures a decision reliability of at least 95% (no more than 5% false-negative error) regarding the compliance of a room with a safety requirement, if the following condition is met [21]:

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

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

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

$U_V(t)$ is the temporal uncertainty in relative units (with coverage factor $k = 2$), the values of which depend on the measurement duration and operation/ventilation mode, and are provided in ANNEX A,

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

4.2.2. The additional criterion for identifying hazardous rooms ensures a decision reliability of at least 95% regarding the non-compliance of a room with a safety requirement, if the following condition is met [22]:

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

where $MF(t)$ is the multiplicity factor in relative units, the values of which depend on the measurement duration (only under normal mode) and are provided in ANNEX A.

4.5. Test Conditions

4.5.1. General

4.5.1.1. Measurements in short-term and long-term modes can be conducted at any time of the year, except for starting short-term measurements during adverse weather conditions. In this case, it is recommended to consider meteorological service forecasts in advance and not to start short-term measurements:

- during abnormally high or low temperatures in the region,
- during high wind speeds and/or strong gusts of wind,
- during prolonged rain and for 1-2 days after it ends.

4.5.1.2. Throughout the building, not just in the tested rooms, all windows and doors should be installed, and the natural and/or forced ventilation system (if provided by the design), as well as heating, water supply, and sewage systems, should be operational. Inspections of new or renovated buildings are recommended to be conducted no earlier than one week after the completion of finishing works. If a new building is put into operation without the interior finishing of the rooms, the absence of interior doors is permissible.

4.5.1.3. During the cold season, buildings or individual apartments with an independent heating system should be inspected only when the heating is turned on, and it should be operational for at least one week before the start of measurements.

4.5.1.4. The microclimatic conditions in the rooms should comply with national requirements, also considering the temperature and humidity limitations of the working ranges of the applied radon measurement methods and instruments. In particular, the temperature and relative humidity of the air in the rooms should not exceed the following ranges for industrial (or residential and public) buildings:

- from +13 to +28 (or from +18 to +26) °C,
- from 15 to 75 (or from 30 to 60) %.

4.5.1.5. During the measurement (sampling) period, it is unacceptable to carry out repair work in the tested room or in the entire building that may affect the air-thermal regime, especially room ventilation.

4.5.1.6. In case of groundwater penetration into basements, as well as the building or part of it (especially the foundation) is in an emergency condition, the building or individual rooms are not inspected.

4.5.2. Ventilation Mode

4.5.2.1. In closed mode with limited ventilation, where all windows and doors in the building (or tested apartment) are constantly closed and forced ventilation is turned off (if provided by the design), the measurement duration should be at least 2 days. If the planned test duration under closed mode is no more than 4 days, preliminary conditioning of the entire building or tested apartment for at least 12 hours under limited ventilation is required. If the planned test duration under closed mode is more than 4 days, then preliminary procedures for preparing the test rooms and the building as a whole are not required.

4.5.2.2. In normal mode, where all rooms and the building as a whole are operated in a regular mode without any restrictions, the measurement duration should be at least 4 days. In this case, no preliminary procedures are required to prepare the tested rooms.

It is important to note that in normal mode, intentionally constantly open or constantly closed windows and doors, as well as intentionally turning off forced ventilation (if provided by the design), can significantly affect the measurement results and, consequently, reduce the reliability of rooms and building testing, especially in short-term measurements.

4.5.2.3. Testing rooms in normal mode is preferable compared to testing in closed mode [22].

4.5.3. Measurement Point Location in Room

4.5.3.1. The measurement point should be located away from windows, doors, and sources of heat, cold, moisture, or drafts, at least 20 cm from walls. It should also be protected from direct sunlight, vibration, and electromagnetic fields, such as those created by a microwave oven or mobile phone (the distance to these devices should be at least 0.5 m).

4.5.3.2. The location of the measurement point should prevent any manipulation of the measurement instrument (sampler), including movement, throughout the entire measurement period.

4.5.3.3. The recommended height for the measurement point is between 0.4 and 2 meters. Under closed mode and in the absence of furniture, measurement on the floor is allowed with a cardboard sheet base, at least 20x20 cm in size.

4.5.3.4. In large rooms, the number of measurement points should be determined at a rate of 1 point per 100 m², and in the case of large warehouse spaces, 1 point per 200-400 m².

4.5.3.5. One device (or sampler) should be placed at each measurement point.

4.5.4. Selection of Tested Rooms in Building

4.5.4.1. The ideal testing strategy covers all rooms in the building; however, this is not a practical approach since most buildings have low radon levels, especially on the upper floors. Therefore, it is rational to start the building inspection with the minimum necessary coverage of tested rooms, mainly located on the ground floor, considering the testing priority according to 4.4.1.8.

4.5.4.2. On the ground floor (immediately above the ground), testing should be conducted in all rooms with prolonged occupancy. In the case of multi-apartment buildings put into operation without interior finishing (and interior doors), the minimum number of measurements on the first floor is determined at a rate of 1 measurement per 50-100 m², but not less than 1 measurement per apartment.

4.5.4.3. On both the floor above the ground floor and the top floor, it is recommended to perform at least 2 tests on each of these floors. In this case, the tested rooms should be in different apartments closest to the stairwell. Between these floors, tests are recommended to be conducted in randomly selected rooms (different apartments), with the number determined at a rate of 2 tested rooms per 5-10 floors.

4.5.4.4. The method of selecting tested rooms, according to 4.5.4.2 and 4.5.4.3, applies to each individual entrance of the inspected building.

4.5.4.5. If there are not enough measurement instruments for the minimum necessary coverage of tested rooms, then the building inspection is carried out in stages at different times, covering one or more entrances per stage.

4.5.4.6. If it is necessary to identify zones of the most intense radon transfer from the soil into the building, measurements (at least 4 days) should be conducted simultaneously in all basement and ground-level rooms with constantly closed doors and windows.

To verify the effectiveness of radon protection measures in the building, measurements (at least 4 days) should be conducted simultaneously in the same operation/ventilation mode and in the same rooms where elevated radon levels were detected before the implementation of protective measures.

4.5.5. Requirements for Measuring Instruments

4.5.5.1. Any sampling methods and measurement instruments can be used for measuring radon concentration, provided they ensure continuous or periodic sampling and/or measurements in short-term or long-term modes. These methods should allow for determining the average radon concentration over the measurement period t (from two days to one year), and the instrumental uncertainty U_D , as outlined in the algorithms in ANNEX B.

4.5.5.2. It is rational to use measurement methods and instruments with a calibration error (or measurement error, if calibration data is unavailable) not exceeding $\pm 40\%$ ($k = 2$) and $\pm (20-30)\%$ ($k = 2$) in short-term and long-term measurement modes, respectively (see ANNEX B).

4.5.5.3. For measuring the temperature and relative humidity of the air in rooms, any electronic devices can be used, provided their measurement ranges comply with the requirements in 4.5.1.4, and the measurement errors for temperature and humidity are no worse than $\pm 1^\circ\text{C}$ and $\pm 3\%$, respectively.

4.6. Measurements

4.6.1. Preparing for Measurements

4.6.1.1. It is recommended to collect information about the tested building, including floor plans and the following data:

- specific name of the building (if applicable),
- location (exact address and/or GPS coordinates),
- purpose (residential/public/office/industrial),
- ownership type (private/shared/municipal/state),
- building status (in use/new with finishing/new without finishing/renovated with finishing/renovated without finishing),
- year (or decade) of commissioning,
- number of floors, including ground and underground levels,
- number of entrances,
- main building material (stone/wood/metal frame/combined),
- foundation type (slab/strip/pile/combined),
- presence of a basement (yes/no),
- ventilation type (natural/forced),
- air conditioning (central/individual/none),
- heating type (central/individual/none),
- water supply type (central/individual/none),
- sewage type (central/individual/none),
- results of previous testing, as well as information on protective measures to reduce radon concentration, if conducted.

4.6.1.2. It is recommended to determine in advance the minimum necessary number of tested rooms, considering their purpose and location based on the building characteristics, also taking into account section 4.5.4 and the available measurement instruments.

4.6.2. Performing Measurements

4.6.2.1. The performance of measurements (sampling) in short-term or long-term modes should comply with the operating instructions of the measurement (sampling) instrument.

4.6.2.2. It is recommended to start room testing with short-term measurements, following the conditions of section 4.5, while recording actual weather (temperature/humidity/wind/precipitation) and microclimatic conditions, as well as the operation/ventilation mode (normal or closed).

4.6.2.3. At the beginning of the measurement (sampling) in each room, the following data should be recorded:

- unique measurement (test) number or code,
- date and time (accurate to one hour),
- room number or code, according to the floor plan,
- room status (with finishing and furniture / with finishing without furniture / without finishing),
- room purpose (bedroom/children's room/living room/office/other/unknown),
- floor level,
- entrance number,
- type (model) of the sampler and/or measuring device,
- number (code) of the sampler and/or measuring device.

4.6.2.4. Upon completion of the measurement (sampling), the date and time (accurate to one hour) should be recorded, as well as the measurement result, if available.

4.6.2.5. Exposed samplers (if used) should be promptly delivered to the laboratory for analysis in accordance with the operating instructions of the measurement instrument.

4.6.3. Expression of Measurement Results

4.6.3.1. The result of each measurement should include the following set of necessary data (regardless of the measurement instrument used):

- unique measurement (test) number or code,
- date and time of the start of the test (accurate to one hour),
- measurement duration (accurate to one hour),
- average radon concentration (Bq/m^3) over the measurement period (test),
- instrumental uncertainty (U_D at $k = 2$), expressed in relative units (e.g., 0.25 or 25%),
- operation/ventilation mode (normal or closed).

4.6.3.2. The set of additional data related to the measurement result and characterizing the test conditions should cover the building characteristics mentioned above (paragraph 4.6.1.1) and the room characteristics (paragraph 4.6.2.3), including data on the measurement instrument and microclimatic conditions (paragraph 4.5.1.4) recorded at the beginning of the measurements. In the case of short-term measurements, the weather conditions at the start of the measurements (temperature/humidity/wind/precipitation) should also be indicated.

4.7. Conformity Assessment

4.7.1. Room Compliance Decision

4.7.1.1. A room complies with a safety requirement if criterion (1) is met.

4.7.1.2. A room does not comply with a safety requirement (measures to reduce radon concentration are required) if criterion (2) is met, or if criterion (1) is not met with a measurement duration of at least 9 months.

4.7.1.3. If criterion (1) is not met in short-term measurements (from 2 to 7 days), this may indicate elevated radon levels in the room. In this case, it is recommended to:

- conduct more accurate measurements in long-term mode (from 2 to 12 months), which increases the likelihood of meeting criterion (1) due to reduced temporal uncertainty, or
- implement measures to reduce radon concentration, following the ALARA principle.

4.7.2. Building Compliance Decisions

4.7.2.1. A building complies with a safety requirement if, with the minimum necessary coverage of tested rooms, each of them meets the safety requirement according to 4.7.1.1.

4.7.2.2. A building does not comply with a safety requirement (measures to reduce radon concentration are required) if, with the minimum necessary coverage of tested rooms, at least one of them does not meet the safety requirement according to 4.7.1.2.

4.7.3. Legal Aspect of Decision

4.7.3.1. In the context of voluntary indoor testing (including paid services), the legal aspect of the decision on the compliance/non-compliance of a room, as well as the building as a whole, with a safety requirement is not particularly important. At the same time, the legal force of such a decision can be of particular importance in the case of tests and measures to protect buildings from radon funded by regional (local) or national budgets.

4.7.3.2. The decision on the compliance/non-compliance of a room, as well as the building as a whole, with a safety requirement can have legal force only if the measurements were conducted within the rules of this document by qualified specialists from an accredited laboratory using measurement instruments with a Calibration Certificate, according to the requirements of ISO/IEC 17025:2017.

4.7.3.3. The valid Calibration Certificate of the measurement instrument should indicate either the maximum relative value of instrumental uncertainty (U_D at $k = 2$), which metrological services may also refer to in their documents as "measurement uncertainty" or "measurement error (with a \pm sign)," or the relative value of the instrumental uncertainty component (U_{CF} at $k = 2$), expressing the calibration error of the measuring instrument, which is necessary for calculating the U_D value based on the algorithms in ANNEX B.

4.8. Quality Assurance

4.8.1. The quality of measurements and the reliability of decisions on the compliance/non-compliance of tested rooms (buildings) with a safety requirement are ensured by strict adherence to the rules of this document, combined with the control and management of such main components of conformity assessment uncertainty as temporal uncertainty $U_V(t)$ and instrumental uncertainty U_D , including the multiplicity factor $MF(t)$, which are used in criteria (1) and (2).

4.8.2. Detailed information on the control and management of temporal and instrumental uncertainties, including the multiplicity factor, is provided in ANNEX A and ANNEX B.

4.9. Test Report

4.9.1. The Test Report should be prepared in accordance with the requirements of ISO/IEC 17025:2017 and include a reference to this document. It should contain seven main sections covering the information as outlined in the paragraphs below.

4.9.1.1. Information about the laboratory that conducted the measurements, including the name and contact details, the validity period and number of the Accreditation Certificate (if available), the data (or code) of the person responsible for conducting the test, and other data according to ISO/IEC 17025:2017. If the measurement (sampling) was conducted voluntarily by a private individual, their data is not required.

4.9.1.2. Information about the measurement instrument, including the model, and the sampler (if used), their numbers, the validity period and number of the Calibration Certificate (if available), as well as the calibration uncertainty (or error) in relative units at $k = 2$ (either measurement uncertainty or measurement error, if specified in the Calibration Certificate).

4.9.1.3. Information about the building, including the floor plan and the list of data according to 4.6.1.1. This should also include the results of previous testing and protective measures to reduce radon concentration, if conducted.

4.9.1.4. Measurement conditions, including the operation/ventilation mode (normal or closed), microclimatic conditions according to 4.5.1.4, and weather data in the case of short-term measurements.

4.9.1.5. Information about each tested room, including the relevant data according to 4.6.2.3, marked on the floor plan, which should be attached to the Test Report if the building testing covered the minimum necessary number of rooms according to section 4.5.4.

4.9.1.6. Measurement results for each tested room, including the measurement (test) number or code, the date and time of the start and end of the test (accurate to one hour), the measurement duration (accurate to one hour), the average radon concentration (Bq/m^3) over the measurement period (test), and the instrumental uncertainty (U_D at $k=2$), expressed in relative units (e.g., 0.25 or 25%). This should also include laboratory measurement data if a sampler with subsequent laboratory analysis was used.

4.9.1.7. The decision on the compliance or non-compliance of each tested room with a safety requirement should consist of two parts:

- Part 1: Calculation of the values of the left side of the inequalities of criteria (1) and (2), as well as the actual value of the reference level (the right side of these inequalities),
- Part 2: Conclusion on the compliance or non-compliance of the tested room with a safety requirement based on the comparison of the data in Part 1, according to section 4.7.1.

4.9.2. The data from the last three paragraphs (4.9.1.5, 4.9.1.6, and 4.9.1.7) can be integrated into a general table in the Test Report.

4.9.3. If the building inspection was conducted with the minimum necessary coverage of tested rooms, allowing for the assessment of the building's compliance with a safety requirement, this should be reported in an additional eighth section of the Test Report with reference to sections 4.5.4 and 4.7.2. Accordingly, the eighth section of the Test Report should provide the decision on the compliance or non-compliance of the building as a whole with a safety requirement, according to section 4.7.2.

4.9.4. If the tested rooms, as well as the building as a whole, comply with a safety requirement, it is recommended to add a reminder at the end of the Test Report, according to 4.4.1.9, about the advisability of conducting repeat indoor radon testing every 3-5 and 10 years in areas with both high and low radon levels in buildings, respectively.

4.A. ANNEX A: Temporal Uncertainty Component in Conformity Assessment

4.A1. The values of temporal uncertainty $U_V(t)$ depending on the measurement duration and operation/ventilation mode are provided in relative units ($k = 2$) in Table 1. This table also provides the relative values of the multiplicity factor $MF(t)$ depending on the measurement duration only in normal mode.

Table 1.

Measurement duration*	Temporal uncertainty $U_V(t)$ [36]		Multiplicity factor $MF(t)$ [22]	
	Operation/ventilation mode			
	Normal	Closed		
Day	2	-	1.05	-
	3	-	1.00	-
	4	1.25	0.95	1.74
	5	1.20	0.90	1.72
	6	1.20	0.80	1.70
	7	1.20	0.75	1.69
	8	1.20	0.70	1.68
	10	1.10	0.65	1.67
	12	1.10	0.60	1.66
	14	1.10	0.55	1.65
Month	20	1.10	0.50	1.61
	1	1.05	0.45	1.56
	2	1.00	0.40	1.48
	3	0.85	0.38	1.44
	4	0.65	0.36	1.42
	5	0.55	0.32	1.37

6	0.45	0.26	1.31
7	0.35	0.20	1.24
8	0.25	0.16	1.20
9	0.17	0.14	1.14
10	0.10	0.09	1.09
11	0.05	0.05	1.05
12	0.00	0.00	1.00

* if the measurement duration is between the tabulated values, then the larger values of $U_V(t)$ and $MF(t)$ are used, for example, $MF(t = 4.8 \text{ day}) = 1.74$.

4.A2. 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 hours) in several hundred buildings of different types located in one or multiple countries under different climatic and geological conditions [21]. 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 and floor level may be discovered, allowing for the ranking of measurement conditions and further reduction of temporal uncertainty [21].

4.A3. The statistical data array used to assess the values of temporal uncertainty is also used to assess the values of the multiplicity factor $MF(t)$ [22].

4.B. ANNEX B : Instrumental Uncertainty Component in Conformity Assessment

4.B1. General

4.B1.1. The general expression for instrumental uncertainty U_D in relative units is as follows [22]:

$$U_D = \sqrt{k^2 \cdot \frac{r/t + r_0/t_0}{(r - r_0)^2} + U_{CF}^2} \quad (\text{B1})$$

where k is the coverage factor (equal to 2),

r is the count rate (in cps) of the gross effect obtained during the period t (sec) of measuring the radon concentration indoors or the radon activity absorbed in the probe,

r_0 is the count rate (in cps) of the background effect obtained during the background measurement period t_0 (sec), according to the instructions of the monitor manufacturer,

U_{CF} is the component of instrumental uncertainty in relative units ($k = 2$), expressing the uncertainty of the instrument calibration and sampling, also considering the most significant influencing factors (if U_{CF} is 0.25 or 25%, then the relative calibration error are expressed as ± 0.25 или $\pm 25\%$).

4.B1.2. Measurement quality is also achieved by controlling instrumental uncertainty, which is related to the analysis of the recorded count rate (or number of counts) during the measurement period, as well as the U_{CF} component, according to (B1). The composition and value of this component depend on the measurement methods, among which the three most popular in international practice for indoor radon measurements are:

1. Short-term measurements using passive radon adsorption with activated charcoal, followed by measuring its activity (Charcoal method),

2. Long-term measurements using Solid State Nuclear Track Detectors (SSNTD) like CR-39 or LR-115, followed by etching and track counting (SSNTD method),

3. Measurements of any duration using active (electronic) radon monitors for continuous radon measurements (CRM method); this method is based on the natural diffusion of radon into the measurement chamber with continuous recording of accumulated counts, for example, every 1, 2 or

3 hours; this method also includes instruments for measuring radon concentration based on forced periodic sampling, including corresponding periodic result recording.

A more detailed algorithm for assessing instrumental uncertainty, including its control, is provided hereafter for each of these three methods.

4.B2. Instrumental Uncertainty of Charcoal Method

4.B2.1. The expression for the relative instrumental uncertainty of the Charcoal method U_D is derived from (B1) and is as follows:

$$U_D = \sqrt{4 \cdot \frac{r/t + r_0/t_0}{(r - r_0)^2} + U_{CFD}^2 + U_{CFS}^2} \quad (B2)$$

where r is the count rate (in cps) of the gross effect obtained during the period t (sec) of measuring the activity of radon adsorbed in charcoal,

r_0 is the count rate (in cps) of the background effect obtained during the background measurement period t_0 (sec) of the detector with "clean" charcoal,

U_{CFD} is the component of instrumental uncertainty in relative units ($k = 2$), expressing the uncertainty of the calibration of the measurement instrument (detector) for radon activity in charcoal, which usually does not exceed 0.15-0.20 ($k = 2$),

U_{CFS} is the component of instrumental uncertainty in relative units ($k = 2$), expressing the uncertainty of the assessment of the volumetric equivalent of the sampler, which usually does not exceed 0.25-0.30 ($k = 2$), or 0.40 ($k = 2$) if the correction associated with the increase in the weight of the charcoal after sampling is not taken into account.

4.B2.2. The quality of measurements using the Charcoal method is achieved through the control of instrumental uncertainty, which is related to the analysis of the recorded pulse count rate, as well as the components U_{CFD} and U_{CFS} , according to (B2). The values of these uncertainty components, as well as the corresponding sensitivity values of the detector (calibration factor) CFD and the volumetric equivalent of the sampler CFS , must be established in the Calibration Certificate.

4.B3. Instrumental Uncertainty of SSNTD Method

4.B3.1. The expression of relative instrumental uncertainty of the SSNTD method U_D follows from (B1) and has the following form [21]:

$$U_D = \sqrt{4 \cdot \frac{N + N_0}{(N - N_0)^2} + U_{CF}^2} \quad (B3)$$

where N is the number of tracks after detector exposure,

N_0 is the average number of background tracks among unexposed detectors,

U_{CF} is the component of instrumental uncertainty in relative units ($k = 2$), expressing the uncertainty of the calibration of the measurement instrument (SSNTD method system), which usually does not exceed 0.15-0.30 ($k = 2$) considering the most significant influencing factors, including exposure duration.

4.B3.2. The quality of measurements using the track method is achieved through the control of instrumental uncertainty, which, according to (B3), is related to the analysis of the number of registered tracks, as well as the component U_{CF} . The value of this uncertainty component, as well as the corresponding sensitivity value (calibration factor) of the track detector CF and the maximum allowable number of background tracks N_0 , must be established in the Calibration Certificate.

4.B4. Instrumental Uncertainty of CRM Method

4.B4.1. The expression for the relative instrumental uncertainty of the CRM method U_D is derived from (B1) and is as follows (with $r_0 = 0$) [22]:

$$U_D = \sqrt{\frac{4}{C(t) \cdot CF \cdot t} + U_{CF}^2} \quad (\text{B4})$$

where $C(t)$ – radon concentration in Bq/m^3 , measured by the monitor over the period t (in hours), determined as the ratio of the average pulse count rate to the monitor's sensitivity,

CF – sensitivity or calibration factor of the radon monitor, expressed in impulses/hour per 1 Bq/m^3 or $1/(\text{h} \cdot \text{Bq/m}^3)$, respectively, determined as the ratio of the average pulse count rate of the monitor to the average radon concentration measured by the reference monitor during the monitor(s) calibrating/checking period,

U_{CF} – component of instrumental uncertainty in relative units ($k = 2$), expressing the uncertainty of the calibration of the measurement instrument, which, for example, for radon monitors such as RadonEye or RadonEye Plus2 (South Korea) and Corentium Home or Wave Radon (Norway) does not exceed 0.30 ($k = 2$) with CF equal to 0.84 $1/(\text{h} \cdot \text{Bq/m}^3)$ for Korean monitors and 0.025 $1/(\text{h} \cdot \text{Bq/m}^3)$ for Norwegian monitors, respectively [22].

4.B4.2. The quality of measurements is achieved through the control of instrumental uncertainty, which is related to the analysis of the CF parameter considering $C(t)$ and t (or the registered pulse count rate by (B1)), as well as the U_{CF} component, according to (B4). The value of this uncertainty component, as well as the corresponding sensitivity value (calibration factor) CF , must be established in the Calibration Certificate.

4.B4.3. Unlike measurement instruments based on Charcoal and SSNTS methods, various types of CRM monitors are produced by a large number of manufacturers from different countries. However, there are still no clear metrological requirements in both international and national regulatory practices regarding standardization, which should ensure the uniformity of indoor radon measurements to assess the compliance of rooms (buildings) with safety requirements [21]. Therefore, recommendations are provided below to regulatory authorities and metrological services, as well as to users and manufacturers of CRM monitors, to maximize their effective application within a rational conformity assessment criterion.

4.B4.3.1. CRM Monitor Calibration with Uncertainty Assessment

4.B4.3.1.1. The uncertainty U_{CF} mainly depends on fluctuations in humidity, temperature, dust concentration, and aerosol composition of the air, as well as radon concentration, whose variation over a wide range can disrupt the linearity of monitor calibration. In addition, variations in the characteristics of the detector itself, as an electronic device, make a greater or lesser contribution, especially taking into account variations in the characteristics of scintillation materials, if used.

Variations in dust concentration and aerosol composition of the air under normal building operating conditions usually do not significantly affect the sensitivity of the monitors over 3-5 years of use. Additionally, it is important to consider that the main target (reference and other control) levels of radon concentration in dwellings and workplaces do not exceed 1000 Bq/m^3 . Therefore, the value of 1000 Bq/m^3 or at least 3000 Bq/m^3 is advisable to accept as the upper limit of the radon concentration measurement range, below which the compliance with the established CF and U_{CF} values is guaranteed, according to 4.B4.3.4. Moreover, the accuracy of measurements of high radon concentrations exceeding 1000 Bq/m^3 practically does not affect the reliability of conformity assessment using criteria (1) and (2) [22].

4.B4.3.1.2. Considering the above, it is allowed (even preferable) to checking/verifying (or calibrating) monitors, in addition to the traditionally used metrological service boxes with stable or smoothly varying radon concentration, in a natural air environment of rooms (with a volume of at least 15 m^3) with characteristic temporal (daily) variations in radon concentration, not exceeding the range from 10 to 1000-3000 Bq/m^3 (approximately), as well as the average radon concentration during the measurement period in the range from 50 to 500-800 Bq/m^3 (approximately) [22].

4.B4.3.1.3. The lower the average radon concentration, the longer the measurement duration t (in hours) should be, which is determined by the following expression derived from (B4) (with $U_{CF} = 0$):

$$t = \frac{4}{C(t) \cdot CF \cdot U_{St}^2} \quad (\text{B4.1})$$

where U_{St} is the statistical component of uncertainty U_D at $k = 2$, expressed in relative units.

The measurement duration should ensure the minimization of the contribution of the statistical component U_{St} , the value of which for both the checked/verified (or calibrated) and reference monitor should not exceed 0.05 when evaluating t using formula (B4.1), choosing the larger value of t for simultaneous (parallel) measurements with monitors of different models [22].

4.B4.3.1.4. The value of U_{CF} for checked monitors of the same model is determined (at $k = 2$) without considering the small contribution of the U_{St} component (less than 5%) based on an expression that includes two uncertainty components, namely, the standard deviation and the calibration factor bias error [22]:

$$U_{CF} = 2 \cdot \sqrt{\frac{\sum(C_i - C_{Avg})^2}{C_{Avg}^2 \cdot (m - 1)} + \left(\frac{C_{Avg}}{C_{Ref}} - 1\right)^2} \quad (\text{B4.2})$$

where C_i is the radon concentration measured on the i -th monitor during the measurement period,

m is the number of checked monitors of the same model (see 4.B4.3.1.6),

C_{Avg} is the average radon concentration across all m monitors,

C_{Ref} is the radon concentration measured in parallel using the reference monitor, which must have a valid Calibration Certificate with established CF and U_{CF} values at $k = 2$ (if $k=1$, then the doubled calibration uncertainty value is taken); if calibration uncertainty data is absent, then the parameter value called "measurement uncertainty" or "measurement error" is used.

If the result by formula (B4.2) is less than the calibration uncertainty of the reference monitor $U_{Ref}(k = 2)$, then the U_{CF} value is taken as equal to U_{Ref} for the checked monitors [22].

4.B4.3.1.5. In the case of a significant contribution of the calibration factor bias error (the last term in equation (B4.2)), the U_{CF} value can be reduced by refining (adjusting) the calibration factor CF using the expression:

$$CF = CF_{Initial} \cdot \frac{C_{Avg}}{C_{Ref}} \quad (\text{B4.3})$$

where $CF_{Initial}$ is the initial calibration factor value.

After setting the refined CF value on all checked monitors, the measurements to evaluate U_{CF} are conducted again, according to 4.B4.3.1.4.

4.B4.3.1.6. If at least 20 monitors of the same model [22] have been checked according to paragraphs 4.B4.3.1.4 and 4.B4.3.1.5, then the CF and U_{CF} values can be applied in the future for the production of new monitors of the same model (or another model, but with the same detector and measurement chamber design) without conducting similar checking for several years or the period of the Calibration Certificate, also considering the results of periodic verification of monitors of the same model, according to 4.B4.3.3.

4.B4.3.1.7. If radon monitors with increased accuracy are to be calibrated with $U_{CF} < 15\text{-}20\%$ ($k = 2$), then measurements are conducted with each monitor individually, and the U_{CF} value is determined using formula (B4.2), in which the first term is not considered, and C_{Avg} is taken as the radon concentration measured by the checked monitor. The individual CF value can also be refined according to formula (B4.3). In any case, the individual U_{CF} value at $k = 2$ cannot be less than the calibration uncertainty of the reference monitor $U_{Ref}(k = 2)$ [22].

4.B4.3.1.8. The reliability of conformity assessment within the criteria (1) and (2) practically does not depend on CF and U_{CF} if the indoor measurement duration does not exceed 1-2 months [22], while

the checking/verifying (or calibrating) procedures for low-sensitivity monitors take significantly more time compared to high-sensitivity monitors, according to (B4.1).

4.B4.3.2. Control of Background of New CRM Monitors

4.B4.3.2.1. An additional metrological characteristic of radon monitors is the detector's own background, which is usually expressed as the equivalent radon concentration in Bq/m³. The background of new radon monitors usually does not exceed 3 (maximum 5) Bq/m³, but during long-term using, the background of the monitors can increase to 10-20 Bq/m³, and with frequent measurement of high radon concentrations, the background can exceed 50-100 Bq/m³. Within the criteria (1) and (2), considering the C_{RL} values, which are usually above 100 Bq/m³, a monitor background below 10 Bq/m³ practically does not affect the reliability of conformity assessment, so it is not considered in the calculations according to expression (B4). An equivalent background exceeding 15-20 Bq/m³ can be tracked and accounted for (by subtracting it), which, however, complicates ensuring measurement quality. Therefore, further use of monitors with a background exceeding 10-15 Bq/m³ is recommended not to be used, at least for indoor radon testing within the criteria (1) and (2) [22].

4.B4.3.2.2. The background of new monitors is determined in an environment maximally purified from radon using one of the following two methods. Method 1 is based on continuous air pumping (filtration) through a sufficient volume of activated charcoal in a closed loop, including a closed box with the checked monitors. Method 2 is based on filling a closed box with the checked monitors with gaseous nitrogen, which has been pre-stored for at least one month in a high-pressure balloon.

4.B4.3.2.3. The duration of background control for new monitors should ensure the minimization of the contribution of the statistical component U_{St} , the value of which should not exceed 0.20-0.30 when evaluating t using formula (B4.1).

4.B4.3.2.4. The upper limit of the permissible background value for new monitors of the same model corresponds to the maximum result of radon concentration measurements among at least 7 checked monitors. The obtained background value can be used in the future to characterize newly produced monitors of the same model (or another model, but with the same detector and measurement chamber design) without conducting similar measurements for several years or the period of the Calibration Certificate.

4.B4.3.3. Periodic Verification of CRM Monitors

4.B4.3.3.1. Periodic verification of radon monitors should be conducted by metrological services at intervals determined by the manufacturer in agreement with the metrological service. If the analysis of the annual verification results of monitors of the same model shows satisfactory statistics (e.g., no more than 1% rejection rate), then it is advisable to increase the verification interval.

It is allowed to conduct independent periodic (every 1-2 years) control of the operation of non-professional radon monitors, whose calibration (or measurement) uncertainty exceeds 30% ($k = 2$). In this case, for parallel comparative measurements of radon concentration, it is necessary to use radon monitors (new or used, having a Calibration Certificate) with established CF and U_{CF} values, as well as background (hereinafter referred to as reference monitors in this section). The description of the procedures for independent parallel measurements, including comparison criteria, is provided below.

4.B4.3.3.2. The control of the background of the checked monitor (which is long-term used) should be conducted in a well-ventilated room, where the average radon concentration according to the reference monitor readings should not exceed 20 Bq/m³ during the entire measurement period.

The duration of the background measurement under such conditions should ensure the minimization of the contribution of the statistical component U_{St} , the value of which should not exceed 0.10 when evaluating t using formula (B4.1), choosing the larger value of t for parallel measurements with monitors of different models.

If the radon concentration measured on the checked monitor exceeds the result on the reference monitor by more than 15 Bq/m³, further use of the checked radon monitor is recommended to be discontinued.

4.B4.3.3.3. Verification of the checked monitor can be conducted in a room with naturally elevated radon concentration, whose fluctuations and average level should correspond to the ranges specified in 4.B4.3.1.2, and the microclimatic conditions of the room should meet the conditions of 4.5.1.4.

The duration of measurements should ensure the minimization of the contribution of the statistical component U_{st} , the value of which should not exceed 0.05-0.10 when evaluating t using formula (B4.1), choosing the larger value of t for parallel measurements with monitors of different models.

If the relative difference between the radon concentration measurement results on the checked and reference monitors ($[C_{Ch} / C_{Ref}] - 1$) exceeds the relative calibration (or measurement) uncertainty value specified in the Calibration Certificate of the checked monitor, its further use should be discontinued.

4.B4.3.4. Main Metrological Characteristics of CRM Monitors

Considering the guidelines and recommendations above, it is advisable to specify the following main metrological (and additional) characteristics for each model of CRM monitor intended for indoor radon measurements within the framework of a rational compliance assessment criterion [22]:

- 1) Monitor Sensitivity (or Calibration Factor CF),
- 2) Calibration Uncertainty of the Monitor U_{CF} , expressed in relative units at $k = 2$ (instead of the traditionally indicated measurement uncertainty or error, which depend on several parameters and are determined by calculation using formula (B4)),
- 3) Background of the New Monitor as the maximum equivalent radon concentration, for example, not more than 3 Bq/m³,
- 4) Upper Measurement Range of Radon Concentration, for example, 1000 or 3000 Bq/m³ within which compliance with the established characteristics 1 and 2 is guaranteed (the lower measurement range of radon concentration depends on sensitivity, calibration uncertainty, measurement duration, and the monitor's background, so it is advisable to limit the indication to characteristic 3, instead of the traditionally indicated lower measurement range or minimum measurable radon concentration, which have no practical significance in the metrological support of indoor radon measurements within the rational approach based on criteria (1) and (2)),
- 5) Measurement Duration (in hours or days) of Radon Concentration in Outdoor (Atmospheric) Air at a Level of 10 Bq/m³ with a statistical uncertainty of 30% ($k = 2$), determined by formula (B4.1),
- 6) Service Life of Non-Professional ($U_{CF} > 30\%$) and Professional ($U_{CF} \leq 30\%$) Monitors, for example, at least 3-5 years and 10 years, respectively, with a rejection rate during annual verification (performance control), for example, no more than (1-2) % and 0.5%, respectively.

4.B4.3.5. Displaying (Output) Measurement Results on CRM Monitors

Manufacturers of CRM monitors should consider the following recommendations to facilitate the effective use of monitors for indoor radon measurements within the framework of a rational conformity assessment criterion [22]:

- 1) Mandatory Display: Periodically updated average radon concentration $C(t)$ for the entire measurement period since the start, including the current measurement duration t (in hours, days, and months), with an update period of 1 or 3 hours for high-sensitivity monitors and 12 or 24 hours for low-sensitivity monitors (the average radon concentration measurement result should be displayed for the first time only after the completion of the first period),
- 2) Additional (Functional) Display: Average radon concentration only for the previous measurement period (without using the moving average principle), with a duration of 1 or 3 hours for high-sensitivity monitors and 12 or 24 hours for low-sensitivity monitors (this display shows

temporary radon fluctuations, although their dynamics do not affect conformity assessment criteria and are unlikely to be of interest to many users),

3) The expression of measured Radon Concentration should also include the display of the calculated value of Instrumental Uncertainty U_D , according to (B4), in relative units at $k = 2$,

4) Monitor design should include a button to start measurements (protected from accidental pressing) and the ability to record results in memory (with one of the aforementioned periods), which can be downloaded,

5) Convenience for metrological control should provide a mode in which, instead of the calculated radon concentration, the registered pulses or average pulse count rate (after the start of measurements) are displayed, including the measurement duration in hours and minutes,

6) Always Display Measurement Results: Regardless of the established upper measurement range of radon concentration and the degree of calibration linearity disruption, always display (and record in memory) the measurement results (up to 999,999 Bq/m³), possibly excluding the U_D value if the upper measurement range is exceeded. Blocking the output of results exceeding the upper measurement range (unfortunately implemented in some monitor models) results in an underestimated average radon concentration during the indoor radon testing at extremely high levels or makes it impossible to determine, significantly complicating work related to building radon protection measures.

5. Conclusions

The international radon regulation system, as outlined in the IAEA Safety Guides, has certain gaps and inconsistencies that need improvement. Among the challenges in designing and conducting indoor radon surveys, a fundamental issue is the long-term neglect by the radon community of a key parameter: the temporal uncertainty of annual average indoor radon concentration – the vital component in conformity assessment of a room (building) with safety requirements. The reference level limits the annual average radon concentration in buildings, which serves as a criterion for the radiation safety of buildings. However, measurements over a full year are rarely conducted. Clearly, the shorter the measurement duration, the higher the temporal uncertainty.

National indoor measurement protocols differ fundamentally in the duration of measurements, which is arbitrarily (subjectively) set by national regulators (from several minutes to six months) without taking into account the quantitative relationship with the reliability of conformity assessment, as temporal uncertainty is not taken into account. This indicates a lack of both decision-making reliability and harmony in international radon regulations.

The solution to this fundamental problem is proposed in combination with the simultaneous resolution of the following related issues:

- **Radon Measurement Aspect:** Implementing a general strategy of indoor radon surveys based on the rational criterion of conformity assessment, taking into account main components such as temporal and instrumental uncertainties. This includes the implementation of the national measurement platform, which will provide the population with simple and accessible (inexpensive) tools for testing their homes and offices. It will also allow for the effective accumulation of indoor testing results in a national database for assessing collective risks due to radon exposure.

- **Legislation Aspect:** Implementing circumstances determining responsibility for indoor radon testing (and mitigation) and canceling excessive focus on radon priority areas. This will enable the development of large-scale (mass) indoor radon testing uniformly throughout the populated area of a country, facilitated by the voluntary participation of the population. The population is quite capable of paying for testing and mitigation services, as shown by the experience of regulation in the US, UK and Sweden. Otherwise, radon regulation turns into an imitation of useful activity.

- **Awareness and building protection aspects.** These are also important components of radon regulation. However, the discussion of the tasks and solutions within these aspects is less in-depth, as the focus of the article remains on the radon measurement aspect.

- **Main research activities.** They are necessary for the sustainable development of a global system of radon regulation.

To effectively implement the entire set of discussed solutions within Actual Needs for Design and Conduct of Indoor Radon Surveys, a Rational Method (protocol) of Indoor Radon Measurements is proposed as a detailed guideline. The Rational Method can serve as a basis for international standardization of indoor radon testing, ensuring decision-making reliability of at least 95%, as well as harmonizing national approaches by considering the features of traditional measurement protocols using both short-term and long-term measurements.

The Rational Method is recommended for consideration by the IAEA in one of its forthcoming advanced Safety Guides and for practical implementation either through the revision of the existing international standard ISO 11665-8, titled "Methodologies for Initial and Additional Investigations in Buildings," or through the development of a new international standard after discussion and acceptance by national regulators in the US, Europe, and other countries. Considering the current revision situation of ISO 11665-8 without any progress over the years, as discussed in detail in section 2.4, it seems appropriate to develop a European standard for indoor radon testing based on the Rational Method within the system of the European Committee for Standardization (CEN).

The proposed solutions aim to achieve the goal of modern design and conduct of indoor radon surveys, which involves large-scale (mass) testing and effectively identify hazardous buildings. This approach relies on convenient tools and active voluntary participation of the population, to be carried out within the framework of national radon regulation. Mass testing of buildings and mitigation (if necessary) through active public participation (including payment for these services, as in the US, UK or Sweden) will enable a global reduction of radiation risk and an improvement of the quality of life of the populations worldwide.

References

1. UNSCEAR, 2008. Sources and Effects of Ionizing Radiation. UNSCEAR Report to the General Assembly United Nations: Vol. 1, Annex B, New York: United Nations Scientific Committee on the Effects of Atomic Radiation.
2. WHO, Housing and Health Guidelines; World Health Organization: Geneva, Switzerland, 2018; ISBN 978-92-4-155037-6. Available online: <https://www.who.int/publications/i/item/9789241550376> (accessed on 6 May 2024).
3. ICRP, The International Commission on Radiological Protection Radiological Protection against Radon Exposure, ICRP Publication 126. Ann. ICRP 2014, 43, 5–73. Available online: <https://www.icrp.org/publication.asp?id=ICRP%20Publication%20126> (accessed on 6 May 2024).
4. IAEA, International Atomic Energy Agency, Radiation protection and safety of radiation sources: International Basic Safety Standards; IAEA Safety Standards Series No. GSR Part 3; International Atomic Energy Agency: Vienna, Austria, 2014. Available online: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1578_web-57265295.pdf (accessed on 5 May 2024).
5. EU-BSS, Council Directive 2013/59/Euratom Laying down Basic Safety Standards for Protection against the Dangers Arising from Exposure to Ionizing Radiation Repealing Directives 89/618, 90/641, 96/29, 97/43 and 2003/122/Euratom. Off. J. Eur. Union 2014. Available online: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:pdf> (accessed on 12 January 2024).
6. WHO, World Health Organization, National Radon Reference Levels, Data by Country. Available online: <https://apps.who.int/gho/data/view.main.RADON03v> (accessed on 12 January 2024).
7. IAEA, International Atomic Energy Agency, National and regional surveys of radon concentration in dwellings: Review of methodology and measurement techniques, IAEA Analytical Quality in Nuclear Applications Series No. 33, IAEA, Vienna (2013).
8. IAEA, International Atomic Energy Agency, WHO, World Health Organization, Protection of the public against exposure indoors due to radon and other natural sources of radiation, IAEA Safety Standards Series No. SSG-32, IAEA, Vienna (2015).

9. IAEA, International Atomic Energy Agency, A Flowchart for the Development of a National Radon Action Plan (RAP), IAEA, Vienna (2017). Available online: <https://www-ns.iaea.org/tech-areas/communication-networks/orpnet/documents/FINAL-radon.pdf> (accessed on 5 May 2024)
10. IAEA, International Atomic Energy Agency, WHO, World Health Organization, Design and conduct of indoor radon surveys, IAEA safety reports series No. 98, IAEA, Vienna (2019).
11. IAEA, International Atomic Energy Agency, Protection against exposure due to radon indoors and gamma radiation from construction materials: methods of prevention and mitigation, Series: IAEA TECDOC series, ISSN 1011-4289; no. 1951, IAEA, Vienna (2021).
12. IAEA, International Atomic Energy Agency, ILB, International Labour Office, Protection of workers against exposure due to radon. IAEA Safety Standards Series No. SSG-91, IAEA, Vienna (2024).
13. Colgan, T., Radon requirements in the international BSS and difficulties in implementation of national action plans. IAEA, Radon National Action Plan Workshop, Paris, France, 30 September 2014.
14. Tsapalov, A.; Kovler, K. Studying temporal variations of indoor radon as a vital step towards rational and harmonized international regulation. *Environ. Chall.* **2021**, *4*, 100204.
15. ANSI/AARST MAH, Protocol for conducting measurements of radon and radon decay products in homes. 2019. Available online: www.radonstandards.us (accessed on 12 January 2024).
16. US EPA. Home Buyer's and Seller's Guide to Radon. United States Environmental Protection Agency; 2018 EPA 402/K-12/002. Available online: www.epa.gov/radon (accessed on 06 January 2025).
17. Kovler, K.; Tsapalov, A. A challenging path to rational and harmonized international regulation of indoor radon. *Radiation Protection Dosimetry* **2023**, *199*, 1047–1055.
18. George, A. The history, development and the present status of the radon measurements programme in the United States of America. *Radiation Protection Dosimetry* **2015**, *167* (1–3), 8–14.
19. 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> (accessed on 06 January 2025).
20. Tsapalov, A.; Kovler, K. Short- versus long-term tests of indoor radon for risk assessment by Monte-Carlo method towards effective measurement strategy. *Indoor Air* **2022**, *32*, e13166.
21. Tsapalov, A.; Kovler, K. Metrology for indoor radon measurements and requirements for different types of devices. *Sensors* **2024**, *24*, 504.
22. Tsapalov A., Kovler K., Bossew P. Strategy and metrological support for indoor radon measurements using popular low-cost active monitors with high and low sensitivity. *Sensors* **2024**, *24*(15), 4764.
23. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories.
24. ICRP. Protection against Radon-222 at home and at work. The international commission on radiological protection. ICRP publication 65. *Ann. ICRP* **1993**, *23*, 1–45.
25. Petermann, E.; Bossew, P.; Hoffmann, B. Radon hazard vs. radon risk—On the effectiveness of radon priority areas. *Journal of Environmental Radioactivity* **2022**, *244–245*, 106833.
26. Tryggve, R. Analysis of radon levels in Swedish dwellings and workplaces; Research Report; Swedish Radiation Safety Authority: Stockholm, Sweden, 2021; ISSN 2000-0456.
27. National Service Center for Environmental Publications (NSCEP). Available online: <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100W9GR.txt> (accessed on 12 January 2024).
28. Radon Atlas of Europe; Available online: <https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation/Digital-Atlas/Indoor-radon-AM/Indoor-radon-concentration> (accessed on 06 January 2025).
29. Cinelli, G., Tollefsen, T., Bossew, P., et al. Digital version of the European Atlas of natural radiation. *Journal of Environmental Radioactivity* **2019**, *196*, 240–252.
30. Petermann, E.; Bossew, P.; Kemski, J.; Gruber, V.; Suhr, N.; Hoffmann, B. A new high-resolution indoor radon map for Germany using a machine learning based probabilistic exposure model. *Environmental Health Perspectives* **2023**, *132*(9), 097009.
31. Rey, JF, Antignani, S, Baumann, S, Di Carlo, C, Loret, N, Gréau, C, Gruber, V, Goyette Pernot, J and Bochicchio, F Systematic review of statistical methods for the identification of buildings and areas with high radon levels. *Front. Public Health* **2024**, *12*, 1460295. doi: 10.3389/fpubh.2024.1460295.

32. Watson, RJ, Smethurst, MA, Ganerød, GV, Finne, I, Rudjord, AL. The use of mapped geology as a predictor of radon potential in Norway. *Journal of Environmental Radioactivity* **2017**, *166*, 341–54. doi: 10.1016/j.jenvrad.2016.05.031.
33. Liu, H, Wang, N, Chu, X, Li, T, Zheng, L, Yan, S, et al. Mapping radon hazard areas using ²³⁸U measurements and geological units: a study in a high background radiation city of China. *Journal of Radioanalytical and Nuclear Chemistry* **2016**, *309*, 1209–15. doi: 10.1007/s10967-016-4717-5.
34. Bachirou, S., Saïdou, C.K., Ii Jenn, Bongue, D., Abba, H.Y., Hosoda, M, et al. Mapping in a radon-prone area in Adamawa region, Cameroon, by measurement of radon activity concentration in soil. *Radiat Environ Biophys.* **2023**, *62*, 427–39. doi: 10.1007/ s00411-023-01042-3
35. Rezaie F, Kim SW, Alizadeh M, Panahi M, Kim H, Kim S, et al. Application of machine learning algorithms for geogenic radon potential mapping in Danyang-gun, South Korea. *Front Environ Sci.* **2021**, *9*:753028. doi: 10.3389/fenvs.2021.753028
36. Tsapalov, A., Kovler, K. Indoor radon regulation using tabulated values of temporal radon variation. *Journal of Environmental Radioactivity* **2018**, *183*, 59–72.
37. Tsapalov, A., Kovler, K. Temporal uncertainty versus coefficient of variation for rational regulation of indoor radon. *Indoor Air* **2022**, *32*, e13098.
38. IAEA, International Atomic Energy Agency, Status of radon related activities in member states participating in technical cooperation projects in Europe, Series: IAEA TECDOC series, ISSN 1011–4289; no. 1810, IAEA, Vienna (2017)
39. UNSCEAR, 2006. Effects of ionizing radiation. Volume I: Report to the general assembly scientific annexes A and B. (UNSCEAR 2006 Report) United Nations publication, New York (United Nations Scientific Committee on the Effects of Atomic Radiation).
40. Pinel, J., Fearn, T., Darby, S., Miles, J. Seasonal correction factors for indoor radon measurements in the United Kingdom. *Radiation Protection Dosimetry* **1995**, *58*(2), 127–132.
41. Miles, J. Mapping radon-prone areas by lognormal modeling of house radon data. *Health Physics* **1998**, *74*(3), 370–378.
42. Burke, Q., Murphy, P. Regional variation of seasonal correction factors for indoor radon levels. *Radiation Measurements* **2011**, *46*(10), 1168–1172.
43. Kozak, K., Mazur, J., Kozłowska, B. et al. Correction factors for determination of annual average radon concentration in dwellings of Poland resulting from seasonal variability of indoor radon. *Applied Radiation and Isotopes* **2011**, *69*(10), 1459–1465.
44. Yarmoshenko, I., Malinovsky, G., Vasilyev, A., Onishchenko, A. Seasonal variation of radon concentrations in Russian residential high-rise buildings. *Atmosphere* **2021**, *12*(7), 930. Doi:10.3390/atmos12070930.
45. Marennny, A., Nefedov, N., Vorozhtsov, A. Results of radon concentration measurements in some regions of Russia. *Radiation Measurements* **1995**, *25*(1-4), 649–653.
46. Karpinska, M., Munich, Z., Kapala, J. Seasonal changes in radon concentrations in buildings in the region of northeastern Poland. *Journal of Environmental Radioactivity* **2004**, *77*(2), 101–109.
47. Bochicchio, F., Campos-Venuti, G., Piermattei, S. et al. Annual average and seasonal variations of residential radon concentration for all the Italian Regions. *Radiation Measurements* **2005**, *40*(2-6), 686–694.
48. Denman, A., Crockett, R., Groves-Kirkby, C. et al. The value of Seasonal Correction Factors in assessing the health risk from domestic radon – A case study in Northamptonshire, UK. *Environment International* **2007**, *33*(1), 34–44.
49. Font, L. On radon surveys: Design and data interpretation. *Radiation Measurements* **2009**, *44*(9-10), 964–968.
50. Friedmann, H. Final results of the Austrian radon project. *Health Physics* **2005**, *89*, 339–348.
51. Di Carlo, C., Ampollini, M., Antignani, S., Caprio, M., Carpentieri, C., Caccia, B., Bochicchio, F. Extreme reverse seasonal variations of indoor radon concentration and possible implications on some measurement protocols and remedial strategies, *Environmental Pollution* **2023**, *327*, 121480, ISSN 0269-7491, <https://doi.org/10.1016/j.envpol.2023.121480>.
52. MetroRADON, Metrology for radon monitoring, 2017-2020, Available online: metroradon.eu (accessed on 06 January 2025).

53. traceRadon, Radon metrology for use in climate change observation and radiation protection at the environmental level, 2020-2023. Available online: traceradon-empir.eu (accessed on 06 January 2025).
54. EMPIR project develops software for conformity assessment accounting for measurement uncertainty. Available online: <https://www.euramet.org/publications-media-centre/news/news/empir-project-develops-software-for-conformity-assessment-accounting-for-measurement-uncertainty> (accessed on 29 December 2024).
55. Towards Effective Radiation Protection Based on Improved Scientific Evidence and Social Considerations—Focus on Radon and NORM (RadoNorm). Available online: <https://cordis.europa.eu/project/id/900009> (accessed on 12 January 2024).
56. ISO 11665-8:2019; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 8: Methodologies for Initial and Additional Investigations in Buildings. International Organization for Standardization: Geneva, Switzerland, 2019.
57. ANSI/AARST MAH-2023, MA-MFLB-2023, MS-QA-2023. Available online: <https://standards.aarst.org/> (accessed on 12 January 2024).
58. 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.
59. 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.
60. JCGM 100:2008; Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement. (Joint Committee for Guides in Metrology). Available online: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43fbaa5-11cf-3f85-4dcd86f77bd6 (accessed on 06 January 2025).
61. EPA Strategic Plan, Strategy 1, Available online: <https://www.epa.gov/planandbudget/strategicplan> (accessed on 06 January 2025).
62. ISO 11665-8:2012; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 8: Methodologies for Initial and Additional Investigations in Buildings. International Organization for Standardization: Geneva, Switzerland, 2012.
63. ISO 11665-1:2019; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 1: Origins of radon and its short-lived decay products and associated measurement methods. International Organization for Standardization: Geneva, Switzerland, 2019.
64. ISO 11665-4:2021; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 4: Integrated measurement method for determining average activity concentration using passive sampling and delayed analysis. International Organization for Standardization: Geneva, Switzerland, 2021.
65. ISO 11665-5:2020; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 5: Continuous measurement methods of the activity concentration. International Organization for Standardization: Geneva, Switzerland, 2020.
66. ISO 11665-6:2020; Measurement of Radioactivity in the Environment—Air: Radon-222—Part 6: Spot measurement methods of the activity concentration. International Organization for Standardization: Geneva, Switzerland, 2020.
67. Janik, M., Tokonami, S., Kranrod, C. et al. Comparative analysis of radon, thoron and thoron progeny concentration measurements. *Journal of Radiation Research* **2013**, *54*(4), 597-610.
68. UNSCEAR, 2006. Effects of ionizing radiation. Volume I: report to the general assembly scientific annexes A and B. (UNSCEAR 2006 Report) United Nations publication, New York (United Nations Scientific Committee on the Effects of Atomic Radiation).
69. Kim, C.-K., Kim, Y.-J., Lee, H.-Y. et al. ²²⁰Rn and its progeny in dwellings of Korea. *Radiation Measurements* **2007**, *42*(8), 1409-1414.
70. McLaughlin, J., M. Murray, L. Currivan et al. Long-term measurements of thoron, its airborne progeny and radon in 205 dwellings in Ireland. *Radiation Protection Dosimetry* **2011**, *145*(2-3), 189-193.

71. Chen, J., D. Moir, A. Sorimachi et al. Characteristics of thoron and thoron progeny in Canadian homes. *Radiat Environ Biophys* **2011**, 50(1), 85-89.
72. Saïdou, S. Tokonami, M. Hosoda et al. From radon and thoron measurements, inhalation dose assessment to national regulation and radon action plan in Cameroon. *Journal of Radiation Protection and Research* **2022**, 47(4), 237-245.
73. Hu, J.; Yang, G.; Kranrod, C.; Iwaoka, K.; Hosoda, M.; Tokonami, S. An Improved Passive CR-39-Based Direct $^{222}\text{Rn}/^{220}\text{Rn}$ Progeny Detector. *Int. J. Environ. Res. Public Health* **2020**, 17, 8569.
74. Sorimachi, A., Tokonami, S., Kranrod, C., Ishikawa, T. Preliminary experiments using passive detector for measuring indoor ^{220}Rn progeny concentration with an aerosol chamber. *Health Phys.* **2015**, 108(6), 597–606
75. Mishra, R., Rout, R.P., Prajith, R. et al. Dynamics and direct sensing of radon progeny. *Journal of Radioanalytical and Nuclear Chemistry* **2021**, 330(3), 1393-1396.
76. Prajith, R., Rout, R.P., Mishra, R. et al. Study on the deposition velocity of $^{222}\text{Rn}/^{220}\text{Rn}$ progeny at varying environmental conditions. *Journal of Radioanalytical and Nuclear Chemistry* **2022**, 331, 5547–5555.
77. Tokonami, S., Sun, Q., Yonehara, H., Yamada, Y. A simple measurement technique of the equilibrium equivalent thoron concentration with a CR-39 detector. *Jpn. J. Health Phys.* **2002**, 37(1), 59-63.
78. Ramola, R., Prasad, M., Rawat, M., Dangwal, A., Gusain, G., Mishra, R., Sahoo, S., Tokonami, S. Comparative study of various techniques for environmental radon, thoron and progeny measurements. *Radiation Protection Dosimetry* **2015**, 167(1–3), 22–28
79. Tsapalov, A.A., Kiselev, S.M., Kovler, K.L., Miklyaev, P.S., Petrova, T.B., Zhukovsky, M.V., Yarmoshenko, I.V., Marennyy, A.M., Tutelyan, O.E., Kuvshinnikov, S.I. Standardization of indoor radon measurements based on rational criterion for conformity assessment. *Radiatsionnaya Gygiena (Radiation Hygiene)*. **2023**, 16(4), 84-104 (In Russian). doi: 10.21514/1998-426X-2023-16-4-84-104.
80. Izgagin, V.S., Zhukovsky, M.V., Onishchenko, A.D. Population exposure by thoron decay products in multi-story buildings on example of large cities in Russia. *Journal of Radioanalytical and Nuclear Chemistry* **2024**, 333, 5295–5306. doi.org/10.1007/s10967-024-09592-6.
81. Antignani, S.; Venoso, G.; Ampollini, M.; Caprio, M.; Carpentieri, C.; Di Carlo, C.; Caccia, B.; Hunter, N.; Bochicchio, F. A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates. *Sci. Total Environ.* **2021**, 762, 144150.
82. Tsapalov, A.; Kovler, K.; Shpak, M.; Shafir, E.; Golumbic, Y.; Peri, A.; Ben-Zvi, D.; Baram-Tsabari, A.; Maslov, T.; Schrire, O. Involving schoolchildren in radon surveys by means of the “RadonTest” online system. *Journal of Environmental Radioactivity* **2020**, 217, 106215.
83. Measurement Results Map by RadonTest Group. Available online: <https://radonmap.online/indoorradon> (accessed on 14 May 2024).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.