16ENV10 MetroRADON

Deliverable D7

Validation report on the traceability of primary and secondary radon calibration facilities in Europe

Czech Metrology Institute (CMI)

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The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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Abstract

Member States of the European Union together with the European Commission have been funding research in the field of metrology (measurement science) under the EMPIR-programme (European Metrology Programme for Innovation and Research), which is administered by EURAMET.

In the 2016 call metrology for environment a consortium of European institutes and universities (composed of BEV/PTP, Austria; BFKH, Hungary; CEA, France; CMI, Czech Republic; IFIN-HH, Romania; PTB, Germany; STUK, Finland; VINS, Serbia; AGES, Austria; BfS, Germany; CLOR, Poland; IRSN, France; JRC, European Commission; SUBG, Bulgaria; SUJCHBO, Czech Republic; UC , Spain; METAS, Switzerland) were granted 3-year funding for a project named MetroRADON (metrology for radon monitoring) which deals with the study and development of novel techniques for metrology of radon monitoring. An important objective of this project was to develop reliable techniques and methodologies to enable traceable radon activity concentration measurements and calibrations at low radon concentrations (100 - 300 Bq m^{-3}) and high radon concentrations (300 Bq m^{-3} to 10 000 Bq m^{-3}) in air. For more information on the project objectives and results, visit www.metroradon.eu.The European Council Directive 2013/59/EURATOM (EU-BSS), laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, has evoked new challenges for the metrology of radon measurements and calibrations in Europe. Since the EU Member States' levels of relevant activity concentration that are laid down in the EU-BSS shall not exceed 300 Bq m^{-3}, new calibration procedures for existing commercial radon monitors have been developed within this project. The Joint Research Project MetroRADON has provided SI traceable metrological resources (calibration and measurement) for the monitoring of radon, which essentially facilitated the harmonized implementation of the new EU-BSS in Europe. In addition, the composition of the partners has contributed to the creation of the metrological infrastructure for radon in Europe suitable for the requirements of the radon action plan requested by the new European Directive.

In the framework of MetroRADON two intercomparison exercises have been conducted to validate the traceability of existing European radon calibration facilities at national metrology institutes and designated laboratories, accredited laboratories, other calibration laboratories and universities over the ranges from 100 Bq/m^3 to 300 Bq/m^3 and 300 Bq/m^3 to 10 000 Bq/m^3.

This document provides results from the validation of the traceability of European radon calibration facilities at stable radon atmosphere in the range from 100 Bq m^{-3} to 300 Bq m^{-3} and in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3} conducted in the framework of the EMPIR Project 16ENV10 "Metrology for radon monitoring" (MetroRADON).

Data from European radon calibration facilities was collected using a questionnaire created especially for the validation of the traceability the Project MetroRADON. The purpose of the questionnaire was to select the appropriate institutes for intercomparisons performed by the German Federal Office for Radiation Protection (BfS) and the National Institute for Nuclear, Chemical and Biological Protection, v.v.i, Kamenna (SUJCHBO).

From March 2018 to February 2020 an interlaboratory comparison in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3} was conducted. In total 15 calibration facilities from 12 different countries of the European Union and one from Montenegro (MNE) participated in the comparison. Among those were 7 national metrological institutes and designated institutes (BEV-PTP, STUK, BFKH, ENEA (Italy), IFIN-HH, MNE (Montenegro), SMU (Slovac Republic)), 5 national authorities for radiation protection (BfS, SUJCHBO, IRSN, CLOR, SSM) and 3 participants from universities (UBB (Romania), LARUC-UNICAN (Spain), UPC (Spain)). The comparison was conducted by BfS.

Verification of secondary standards of European calibration laboratories in the range from 100 Bq m^{-3} to 300 Bq m^{-3} was performed by SUJCHBO in the period from October 2019 to April 2020. Eight European laboratories have participated in the intercomparison of secondary standards, including SUJCHBO, and nine measuring devices were calibrated.

Scope

Radon is estimated to cause between 3 % and 14 % of all lung cancer cases, depending on the average radon level in the country. For Europe, this corresponds to about 15 to 20 thousand people dying per year by lung cancer caused by radon exposure. The legal implementation of the new EU-BSS claims a metrological sound basis of radon protection for European citizens. This is one of the main objectives of the new EU-BSS, which have to be implemented by national legislatives in the coming years.

The traceability of measurements plays an important role in many quality systems. The desire to improve and harmonize radon measurements in air arose during the last quarter of the 20th century.
The aim of this work has been to validate the traceability of existing European radon calibration facilities at NMIs/DIs, accredited laboratories, other calibration laboratories and universities over the ranges from 100 Bq m^{-3} to 300 Bq m^{-3} and 300 Bq m^{-3} to 10 000 Bq m^{-3}.

Two comparisons have been performed. They have allowed the operators of radon calibration facilities to reduce the relative uncertainties related to their facilities. These international comparisons have fulfilled the need to provide confidence in the capability of European radon calibration facilities in the field of radon activity concentration measurements in air.

The traceability to primary standards used for radon activity concentration in air measurement to European radon calibration facilities have been established by using existing primary radon gas standards and new radon activity standardsdeveloped in MetroRADON, and two different approaches for validation have been used:

1. the first way of validation has been designed for one reference device calibrated with a primary radon gas standard was shipped to European radon calibration facilities for a comparison with their existing secondary standards. Intercomparisons have been conducted using a calibrated instrument to validate the traceability and performance of European radon calibration facilities in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3},

2. secondary standard devices used by European radon calibration facilities were calibrated in the same place with traceability to the new radon gas standards. The performance of European radon calibration facilities have been validated using a reference device calibrated in a stable reference atmosphere of the range from 100 Bq m^{-3} to 300 Bq m^{-3} with traceability to a primary standard.

The comparison at three different levels of radon activity concentration (400 Bq/m³, 1 000 Bq/m³ and 6 000 Bq/m³) was conducted by the German Federal Office for Radiation Protection (BfS). The results of the interlaboratory comparison show that, taking into account the statistical uncertainties, the ratios of radon activity concentrations are identical for all exposure values and for the summary of all values. It can be assumed that radon activity concentration realized by the European calibration facilities fluctuate around a common mean value. The intercomparison performed by the staff of SUJCHBO was realised at two levels of radon activity concentrations, at 200 Bq m^{-3} and at 300 Bq m^{-3}. The analysis of individual parameters of the participant's performance shows that the results of the secondary standards of the European calibration laboratories are at a very good level. The detailed results of these two performed validations and results from the questionnaire are given in the Annex.

Summary

The traceability and quality assurance of radon calibration facilities as well as the development of methods have been concerned within the MetroRADON project. The electronic instruments of the type AlphaGUARD were selected as comparison devices due to their commonness. The devices were compared to each participant's secondary standard, which are used for the calibration of the end-user devices.

In total 15 calibration facilities from 12 different countries of the European Union and one from Montenegro participated in the validation of the traceability in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3}. The comparison device of type AlphaGUARD was sent to each participant by German Federal Office for Radiation Protection (BfS). The participants were to expose the comparison device at three different levels of radon activity concentration: 400 Bq/m^3, 1 000 Bq/m^3 and 6 000 Bq/m^3. It can be assumed that radon activity concentration realized by the European calibration facilities fluctuate around a common mean value. For exposures above 1 000 Bq/m^3 the range of variation of the common mean value was about 4 % with a coverage interval of 95 %. For the exposure level of 400 Bq/m^3, the 95 % coverage interval increased to about 6 %. The participants performed their measurements under different climatic conditions. The statistical analysis revealed a correlation between the results of the intercomparison and the air pressure at an exposure level of 6 000 Bq m^{-3}. The European radon calibration facilities trace back their primary quantities to the national metrological institutes PTB (Germany), LNHB (France) and NIST (USA). The statistical analysis did not show any evidence that the different traceability chains influence the result of the intercomparison or the performance of the calibration facilities in Europe.

Eight European laboratories participated in the intercomparison in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3}. The calibration was performed by the SUJCHBO using the unique equipment developed in MetroRADON for testing of measuring devices at low-level radon activity concentrations. The intercomparison was realised at two levels of radon activity concentrations, at 200 Bq m^{-3} and at 300 Bq m^{-3}. The analysis of individual parameters of the participant's performance shows that the results of the secondary standards of the European calibration laboratories are at a very good level.

The interlaboratory comparison of secondary standards of European radon calibration facilities for radon calibration is a powerful tool to detect discrepancies in traceability and to ensure the quality of radon measurements in Europe. Traceability of European radon calibration facilities was found to be good overall.

List of Attachments

The results of these two performed validations and results from the questionnaire are summarized in the following reports (see attachments A, B and C):

- A: Activity No. 5.1 – Questionnaire to selected European calibration facilities for radon concentration measurement in air,
- B: Activity No. 5.2 – Validation of the traceability, performance and precision of European radon calibration facilities in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3},
- C: Activity No. 5.3 – Validation of the traceability of European radon calibration facilities at stable radon atmosphere in the range from 100 Bq m^{-3} to 300 Bq m^{-3}.

Attachment A: Activity No. 5.1 – Questionnaire to selected European calibration facilities for radon concentration measurement in air

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Activity No. 5.1

Questionnaire to selected European calibration facilities for radon concentration measurement in air

BFKH

Submission: February 2018

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Introduction

The Member States of the European Union together with the European Commission funding research in the field of metrology (measurement science) under the EMPIR-programme (European Metrology Programme for Innovation and Research), which is administered by EURAMET.

In the 2016 call “metrology for environment” a consortium of European institutes was granted a 3-year funding for a project named MetroRADON. A main objective of this project is to develop reliable techniques and methodologies to enable SI traceable radon activity concentration measurements and calibrations at low radon concentrations (100 - 300 Bq m^{-3}) and high radon concentrations (300 – 10 000 Bq m^{-3}).

About the questionnaire

The main objective of this questionnaire was to serve European radon calibration facilities in a better way by identifying needs and work to provide solutions to that effect. The project consortium was very open to requests and suggestions on what needs to be improved with regards to measurements and monitoring of radon.

Each partner institute was in charge of collecting data from European radon calibration facilities in its country (and in some cases neighboring counties). The data were then transferred to the BFKH, Hungary, who compiled the data. The data is handled confidentially.

Participants and characterization

The questionnaire was completed by the following institutes:

- Czech Metrology Institute (CMI) - Czech Republic
- National Institute for Nuclear, Chemical and Biological Protection (SUJCHBO) - Czech Republic
- Metrology and Technical Supervisory Department, Government Office of the Capital City Budapest (BFKH) - Hungary
- Physikalisch-technischer Prüfdienst (BEV-PTP) - Austria
- Federal Office for Radiation Protection (BfS) - Germany
- Central Laboratory for Radiological Protection (CLOR) - Poland
- Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH) - Romania
- Institute for Radiological Protection and Nuclear Safety (IRSN) - France
- Joint Research Centre (JRC) - European Union
- Radiation and Nuclear Safety Authority (STUK) - Finland
- University of Cantabria (UC) - Spain
- Hungarian Academy of Sciences Institute for Nuclear Research (ATOMKI) - Hungary
- National Public Health Centre (OSSKI) - Hungary
- Silesian Centre for Environmental Radioactivity, Central Mining Institute (GIG) - Poland
- Physikalisch-Technische Bundesanstalt (PTB) - Germany
- Slovak Institute of Metrology, Department of Ionizing Radiation (ÚNMS SR) - Slovak Republic
- “Constantin Cosma” Radon Laboratory, Babes Bolyai University, Faculty of Environmental Science and Engineering - Romania
- Laboratory of Rn-222 studies of the Institute de Tècniques Energètiques of the Universitat Politècnica de Catalunya – Spain
- Institute of Radiochemistry and Radioecology , University of Pannonia- Hungary

Nine of these participants are national metrology institutes (BFKH, CMI, PTB, ÚNMS SR and BEV-PTP) or designated institutes (IFIN-HH, IRSN, STUK and BfS). Among the participants are four research institutes, four universities and a national public health centre.

Four participants are accredited for radon measurements, two organizations are self-declared for this activity, three institutes are accredited but not for radon measurements exactly, nine institutes have no accreditation status at all.

Results

Measuring instruments:

Radon measurements require special equipment. The following instruments represent the highest metrological level of radon activity concentration:

- ten participants use *AlphaGuard*s
- two institutes use liquid-scintillation counting (LSC) technique with radon standardization
- one participant uses a special scintillation chamber combined with a nuclear spectrometer and
- one organization reports using *Atmos 12DPX*.

AlphaGuard, LSC, scintillation chamber, *Atmos 12DPX*, can be used as working standard, too.

Standard materials of calibration

For accurate radon measurements the use of calibrated or standard material for calibration of radon monitors is necessary. The mentioned methods are the use of

- standard transfer instruments (with a Ra-226 source), whichwere applied by nine participantsand
- radon gas standards whichwere applied by six participants.

Both solutions together are used only by one institute.

Calibration range and uncertainty:

Fig 1. illustrates the reported calibration ranges.

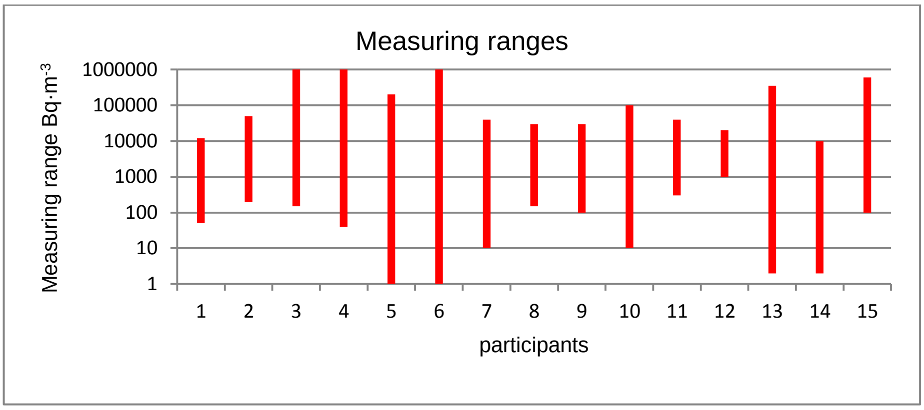

Fig 1. Calibration ranges reported by the participants.

Broad values are covered by the calibration ranges (1 Bq/m^3 – 1 MBq/m^3). Typical calibration ranges of individual institutes were two to three orders of magnitude. The participant covering the largest measurement range can measure six orders of magnitude, which can be reached by employing a combination of various measurement devices. Radon measurement below 10 Bq/m^3 is a challenge for most participants and it could be reached by three participants.

Uncertainties were reported by ten organizations (Fig 2.). The lowest reported measurement uncertainty was about 2.5 % (k = 1), but this value is dependent on the concentration of measured radon.

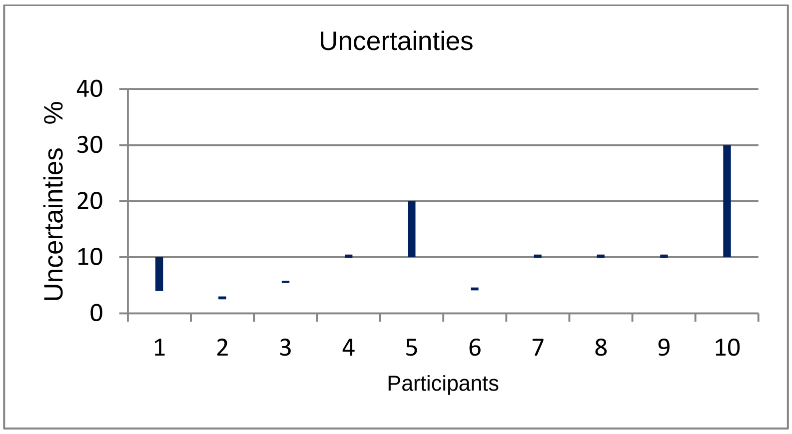

Fig 2. The uncertainties of calibration capabilities (the participant's numbers are not the same as in Fig 1.)

Number of calibrations

The number of radon calibrations performed by the participants is shown in Fig. 3. The bigger part of the participants typically perform 1 to 10 calibrations per year. The reported maximum amount of yearly calibrations was 206, which is assumed to mean that a calibration was performed for every measurement point.

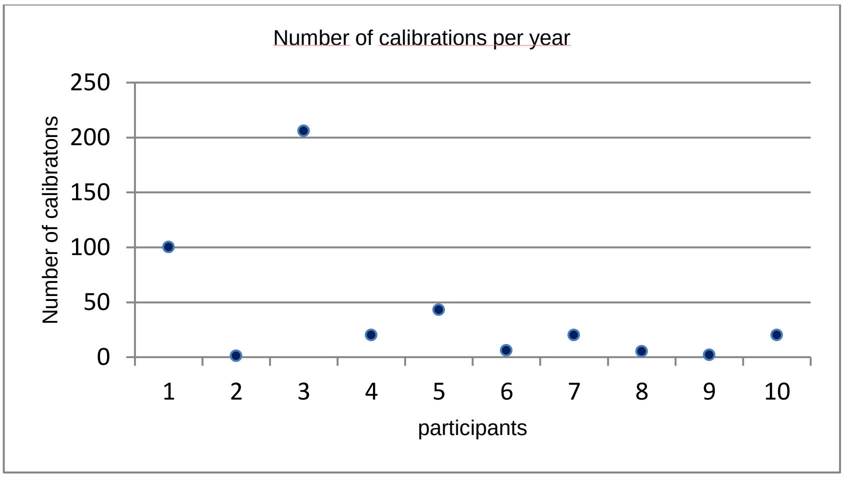

Fig 3. Number of calibrations per year

Size of the radon chamber

For standardization of radon measurement a properly defined volume is necessary. The type of chambers was reported in various sizes by the participants. The minimum size of the reported equipment was 0.2 m^3 and the maximum size was 20 m^3.

Climatic condition and other parameters

An important part of the standardisation work is the appropriate monitoring and controlling of environmental conditions. The temperature and humidity values are shown by Table 1 and Table 2.

Table 1. Range of calibration temperatures reportedby the participants.

Temperature (°C)				
Participant	Monitoring		Control	
	from	to	from	to
1	20	23	-2	40
2			5	50
3	15	25		
4	18	24		
5	21	23	10	30
6	15	25		
7	10	35		
8			4	22
9	15	25		
10			10	30
11			-20	60
12	19	25		
13	15	25		

Table 2. Range of calibration humidities reported by the participants.

Humidity (rel. %)				
Participant	Monitoring		Control	
	from	to	from	to
1	30	65	10	90
2			20	90
3			20	90
4	0	10		
5	45	55	30	80
6	30	60		
7	0	80		
8			10	99
9	20	50		
10			10	95
11			20	90
12	40	60		
13	20	90		

Some participants monitor additional parameters like the aerosol particle concentration and size distribution, the radon decay products concentration and fractionalization, equilibrium factor of radium-radon and gamma-ray dose or dose rate.

Conclusion

National metrology and designated institutes, research institutions, universities and a national public health centre have participated and filled in the questionnaire form. A part of these organizations is accredited for radon measurements.

AlphaGuard is the most commonly used instrument for radon measurement, and is both used as a highest level standard for metrology and a working standard. A broad measurement range can be achieved with the combination of measurement devices. The number of calibrations per year shows significant differences among the institutes. Benchmarking of calibration quality needs more observation and information. Radon chambers are an important part of the calibration process, and very different sizes (0.2 - 20 m^3) are used among the institutes.

Attachment B: Activity No. 5.2 – Validation of the traceability, performance and precision of European radon calibration facilities in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3}

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Activity No. 5.2

Validation of the traceability, performance and precision of European radon calibration facilities in the range from 300 Bq m^{-3} to 10 000 Bq m^{-3}

Federal Office for Radiation Protection (BfS), Germany

Submission: 15. May 2020

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Summary

Task A5.2.1

BfS will select a suitable reference instrument for use as the transfer standard and will prepare it for the intercomparison. The instrument will be a calibrated instrument with good linearity, a high measurement range (at least from 300 Bq/m^3 to 10 000 Bq/m^3), good repeatability of the measurement indication, sufficient mechanical robustness, and ease of use.

BfS selected an electronic instrument from type AlphaGUARD PQ 2000 PRO TTL which measures the activity concentration of radon-222 in air. The instrument is robust and reliable under various environmental conditions and is easy to use. The measurement results are stored unchangeably in an internal memory with sufficient capacity for comparison exercises.

Before the comparison started, the instrument was calibrated at BfS in three atmospheres with stable radon activity concentrations in the range between 300 Bq/m^3 and 12 000 Bq/m^3. The calibrations in stable atmospheres were repeated in January 2019 and after the last run of the comparison in March 2020. The linear relationship between the indicated value and the radon activity concentration in air was proven.

Task A5.2.2

BfS together with CMI will ask a representative number of European radon calibration facilities (around 10) selected in A5.1.3 to participate and the intercomparison will be scheduled. The target is to include at least 7 facilities. In particular, the calibration facilities of the WP5 partners (BEV-PTP, BFKH, CMI, IFIN-HH, STUK, BfS, CLOR, IRSN, JRC, SUJCHBO and UC) will be considered for participation in the intercomparison.
BfS with CMI and IRSN will develop the protocol for the comparison, including developing a form for the participants to complete documenting their calibration procedures and the accompanying measures for quality assurance, which are carried out at their calibration facilities.

In total 15 calibration facilities from 12 different countries of the European Union and one from Montenegro participated in the interlaboratory comparison. Among those were national metrological institutes and designated institutes, national authorities for radiation protection and participants from universities. A protocol was developed which was handed out to each participant in advance to inform them about the course of the comparison and the handling of the comparison device. The participants were requested to record the checks of the comparison device carried out on-site and essential data to verify the exposures. In order to facilitate these records as well as the report of the results standardized reporting forms were developed.

The EMPIR project collaborators acted as an advisory group. The basic design of the interlaboratory comparison was developed in consultation with the members of the advisory group. The coordinator (BfS) regularly reported on the current status to the EMPIR project collaborators.

Task A5.2.3

BfS will send the reference instrument prepared in A5.2.1 to the selected radon calibration facilities that agreed to participate in A5.2.2 for them to carry out the calibrations.
Each participant in the intercomparison will calibrate the reference instrument over the measurement range from 300 Bq/m^3 up to 10 000 Bq/m^3. Each participant will then send their results on a calibration certificate and accompanying documentation to BfS. After a participant has completed their calibrations, the reference instrument will be sent back to BfS for an intermediate check of the instrument before it is sent to the next participant.

The comparison device was sent to each participant and made available to the participant for a pre-defined period of time to carry out the exposures. The participants were to expose the comparison device at 3 different levels of radon activity concentration: 400 Bq/m^3, 1 000 Bq/m^3 and 6 000 Bq/m^3. In certain cases, other exposures were also allowed. Regular checks and controls during the comparison, carried out by Bf,S ensured the quality of the measurements. BfS established provisions for safe transport and the integrity of the comparison device.

Task A5.2.4

BfS, CMI, IRSN and SUJCHBO will analyse the results of the calibrations from A5.2.3 regarding their closeness of agreement (precision). The assessment will be based on a statistical analysis. The deviations of the calibration results will be identified and analysed, and conclusions drawn for the realization of radon activity concentration in air at the European radon calibration facilities in the range from 300 Bq/m^3 to 10 000 Bq/m^3.
The performance and the measures for quality assurance of the respective calibration facilities will be assessed based on the information about the calibration procedures obtained from the forms and the calibration certificates

The results of the interlaboratory comparison show that, taking into account the statistical uncertainties, the ratios of radon activity concentrations are identical for all exposure values and for the summary of all values including singular exposures. It can be assumed that radon activity concentration realized by the European calibration facilities fluctuate around a common mean value. Its range of variation is a measure of the degree of agreement between the participants. For exposures above 1 000 Bq/m^3 the range of variation of the common mean value is about 4 % with a coverage interval of 95 %. For the exposure level of 400 Bq/m^3, the 95 % coverage interval increases to about 6 %.

The participants performed their measurements under different climatic conditions. Although no influence should be observed, the statistical analysis revealed a correlation between the results of the intercomparison and the air pressure at an exposure level of 6 000 Bq/m^3. This effect could not be clarified in this study and requires further investigations.

The European radon calibration facilities trace back their primary quantities to the national metrological institutes PTB (Germany), LNHB (France) and NIST (USA). The statistical analysis did not show any evidence that the different traceability chains influence the result of the intercomparison or the performance of the calibration facilities in Europe.

The interlaboratory comparison of European radon calibration facilities is a powerful tool to detect discrepancies in traceability and to ensure the quality of radon measurements in Europe. It is strongly recommended to carry out the interlaboratory comparison regularly.

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1 Introduction

In the context of the implementation of the European Council Directive 2013/59/EURATOM into national law, in particular the related regulations on protection against exposure to radon (Rn-222) at home and at work, the European metrological institutes are requested to establish a harmonised quality level for the measurement quantity radon activity concentration. The realization of the quantity with a high degree of agreement between the metrological institutes ensures that calibrations of measuring instruments are comparable and thus the measurement results are mutually recognised in the European member states.

In the framework of the EMPIR Project 16ENV10 *Metrology for radon monitoring* (MetroRADON), an interlaboratory comparison was initiated in order to validate the traceability of European radon calibration facilities and to demonstrate their performance in calibrating radon measuring instruments in the range from 300 Bq/m^3 to 10 000 Bq/m^3. Calibration services from different EU member states, which preferably represent the respective national reference for the quantity radon activity concentration in air, were encouraged to participate in the comparison. The European Metrology Programme for Innovation and Reasearch (EMPIR) is an integrated part of Horizon 2020, the EU Framework Programme for Research and Innovation.

2 Objective

The objective of the interlaboratory comparison was to determine the degree of agreement in the realization of the activity concentration of radon-222 in air in the facilities of the participating laboratories. For this purpose, the same measurement device with appropriate metrological characteristics was made available to each participant to measure this quantity. The participants ensured that the quantity was performed in atmospheres of their own facilities, established according to their own procedures and requirements on traceability. The measurement device, which is denoted as "comparison device" in the following, was exposed in these atmospheres.

After completing the exposures, the measured values ascertained by the comparison device were compared to the values of the radon activity concentration specified by the participant. The compilation of the comparative values obtained from each participant showed the mutual differences in the realization of the radon activity concentration and thus the uncertainties at the dissemination of the quantity to third parties by calibration of instruments. The degree of agreement between the participants in the realization of the quantity was analysed.

According to the information provided by the participants, the traceability chains of the quantity radon activity concentration in Europe were outlined. Influences on the calibrations due to the different traceability chains were assessed.

The interlaboratory comparison was conducted by the German Federal Office for Radiation Protection (BfS) and took place in the period from March 2018 (first participant) to February 2020 (last participant).

3 Participants

In total 15 calibration facilities from 12 different countries of the European Union and one from Montenegro (MNE) participated in the interlaboratory comparison. Most participants were among the collaborators of the project MetroRADON, except ENEA, UBB, UPC, SSM and SMU. Table 1 collocates the calibration facilities involved in the comparison.

The pool of participants encompassed 7 national metrological institutes and designated institutes (BEV-PTP, STUK, BFKH, ENEA, IFIN-HH, MNE, SMU), 5 national authorities for radiation protection (BfS, SUJCHBO, IRSN, CLOR, SSM) and 3 participants from universities (UBB, LARUC-UNICAN, UPC).

As assumed at the beginning of the study and also confirmed at the end, the traceability chain for the quantity radon activity concentration was heterogeneous, so that even metrological institutes were traced back to institutions that carry a secondary standard, but which were not recognised by national or international agreements for the realization of the quantity. For this reason, it was decided not to exclude calibration entities that expressed an interest from the comparison. Thus the original objective of the project was achieved.

The considerable number of participants from various European countries with different positions in the metrological hierarchy and thus different positions in the traceability chain of the considered quantity allowed a representative validation of the performance and quality in the calibration of radon measuring devices.

Table 1: Calibration facilities participating in the interlaboratory comparison (sorted alphabetically by country)

Short Name	Institute and Address	Country
BEV-PTP	BEV-PTB, Physikalisch-technischer Prüfdienst, Bundesamt für Eich- und Vermessungswesen Arltgasse 35, 1160 Wien	Austria
SUJCHBO	Státní ústav jaderné, chemické a biologické ochrany Kamenna 71, 262 31 Milin	Czech Republic
STUK	Radiation and Nuclear Safety Authority Laippatie 4, 00880 Helsinki	Finland
IRSN	Institut de Radioprotection et de Sûreté Nucléaire 31 avenue de la division Leclerc, 92262 Fontenay-aux-Roses	France
BfS (Coordinator)	German Federal Office for Radiation Protection Köpenicker Allee 120 – 130, 10318 Berlin	Germany
BFKH	Budapest Főváros Kormányhivatala Németvölgyi út 37-39, 1024 Budapest	Hungary
ENEA	CRE ENEA Casaccia via Anguillarese, 123 - Santa Maria di Galeri, 00123 Roma	Italy
MNE	Bureau of Metrology Arsenija Boljevića bb, 81000 Podgorica	Montenegro
CLOR	Central Laboratory for Radiological Protection Konwaliowa 7, PL 03-194 Warsaw	Poland
IFIN-HH	Institutul National de Cercetare-Dezvoltare pentru Fizica si Inginerie Nucleara “Horia Hulubei” 30 Reactorului St., 077125 Magurele, Ilfov County, POB MG-6	Romania
UBB	“CONSTANTIN COSMA” RADON LABORATORY, Babes – Bolyai University, Faculty of Environmental Science and Engineering Fantanele 30, 400294 Cluj-Napoca	Romania
SMU	Slovak Institute of Metrology, Dept. of Ionizing Radiation Karloveská 63, 842 55 Bratislava	Slovak Republic
LARUC-UNICAN	Radon Group, Laboratory of Environmental Radioactivity of the University of Cantabria (LARUC) C/ Cardenal Herrera Oria S/N, 39011 Santander, Cantabria	Spain
UPC	Laboratory of 222Rn studies (LER) of the Institut de Tècniques Energètiques (INTE) of the Universitat Politècnica de Catalunya (UPC), Campus Diagonal Sud, Edificio PC (Pavelló C) Av. Diagonal, 647, 08028 Barcelona	Spain
SSM	Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority), Mätning av joniserande strålning (Radiation Measurements) Solna strandväg 96, SE-171 16 Stockholm	Sweden

4 Organization and methodology

4.1 The comparison device

BfS selected an electronic instrument from type AlphaGUARD PQ 2000 PRO TTL (SN 1336) which measures the activity concentration of radon-222 in air (Figure 1). This type of measurement device is a standard instrument for radon measurements and is, therefore, especially suitable as a comparison device. As the comparison shows, most participating institutions use the same type of instrument as a laboratory reference.

The instrument is robust and reliable under various environmental conditions and is easy to use. The measurement results are stored unchangeably in an internal memory with sufficient capacity for comparison exercises. During the comparison, the instrument operated in the diffusion mode with an integration time of 10 minutes.

The instrument was calibrated and checked before, during and after the interlaboratory comparison in order to ensure the repeatability and traceability of the measurements. The relevant settings and information for participants are summarised in Table 2.

Table 2: Relevant settings of the comparison device and information for participants

Parameter	Value	Remarks
Calibration Factor	1	The value of the calibration factor does not represent the value ascertained by BfS. Therefore, the indication of the device does not correspond to the true value.
Integration time	10 minutes*	The participating laboratory must make sure that the time duration of each exposure is long enough to ensure that the indication of the device is representative for the radon activity concentration, and to obtain a good statistic by taking a sufficient number of measurements.
Date and Time	Central European Time	When the device is used in other time zones, the participating laboratory shall take into account the time shift in comparison to the time basis of local instruments.
Mode of Operation	Diffusion	
User background (USR-BGR)	0	The measurement data will be manually reduced by the background after exposure.

* In contradiction to the discussions at the EMPIR meeting in Braunschweig, February 2018, it was decided to set an integration time of 10 minutes. This enabled more measurements to be taken during the decisive duration of exposure. The larger variations of the single values were accepted.

Figure 1: The comparison device, AlphaGUARD (Type PQ 2000 PRO TTL, SN 1336)

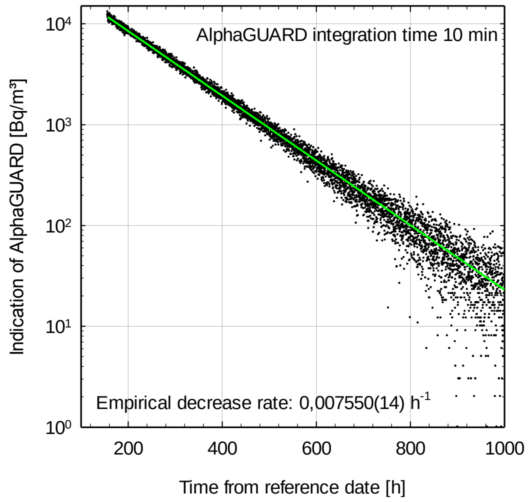

Figure 2: Linearity check of the comparison device

Table 3: Calibrations of the comparison device at fixed levels of the radon activity concentration C_{ref}

Date	C_{ref} (Bq/m³)	k_c	$U(k_c)$*
Dec 2017	330	0,98	0,08
	1 480	0,97	0,06
	5 750	0,97	0,05
	11 800	0,98	0,05
Jan 2019	470	0,93	0,08
	5 630	0,99	0,06
March 2020	347	1,00	0,13
	1 270	0,99	0,06
	5 582	1,00	0,05
	10 710	0,98	0,05

* Coverage factor *k = 2*

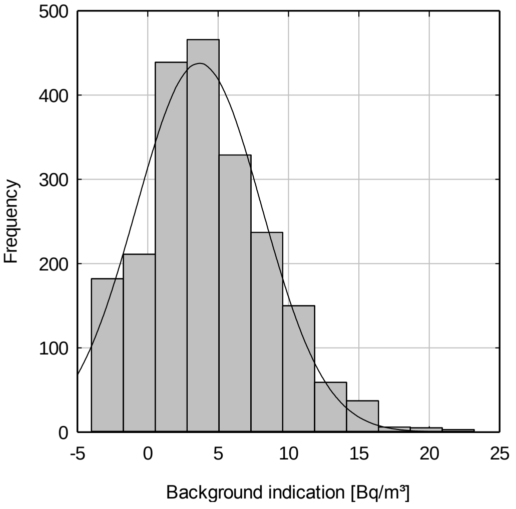

Figure 3: Frequency distribution of background indications

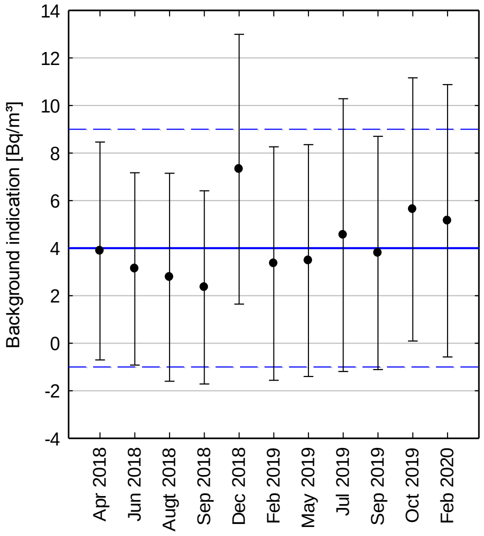

Figure 4: Results from repeated background measurements taken during the course of the interlaboratory comparison

Before the comparison started, the comparison device was calibrated at BfS in three atmospheres with stable radon activity concentrations in the range between 300 Bq/m³ and 12 000 Bq/m³. The calibrations in stable atmospheres were repeated in January 2019 and after the last run in March 2020. The results of these calibrations are summarised in Table 3. The calibration factor, k_c, is given as $k_c = C_{ref}/(I_{tcd} - I_{tcd,0})$, where C_{ref} is the reference activity concentration of radon-222 established in the BfS calibration facility. I_{tcd} is the indication of the comparison device expressed in the unit Becquerel per cubic meter. The background indication is represented by $I_{tcd,0}$. As shown in Table 3 and taking into account the uncertainty, the calibration factor is constant over the entire range examined. Its value is a few percent below 1, which indicates a slightly higher measured value than the reference value. Table 3 shows that the calibration factor was not subject to any changes during the period of comparison.

A calibration factor, which is constant over the entire range, points out the linear relationship between the indicated value and the radon activity concentration in air. As the linearity of the indication is a key requirement for the use of the comparison device in the interlaboratory comparison, an additional test for linearity of the indication was performed. Radon-222 supplied by a gas standard was transferred into an airtight chamber in which the comparison device was previously placed to measure the radon decrease. The results of the measurements are shown in Figure 2. The radon activity concentration decreases from about 10 000 Bq/m³ to below 100 Bq/m³. When the atmosphere is confined in an airtight chamber, the decrease follows the radioactive decay with a rate, which is equivalent to the radioactive decay constant of radon-222. The empirically found rate of decrease corresponds to the decay constant of radon-222 (Figure 2). On a semi-logarithmic scale, the measured radon activity concentration is linearly correlated with time, which represents the actual radon activity concentration in the atmosphere. From Figure 2 it follows that the indication of the comparison device is linear over the entire range of the radon activity concentration relevant for the interlaboratory comparison.

The calibration measurements were flanked by regular background measurements. For this purpose, the device was enclosed in a volume that was flushed with low-radon air. Low-radon air was attained by ageing the air. For this, the air delivered in pressure bottles was stored for several weeks before use. The thus resulting radon concentration in the volume was considered negligible (zero) and the device indicated the datum error for zero value of radon activity concentration. Figure 3 shows exemplary the frequency distribution of the background measurements. It was assumed that the background indications are normally distributed around the average. Due to device-specific data processing, the background can also have negative values. The background of the comparison device was measured before each run. The results are shown in Figure 4. The background was constant over the whole period of the interlaboratory comparison and was determined with (4 ± 5) Bq/m³.

Visual inspections of the comparison device for damage, including damage to the diffusion filter, checking for proper functioning and checking the set measurement parameters (e.g. calibration factor) completed the regular checks before deploying the device for the next run. The checks performed were recorded in the documentation of the comparison.

4.2 Procedure

The interlaboratory comparison was conducted by the German Federal Office for Radiation Protection (BfS). The EMPIR project collaborators acted as an advisory group. The basic design of the interlaboratory comparison was developed in consultation with the members of the advisory group. The coordinator regularly reported on the current status to the EMPIR project collaborators. A protocol was developed which was handed out to each participant in advance to inform them about the course of the comparison and the handling of the comparison device. The protocol is given in Annex A: Information for the participants on the course of the interlaboratory comparison.

The selected comparison device is owned by BfS. For legal protection, a cooperation agreement on mutual rights and obligations was concluded between the BfS and each participant (Annex B: Cooperation agreement).

The comparison device was sent to each participant and was made available to the participant for a predefined time duration, in order to perform the exposures. After performing the exposures, the device had to be returned to BfS (Figure 5). During the intermediate time, when the device is at BfS, the proper operation of the device and its compliance with metrological requirements were checked.

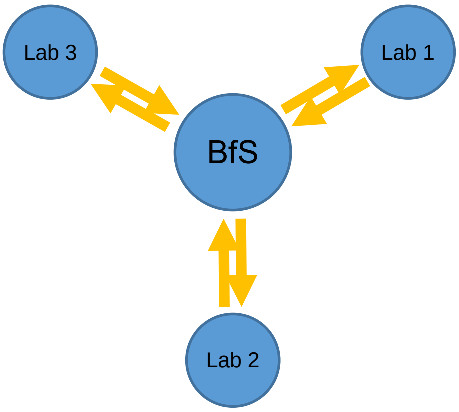

Figure 5: Scheme of the course of interlaboratory comparison

BfS ordered a parcel service for shipment of the comparison device from BfS to the participant and back. Arrangements were made to pack the device and accessories safely. A transport box was used for the dispatch. A list of all shipped items was attached. The participant ensured that the device and any accessories supplied were packed in the transport box by the specified return date and time and that the transport box was marked for shipping. The device was turned off during transport.

As the coordinator, BfS took up a special role in the intercomparison by providing the comparison device. The exposures carried out by the other participants were set in relation to the comparison device, which was calibrated by the BfS in advance. The comparison device served to transfer the quantity and thus enabled the mutual comparability of their realizations at different locations. The device did not represent the comparison reference value.

4.3 Exposures

The objective of the project required the validation of the performance of European calibration facilities in the range between 300 Bq/m³ and 10 000 Bq/m³. However, the best possible comparison of the results of different facilities will only be achieved if the dispersion of the exposures imposed on the comparison device is kept within a narrow range. In order to meet the requirements of the project, the advisory group decided on 3 different exposure levels: one each at a low, medium and high value in the specified range of radon activity concentration (Table 4). As the focus of the overall project was on improving the metrology for radon in the low range between 100 Bq/m³ and 300 Bq/m³, for which calibration methods had to be developed, the nominal value of 400 Bq/m³ was chosen for the comparison. It covered the lower range of the required radon activity concentration and established the connection to those activity concentrations which were in the focus of the overall project.

Table 4: Nominal levels of the radon activity concentrations
for the exposure of the comparison device

No.	**Nominal value (Bq/m³)**	**Range of accepted deviation (Bq/m³)**
1	400	350 - 450
2	1 000	900 - 1 100
3	6 000	5 500 - 6 500

The medium and high nominal values of 1 000 Bq/m³ and 6 000 Bq/m³ represent radon activity concentrations, which are frequently requested calibration points by end-users and can be measured with less statistical uncertainty. The value of 1 000 Bq/m³ was included in a previous comparison of calibration facilities for radon activity concentration, which was carried out within the framework of the Euromet Project 657 [1].

In practice, the participants cannot exactly adhere to the specified nominal values, deviations must be accepted. Therefore, the advisory group decided on accepted ranges within which the respective activity concentration should be realized. These ranges are given in Table 4.

With the exception of a few participants, most of the participants were able to meet these requirements. The main reasons for not achieving the nominal radon activity concentrations within their accepted deviations were generally,

1. the participants were not able to keep the activity concentration constant over the duration of exposure, as the activity concentration decreases over time, mainly due to radioactive decay, or
2. the radon sources available in the participant's laboratories and/or the methods used to create the radon atmosphere were not suitable for reaching predetermined concentrations.

It was decided to take also into consideration the results from exposures outside the accepted deviations from nominal values. However, only those results were included in the evaluation of this comparison for which the exposures were within the accepted deviations. Since most of the participants met the specified requirements for the level of radon activity concentration, this procedure did not affect the final result of the interlaboratory comparison. Singular results obtained with values outside the accepted ranges complement the final result and show that the conclusions can be extended to the whole range of radon concentration from low to high values according to the original requirements of the project.

4.4 Reports provided by the participants

The participants were requested to record the checks of the comparison device carried out on-site and the essential data to verify the exposures. In order to facilitate and standardize the records, the form given in Annex C was developed. In addition to checking the proper functioning of the comparison device, the participant had to provide the data of the relevant reference periods. The relevant reference period was the time interval within which the radon atmosphere of the participant met the quality requirements for carrying out his comparative measurements. With the information on the relevant reference period, the data read out from the comparison device could be selected for the same time interval so that the comparability of the measurement results of the participant and those of the comparison device was ensured.

The information on the comparative measurements of the participants as well as the results and uncertainties were given in the standard report of results. The form is included in Annex D. In order to determine the metrological status, the participant was asked to provide a brief description of the procedures to establish the exposures, information on the type of local reference instrument and how it works, and information on traceability to primary standards. The exposure data were presented in a table containing the values of the radon activity concentration, C_{RefLab}, being averaged over the respective relevant reference period and the attributed measurement uncertainty. C_{RefLab} is determined with the equipment of the participant. The results should be reported for the local climatic conditions at the time of exposure. Additionally, the mean values of temperature, air pressure and relative humidity should be given. Optionally, the participant could also make a correction for climatic conditions to correct the results for standard room conditions (temperature of 20 °C, relative humidity of 50 % or air pressure of 1013 hPa). With one exception, the participants gave the results for the climatic conditions prevailing during the exposures.

The measurement uncertainties had to be given as extended uncertainties resulting from the standard uncertainties of measurement calculated according to the procedures of the participant and multiplied by a coverage factor $k = 2$.

4.5 Methods for evaluation

The quantity, which makes the performance of the participant comparable, is the ratio, R, of the radon activity concentration, C_{RefLab}, provided by the participant as average value for the relevant reference period to the mean radon activity concentration of the comparison device, C_{CD}, measured within the same time interval,

$$R = \frac{C_{\mathrm{RefLab}}}{C_{\mathrm{CD}}} \tag{1}$$

The standard uncertainty $\Delta R = u(R)$ is calculated from the uncertainty propagation of Equation (1). The relative uncertainty is given by

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta C_{\mathrm{RefLab}}}{C_{\mathrm{RefLab}}}\right)^2 + \left(\frac{\Delta C_{\mathrm{CD}}}{C_{\mathrm{CD}}}\right)^2} \tag{2}$$

$\Delta C_{\mathrm{RefLab}} = u(C_{\mathrm{RefLab}})$ is the combined uncertainty for a coverage factor of $k = 1$ as provided by the participant determined according to its own procedures. The uncertainty includes the statistical variation from repeated observations (type A evaluation of standard uncertainty) and contributions from other sources, in particular from data provided in calibration and other certificates (type B evaluation of standard uncertainty) [2]. $\Delta C_{\mathrm{CD}} = s(C_{\mathrm{CD}})$ is the uncertainty of the mean radon activity concentration determined by the comparison device. It is given by the standard deviation, $s(C_{\mathrm{CD}})$, of the mean,

$$s(C_{\mathrm{CD}}) = \sqrt{\frac{\sum\left(C_{\mathrm{CD,j}} - C_{\mathrm{CD}}\right)^2}{n(n-1)}} \tag{3}$$

$C_{\mathrm{CD,j}}$ is the j^{th} of n measurements taken with the comparison device. Other contributions to the uncertainty, particularly due to calibration factor were not considered. This is due to the basic purpose of the comparison device, which is not to measure the exact value of the radon activity concentration, but to provide an indication that depends linearly on the true value of the radon activity concentration. Linearity has to be warranted at least within the accepted ranges of nominal values of the radon activity concentration. The preliminary investigations of the comparison device showed that the linearity can be assumed over the entire range up to a radon activity concentration of 10 000 Bq/m³.

It should be noted that the simple averaging of the measurements performed with the comparison device and the use of Equation (3) is valid if the activity concentration is kept constant during the relevant reference period. If this cannot be ensured by the participant, the change in activity concentration over time must be well known and taken into account when determining the comparative value, C_{CD}. In such cases the participant had to provide information on how the comparative value is determined from the readings of the comparison device. In general the radon activity concentration established in a confined atmosphere decreases due to radioactive decay. The comparative value at the reference time t_{ref} is given by averaging the measured values corrected for the reference time,

$$C_{\mathrm{CD}}(t_{\mathrm{ref}}) = \frac{1}{n}\sum_{j} C_{\mathrm{CD},j}\, e^{-\lambda(t_{\mathrm{ref}} - t_j)} \tag{4}$$

where t_j represents the measurement time of $C_{\mathrm{CD},j}$ and ⍰ the decay constant for radon-222. Equation (4) must be modified accordingly if the rate of decrease differs from that of radioactive decay.

When the parameter R_i denotes the ratio R calculated for the i^{th} of n participants and u_i is the standard uncertainty attributed to R_i, the collective average, R_{w}, is determined by

$$R_w = \frac{R_1/u_1^2 + \cdots + R_n/u_n^2}{1/u_1^2 + \cdots + 1/u_n^2} = \sum_{i=1}^{n} w_i R_i \tag{5}$$

where w_i represents the weighting for the ratio R_i,

$$w_i = \frac{1/u_i^2}{\sum_{i=1}^{n} 1/u_i^2} \tag{6}$$

As in the calculation of the collective average the ratio of the individual participant is weighted according to the attributed uncertainty, the impact on the collective average of participants with lower uncertainties is stronger than for other participants. Assuming that R_w is normally distributed with weights defined in Equation (6) and that the R_i are independent, the corresponding variance is given by [2], [3]

$$\sigma^2(R_\mathrm{w}) = u^2(R_\mathrm{w}) = \frac{1}{\frac{1}{u_1^2} + \cdots + \frac{1}{u_n^2}} = \frac{1}{\sum_{i=1}^{n} \frac{1}{u_i^2}} \tag{7}$$

5 Results

5.1 Inspection and compilation of data

Table 5 lists the laboratory reference instruments used by the participants for the comparison measurements. Most participants deploy an AlphaGUARD type instrument. An ATMOS 12DPX is used by two participants and a Radon Scout by one participant. AlphaGUARD and ATMOS use ionization chambers (single- or multi-wire) for radiation detection. The Radon Scout works with high voltage enrichment and alpha pulse counting by means of a semiconductor detector. In contrast to AlphaGUARD and Radon Scout, which operate in diffusion mode, the ATMOS type instrument operates in flow-through mode.

The vast majority of the participants were able to prove the traceability of the quantity through an unbroken chain of calibrations at recognised bodies. Excluded from this are participants 10 and 11, who have traced back their measurements through factory calibration. Factory calibration is a service provided by the manufacturer

Table 5: Laboratory reference instrument used for the comparison

Participant code	**Laboratory reference**	**Remarks**
1	AlphaGUARD PQ2000 Pro	
2	Scintillation Cells/Reference: AlphaGUARD PQ2000	Scintillation cells used as working standard, traced back to AlphaGUARD
3	AlphaGUARD P30	
4	AlphaGUARD	
5	AlphaGUARD PQ2000 Pro	Comparison device
6	AlphaGUARD PQ2000 Pro	
7	AlphaGuard/MR1 MiAm (Lucas scintillation cell).	Simultaneous measurements with two different instruments
8	AlphaGUARD D/DF 40	
9	AlphaGUARD PQ2000	
10	Radon Scout	
11	AlphaGUARD PQ2000	
12	AlphaGUARD DF2000	
13	AlphaGUARD/Atmos 12DPX	Atmos operates in flow-through mode
14	Atmos 12 DPX	Atmos operates in flow-through mode
15	AlphaGUARD PQ2000 Pro	

Table 6: Exposure and climatic data, and their allocation to the different exposure levels (Exp.Lev.); data without allocation are given as singular exposures; R is the ratio of the radon activity concentration determined by the participant, C_{RefLab}, to that of the comparison device, C_{CD}; s is the standard deviation of the mean; uncertainties are given for a coverage factor of $k = 1$

Exp. Lev.	Part. Code	Comparison Device		Participant		Ratio		Temp.	Pressure	rel. Hum.
		C_{CD} (Bq/m³)	$s(C_{CD})$ (Bq/m³)	C_{RefLab} (Bq/m³)	$u(C_{RefLab})$ (Bq/m³)	R	$u(R)$	T (°C)	p (hPa)	$r.H.$ (%)
400 Bq/m³	1	424	15	400	22	0,943	0,065	22,6	995	46
	2	386	5	392	12	1,016	0,033	20,9	948	65
	3	381	4	404	10	1,060	0,026	20,0	1 002	47
	4	384	2	392	5	1,021	0,014	29,0	996	<10
	6	435	16	441	60	1,014	0,140	25,5	1 000	35
	9	393	8	432	22	1,099	0,056	18,3	1 006	35
	10(1	353	12	438	66	1,241	0,154	24,5	1 015	20
	12	416	13	400	15	0,962	0,049	25,8	982	57
	13	409	12	402	29	0,984	0,078	17,7	1 022	43
	14	435	8	458	18	1,053	0,043	20	1 013	50
	15	418	5	407	10	0,974	0,028	19,0	990	32
1 000 Bq/m³	1	1 033	16	1 024	32	0,991	0,035	22,8	994	45
	2	1 015	13	1 039	22	1,024	0,025	20,7	949	63
	3	1 015	6	1 065	23	1,049	0,023	19,9	1 007	54
	4	987	6	1 009	12	1,022	0,013	28,0	999	<10
	6	977	46	1 032	113	1,056	0,120	25,7	1 004	36
	8	1 099	24	1 072	52	0,975	0,053	--	--	--
	9	902	11	964	56	1,069	0,059	20,2	1 015	56
	10(1	955	20	1 093	109	1,145	0,102	24,8	1 076	22
	11(1	879	3	859	2(2	0,977	0,004(2	24,1	974	40
	12	934	25	965	36	1,033	0,046	26,4	980	56
	13	1 034	10	1 034	58	1,000	0,057	18,0	1 024	44
	14	1 112	11	1 163	44	1,046	0,039	20	1 013	50
	15	1 056	9	1 046	26	0,991	0,026	19,0	1 017	34
6 000 Bq/m³	1	6 144	52	6 189	156	1,007	0,027	22,9	1 000	46
	2	5 783	47	6 030	120	1,043	0,021	21,1	952	62
	3	5 807	38	5 993	134	1,032	0,023	20,1	998	43
	4	6 168	22	6 224	65	1,009	0,011	29,0	996	<10
	6	6 424	126	6 378	440	0,993	0,072	25,2	1 008	37
	9	5 650	45	5 580	195	0,988	0,036	22,0	1 021	34
	10(1	6 516	56	7 916	317	1,215	0,041	23	1 015	30
	11(1	5 151	24	4 926	23(2	0,956	0,007(2	25,2	974	50
	12	5 575	57	5 637	211	1,011	0,039	26,9	979	53
	13	6 133	62	5 981	171	0,975	0,030	18,7	1 028	46
	14	6 094	41	6 265	228	1,028	0,037	20	1 013	50
	15	6 772	31	6 775	162	1,000	0,024	20,0	1016	23
Singular Exposures	11(1	184	1	180	1(2	0,978	0,008(2	24,9	971	51
	7	1 456	8	1 452	36	0,997	0,026	24	999	67
	8	2 691	63	2 594	69	0,964	0,035	--	--	--
	7	4 129	13	4 184	105	1,013	0,025	24,5	1 007	46
	8	8 872	32	9 044	30	1,019	0,005	--	--	--
	7	9 096	29	9 096	227	1,000	0,025	23,4	998	74

Values were rounded to the last indicated digit.

(1 Participants with factory calibration

(2 Incomplete uncertainty budget

and is part of the manufacturing or delivery process. Although manufacturers also trace their measurements back to recognized bodies, compliance with quality standards and their independent surveillance need not be demonstrated. The values of these participants show that either the ratios or the associated uncertainties differ significantly from the values of the other participants.

Table 6 compiles the exposure and climate data and their allocation to the different exposure levels. The exposure data comprise the comparative values of radon activity concentrations and the attributed uncertainties. The values provided by the participants, C_{RefLab}, are assigned to the respective comparative values, C_{CD}, determined from measurements of the comparison device. The uncertainties are given for a coverage factor of $k = 1$. The standard deviation of the mean, $s(C_{\mathrm{CD}})$, is the attributed uncertainty of the comparative value, C_{CD}. The uncertainty of C_{RefLab} is determined by the participants according to their own procedures. In this interlaboratory comparison, the methods used for calculating the uncertainties were not evaluated. An exception is participant 11 with very low uncertainties. It was found that these uncertainties represent the statistical deviation from repeated observations, but not the contributions of other sources.

Figure 6 outlines the ratios R (except for participants 10 and 11) for the different radon activity concentrations as determined by the comparison device. The error bars indicate the uncertainties for a coverage factor of $k = 1$.

5.2 Consistency check

A check of mutual consistency is required by the BIPM consultative committee CCQM [2]. It aims to test the hypothesis that the participants have a common mean value and that the deviations from this value are normally distributed.

The consistency check is performed by a chi-squared test over the number of n measurements (or participants). The observed test parameter χ^2_{obs} is calculated by

$$\chi^2_{\mathrm{obs}} = \sum_{i=1}^{n} \left(\frac{R_i - R_{\mathrm{w}}}{u_i} \right)^2 \tag{8}$$

According to CCQM [2] the test parameter is compared with the quantile of the chi-squared distribution for the significance level $1 - \alpha$ with $\alpha = 0{,}05$. The following decisions have to be made:

a) If $\chi^2_{\mathrm{obs}} < n - 1$ the results are mutually consistent and the uncertainties account fully for the observed dispersion of the values;

b) If $n - 1 \leq \chi^2_{\mathrm{obs}} < \chi^2_{0{,}05;n-1}$ the data provide no strong evidence that the reported uncertainties are inappropriate, but there remains a risk that additional factors are contributing to the dispersion;

c) If $\chi^2_{\mathrm{obs}} > \chi^2_{0{,}05;n-1}$ the data should be considered as mutually inconsistent.

The results of the consistency checks are summarised in Table 7. The tests were performed for each exposure level and for the complete data set of all levels including singular exposures. All participants of the respective levels were included in the calculations, with the exception of participants 10 and 11.

Table 7: Chi-squared consistency check for the different radon levels and for all levels

Exposure level	**Number of measurements n**	χ^2_{obs} **(observed)**	$\chi^2_{0{,}05;n-1}$ **(tabulated)**
400 Bq/m³	10	10,45	16,92
1 000 Bq/m³	11	5,49	18,31
6 000 Bq/m³	10	5,16	16,92
All levels including singular exposures	36	25,17	49,80

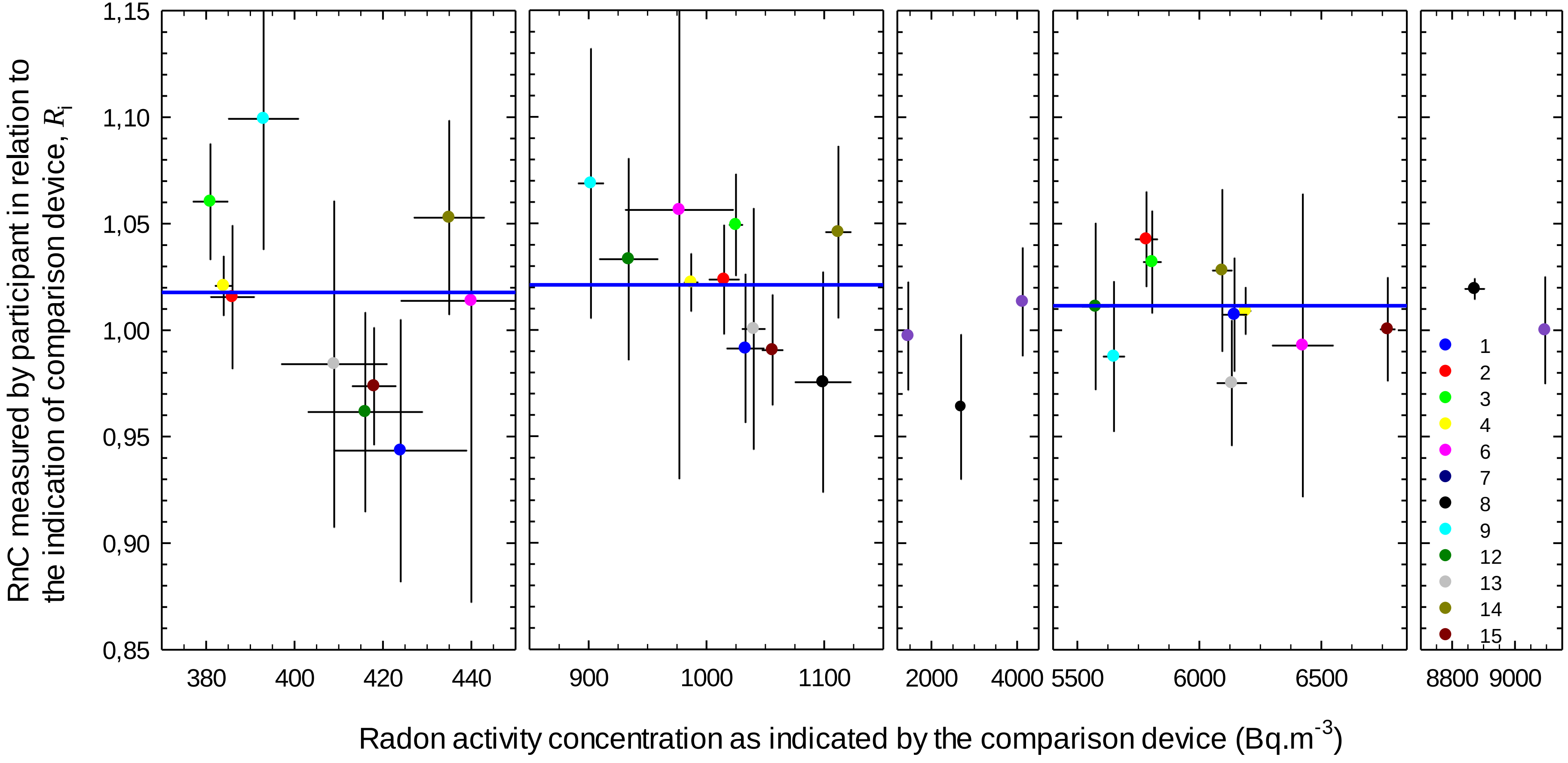

Figure 6: Ratio of the mean radon activity concentration (RnC) determined by the participant to that of the comparison device given for the different exposures; error bars indicate the uncertainties for a coverage factor of k = 1; results of the same participant are indicated by the same color; blue straight lines indicate the uncertainty-weighted collective average, R_w, for each range

Table 7 shows that with exception of the radon level of 400 Bq/m³ the criterion $\chi^2_{\text{obs}} < n - 1$ is fulfilled. Therefore, the conclusion can be drawn that the results are mutually consistent and the uncertainties account fully for the observed dispersion of the values. For the radon level of 400 Bq/m³ the observed test parameter is below the tabulated value $\chi^2_{0{,}05;n-1}$. At the stated significance level, the mutual consistency of the data can be assumed. However, the test parameter is greater than $n - 1$. According to CCQM it cannot be excluded that an additional factor contributes to the dispersion. The higher value of the observed test parameter is caused by results that have increased deviations from the collective mean without being compensated by a corresponding uncertainty. In these cases, the attributed uncertainty is too small for the observed deviation from the mean value.

A possible reason for this could be higher uncertainties in the reproducibility of low radon activity concentrations by the measuring instruments used. It must be assumed that the uncertainties of the reproducibility at repeated exposures are not or not fully reflected in the uncertainty budget of the instruments. For higher radon activity concentrations these uncertainties are obviously too small to have a decisive influence on the measurements.

Regarding the data set used, it can be concluded that there is no evidence of significant inconsistency both for each of the radon levels and in the overall exposure range.

However, the consistency of the data set fails if the results of participant 11 or the result of participant 10 for the exposure level of 6 000 Bq/m³ were included. In contrast, the results of participant 10 for the exposure levels of 400 Bq/m and 1 000 Bq/m³ do not affect the consistency of the data set. In order to ensure the consistency of the data set and to increase the degree of representativeness of the intercomparison, the data of participants 10 and 11 were not included in the determination of the collective average and the comparison reference value. Due to its special status, the coordinator (BfS, code 5) in Table 6 is also disregarded and excluded from further consideration.

5.3 The uncertainty-weighted collective average

Table 8 shows the uncertainty-weighted collective average, R_{w}, for the different exposure levels. R_{w} is calculated from Equation (5). The square root of the variance from Equation (7) is the standard uncertainty, $u(R_w)$, given in column 3 of Table 8. The values of the collective average obtained for the various exposure levels agree very well, taking into account the standard uncertainties.

Assuming that the data of the comparison device always determine the respective true value of the radon activity concentration over the whole range and the measurements performed by the participants are normally distributed around this true value, then it is expected that the uncertainty–weighted collective average is compensated, resulting in $R_{\text{w}} = 1$. However, the calculated R_{w} shows a significant bias of about 1,5 % above the expected compensation value. In fact, the comparison device does not determine the true value, but an

Table 8: Uncertainty-weighted collective average and its standard uncertainty for the different exposure levels

Exposure level	Uncertainty-weighted collective average $\boldsymbol{R_{\text{w}}}$	Standard uncertainty associated with $\boldsymbol{R_{\text{w}}}$ $\boldsymbol{u(R_{\text{w}})}$
400 Bq/m³	1,018*	0,010
1 000 Bq/m³	1,021*	0,009
6 000 Bq/m³	1,012*	0,007
6 000 Bq/m³ including singular exposures	1,015	0,004
All levels including singular exposures	1,016	0,003

* Indicated by blue straight lines in Figure 6

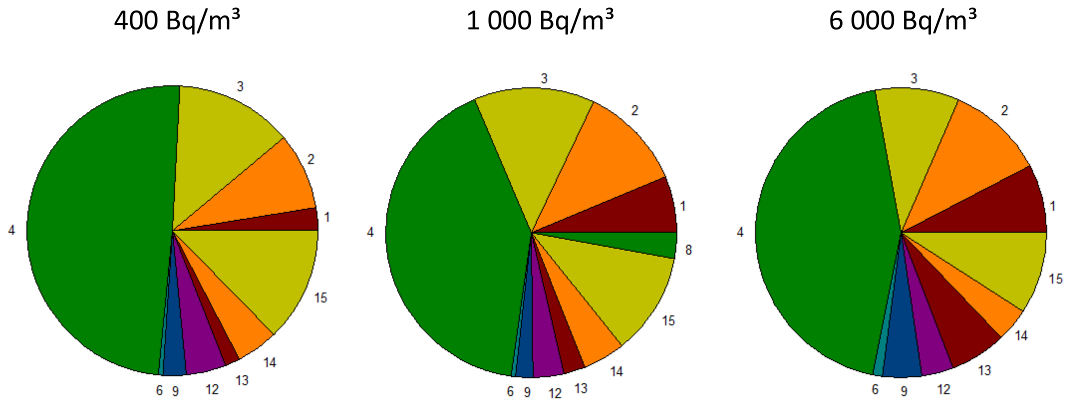

Figure 7: Weights of the different participants calculated according to their reported uncertainties; given for the 3 nominal exposure levels; participants with singular exposures are not included; numbers identify the participants

estimate of the true value, since its measurements and calibration are subject to uncertainties. The slight increase of R_w indicates that the measurements of the comparison device are on average 1.5 % too low to compensate for the measurement deviations of the participants.

Figure 7 shows the weights of the respective participant for the different exposure levels. The weights were calculated from the reported uncertainties according to Equation 6. The lower the reported uncertainty, the higher the weight of the corresponding result in the calculation of the collective average. From Figure 7 it can be concluded that the most participants report the results with similar uncertainties. Exceptions are participant 4 and participant 6. The former reported significantly lower uncertainties, giving the participant a higher weight and thus a greater influence on the collective average. Participant 6 reported higher uncertainties, which lead to lower weights.

6 Discussions

6.1 The key comparison reference value

The key comparison reference value (KCRV) is the value of the quantity representing the specific property of a material under consideration [2]. The specific property, which is under consideration in this interlaboratory comparison, is the activity concentration of radon-222 in air. The challenge here is that the atmosphere containing radon was established in the facilities of the participants. The levels of the radon activity concentration were not equal, but different for each participant. Furthermore, the purpose of this comparison is to cover a range over two orders of magnitude. This was eventually realized by 3 different main ranges of the radon activity concentration and additional singular exposure levels.

In order to verify the performance of the participants a comparator was needed, enabling the normalization of the different levels of the radon activity concentration. The comparison device provided by the coordinator was used as the comparator. As the comparison device is characterized by an indication, which is verifiably linear over the entire range, the comparison of the different radon activity concentrations found in the participant's facilities is made possible by their ratio to the indication of the comparison device as is given in Equation (1). From the ratios the uncertainty-weighted collective average, R_w, is calculated by Equation (5). The application of R_w as KCRV has however various disadvantages:

1. The observed R_{w} has a bias of about 1,5 % (Table 8) compared to the expected value of $R_{\mathrm{w}} = 1$, which would result if the comparison device were to represent the collective mean and thus all individual contributions were compensated. The analysis also shows that the mean value of the radon activity concentrations supplied by the participants is slightly higher than the corresponding mean value of the comparison device, $\bar{C}_{\mathrm{RefLab}} > \bar{C}_{\mathrm{CD}}$. This non-equivalence may have the following reasons:
    a) There is a systematic bias in the realization of the radon activity concentration by the participating facilities.
    b) The measurements taken by the comparison instrument differ systematically from the measurements of the participants.

2. The standard uncertainty associated with the weighted collective average is associated with the reported values according to Equation (7). The dispersion of the reported measurement values is obviously smaller than expected on the basis of their stated uncertainties. This leads to too small values for $u(R_w)$ as given in Table 8. Consequently, the reciprocal square root of the sum of the weights becomes too small with increasing number of participants, so that many laboratories are outside the uncertainty interval [3], [4], [5].

The measurements taken by the comparison device are subject to uncertainties, which in turn are caused by uncertainties in the realisation of the radon activity concentration in the facility of the coordinator and the calibration of the device in it. For this reason, greater importance is attached to the average value, which includes all participants. This average value should therefore be used as a reference for the interlaboratory comparison. As a consequence, it is assumed that the comparison device measures values that are on average about 1.5% too low compared to the values of the participants.

In order to overcome the above disadvantages and to device a balanced mean that is accepted as a reference value, the parameter R_i^* is calculated for the i^{th} participant, defined by the ratio

$$R_i^* = \frac{R_i}{R_\mathrm{w}} \tag{9}$$

The expectation value, $E(R_i^*)$, is the weighted sum over each participant,

$$E(R_i^*) = \sum_{i=1}^{n} w_i R_i^* = \frac{1}{R_\mathrm{w}} \sum_{i=1}^{n} w_i R_i = 1 \tag{10}$$

The weights, w_i, are given by Equation (6). The new parameter R_i^* excludes the influence of the comparison device. It implies that the ratios R_i calculated for the participants are normally distributed around the common mean value given by the expectation value $E(R_i^*) = 1$. The expectation value is the comparison average and represents the KCRV.

The variance of the KCRV is the weighted root mean square deviation,

$$\sigma^2 = \sum_{i=1}^{n} w_i (R_i^* - 1)^2 = \sum_{i=1}^{n} w_i \left(R_i^{*2} - 2R_i^* + 1\right) = \sum_{i=1}^{n} w_i R_i^{*2} - 1 \tag{11}$$

After replacing the weights by Equation (6), it follows

$$\sigma^2 = \frac{\sum_{i=1}^{n} \frac{1}{u_i^2} \sum_{i=1}^{n} \frac{R_i^2}{u_i^2}}{\left(\sum_{i=1}^{n} \frac{R_i}{u_i^2}\right)^2} - 1 \tag{12}$$

The standard uncertainty associated with the KCRV is the square root of the variance. It expresses the range of variation within which a certain radon activity concentration is realized in the atmospheres of European radon calibration facilities and is thus a measure of the degree of agreement between the participants. The 95 % coverage interval of the range of variation is given in Table 9. At lower exposure levels the detection interval is higher than at higher exposure levels. The distribution of the single data after adjustment for the comparison average ($KCRV = 1$) is shown in Figure 8. The KCRV and the coverage intervals are represented by blue lines. Although single participants lie outside the coverage interval, they cannot be considered outliers. Taking into account their uncertainties, their deviation is not significant (see also chapter 6.2).

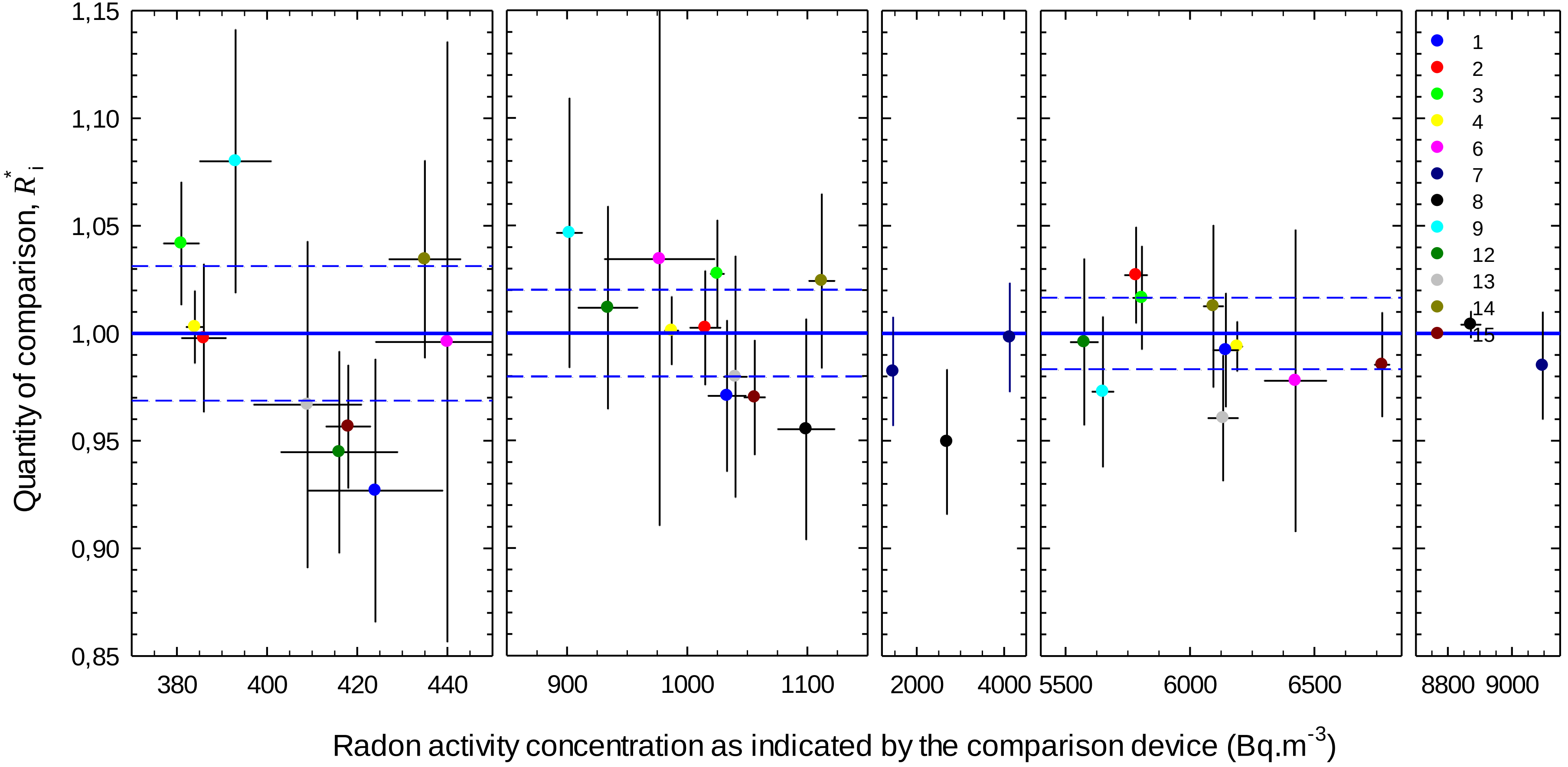

Figure 8: Quantity of comparison (R_i^*) and attributed uncertainties after adjustment for the comparison average; blue straight lines represent KRCV = 1; dashed blue lines cover the range of variation for a coverage factor of *k* = 1; singular exposures between 1 500 Bq/m³ and 5 000 Bq/m³ as well as above 8 800 Bq/m³ were corrected by a common mean that includes all exposures above 1 500 Bq/m³; error bars indicate the uncertainties for a coverage factor of *k* = 1; results of the same participant are indicated by the same color

Table 9: Standard uncertainty and coverage interval for the different exposure levels

Exposure level	Standard uncertainty associated with KCRV = 1 (%)	95 % coverage interval ($k = 2$) for the realization of the radon activity concentration (%)
400 Bq/m³	3,2*	6,3
1 000 Bq/m³	2,0*	4,0
6 000 Bq/m³	1,7*	3,4
6 000 Bq/m³ including singular exposures	1,2	2,4
All levels including singular exposures	1,7	3,4

* Indicated by blue dashed lines in Figure 8

Table 10: Coverage interval for the realization of the radon activity concentration obtained in this study and in the EUROMET Project 657

Exposure level	95 % Coverage Interval ($k = 2$)	
	This study (all participants)	EUROMET Project 657 (Final Report 2005)
400 Bq/m³	0,063	--
1 000 Bq/m³	0,040	0,057
3 000 Bq/m³	--	0,075
6 000 Bq/m³	0,034	--
10 000 Bq/m³	--	0,081

Already in 2005, a comparison of calibration facilities for radon activity concentration was carried out within the framework of the Euromet Project 657 [1]. The comparison of the 95 % coverage intervals for the KCRV obtained in this and in the previous study is shown in Table 10. Regardless of the different exposure levels as well as the calculation of the coverage intervals, a slight improvement in agreement on the realization of the quantity can be assumed. This is particularly evident at higher exposures.

6.2 Alternative selection of the key comparison reference value

Since the values for $u(R_w)$ as given in Table 8 are not reasonable for quantifying the uncertainty of the KCRV, the method of the power-moderated mean was proposed as an alternative for the determination of the uncertainty [5]. The method applies to data which are mutually independent and normally distributed around the same value. Its results are generally intermediate between arithmetic and weighted mean [5]. The method is recommended in cases where the condition $n - 1 \leq \chi^2_{\mathrm{obs}}$ is obtained. This concerns the data for the exposure level of 400 Bq/m³.

The calculations of the power-moderated mean were performed using the Excel-sheet *MET511639suppdata.xlm,* which is available for download on the Internet [6]. The automatic algorithm for moderating the relative weighting was used. Table 11 shows the values of the power-moderated mean and the corresponding standard uncertainties calculated with the Excel-sheet. Participants 10 and 11 were excluded from the calculations.

Table 11: Power-moderated mean and its standard uncertainty for the different exposure levels calculated using the Excel-sheet *MET511639suppdata.xlm*

Exposure level	**Power-moderated mean $\boldsymbol{R_{w,\mathrm{pm}}}$**	**Standard uncertainty associated with $\boldsymbol{R_{w,\mathrm{pm}}}$ $\boldsymbol{u(R_{w,\mathrm{pm}})}$**
400 Bq/m³	1,016	0,013
1 000 Bq/m³	1,021	0,009
6 000 Bq/m³	1,011	0,008
6 000 Bq/m³ including singular exposures	1,014	0,004
All levels including singular exposures	1,016	0,004

The comparison with the complementary data of the uncertainty-weighted collective average in Table 8 does not show relevant differences. Due to the consistent data sets, the power-moderated means approach the classical weighted means. The method of power-modulated means offers no improvement and will therefore not be discussed further in this study.

The approach provided by the Excel-sheet MET511639suppdata.xlm was also used for the identification of extreme values. Extreme values are indicated when the difference between the measured ratio and the power-moderated mean, $d_i = R_i - R_{\mathrm{w,pm}}$, exceeds the constraint specified by [5]

$$|d_i| > k \cdot u\left(R_{\mathrm{w,pm}}\right) \sqrt{\left(\frac{1}{w_i} + 1\right)} \tag{13}$$

For a coverage factor $k = 2$, no extreme values were found in the underlying data set. However, if the results of the participants 10 and 11 are included, the outcome is the same as for the consistency check in chapter 5.2: All results of participant 11 and the result of participant 10 for the exposure level of 6 000 Bq/m³ are classified as extreme values (outliers).

6.3 Influence of climatic conditions during the calibrations

Most participants reported their results for the climatic conditions (temperature, relative humidity and air pressure) in the laboratory at the time of exposure. Corrections for standard room conditions (temperature of 20 °C, relative humidity of 50 % or air pressure of 1013 hPa) were not required. Only one participant (code 14) reported his results for standard room conditions. Figure 9 presents a 3-dimensional plot of the climatic conditions prevailed during the exposures. The exposures at the facilities were performed within a wide range of climatic conditions ranging for temperature from about 18 °C to 28 °C, for air pressure from 950 hPa to 1024 hPa and for the relative humidity from below 10 % to 63 %.

The different climatic conditions raise the question of their influence on the results of this study. The multiple correlation method was used for the test. It describes the power of the association between a specified random variable and a group of independent random variables. The multiple correlation coefficient is always between 0 and 1 and the closer it is to 1, the more the specified variable is determined by a linear combination of the other variables.

Only those participants were included in the test who could be assigned the nominal exposure values of 400 Bq/m³, 1 000 Bq/m³ and 6 000 Bq/m³ and whose climatic conditions deviated from the standard room conditions. This was fulfilled by 9 participants.

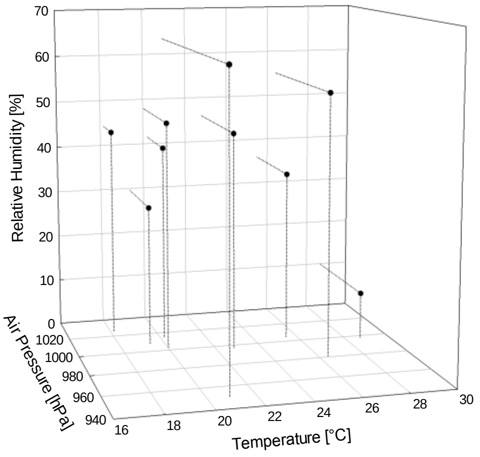

Figure 9: Average values of temperature, air pressure and relative humidity during the exposures, as reported by the participants

For a given exposure level, the multiple correlation coefficient, $r_{R,(T,p,rH)}$, of the ratios R_i^* according to Equation (9) and the group of the climatic parameters temperature (T), air pressure (p) and relative humidity (rH) is determined from the square root of [7], [8], [9]

$$r^2_{R,(T,p,rH)} = \begin{pmatrix} r_{R,T} \\ r_{R,p} \\ r_{R,rH} \end{pmatrix}^T \begin{pmatrix} 1 & r_{T,p} & r_{T,rH} \\ r_{T,p} & 1 & r_{p,rH} \\ r_{T,rH} & r_{p,rH} & 1 \end{pmatrix}^{-1} \begin{pmatrix} r_{R,T} \\ r_{R,p} \\ r_{R,rH} \end{pmatrix} \quad (14)$$

where $r_{x,y}$ represents the Pearson correlation coefficient [7] for the variables *x* and *y*. The Pearson correlation coefficient is a measure of the strength of a linear association between the two variables and is calculated by

$$r_{x,y} = \frac{\sum_{i=1}^{o}(x_i - \bar{x}_i)(y_i - \bar{y}_i)}{\sqrt{\sum_{i=1}^{o}(x_i - \bar{x}_i)^2 \sum_{i=1}^{o}(y_i - \bar{y}_i)^2}} \quad (15)$$

The summations run over the number of participants, $o = 9$, involved in the test. The parameter $r^2_{R,(T,p,rH)}$ is also denoted as coefficient of determination of the multiple correlation.

In order to assess the significance of a given $r^2_{R,(T,p,rH)}$, the ratio F is computed as [7], [8], [9]

$$F = \frac{r^2_{R,(T,p,rH)}(o - 1 - q)}{q\left(1 - r^2_{R,(T,p,rH)}\right)} \quad (16)$$

Table 12: Results of the test for multiple correlation; number of observed characteristics (temperature, air pressure, relative humidity); $q = 3$, degree of freedom $o - 1 - q = 5$, $a = 0{,}05$.

	Coefficient of determination (pairwise)						**Parameter of multiple correlation**		**Quantile, tabulated**
Exp. Level	$r^2_{R,T}$	$r^2_{R,p}$	$r^2_{R,rH}$	$r^2_{T,p}$	$r^2_{T,rH}$	$r^2_{p,rH}$	$r^2_{R,(T,p,rH)}$	F	$F_{3,5;0,95}$
400 Bq/m³	0,052	0,021	0,042	0,039	0,122	0,270	0,157	0,311	5,409
1 000 Bq/m³	0,048	0,001	0,072	0,099	0,221	0,148	0,391	1,068	
6 000 Bq/m³	0,003	**0,746**	0,123	0,079	0,131	0,251	**0,857**	**9,990**	

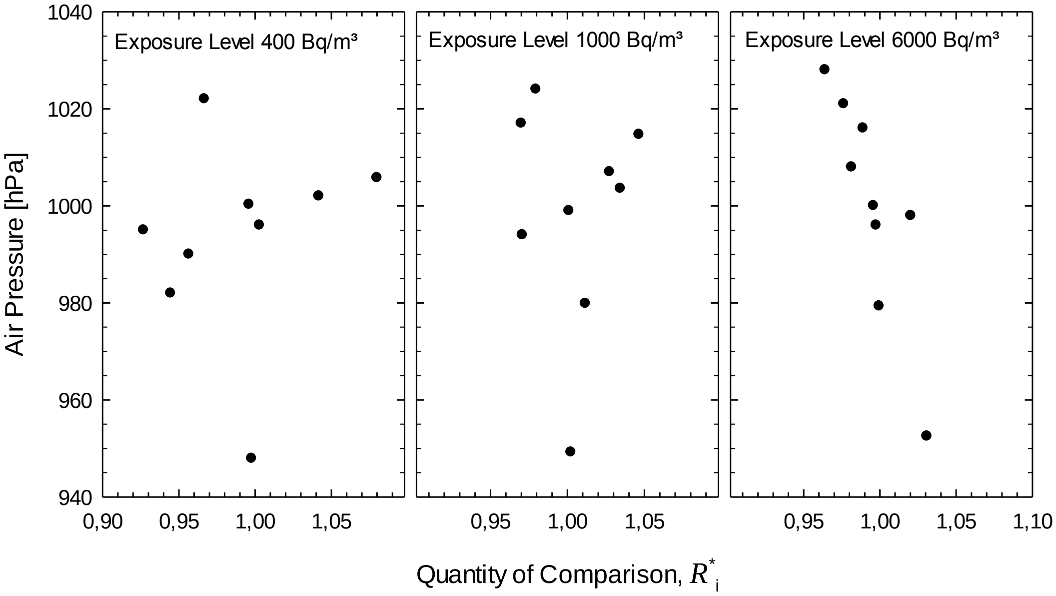

Figure 10: Dependency between ratio R_i^* and air pressure for the three different exposure levels; a correlation must be assumed for the level of 6 000 Bq/m³; the correlation is rejected for the lower exposure levels

The ratio F is distributed under the null hypothesis as a Fisher distribution with q and $o-1-q$ degrees of freedom. The value for q is the number of the independent variables temperature, air pressure and humidity, therefore, $q=3$. The coefficient of determination, $r^2_{R,(T,p,rH)}$, is significant for a level $1-\alpha$, if $F \geq F_{q,o-1-q;1-\alpha}$.

Table 12 shows the results of the calculations. Besides the values for multiple correlation, the coefficients of determination for the pairwise correlations, $r^2_{x,y}$, are also given. The ratio F is compared to the tabulated quantile, $F_{3,5;0,95}$, of the Fisher distribution for $\alpha = 0{,}05$. Since $F > F_{3,5;0,95}$ for the exposure level of 6 000 Bq/m³, a correlation must be assumed. The coefficient of determination for the pairwise correlation indicates a dominant dependency of the ratio R_i^* from the air pressure, p. This dependency is also obvious in Figure 10 representing the dependency between the ratio R_i^* and the air pressure for the three different exposure levels.

The correlation between the ratio R_i^* and the air pressure at the exposure level of 6 000 Bq/m³ was not expected and is surprising. Both the participants' instruments and the comparison device use the principle of ionization of air molecules for measurement, and in most of the cases, the type of instrument used by the participants is the same as that of the comparison device. It should therefore be assumed that the climatic conditions affect the instruments in the same way and the effects on the measurement results cancel each other out when calculating the ratios. In opposite to the lower exposure levels, this was not the case for the exposure level of 6 000 Bq/m³. This effect could not be clarified in this study and requires further investigations.

6.4 Traceability and correlations between the participants

The participants were requested to provide information on how the traceability of the radon activity concentration is realized. From this information the chart in Figure 11 was developed, which shows the status of the traceability at the start of the interlaboratory comparison in 2018.

The radon activity concentration is a combined quantity consisting of the activity of the gaseous nuclide radon-222 (^{222}Rn) and the volume. The volume is the capacity of the enclosed space containing the atmosphere for the realization of the quantity. There are three main branches through which the quantity activity is traced back. The roots of the branches are the national metrological institutes PTB (Germany), LNHB (France) and NIST (USA), which hold the primary quantities. The combined quantity radon activity concentration is realized in secondary reference facilities operating at PTB (Germany), BfS (Germany), IRSN (France) and ENEA (Italy).

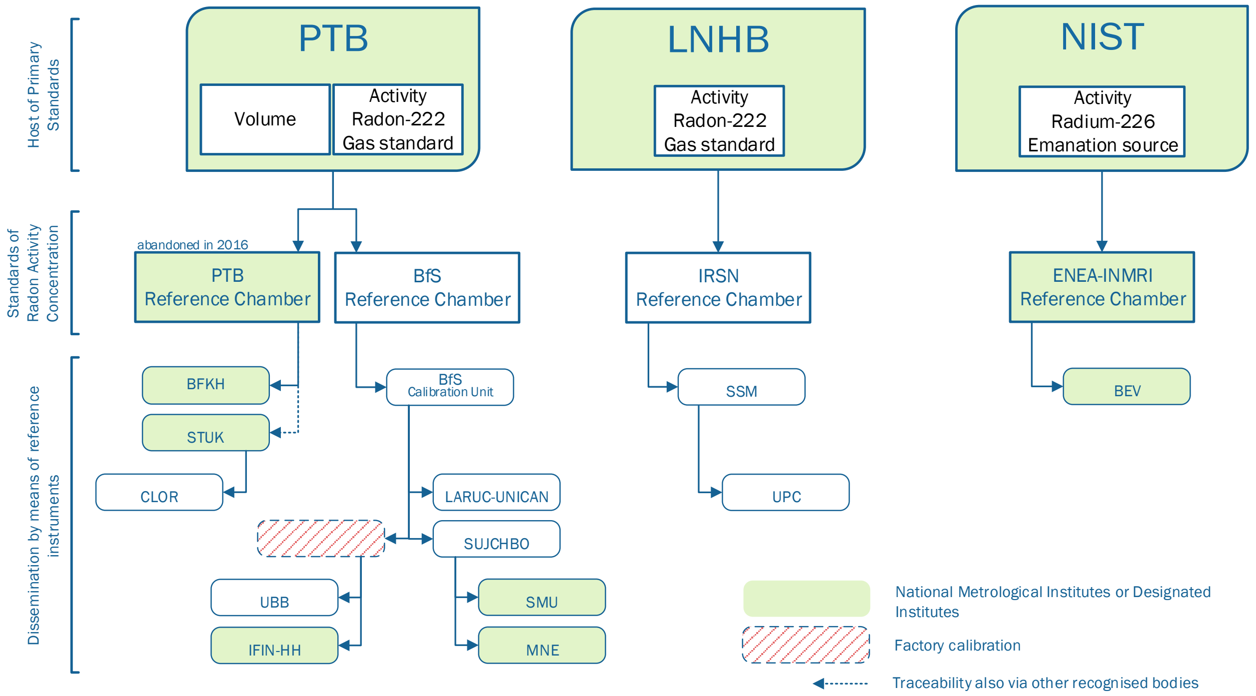

Figure 11: Chart of traceability of European calibration facilities for radon, status at the start of the interlaboratory comparison (2018)

only provided information on the traceability of the activity. It should be noted that PTB has abandoned its reference chamber in 2016. Facilities, which had used the PTB reference chamber to ensure the traceability, will have to undertake a rearrangement after the validity of the traceability has expired. Since 2020, the reference chamber of the BfS has changed the traceability of the quantity activity to LNHB by means of a gas standard. In order to adjust the radon activity concentrations to predetermined values that remain constant over a long period of time, emanation sources will gain increasing importance.

The chart in Figure 11 reveals that the secondary reference facilities that realize the combined quantity are not exclusively operated by metrological institutes, but also at bodies that are not recognised by national or international agreements. Regular comparisons between the secondary reference facilities should therefore be initiated in order to harmonise the realization of the relevant quantity. This will help to ensure the quality of radon measurements in Europe.

A prerequisite of the previous discussions was that the results reported by the participants were normally distributed around a common mean value. Due to the existence of three different branches in traceability, it cannot be excluded that discrepancies in the realizations of the quantity are transferred to the following facilities in the traceability chain. Such correlations would affect the prerequisite of a normally distributed data set.

The data set was tested for correlation using the Pearson correlation coefficient [7]. The coefficient, r_{R_i,R_k}, is calculated using the relevant data according to

$$r_{R_i,R_k} = \frac{\sum_{j=1}^{o}\left(R_{i,j}-\bar{R}_{i,j}\right)\left(R_{k,j}-\bar{R}_{k,j}\right)}{\sqrt{\sum_{j=1}^{o}\left(R_{i,j}-\bar{R}_{i,j}\right)^2 \sum_{j=1}^{o}\left(R_{k,j}-\bar{R}_{k,j}\right)^2}} \qquad (17)$$

where $R_{i,j}$ and $R_{k,j}$ are the ratios corresponding to Equation (9) for the exposure level j of the i^{th} or k^{th} participant, respectively. $\bar{R}_{i,j}$ and $\bar{R}_{k,j}$ are the respective mean ratios for the i^{th} or k^{th} participant. The summations run across the nominal exposure levels of 400 Bq/m³, 1 000 Bq/m³ and 6 000 Bq/m³, represented by the number of observations, $o = 3$. Participants with exposures that were not assigned to each of these nominal levels were not included in the test.

Table 13: Matrix of the coefficient of determination, $r^2_{R_i,R_k}$, calculated for the considered participants

	SUJCHBO	STUK	IRSN	BEV	BFKH	CLOR	LARUC-UNICAN	SSM	SMU	UPC
SUJCHBO	1,00	0,81	1,00	0,71	0,41	0,97	0,42	0,89	0,18	0,89
STUK		1,00	0,85	0,99	0,06	0,92	0,06	0,99	0,61	0,99
IRSN			1,00	0,75	0,36	0,99	0,37	0,92	0,22	0,92
BEV				1,00	0,02	0,84	0,02	0,94	0,72	0,95
BFKH					1,00	0,26	1,00	0,12	0,18	0,12
CLOR						1,00	0,27	0,97	0,32	0,97
LARUC-UNICAN							1,00	0,13	0,17	0,12
SSM								1,00	0,49	1,00
SMU									1,00	0,50
UPC										1,00

Table 14: Correlations between different participants found for a significance level of $\alpha = 0{,}1$ (indicated by ⍰)

	SUJCHBO	STUK	IRSN	BEV	BFKH	CLOR	LARUC-UNICAN	SSM	SMU	UPC
SUJCHBO			*							
STUK				*				*		*
IRSN						*				
BEV										
BFKH							*			
CLOR										
LARUC-UNICAN										
SSM										*
SMU										
UPC										

The hypothesis that there is no correlation between the i^{th} and k^{th} participant is tested against the hypothesis that there is a correlation using the test parameter [7]

$$t = \frac{r_{R_i,R_k}\sqrt{o-2}}{\sqrt{1-r^2_{R_i,R_k}}} \tag{18}$$

The hypothesis of no correlation has to be rejected if $|t| > t_{o-2;1-\alpha/2}$, where $t_{o-2;1-\alpha/2}$ is the quantile of the Student's t-distribution for the two-sided test with a degree of freedom of $o - 2 = 1$ at the significance level $1 - {}^{\alpha}/_{2}$.

Table 13 shows the matrix of the coefficient for determination given as the squared correlation coefficient for the participants included in the test. The resulting correlations between different participants, which are significant on a level $\alpha = 0{,}1$, are highlighted in

Table 14. As no other correlations were found between participants in the same traceability chain and the other correlations found cannot be reasonably explained on the basis of the information available, it is assumed that these are random correlations. If the significance level is increased to $\alpha = 0{,}05$, only the correlations between SUJCHBO and IRSN, BFKH and LARUC-UNICAN, and SSM and UPC remain, for which there is still no reasonable explanation.

There are no serious objections to the assumption of a normally distributed data set. Discrepancies in the realizations of the quantity that may occur between the different traceability chains do not affect the result of the intercomparison or the performance of the calibration facilities in Europe.

7 Conclusion

From March 2018 to February 2020 an interlaboratory comparison was conducted in the framework of the EMPIR Project *Metrology for radon monitoring*. In total 15 calibration facilities from 12 different countries of the European Union and one from Montenegro participated in the interlaboratory comparison. Among those were national metrological institutes and designated institutes, national authorities for radiation protection and participants from universities.

The comparison was conducted by the German Federal Office for Radiation Protection (BfS). BfS selected an electronic instrument of the type AlphaGUARD as a comparison device. The device was sent to each participant. The participants were to expose the comparison device at 3 different levels of radon activity concentration: 400 Bq/m³, 1 000 Bq/m³ and 6 000 Bq/m³. In certain cases other exposures were also allowed.

The parameter allowing to assess the performance of the participants was the ratio of the radon activity concentration realized in the facility of the participant for the relevant reference period to the mean of the values measured by the comparison device over the same period.

The inspection of the results identified two participants whose results were to be classified as extreme values (outliers). The extreme values occurred in the results of participants who had traced back their measurements using factory calibration.

The results of the interlaboratory comparison show that, taking into account the statistical uncertainties, the ratios of radon activity concentrations are identical for all exposure values and for the summary of all values including singular exposures. It can be assumed that radon activity concentration realized by the European calibration facilities fluctuate around a common mean value. Its range of variation is a measure of the degree of agreement between the participants. For exposures above 1 000 Bq/m³ the range of variation of the common mean value is about 4 % with a coverage interval of 95 %. For the exposure level of 400 Bq/m³, the 95 % coverage interval increases to about 6 %.

The participants performed their measurements under different climatic conditions. Although no influence should be observed, the statistical analysis revealed a correlation between the results of the intercomparison and the air pressure at an exposure level of 6 000 Bq/m³. This effect could not be clarified in this study and requires further investigations.

The European radon calibration facilities trace back their primary quantities to the national metrological institutes PTB (Germany), LNHB (France) and NIST (USA). The statistical analysis did not show any evidence that the different traceability chains influence the result of the intercomparison or the performance of the calibration facilities in Europe.

The interlaboratory comparison of European radon calibration facilities is a powerful tool to detect discrepancies in traceability and to ensure the quality of radon measurements in Europe. It is strongly recommended to carry out the interlaboratory comparison regularly.

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Annex A: Information for the participants on the course of the interlaboratory comparison

MetroRADON

Task 5.2

Validation of traceability, performance and precision of European radon calibration facilities in the range from 300 Bq/m^3 to 10 000 Bq/m^3

(Radon intercomparison)

The aim of this task is to validate traceability of European radon calibration facilities and to demonstrate their performance in calibrating radon measuring instruments in the range from 300 Bq/m^3 to 10 000 Bq/m^3, as well as the closeness of agreement between the calibration results (precision).

An intercomparison will be conducted for that purpose of validation of the traceability. The participating calibration facilities selected in Task 5.1, will preferably be situated in different Member States and should represent the respective national reference for the quantity radon activity concentration in air. A suitable transfer standard will be selected and the organisations selected in Task 5.1 will be contacted with the aim of ensuring participation of at least 7 radon calibration facilities. The protocol for the comparison will be developed and agreed, the transfer standard circulated to the participants for their measurements and the results analysed.

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I. Instrument and Methodology

The German Federal Office for Radiation Protection (BfS) provides an electronic radon instrument ALPHAGUARD (Type PQ 2000 PRO TTL, SN 1336) as transfer comparison device for the intercomparison. The device is owned by BfS, and will be made available to the participating laboratory for a predefined time duration, in order to perform the exposures. After performing the exposures, the device has to be sent back to BfS. The total time for which the transfer comparison device will be placed at the disposal of the laboratory is 2 weeks (10 workdays) at the maximum.

The transfer comparison device will be sent consecutively to each of the participating laboratory. During the intermediate time, where the device is at BfS, the proper operation of the device and its compliance with metrological requirements will be checked.

In advance of the intercomparison, BfS will conclude a Cooperation Agreement with each participating laboratory (see appendix). Only after signing this agreement, the laboratory is entitled to participate.

Because of the large number of laboratories that request participation and the short time scheduled, the intercomparison will be carried out in two stages. In the first stage mainly the national metrological institutes are involved. The second stage will expand the intercomparison to the other laboratories. It is intended to accomplish the first stage by June 2019. The time schedule for the first stage is given in the appendix.

II. Transport

BfS will order a parcel service for shipment of the transfer comparison device from BfS to the participating laboratory and back to BfS. BfS bears the costs for shipment.

The device and accessories are packed safely and shipped in a transport box. A list of every item shipped will be included.

The participating laboratory shall ensure that by the date and time set for sending back, the device and every included accessories are packed in the transport box and labelled for shipping. The goods will be collected by the parcel service ordered by BfS.

During transport, the device shall be turned off.

III. Exposures

After receipt of the transfer comparison device, the participating laboratory should check it for intactness. The device is delivered with fully charged battery. The data memory is empty.

The device is capable for operation without external power supply over several days. In order to recharge the battery or to operate under continuous external power, a power supply is provided.

BfS has preset every setting for the device (Tab. A1). The participating laboratory should not change any of the settings. Even the background of the device is already determined by BfS. Although ALPHAGUARD provides measurements of the temperature, the humidity and the air pressure, these measurements are not evaluated and discarded. Climatic parameter should be monitored by the laboratory with its own equipment.

Tab A1: Relevant settings of the transfer comparison device and advices to the laboratory

Parameter	Value	Remarks
Calibration Factor	1	The value of the calibration factor does not represent the value ascertained by BfS. Therefore, the indication at the device will not correspond to the true value.
Integration time	10 minutes*	The participating laboratory must make sure that the time duration of each exposure is long enough to ensure that the indication of the device is representative for the radon activity concentration, and to obtain a good statistic by taking a sufficient number of measurements.
Date and Time	Central European Time	When the device is used in other time zones, the participating laboratory shall take into account the time shift in comparison to the time basis of local instruments.
Mode of Operation	Diffusion	
User background (USR-BGR)	0	The measurement data will be manually reduced by the background after exposure.

* In contradiction to the discussions at the EMPIR meeting in Braunschweig, February 2018, it was decided to set an integration time of 10 minutes. This enables to take more measurements during the decisive duration of exposure. The larger variations of the single values are accepted.

Tab A2: Nominal levels of radon activity concentration to be established for the different radon atmospheres and accepted deviations

No.	Nominal Level (Bq m^{-3})	Accepted Deviation (Bq m^{-3})
1	400	350 to 450
2	1000	900 to 1100
3	6000	5500 to 6500

When turning on the transfer comparison device, an initializing phase starts, which lasts about 10 minutes. After this, the device is in the operation mode, taking measurements of the radon activity concentration. The device indicates 90% of the radon activity concentration after 30 minutes. The laboratory should check the indication of date and time. If necessary, the laboratory should record the time indicated by the device and the local time, as well.

The transfer comparison device is placed in the corresponding radon atmosphere to perform exposures in agreement with the procedures of the laboratory. According to Tab. A2, the device has to be exposed in three radon atmospheres each with different radon activity concentration. The target levels of the respective radon activity concentration should be the nominal levels of Tab. A2. The actual level can deviate from the nominal level in the ranges specified in column 3 of Tab. A2.

The laboratory shall record all relevant information accumulated during the course of performing the exposures. A provisional draft for recording the exposure stages is given in the appendix (see Records on the Intercomparison). It should be extended by the laboratory. The records on the intercomparison should be delivered to BfS.

It is not intended that the laboratory will read out the exposure data from the transfer comparison device. Instead, the read out of the data ascertained from the device and stored in its memory will be carried out by BfS after returning.

IV. Reporting of Results

After arrival of the transfer comparison device at BfS, the stored data of exposure will be read out. The times and the values of the single radon activity concentrations determined by the device will be collocated in an Excel sheet, and delivered via e-mail back to the laboratory. The single measurement data are provided with a correction for background and the application of the calibration factor of BfS. It should be noted that the BfS will check the calibration of the transfer comparison device at the end of intercomparison. Subject to a final correction, the results should therefore be considered as preliminary.

The laboratory will issue a report on the intercomparison. The report shall contain the following information at least:

- name and address of the laboratory
- name and e-mail of the person(s) in charge
- a short description of the procedures of the laboratory, information about the local reference instrument for the radon activity concentration, information about traceability to primary standards
- operating conditions during the exposures: average values of temperature, rel. humidity and air pressure
- measurement results specified for each exposure:
    (1) The mean value of radon activity concentration measured by the transfer comparison device. This value is determined from the collocated list of single measurement data provided by BfS after reading out the data from the device. The single measurement data are provided with a correction for background and the application of the calibration factor of BfS.

    (2) The measurement uncertainty of the value given under item (1).

    (3) The mean value of the radon activity concentration established in the radon atmosphere of the laboratory. This value is determined with the equipment of the laboratory.

    (4) The measurement uncertainty of the value given under item (3).

The measurement uncertainties shall be given as expanded uncertainties resulting from the standard uncertainties of measurement multiplied by a coverage factor k=2.

The results are given for the local climate conditions (temperature, rel. humidity and air pressure) in the laboratory at the time of exposure. If the laboratory were to take the view that a correction for climate condition is necessary, it should correct the results for standard room conditions (temperature of 20°C, rel. humidity of 50% or air pressure of 1013 hPa).

A draft of the report of results is outlined in the appendix. The draft can be individually adapted to the needs of the laboratory. In cases where the laboratory has an own standard form for reporting of results, the laboratory should use the standard form.

The report of results shall be delivered to BfS via e-mail.

Annex B: Cooperation agreement

Cooperation Agreement

In the framework of the *EMPIR Project Metrology for Radon Monitoring* the German Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, hereinafter referred to as the "BfS") conducts a radon intercomparison to validate the traceability, performance and precision of European radon calibration facilities (hereinafter referred to as the "Facility").

The BfS provides an electronic radon instrument ALPHAGUARD (Type PQ 2000 PRO TTL, SN 1336 hereinafter referred to as the "Instrument") for the intercomparison. The Instrument is the property of BfS.

BfS makes the Instrument available to the Facility exclusively for the purpose of the intercomparison carried out in the framework of the *EMPIR Project Metrology for Radon Monitoring*. Improper use, in particular the use for other purposes than agreed with BfS and the dissemination to third parties, is not permitted. The Facility does not acquire ownership rights to the Instrument, included accessories, software or data.

BfS will place the Instrument at the disposal of the Facility for 2 weeks (10 workdays) at the maximum. The Facility is liable for loss and damages during that period of time. Upon expiry of the time of disposal, the Instrument has to be sent back to BfS. In cases of late provision of the Instrument including accessories, the Facility bears all associated costs for shipment.

The services of BfS and those of the Facility, performed for the purpose of the radon intercomparison, are free of charge each other.

This Agreement shall be governed by and construed in accordance with the laws of Germany.

For the BfS: For the Facility:

……………………………………………………. ……………………………………………………..

Date and Signature Date and Signature

Dr. Frank Wissmann
Head of Department UR
Bundesamt für Strahlenschutz (BfS)

Please add name of the subscriber in capital letters,
position of the subscriber,
name of the facility

Please print out the Cooperation Agreement and send it back to BfS after signature (e-mail: tbeck@bfs.de)

Annex C: Standardisation of the records made by the participants

	Records on the Intercomparison	
Name of Laboratory:		

	Transfer comparison device	
	Designation	ALPHAGUARD
	Type	PQ 2000 PRO TTL
	SerialNo.	1336

1	**Checking the device for measurement capability**	
		Records and statements
	Battery power	o.k.? (green light is on after turning on device)
	Mode of operation	Diffusion (preset)
	Time interval of integration	1o minutes (preset)
	Indication of date and time	o.k.?, time difference to local time?
	Check diffusion filter for damages	Damages:yes/no
	Visual inspection of general state	o.k.?
Date and Signature		

	Records on the Intercomparison	
Name of Laboratory:		

2	**Exposures**	
		Records and statements
2.1	**Exposure No. 1**	
	Level of radon activity concentration in Bq·m^{-3}	
	Turn on the device Place device in radon atmosphere, (Plug in power supply, if necessary)	o.k.?
	Date and time of commencement of exposure	Local date and time
	Further relevant information about the operation of the facility and monitoring the atmosphere (e.g. air pressure in hPa, temperature in °C)	
	Date and time of finalizing the exposure	Local date and time

	Records on the Intercomparison	

Name of Laboratory:

2.2	**Exposure No. 2**	
	Level of radon activity concentration in Bq·m^{-3}	
	Turn on the device Place device in radon atmosphere, (Plug in power supply, if necessary)	o.k.?
	Date and time of commencement of exposure	Local date and time
	Further relevant information about the operation of the facility and monitoring the atmosphere (e.g. air pressure in hPa, temperature in °C)	
	Date and time of finalizing the exposure	Local date and time

	Records on the Intercomparison	
Name of Laboratory:		

2.3	**Exposure No. 3**	
	Level of radon activity concentration in Bq·m^{-3}	
	Turn on the device Place device in radon atmosphere, (Plug in power supply, if necessary)	o.k.?
	Date and time of commencement of exposure	Local date and time
	Further relevant information about the operation of the facility and monitoring the atmosphere (e.g. air pressure in hPa, temperature in °C)	
	Date and time of finalizing the exposure	Local date and time

	Records on the Intercomparison	
Name of Laboratory:		

3	**Preparation for Shipment**	
		Records and statements
	Turn off the device	o.k.?
	Are the device and included accessories (according to list) safely packed in the transport box?	o.k.?
	Prepare the transport box for shipment (tightly closed and labelled)	o.k.?
Date and Signature		

Annex D: Standard results report

	Report of Results	

Name of Laboratory:

	Transfer comparison device	
	Designation	ALPHAGUARD
	Type	PQ 2000 PRO TTL
	SerialNo.	1336

Short description of the procedures applied for exposing the transfer comparison device,
Information about the local reference instrument for the radon activity concentration,
Information about traceability to primary standards

The results of the intercomparison are summarized in the table. Besides the exposure data, the mean values of temperature, *T*, air pressure, *p*, and relative humidity, *r.H.* of the radon atmospheres are given. This serves the purpose to characterise the measurement conditions during the exposures.

Table: Summary of results for the exposures No. 1, 2 and 3

No	$C_{M,net}$ [Bq·m^{-3}]	$U(C_{M,net})$ [Bq·m^{-3}]	C_{RefLab} [Bq·m^{-3}]	$U(C_{RefLab})$ [Bq·m^{-3}]	T [°C]	p [hPa]	$r.H.$ [%]
1							
2							
3							

	Report of Results	

Name of Laboratory:

$C_{M,net}$ is the mean value of radon activity concentration measured by the transfer comparison device. This value is determined from the collocated list of single measurement data provided by BfS after reading out the data from the device. The single measurement data are provided with a correction for background and the application of the calibration factor of BfS. For the determination of $C_{M,net}$ only those measurement data are considered, which are taken in the decisive reference period.

C_{RefLab} is the mean value of the radon activity concentration established in the radon atmosphere of the laboratory. This value is determined with the equipment of the laboratory. For the determination of C_{RefLab} only those measurement data are considered, which are taken in the decisive reference period.

The measurement uncertainty given as expanded uncertainty resulting from the standard uncertainty of the corresponding mean value multiplied with a coverage factor k=2. The standard uncertainty of the mean value is calculated from the statistical variation of the single measurements around this mean value. The following expanded uncertainties are included in the table:

$U(C_{RefLab})$	Measurement uncertainty of C_{RefLab}
$U(C_{M,net})$	Measurement uncertainty of $C_{M,net}$

……………………………………………….
Date and Signature

Name and e-mail of the person in charge (use capital letters)

Attachment C: Activity No. 5.3 – Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq m^{-3} to 300 Bq m^{-3}

16ENV10 MetroRADON

Activity No. 5.3

Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3}

NATIONAL INSTITUTE FOR NBC PROTECTION (SÚJCHBO,v.v.i.)

Kamenna 71, Czech Republic

Submission: 15th May 2020

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research and innovation programme and the EMPIR Participating States

Content

1 Introduction

Task 5.3: Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3}

The aim of this task is to validate the traceability of the European radon calibration facilities by comparison of the secondary standards used by European radon calibration facilities in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3} to the reference device calibrated in a reference radon atmosphere traceable to a primary standard. The validation exercise will be organized, scheduled and a reference laboratory selected. The European radon calibration facilities will send their secondary standards which are used for the calibration of the end-user devices to the reference laboratory, which will compare the secondary standards against a reference device calibrated in A1.3.2 and tested in A1.3.3 in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3}. The reference laboratory will evaluate any deviations in the existing calibration of the secondary standard. A report will be produced for each calibration by the reference laboratory detailing results and any deviations, and the reports will be sent to the relevant European radon calibration facilities. A validation report on the traceability of primary and secondary radon calibration facilities in Europe will be produced together with a guideline and recommendations on metrologically sound calibration and measurement procedures for the determination of radon concentration in air.

Activity number 5.3.1: *Following the development of constant radon activity concentrations in reference chambers and calibration procedures in A1.3.1, A1.3.2 and A1.3.3 respectively, CMI with BFKH, BfS, IRSN and SUJCHBO with support of other WP5 partners (BEV-PTP, CLOR, IFIN-HH, JRC, STUK and UC) will organise an exercise to validate the traceability of the secondary standards used by the European radon calibration facilities selected in A5.1.3. The schedule for the validation exercise will be produced and agreed and any necessary documentation produced for the exercise.*

In WP 1, the National Institute for Nuclear, Chemical and Biological Protection (SUJCHBO),in cooperation with the Czech Metrology Institute (CMI) has developed a unique device for the calibration of measuring instruments at low-level radon activity concentrations (Low-Level Radon Chamber, LLRCH). The evaluation and calibration of measuring devices for radon requires long-term stable conditions of radon activity concentration. During many experiments which required the adjustment of a various low-level radon activity concentrations, the air-tightness and the sustainability of long-term stable radon atmospheres in the LLRCH was verified. Based on these findings, it was possible to organize an intercomparison exercise to verify the traceability of secondary standards used by European radon calibration laboratories selected in A5.1.3. For this intercomparison, the manual "**Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3}**" was prepared together with the schedule of the intercomparison. The exercise, in which secondary standards of European calibration laboratories were calibrated, was performed by SUJCHBO in the period from October 2019 to April 2020.

Activity number 5.3.2: *A reference laboratory will be selected by BFKH, CMI, IFIN-HH, BfS, IRSN, and SUJCHBO from BFKH, IFIN-HH, BfS, IRSN, and SUJCHBO. European radon calibration facilities selected in A5.1.3 will send their radon secondary standards to the selected reference laboratory. The selected reference laboratory will compare and calibrate the secondary standards received from the European radon calibration facilities to the reference device calibrated in A1.3.2. The reference laboratory will evaluate any deviations in the existing calibration of the secondary standards in the range from 100 Bq·m*$^{-3}$ *to 300 Bq·m*$^{-3}$*. A report will be produced for each calibration by the reference laboratory detailing the results and any deviations, and the reports then sent to the relevant European radon calibration facilities. The reference laboratory will keep partners informed of the progress by e mail.*

SUJCHBO was selected as the reference laboratory to organize the intercomparison measurement. Selected European laboratories sent their secondary standards for the calibration to the SUJCHBO reference laboratory according to a pre-approved schedule during the period from October 2019 to April 2020 (see Appendix A). Eight European laboratories have participated in the intercomparison – BEV-PTV, UPC, IRSN, STUK, IFIN-HH, CLOR, BfS, and SUJCHBO. The instruments were calibrated at two levels of radon activity concentration – 200 Bq·m^{-3} and 300 Bq·m^{-3}. At the same time, the device’s background in an atmosphere with zero radon activity concentration was recorded. Results of the calibration of secondary standards were evaluated in accordance with ČSN ISO 13528 “Statistical methods for the use of proficiency testing by interlaboratory comparison”. A calibration certificate was issued for each participant.

2 Purpose

The main purpose of verifying the secondary standards of European calibration laboratories was to determine the value of reproduction in the implementation of the radon activity concentration in air in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3}. The equipment for testing of secondary measuring devices at low-level radon activity concentrations is owned by SUJCHBO. The equipment was developed and tested within MetroRADON WP1. Participant’s devices were exposed in two levels of radon activity concentration, at 200 Bq·m^{-3} and 300 Bq·m^{-3}. During the calibration process, the background of the device in the atmosphere with zero radon activity concentration was determined.

3 Participants

Eight European laboratories have participated in the intercomparison of secondary standards, including SUJCHBO, and nine measuring devices were calibrated. In seven cases, AlphaGuards operated in diffusion mode were used. One AlphaGuard was calibrated in flow-through mode. In one case, a RadonScout was used for the intercomparison. Table 1 gives a list of participants.

Table 15 – List of participants

Institution	Address	E-mail address
BEV-PTP	PTP/BEV – Physikalisch-technischer Prüfdienst, Bundesamt für Eich- und Vermessungswesen Arltgasse 35, 1160 Wien Austria	AlphaGuard PQ2000 Pro
UPC	Laboratory of 222Rn studies (LER) of the Institut de Tecniques Energetiques (INTE) of the Universitat Politecnica de Catalunya (UPC) Campus Diagonal Sud, Edificio PC (Pavello C) Av. Diagonal 647, 08028 Barcelona Spain	AlphaGuard PQ2000 Pro
IRSN	PSE-ENV/SEREN/BERAD 31 avenue de la Division Leclerc B.P. 17-92262 Fontenay-aux-Roses Cedex France	AlphaGuard PQ2000
STUK	STUK - Radiation and Nuclear Safety Authority Laippatie 4, Helsinki Finland	AlphaGuard PQ2000
IFIN-HH	IFIN-HH 30 Reactorului St. 077125 Magurele, Ilfov County, POB MG-6 Romania	RadonScout
CLOR	Central Laboratory for Radiological Protection Konwaliowa 7, PL 03-194 Warsaw Poland	AlphaGuard DF2000
BfS	Bundesamt für Strahlenschutz Radonmetrologie UR1 Kopenicker Allee 120 – 130, 10318 Berlin Germany	AlphaGuard DF2000
SUJCHBO	National Institute for Nuclear, Chemical and Biological Protection Kamenna 71, 262 31 Milin Czech Republic	AlphaGuard DF2000 AlphaGuard PQ2000

4 Used equipment

To verify the secondary standards of European calibration laboratories, which are used for the calibration of end-user devices, the National Institute for Nuclear, Chemical and Biological Protection, v.v.i, Kamenna (SUJCHBO) was selected as reference laboratory. As part of the WP1 task, SUJCHBO in cooperation with the Czech Metrology Institute, Prague (CMI) have developed a device for the calibration of measuring devices at low-level radon activity concentrations (Low-Level Radon Chamber, LLRCH). The equipment consists of a radon chamber LLRCH (Low-Level Radon Chamber) with a volume of 324 liters (Figure 1), a flow-through source of radon type RF 5 with an activity of 4 955 Bq (certificate No. 1035-SE-40456-19, CMI Prague), a calibrated mass flow controller type Bronkhorst EL-Flow (calibration sheet 6013-KL-M0406-19, CMI Brno) and a humidifier. The equipment meets the condition of relative uncertainty less than 5 % (k = 1) for calibration of measuring instruments at low-level radon activity concentrations (100 Bq·m^{-3} to 300 Bq·m^{-3}).

Figure – 1 Low-Level Radon Chamber LLRCH in SUJCHBO laboratory

Simultaneously with the participant's device, the AlphaGuard DF2000 device (owned by SUJCHBO, henceforth referred to as reference device) was placed into the Low-Level Radon Chamber as a reference device. This AlphaGuard was calibrated by BfS Berlin in March 2019 (Calibration Certificate R-19-1). In some cases, an AlphaGuard PQ2000 device (owned by SUJCHBO) was also placed into the LLRCH radon chamber together with a participant’s device. SUJCHBO’s AlphaGuard PQ2000 was calibrated by BfS Berlin in October 2017 (certificate 1218) and calibrated by PTB Braunschweig in October 2012 (certificate PTB-6.13-77-Rn222-S).

Figure 2 represents a simplified scheme of the equipment construction for testing of measuring devices at low-level radon activity concentrations.

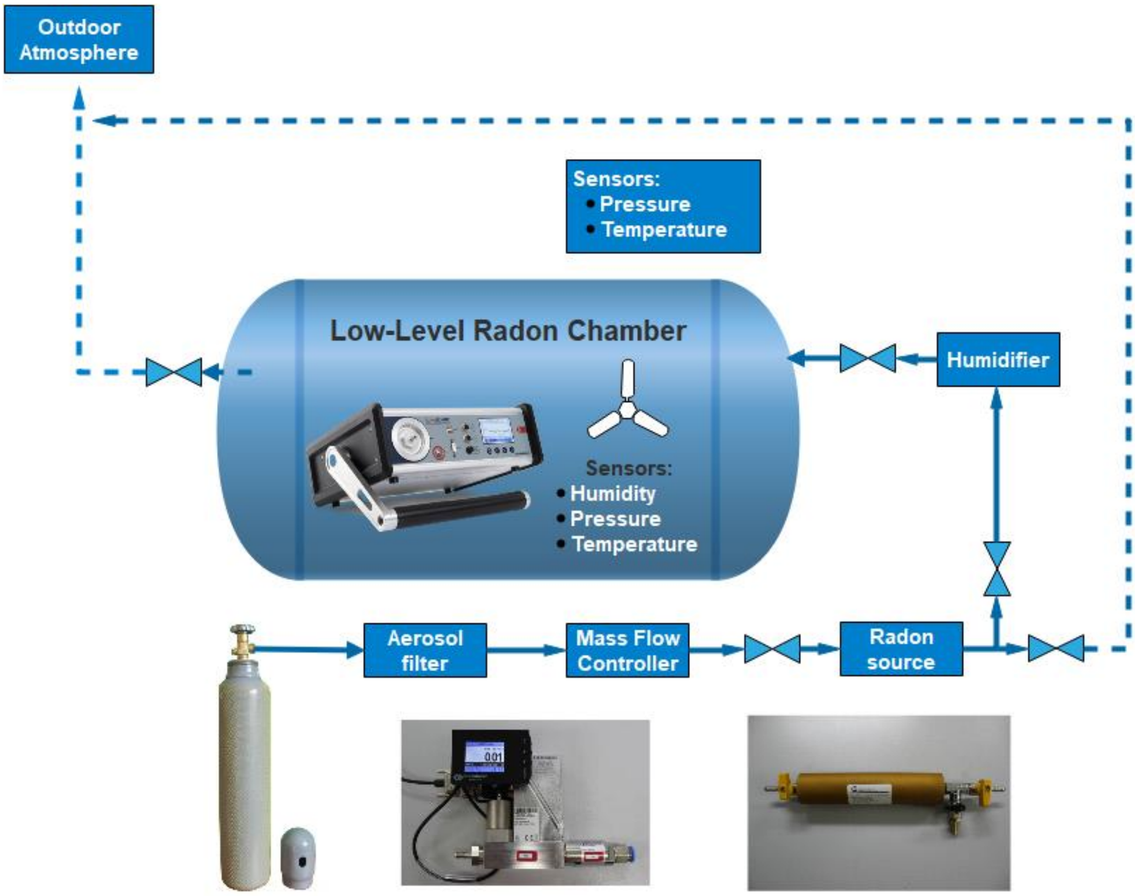

Figure 2 – Schematic of equipment for calibration of measuring instruments at low-level radon activity concentrations

5 Method

Verification of secondary standards of European calibration laboratories was performed by SÚJCHBO, v.v.i. Kamenna in the period from October 2019 to April 2020. For these purposes, the manual "Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq·m^{-3} to 300 Bq·m^{-3} was prepared. This manual was sent to the participants by e-mail. This document (Appendix A) describes all conditions of the intercomparison including the transport of instruments, exposures of instruments and the evaluation of results. The document also includes the "Exposure Record" (filled out by SUJCHBO reference laboratory) and "Record of mutual comparison" (filled out by individual participants). The calibration of secondary standards was performed according to a previously prepared schedule (see Appendix A) at two levels of radon activity concentration: 200 Bq·m^{-3} and 300 Bq·m^{-3}. During the calibration process, the background of the device in an atmosphere with zero radon activity concentration was determined. Temperature, air pressure and relative humidity were monitored during all exposures. The exposure was conducted at SUJCHBO for at least 24 hours for each level of radon activity concentration. During all measuring campaign, the average value of temperature was 22,3 ºC, the average value of air pressure was 955,8 hPa and the average value of relative humidity was 51,2 %. The processing of results was done by each participant using their individual process.

6 Results

6.1. Measurement results with AlphaGuard DF2000

The reference device was placed in the LLRCH radon chamber together with an individual calibrated participant's device. Except for one case, all participant’s devices were calibrated separately. In one case, two participant’s devices were calibrated in the LLRCH at the same time.

The following Figures show the measurement results obtained with the reference device (SUJCHBO´s AlphaGuard DF2000) for each exposure in individual measuring campaigns due to the schedule for radon atmospheres with radon activity concentrations of 200 Bq·m^{-3} (Figure 3) and of 300 Bq·m^{-3} (Figure 4). The average value of the radon activity concentration for atmospheres of 200 Bq·m^{-3} was (202 ± 4) Bq·m^{-3}. The average value of the radon activity concentration for atmospheres of 300 Bq·m^{-3} was (302 ± 3) Bq·m^{-3}. The mean background value under the condition with air free from radon inside the LLRCH was (1.9 ± 0.2) Bq·m^{-3}.

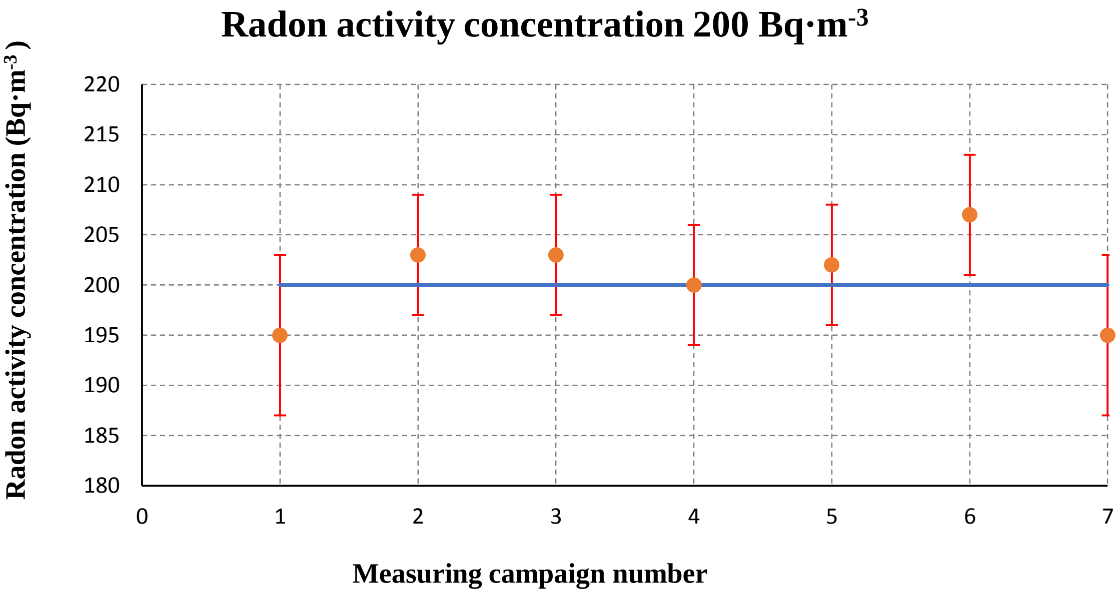

Figure 3 – Measurement results of the reference device for 200 Bq·m^{-3}

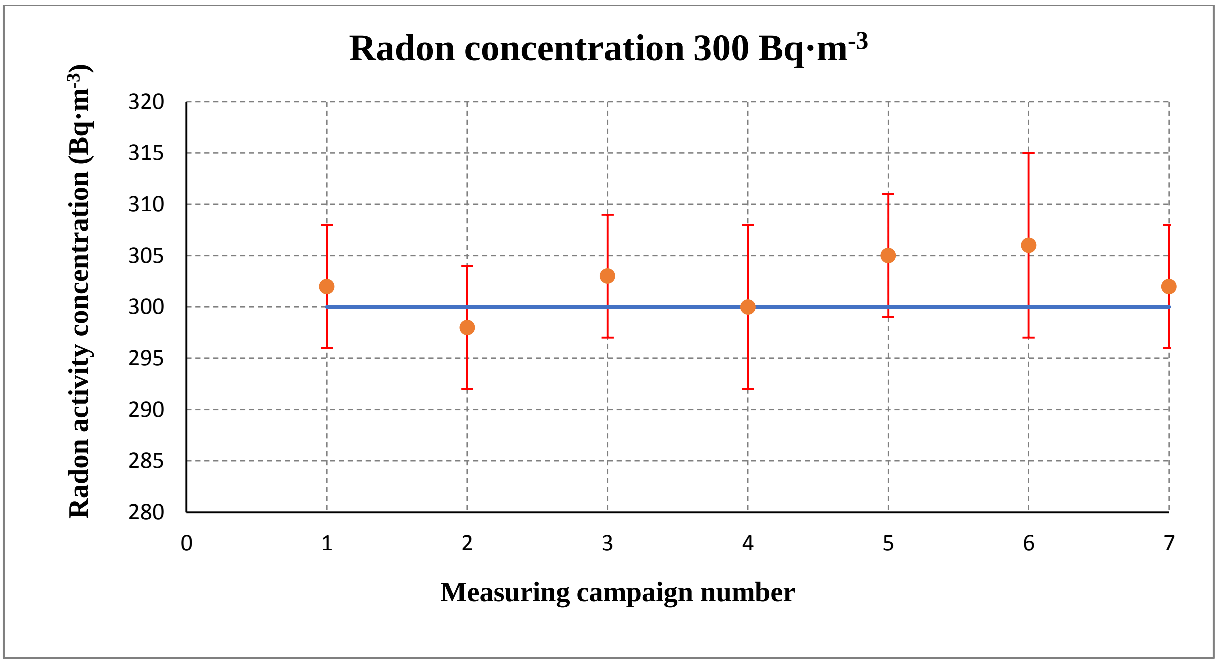

Figure 4 – Measurement results of the reference device for 300 Bq·m^{-3}

6.2 Results of the participants

The exposure was conducted at SUJCHBO for at least 24 hours for each level of radon activity concentration. The processing of results was done by each participant using their individual process.

6.2.1. Results of participants in an atmosphere with zero radon activity concentration (background)

The following Table 2 and Figure 5 summarize results of measurements in an atmosphere with zero radon activity concentration (instrument background measurements). The Table also includes two devices owned by SUJCHBO, participant's code 8 was assigned to reference AlphaGuard DF2000 (reference device) and code 9 to SUJCHBO's AlphaGuard PQ2000. The given results are average values from individual measurements. The average radon activity concentration (reference level of radon activity concentration) was calculated from values obtained in five measuring campaigns by the reference device AlphaGuard DF2000.

Table 16 – Results of participants in an atmosphere with zero radon concentration

Participant's code	$a_{v,Rn}$ (Bq·m^{-3})	$s(a_{v,Rn})$ (Bq·m^{-3})	**$a_{v,Rn}$ … the average participant´s value of radon activity concentration in the exposure period (results were sent to SUJCHBO by the participant after the device exposition)** **$s(a_{v,Rn})$ … participant´s measurement uncertainties (results were sent to SUJCHBO by the participant after the device exposition) - it is an expanded uncertainty – the product of the standard measurement uncertainty and the coverage factor k = 2**
1	4	3	
2	1	0	
3	2,1	0,2	
4	5	3	
5	6,8	1,2	
6	0,4	0,7	
7	15,4	1,4	
8	1,9	0,2	
9	26,2	3,0	

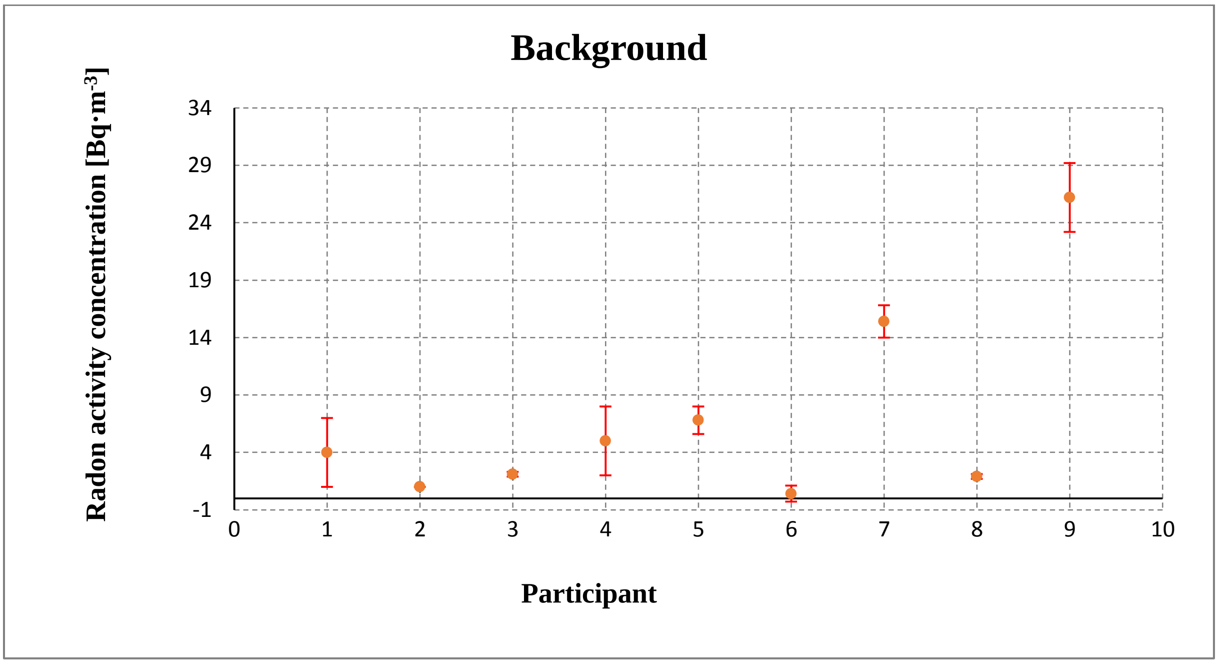

Figure 5 – Background values of individual participants' devices

The results of the verification of secondary standards are processed in accordance with the standard ČSN ISO 13528 "Statistical methods used in proficiency testing by interlaboratory comparison".

Based on data from participants, the following are calculated for each level:

1) <u>Determination of z score:</u>

$$Zi = \frac{(Xi - Xpt)}{\delta pt}$$

where Xi is participant's result

Xpt is reference value

δpt is standard deviation (in this case 10 %)

The level of standard deviation 10 % was determined based on experiences with previous rounds of proficiency testing for the same measurement with comparable property values, and where participants use compatible measurement procedures.

Interpretation of z score

$\lvert z\rvert \leq 2{,}0$	the result is considered acceptable
$2{,}0 < \lvert z\rvert < 3{,}0$	the result is considered a source of warning
$\lvert z\rvert \geq 3{,}0$	the result is considered unacceptable

2) Deviation estimation (measurement error)

Deviation estimate calculation

$$Di\% = 100\,.\frac{(Xi - Xpt)}{Xpt}$$

where Xi is participant's result

Xpt is reference value

6.2.2. Participants' results for level 200 Bq·m^{-3}

The measurement results are shown in the Table 3.

In order to obtain more results for evaluation and improve the statistics, the number of devices was increased with two devices owned by SUJCHBO, participant code 8 was assigned to AlphaGuard DF2000 (reference device) and code 9 to AlphaGuard PQ2000. The results given in Table 3 are average values from individual measurements. The average radon activity concentration (reference level of radon activity concentration) was calculated from values obtained in six measuring campaigns by the reference device AlphaGuard DF2000.

Table 17 – Participants' results for level 200 Bq·m^{-3}

Participant's code	**$a_{v,Rn}$ (Bq·m^{-3})**	**s($a_{v,Rn}$) (Bq·m^{-3})**	**z-score (-)**	***D*** **(%)**	**$a_{v,Rn}$ … the average participant´s value of radon activity concentration in the exposure period (results were sent to SUJCHBO by the participant after the device exposition)** **s($a_{v,Rn}$) … participant´s measurement uncertainties (results were sent to SUJCHBO by the participant after the device exposition) - it is an expanded uncertainty – the product of the standard measurement uncertainty and the coverage factor k = 2**
1	201	9	0,1	0,5	
2	203	6	0,3	1,5	
3	196	6	-0,4	-2,0	
4	208	18	0,8	4,0	
5	194	9	-0,6	-3,0	
6	201	15	0,1	0,5	
7	202	8	0,2	1,0	
8	202	4	0,2	1,0	
9	199	6	-0,1	-0,5	

Measurement results, values of *z* score and participants measurement deviations for exposures to radon atmospheres of 200 Bq·m^{-3} are shown in Figures 6, 7 and 8.

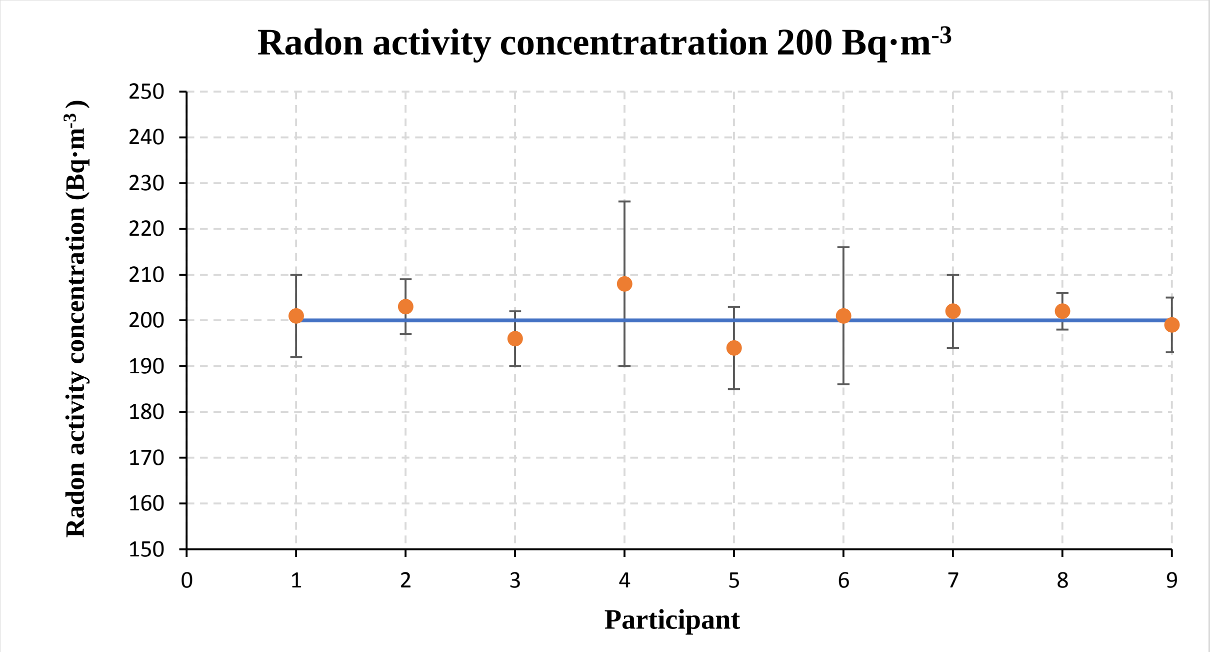

Figure 6 – Results of individual participants for radon atmospheres of 200 Bq·m^{-3}

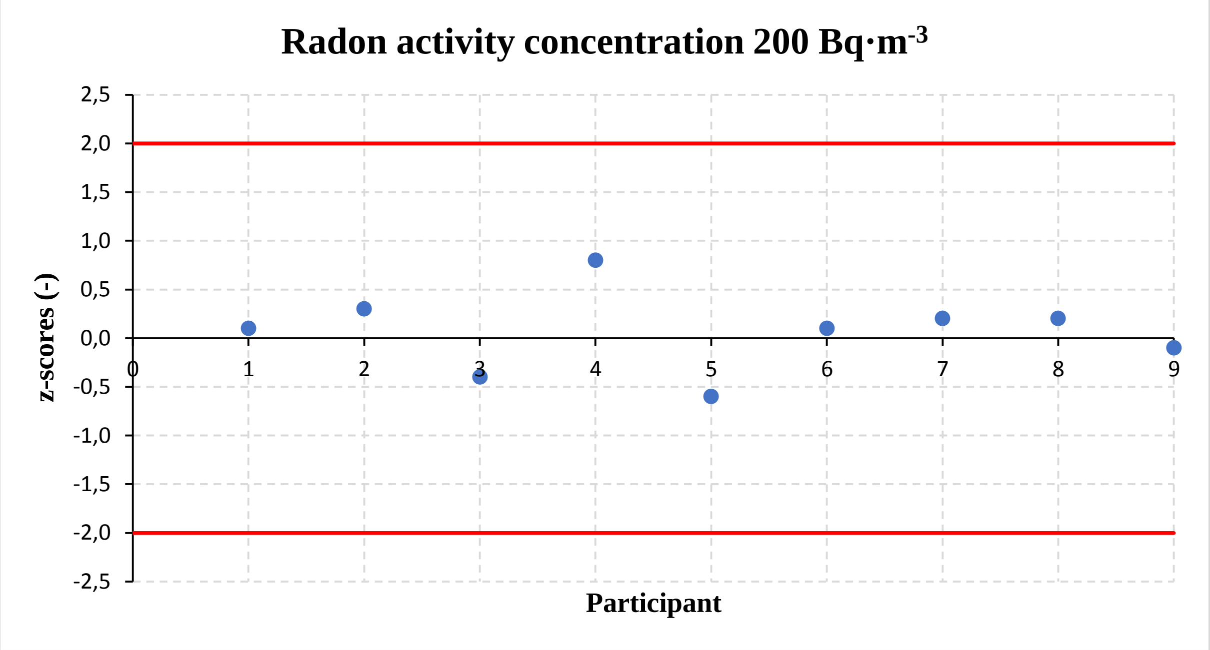

Figure 7 – z-scores of individual participants for radon atmospheres of 200 Bq·m^{-3}

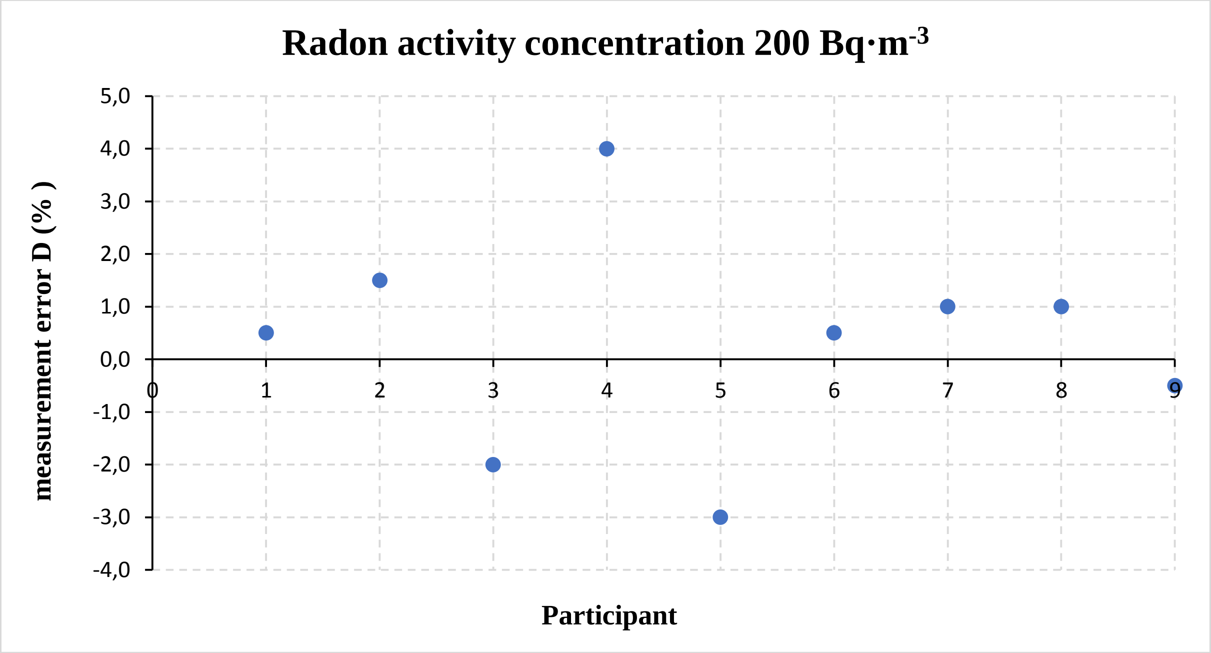

Figure 8 – Values for estimating the deviation D of individual participants from the reference value (obtained with the reference device) for radon atmospheres of 200 Bq·m^{-3}

6.2.3. Participants' results for level 300 Bq·m^{-3}

In order to obtain more results for evaluation and improve the statistics, the number of devices was increased with two devices owned by SUJCHBO, participant's code 8 was assigned to AlphaGuard DF2000 (reference device) and code 9 to AlphaGuard PQ2000. Results mentioned in Table 4 are average values from individual measurements. The average radon activity concentration (reference level of radon activity concentration) was calculated from values obtained in six measuring campaigns by the reference device AlphaGuard DF2000.

Table 18 – Participants' results for radon atmospheres of 300 Bq·m^{-3}

Participant's code	$a_{v,Rn}$ (Bq·m^{-3})	s($a_{v,Rn}$) (Bq·m^{-3})	z-score (-)	*D* (%)
1	306	12	0,6	2,0
2	290	6	-1,0	-3,3
3	288	8	-1,2	-4,0
4	292	18	-0,8	-2,7
5	290	10	-1,0	-3,3
6	291	21	-0,9	-3,0
7	300	10	0	0
8	302	3	0,2	0,7
9	289	6	-1,1	-3,7

$a_{v,Rn}$ … the average participant´s value of radon activity concentration in the exposure period (results were sent to SUJCHBO by the participant after the device exposition)

s($a_{v,Rn}$) … participant´s measurement uncertainties (results were sent to by the participant after the device exposition) - it is an expanded uncertainty – the product of the standard measurement uncertainty and the coverage factor k = 2

Measurement results, values of *z* score and participants measurement deviations under the level of 200 Bq·m^{-3} are shown in the following Figures 9, 10 and 11.

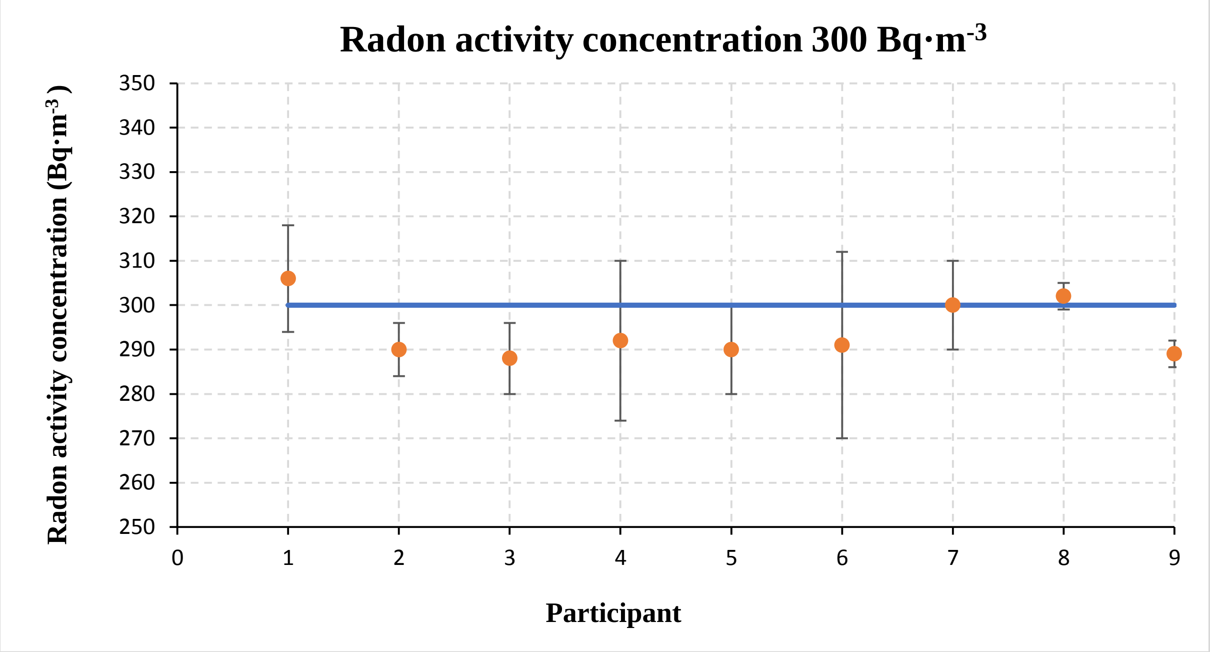

Figure 9 – Results of individual participants for radon atmospheres of 300 Bq·m^{-3}

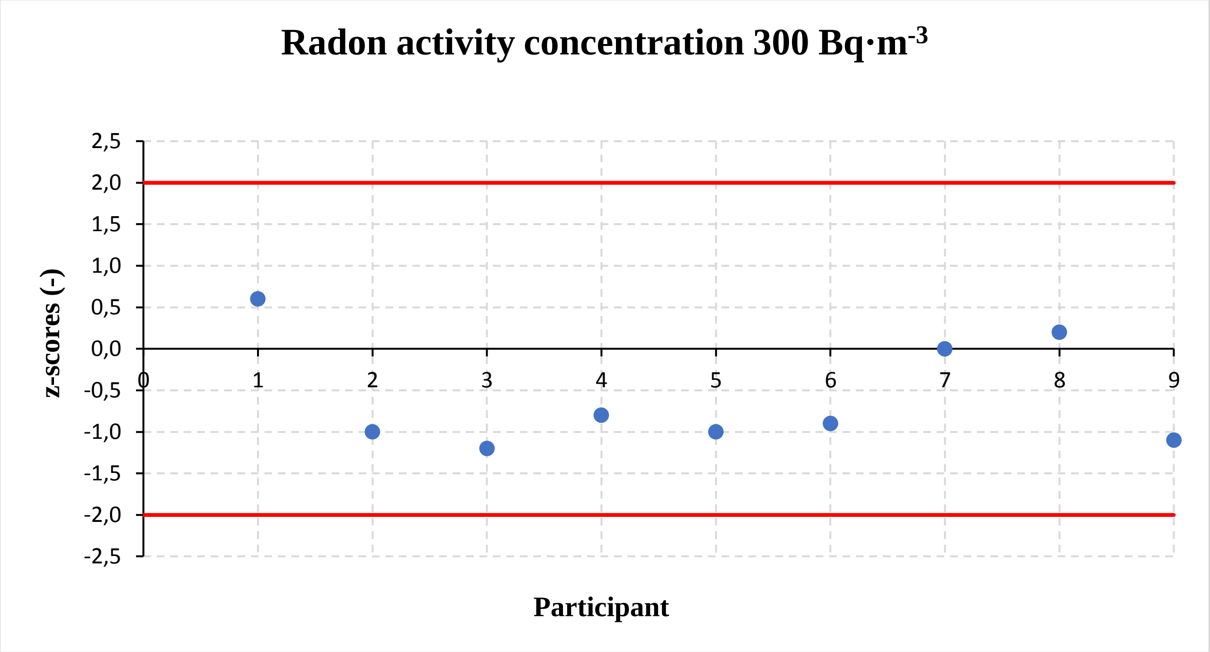

Figure 10 – z-scores of individual participants for radon atmospheres of 300 Bq·m^{-3}

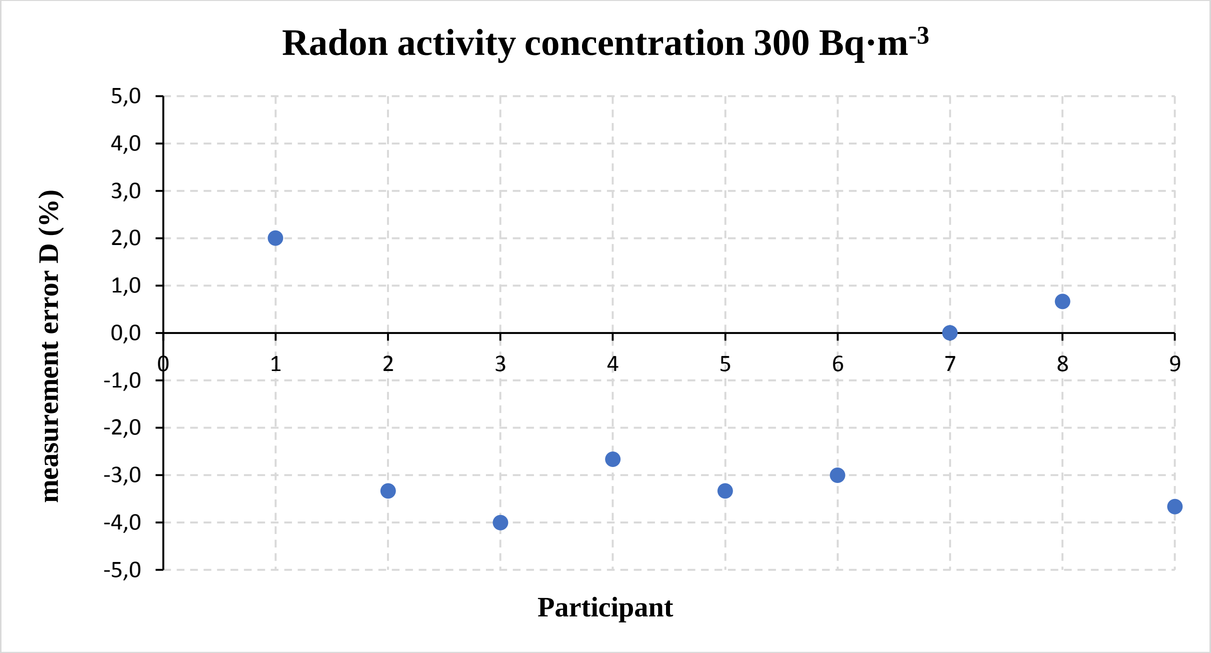

Figure 11 – Values for estimating the deviation D of individual participants from the reference value (obtained with the reference device) for radon atmospheres of 300 Bq·m^{-3}

7 Conclusion

The calibration of secondary standards of European calibration laboratories was performed during the period from October 2019 to April 2020. Eight European laboratories participated in the intercomparison. The calibration was performed by the staff of SUJCHBO using the unique equipment developed in MetroRADON for testing of measuring devices at low-level radon activity concentrations. The intercomparison was realised at two levels of radon activity concentrations, at 200 Bq·m^{-3} and at 300 Bq·m^{-3}. During the calibration process, all device's backgrounds were determined.

The *z* score and the estimation of deviation were the main parameters for comparison of participant's performance.

For the level of 200 Bq·m^{-3}, the values of the *z* score vary from -0.6 up to 0.8 and the value of the deviation estimation ranges from -3.0 % up to 4.0 %.

For the level of 300 Bq·m^{-3}, the values from the *z* score range from -1.2 up to 0.6 and the value of the deviation estimation ranges from -4.0 % up to 2.0 %.

The analysis of individual parameters (maximum *z* score, maximum estimation of the deviation) of the participant's performance shows that the results of the secondary standards of the European calibration laboratories are at a very good level.

Verification of secondary standards of European calibration laboratories for radon calibration is an effective tool for detecting discrepancies in traceability and ensuring the quality of radon measurements in Europe. It is strongly recommended that calibrations and verifications are performed on a regular basis.

8 List of Appendices

Appendix A	Intercomparison of European radon calibration facilities in the reference radon chamber of SUJCHBO
	Appendix 1 Schedule of Intercomparison
	Appendix 2 Technical records
	Appendix 3 Participant's results
Appendix B	Example of calibration report

Intercomparison of European radon calibration facilities in the reference radon chamber of SUJCHBO

WP5: Validation of traceability of European radon calibration facilities

Task 5.3: Validation of the traceability of European radon calibration facilities at stable radon atmospheres in the range from 100 Bq m^{-3} to 300 Bq m^{-3}

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SÚJCHBO, v.v.i.
JRP EMPIR 16ENV10: MetroRADON

Metrology for Radon monitoring

Content

Introduction

This document describes the realisation of comparative measurement under Task 5.3 of the European project JRP EMPIR 16ENV10 (MetroRADON).

A procedure for calibration of the continuous measuring radon devices during low activity concentration (from 100 Bq/m^3 to 300 Bq/m^3) has been developed within WP1. Czech Metrology Institute in Prague together with SÚJCHBO have developed and tested a long-term stable standard source ^{222}Rn with a low emanation of radon activity. The source generates the known radon activity concentration in airflow. This source has been tested by the BfS in Berlin. SUJCHBO has developed a newly Low-Level Radon Chamber (LLRCH) with volume 324 litres, and this source allows to keep a time stable level of the radon activity concentration for several days. The equipment meets the condition of relative uncertainty for measuring instruments calibration at low-radon activity concentrations (100 Bq/m^3 to 300 Bq/m^3) under 5 % (for the coverage factor k = 1).

An intercomparison measurement with selected European laboratories will be performed in the SUJCHBO Laboratory within WP5 under task 5.3. The objective of this task is to verify secondary standards used for the calibration of terminal equipment. The secondary standards will be calibrated between 100 Bq/m^3 and 300 Bq/m^3. A report summarising the results will be prepared for each calibration separately.

Description of the technical infrastructure

A technical infrastructure which allows sustaining of the long-term stable radon activity concentration will be used for the comparison. The construction of the equipment consists particularly of the airtight Low-Level Radon Chamber (LLRCH) with the inner volume of 324 litres; the humidifier, the flow-through source of Rn-222 type RF 5, the mass flow controller of type Bronkhorst EL-Flow, the aerosol filter and the air pressure bottle as the source of radon free air. The main parts of this infrastructure are presented in Figure 1.

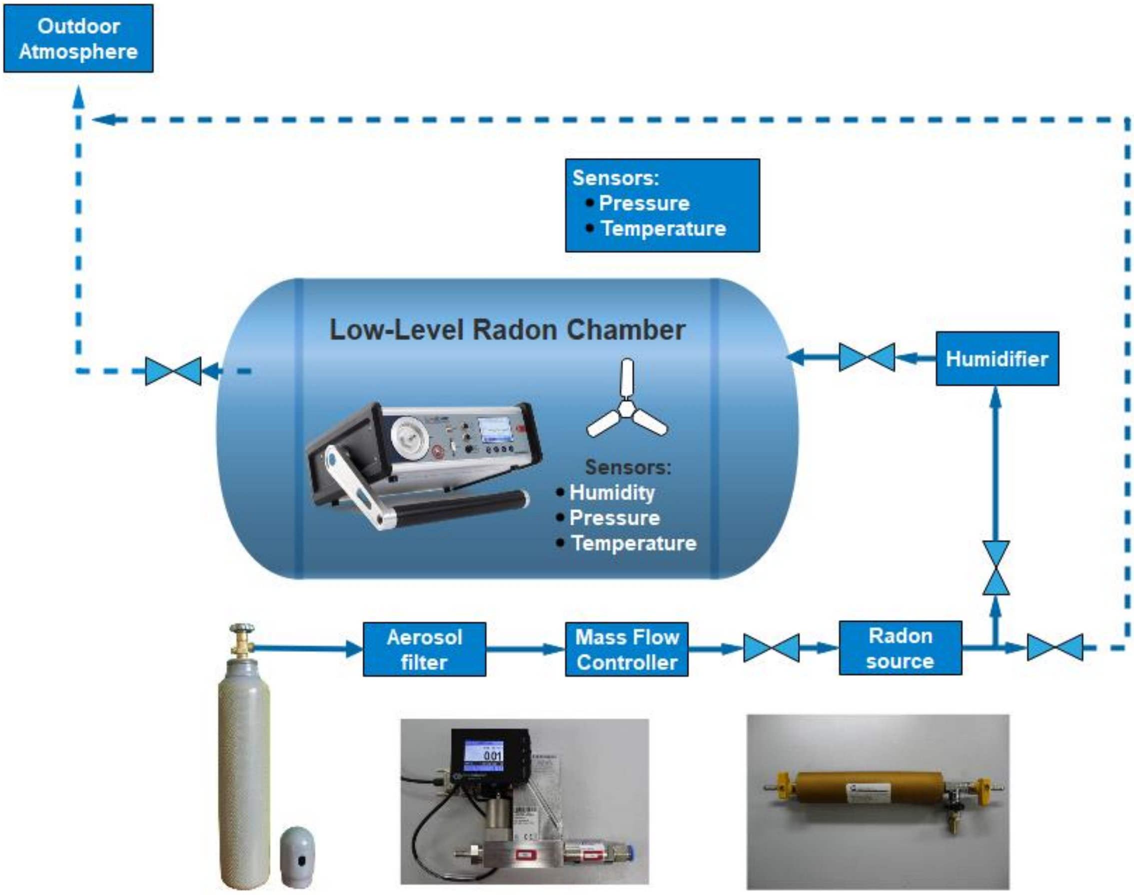

Figure 12 The scheme of the technical infrastructure for preparing of the low-level, long-term radon activity concentration.

For achieving a low-level radon activity concentration inside of the chamber, it is necessary to ensure a constant supply of radon and provide defined ventilation in the Chamber. At low radon activity concentration, it is difficult to obtain sufficiently "clean" air needed to ensure the ventilation. Radon activity concentration in outdoor air in the SUJCHBO area in Kamenna can reach from tens to hundreds of Bq/m^3. For this reason, the device uses enough "old" air from the pressure vessel as a source of air free from the radon. The air passes through the protective aerosol filter and the calibrated mass-flow controller type Bronkhorst EL-Flow into the source of radon. The reference radon atmosphere is ensured by the flow source of radon type RF 5 with activity 4955 Bq developed by the Czech Metrology Institute, regional Inspectorate in Prague. The air-radon mixture is further passed through a humidifier. The main part of the device is gas-tight radon chamber LLRCH (Low-Level Radon Chamber) with an inner volume of 324 litres. Homogeneity of the inner atmosphere is ensured by a continuously controllable fan which allows the setting of airflow in the range from 0.1 m/s to 3.5 m/s. The climatic conditions are monitored by the temperature, relative humidity, and the inner and outer atmospheric pressure gauges.

Radon reference level

The design of the device was based on a constant supply and constant ventilation model.

$$a(t) = a_o\ .e^{-(\lambda+k).t} + \frac{R}{V(k+\lambda)}\left(1 - e^{-(\lambda+k).t}\right)$$

$a(t)$	....	radon activity concentration in time t (Bq·m^{-3})
a_o	....	radon activity concentration in time zero (Bq·m^{-3})
λ	....	radon decay constant (h^{-1})
k	....	air exchange intensity (h^{-1})
t	....	time (h)
R	....	radon input rate (Bq·h^{-1})
V	....	volume of radon chamber (m^{3})

For the steady-state (t = ∞) at a constant air exchange intensity and constant radon input rate, the following applies:

$$a_{V,Rn} = R_{Rn} /\left(Q_{settled}\ .\ \frac{M.p_{\text{at Q calibration}}}{R.T_{\text{at Q calibration}}} / \frac{M.p_{\text{at confrontation}}}{R.T_{\text{at confrontation}}} + \lambda.V\right)$$

$a_{V,Rn}$	....	radon activity concentration (Bq·m^{-3})
$Q_{settled}$	....	flow rate (m^{3}·h^{-1})
M	....	molar mass (kg·mol^{-1})
$p_{\text{at Q calibration}}$	....	air pressure 1013,25 (hPa)
R	....	molar gas constant (J·mol^{-1}·K^{-1})
$T_{\text{at Q calibration}}$	....	temperature 273,16 (K)
$p_{\text{at Rn confrontation}}$	....	air pressure (Pa)
$T_{\text{at Rn confrontation}}$	....	temperature (K)
λ	....	radon decay constant (h^{-1})
V	....	volume of radon chamber (m^{3})
R_{Rn}	....	radon emanation power (Bq·h^{-1})

Uncertainty in determining the radon reference level

The required value of radon activity concentration is 100 Bq/m^3; the inner volume of the Chamber is 0,324 m^3; the flow rate is 0,3252 m^3/h.

The following applies to the calculation of the radon activity concentration:

$$a_{V,Rn} = R_{Rn} /(Q_{settled} . \frac{M.p_{\text{at Q calibration}}}{R.T_{\text{at Q calibration}}} / \frac{M.p_{\text{at confrontation}}}{R.T_{\text{at confrontation}}} + \lambda_{Rn}.V)$$

Quantity X_i	Estimate x_i	Reliability $u(x_i)$	Sensitivity coeficient c_i	Uncertainty contribution $u_i(y)$
R_{Rn}	37,44 Bq·h^{-1}	0,72 Bq·h^{-1}	2,67 h·m-^{3}	1,9 Bq·m^{-3}
$Q_{settled}$	0,3252 m^3·h^{-1}	0,0010 m^3·h^{-1}	267 h·Bq·m^{-6}	0,27 Bq·m^{-3}
M	0,02895 kg·mol^{-1}	2.10^{-5} kg·mol^{-1}	3333 Bq·mol/(kg·m^3)	0,06 Bq·m^{-3}
$p_{\text{at Q calibration}}$	101,3325 kPa	0,4 kPa	0,9869 Bq/(kPa·m^3)	0,4 Bq·m^{-3}
R	8,314 J·mol^{-1}·K^{-1}	10^{-9} J·mol^{-1}·K^{-1}	12,03 Bq·K·mol/(J·m^3)	negligible
$T_{\text{at Q calibration}}$	273,16 K	0,60 K	0,366 Bq/(K·m^3)	0,22 Bq·m^{-3}
$p_{\text{at Rn confrontation}}$	96,290 kPa	0,4 kPa	1,0385 Bq/(kPa·m^3)	0,42 Bq·m^{-3}
$T_{\text{at Rn confrontation}}$	296,95 K	0,58 K	0,3368 Bq/(K·m^3)	0,20 Bq·m^{-3}
λ_{Rn}	0,007554 h^{-1}	0,000003 h^{-1}	86,5 h·Bq·m^{-3}	2,6.10^{-4} Bq·m^{-3}
V	0,324 m^3	0,002 m^3	2,017 Bq·m^{-6}	0,004 Bq·m^{-3}
$a_{V,Rn}$	100 Bq·m^{-3}			**2,0 Bq·m^{-3} (2,0 %)**

The table shows an expanded uncertainty - the product of the standard measurement uncertainty and the coverage factor k = 2 (which corresponds to a coverage probability of about 95 % for normal distribution) following the EA 04/02.

Transport

Participants of the intercomparison will arrange a transport company for the shipment of their secondary standard to SUJCHBO and back and will also cover all transfer fees. Individual organisations will be gradually asked to send their secondary standard to the reference laboratory of SUJCHBO according to the attached timetable (see Appendix 1). The Participant´s standard, together with necessary accessories will be safely packed and transported in a shipping box. The Participant will ensure the timely delivery of the device following the agreed date.

Upon delivering the Participant´s device, SUJCHBO will check the integrity of the shipping package and its secondary standards.

The shipping address is:

MSc. Josef Vosahlik
SUJCHBO, v.v.i
Kamenna 71, Milin 262 31
Czech Republic

Device exposition

The Participant guarantees a sufficient memory capacity of the device for about ten days. The Participant will also note the possibility of operating the device via batteries or only with an external power source. The device time-unit will be set to Central European Time. The sampling interval will be set to 60 minutes.

Intercomparison measurement will be performed under two levels of the radon activity concentration: 200 Bq/m^3 and 300 Bq/m^3. The background of the device will also be determined. A temperature, air pressure and relative humidity will be monitored during all exposure. Each device will be compared individually. The time required for the intercomparison measurement of each secondary standard is estimated for approximately two weeks. After the measurement is finished, the Participant will be asked to ensure the reshipment of the device back. The final version of the Intercomparison schedule will be prepared based on possibilities of SUJCHBO and all individual Participants.

Together with the Participant`s device, the AlphaGuard DF 2000 (owned by the SUJCHBO) will be placed into the Low-Level Radon Chamber. This reference measuring device has been calibrated in the BfS Berlin (Calibration Certificate No R-19-1).

Measurement results

After receiving the device back and processing of results, the Participant will send measurement results as an average value for a predefined time interval via email to vosahlik@sujchbo.cz or eliskafialova@sujchbo.cz. SUJCHBO will share the time interval upon the return of the instrument in the form of an Exposure record (see Appendix 2). The Participant´s results will contain expanded measurement uncertainty as a product of standard uncertainty and coverage factor k = 2 (it corresponds for normal distribution to 95% probability of coverage). The results will also include the name and address of the laboratory, the name and email address of the responsible person, the type of secondary equipment and its serial number - see Participants results in Appendix 3.

List of Participants

Institution	Address	E-mail address
BEV-PTP	PTP/BEV – Physikalisch-technischer Prufdienst, Bundesamt fur Eich- und Vermessungswesen Arltgasse 35	Hannah.wiedner@bev.gv.at

	1160 Wien, Austria	
UPC	Laboratory of 222Rn studies (LER) of the Institut de Tecniques Energetiques (INTE) of the Universitat Politecnica de Catalunya (UPC) Campus Diagonal Sud, Edificio PC (Pavello C) Av. Diagonal,647 08028 Barcelona, Spain	Claudia.grossi@upc.edu
IRSN	IRSN PSN-RES/SCA/LPMA BP 68-91192 Gif sur Yvette Cedex, France	Nathalie.michielsen@irsn.fr
STUK	STUK - Radiation and Nuclear Safety Authority Laippatie 4 Helsinki, Finland	Tuukka.turtiainen@stuk.fi
IFIN-HH	IFIN-HH 30 Reactorului St. 077125 Magurele, Ilfov County, POB MG-6 Romania	Aluca@nipne.ro
CLOR	Central Laboratory for Radiological Protection Konwaliowa 7 PL 03-194 Warsaw	Woloszczuk@clor.waw.pl
BfS	Bundesamt fur Strahlenschutz Radonmetrologie UR1 Kopenicker Allee 120 – 130 10318 Berlin Germany	Tbeck@bfs.de

Measurement evaluation

The Participant will receive the List of technical records (Appendix 2) together with the returned instrument. In the List, there will be noted the time of exposure and a climatic condition monitored during the calibration. The Participant will send his/her results (the average radon activity concentration in the defined time of exposure together with expanded uncertainty) according to the chapter “Measurements results”.

The results of each measurement will be evaluated individually following the accredited calibration methodology AMS-R. The form of a Calibration Certificate will summarize the measurement results for each Participant.

Conclusion

After the Intercomparison is completed, a Report will be drawn up summarising all the results of each Participant. The results will be presented anonymously (indicated by numbers). Only a particular Participant will know the numeric designation. The Report will be used as a basis for the preparation of an article which will be published in an impact journal.

Appendix 1 Schedule of Intercomparison

Each Participant will choose a suitable term.

Start of the comparison	**End of the comparison**	**Name of the participated Institution**
30th September 2019	13th October 2019	-
14th October 2019	27th October 2019	-
28th October 2019	10th November 2019	BfS
11th November 2019	24th November 2019	IRSN
25th November 2019	8th December 2019	STUK
6th January 2020	19th January 2020	INTE-UPC
20th January 2020	2nd February 2020	BEV-PTP
3rd February 2020	16th February 2020	CLOR
13th April 2020	24th April 2020	IFIN-HH

Appendix 2 Technical records

This table will be filled by the SUJCHBO and will be sent to the Participant after finishing of the device exposures.

Institution Name of the Participant Contact information	

Exposure No 1

Turn on the device	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Temperature [^{o}C]	
Air pressure [hPa]	
Relative humidity [%]	

Exposure No 2

Turn on the device	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Temperature [^{o}C]	
Air pressure [hPa]	
Relative humidity [%]	

Exposure No 3

Turn on the device	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Temperature [^{o}C]	
Air pressure [hPa]	
Relative humidity [%]	

Appendix 3 Participant´s results

This table will be filled by the Participant after the processing of results and will be sent to the SUJCHBO via e-mail vosahlik@sujchbo.cz or fialovaeliska@sujchbo.cz.

Intercomparison records	
Institution	
Name of the representative person	
Calibrated device	
Device S/N	

Participant´s results:

Exposure No 1	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Level of radon activity concentration in Bq/m^3	

Exposure No 2	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Level of radon activity concentration in Bq/m^3	

Exposure No 3	
Date and time of the start of exposure	
Date and time of the finish of exposure	
Level of radon activity concentration in Bq/m^3	

Date and Signature:

NATIONAL INSTITUTE FOR NBC PROTECTION

/SÚJCHBO, v.v.i./

KAMENNÁ 71, 262 31 MILÍN, CZECH REPUBLIC

Tel.: +420 318 600 200 Fax: +420 318 626 055 E-mail: sujchbo@sujchbo.cz

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CALIBRATION REPORT

Client	
Client´s representative person	
Calibrated device	
Device S/N	
Date of the calibration	

Results

Exposure No. 1

Client´s results (Bq m^{-3})	Calibration lab´s results (Bq m^{-3})	T (°C)	p (hPa)	r.H. (%)
±	±			

Ratio of result (related to Calibration laboratory) is

Exposure No. 2

Client´s results (Bq m^{-3})	Calibration lab´s results (Bq m^{-3})	T (°C)	p (hPa)	r.H. (%)
±	±			

Ratio of result (related to Calibration laboratory) is:

Ing. Josef Vošahlík
Head of the Authorised Metrological Center
SUJCHBO, v.v.i., Kamenna

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