Review (Invited)

Intercomparisons Exercises of Radon and Thoron Monitors Provided by Four Laboratories: A Review

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Indoor radon and thoron concentration measurements have been intensively carried out since the 1980s for assessment of radiation doses to workers and the general public. For example, the European Union countries established reference levels for indoor radon concentration in relation to national action plans to address long-term risk from radon exposures. Measurements done using a reliable method are the only way to investigate radon concentration levels. In order to ensure the quality of measurements, intercomparisons among laboratories are performed, as one verification method. The primary purpose of this paper is to provide a concise review of intercomparisons of radon and thoron monitors carried out by four institutions: NIRS (Japan), PHE (UK), BfS (Germany) and SURO (Czech Republic). The different measurement set-ups, evaluation methods and statistical treatments utilized by those institutions are described.

KEY WORDS: intercomparisons, radon, thoron, proficiency testing, bias evaluation, uncertainty.

I INTRODUCTION

Inhalation of radon (^{222}Rn) and its short-lived decay products and products of the thoron (^{220}Rn) series accounts for more than half of the effective dose from natural radiation sources.¹⁾ In several areas of the world, elevated radon concentrations have been found, and therefore concern about health risks from radon has been intensified.

The US Environmental Protection Agency (EPA) estimated that about 15,000 to 20,000 lung cancer deaths in the USA each year were related to indoor radon.²⁾ The latest investigation in Europe showed that radon in homes accounted for about 9% of the deaths from lung cancer and hence 2% of all cancer deaths.³⁾

Radon gas exists everywhere because it is released in the radioactive decay of uranium, thorium and radium in rocks and soil. Outdoor radon annual concentration levels are usually very low, e.g. 6 Bq m^{-3} in Japan and 10 Bq m^{-3} in Italy.^{4,5)} Indoor radon concentrations depend on many factors, such as local geology, quality of basement structures, building materials, ventilation, and behaviour of occupants. In many countries surveys of radon levels in different living environments (dwellings, workplaces, hospitals, schools, kindergartens and caves) have been carried out to determine

average exposures and to recognize locations where high radon levels occur.^{6–10)}

The radon concentration levels at which remediation action should be taken to reduce the environmental levels are known as the reference or action levels and they differ country by country. For example, in 2007 the WHO reported the reference levels were set in Czech Republic at 400 Bq m^{-3} for existing dwellings and at 200 Bq m^{-3} for new dwellings and in Switzerland, the levels were 400 Bq m^{-3} for existing dwellings and $1,000\text{ Bq m}^{-3}$ for new ones; in the USA, the levels for both existing and new dwellings were 148 Bq m^{-3} , but in Germany, the levels for both were only 100 Bq m^{-3} .¹¹⁾ Moreover, in some countries, e.g. Japan and Italy, WHO reported the reference levels had not been established yet.

However, a new directive in the European Union is imposing an obligation onto member states to establish national reference levels for indoor radon concentrations;¹²⁾ specifically, the reference levels for the annual average concentration in air shall not be higher than 300 Bq m^{-3} . This contrasts with the WHO's recommended reference level of 100 Bq m^{-3} .

The only way to know whether a radon level is elevated is to test of it. However, as mentioned earlier, many radon surveys have been initiated, but they have used many different measurement passive monitors (etch track detectors, activated charcoal and electret) and active instruments (ionization chambers, scintillation cells and solid state detectors). Although the working principles are similar, it is difficult in practice to maintain a reasonable and accurate standard of measurement and quality. In addition, new laboratories and companies continually enter the field of radon and radon

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isotopes measurements and new measurement techniques and devices are still being developed.^{13–15)} Consequently, it is necessary to improve and standardize technical methods of measurements and to ensure that radon testing devices and radon laboratories provide accurate and reliable data on radon levels. One of the quality assurance verification methods available is intercomparison of radon and thoron monitors used by different laboratories.

Four institutions such as: **NIRS** —National Institute of Radiological Sciences, Japan (from April 1, 2016 this became the National Institutes for Quantum and Radiological Science and Technology (QST/NIRS)); **PHE** —Public Health England, UK (former known as the Health Protection Agency (HPA) and National Radiological Protection Board (NRPB)); **BfS** —The Bundesamt für Strahlenschutz, the German Federal Office for Radiation Protection, and **SURO** —National Radiation Protection Institute of the Czech Republic provided periodically intercomparisons of passive radon and thoron monitors.

The method for the determination radon concentration in the atmosphere is not regulated nor standardized by the Japanese Industrial Standard neither other standardization board and thus there is no reference institute in Japan for radon measurement. However, the NIRS constructed the 25 m³ walk-in radon chamber and the various studies, such as calibration, evaluation and intercomparison can be conducted.^{16, 17)} The first radon international intercomparison at NIRS was carried out in 2007 whereas thoron intercomparison started from 2009 and until now six radon and five thoron intercomparisons were done.^{18–20)}

The present PHE laboratory intercomparison programme, which was developed with broad international participation, following standard and agreed test and interpretation protocols, has been designed to provide participants with a routine benchmark performance standard. The intercomparison programme was established by the National Radiological Protection Board (NRPB) and has operated since 1982. It is now run by the PHE Centre for Radiation, Chemical and Environmental Hazards (CRCE).²¹⁾

The Federal Office for Radiation Protection (BfS) operates a calibration service laboratory to assure the quality of measurements of radon and radon progenies. The BfS Radon Calibration Service Laboratory quality management system acts in accordance to norm DIN EN ISO/IEC 17025 and is periodically audited by the German Accreditation Body (DAkS).²²⁾

The National Radiation Protection Institute (SURO) of Prague is accredited by the Czech National Accreditation body for radon measurements performed in a house.²³⁾

In this paper the different measurement set-ups, evaluation methods and statistical treatments utilized by those institutions for intercomparisons are described.

II QUALITY ASSURANCE AND QUALITY CONTROL FOR RADON AND THORON MEASUREMENTS

Some countries have well-established radon measurement services and certain levels of laboratory organizational and

technical competences are required for the services, e.g. in Czech Republic, Germany, and the USA.

In the US state of Rhode Island, for example, its Department of Health (RIDOH) provides regulations for the licensing and/or certification of persons who engage in radon activities and specifies requirements related to the safe mitigation of radon and radon progeny hazards. Moreover, the measurement methods and protocols that are employed must be accepted by RIDOH and the USA Environmental Protection Agency National Radon Measurement Proficiency Program (EPA RPP). According to the EPA RPP a laboratory is considered proficient in radon testing when results of their method during intercomparison are within 25% of the value obtained by a reference instrument.²⁴⁾

The intercomparison should be part of quality assurance (QA) and quality control (QC) processes. The terms “quality assurance” and “quality control” are often used interchangeably to refer to ways of ensuring the quality of a service, e.g. radon and thoron measurements. The terms, however, have different meanings. ISO 9000 defines QA as “part of quality management focused on providing confidence that quality requirements will be fulfilled”.²⁵⁾ The American Society for Quality (ASQ) defines assurance, in general, as the “act of giving confidence, the state of being certain or the act of making certain” and it defines QA as “the planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled.” On the other hand the ASQ defines control as “an evaluation to indicate needed corrective responses; the act of guiding a process in which variability is attributable to a constant system of chance causes” and QC as “the observation techniques and activities used to fulfil requirements for quality.”²⁶⁾ In the particular case of radon, the US EPA prepared the “Guidance on Quality Assurance” under the EPA RPP for providing information requirements and procedures regarding QA of radon measurement.²⁷⁾ The Guidance emphasized that QA and QC must be an integral part of any measurement survey. Measurement results should meet the estimation and accuracy requirements of QA and QC programs. Lack of good documentation for both measurements and device tests, e.g. how the calibration factor was determined, what is the lower limit of detection, etc., may affect the quality of measurements. In the Guidance the elements of a QA program for radon end decay-product measurements are described in six sections.

The first one is quality management such as commitment, quality assurance planning and quality objectives. The measurements are carried out by small laboratory groups or small companies with a limited number of staff. This is an advantage regarding QA management because one person may be responsible for all company policies.

The next section specifies QA documentation referenced in the Quality Assurance Plan (QAP). A QAP is a written document, which presents, in specific terms, the policies, organization, objectives, functional activities, and specific QA and QC activities that are designed to achieve the objectives of the project.²⁸⁾

The third section is devoted to initial and periodic

measurement system calibrations.

There are many QC measurements that are performed to assess the quality of procured materials and equipment, the continued performance of instruments and procedures, estimated errors of imprecision and bias (quantitative terms describing the difference between the average of measurements made on the same object and its true value), as well as contributions of field and laboratory background activity. An intercomparison is one of the most important ways to perform the QC measurements. These problems are described in section four.

Section five discusses corrective actions. These actions may be necessary as a result of unsatisfactory QC results, client dissatisfaction, audit reports, etc.

The last section focuses on training personnel. All personnel involved in any function affecting data quality (detector custody, sample analysis, data reduction, and QA) should receive training in their appointed jobs that allows them to contribute to the reporting of complete and high quality data.

III ORGANIZATION OF INTERCOMPARISON EXERCISES

The list of laboratories organizing intercomparisons periodically for radon and thoron passive detectors is presented in **Table 1**.

The intercomparison exercises typically proceeded as follows. First the organizer obtained potential participants by an open call for them and the selected laboratories sent monitors to the organizer (testing laboratory). Next step monitors were exposed in radon, thoron or both type chambers in different radon, thoron as well as environmental

conditions. Then, after exposure, monitors were returned to the participants for evaluation. Finally, the organizer collected the data from the participants and based on an evaluation method published a report comparing the results of each participating laboratory, both among themselves as well as with the reference values.

IV MATERIALS AND METHODS

The detailed characteristics of four radon and two thoron chambers are presented in **Table 2**. All chambers were made of stainless steel. The radon chamber volumes varied from 0.4 to 45 m³. In addition, the walls of the SURO radon chamber had been sprayed with a special material similar to plaster used in dwellings for better simulation of living conditions in dwellings.

The AlphaGUARD was the most used primary instrument for radon determination; the PHE used the ATMOS 12 as the primary instrument and the AlphaGUARD was the secondary device as well as the BfS used the scintillation cell. All laboratories calibrated their primary instrument under the PTB

Table 1 List of laboratories providing intercomparison exercises.

Laboratory	Instruments	Atmosphere	Period
NIRS	Active	Radon	Every one or two years
	Passive	Thoron	
PHE	Passive	Radon	Every year
BfS	Passive	Radon	Every year
SURO	Active	Radon	Upon request
	Passive	Thoron	

Table 2 Characteristics of radon and thoron chambers.

Laboratory	Inner volume	Inner wall material	Reference instruments	Gas source	Temperature	Relative humidity	Equilibrium factor, F	Operation mode
Rn chamber								
NIRS ⁵⁴⁾	25 m ³	Stainless steel	AlphaGUARD (calibrated at PTB* and KRISS**) and scintillation cell	Dry ²²⁶ Ra	5–30°C	30–90%	0–0.2	Dynamic
PHE ^{40, 55)}	43 m ³	Stainless steel	ATMOS 12 DPX (PTB calibration), AlphaGUARD ionisation chamber (PTB calibration)	Dry ²²⁶ Ra	Ambient	Ambient	0.44–0.51	Static
BfS ⁵⁶⁾	0.4, 11 and 30 m ³	Stainless steel	Flow-through scintillation cells (PTB calibration)	Dry ²²⁶ Ra	–5–50°C	10–95%	0.1–0.9	Static
SURO ⁵⁷⁾	45 m ³	Sandwiched (metal-insulator-metal) and sprayed with a special material	AlphaGUARD (PTB calibration) and scintillation cells (SURO calibration)	Dry ²²⁶ Ra	8–45°C	5–95%	0.01–0.9	Dynamic/static
Tn chamber								
NIRS	150 dm ³	Stainless steel	RAD7 (PTB calibration) and scintillation cell	Lantern mantle ²²⁶ Ra/ ²²⁸ Th	Ambient	5–60%	Being planned	Dynamic
SURO	150 dm ³	Stainless steel	RAD7 (PTB calibration)	emanation source	Ambient	Ambient	Not available	Dynamic/static

* PTB —The Physikalisch-Technische Bundesanstalt, the National Metrology Institute of the Federal Republic of Germany.

** KRISS —The Korea Research Institute of Standards and Science.

reference atmosphere.²⁹⁾

The Alpha-GUARD monitor (Saphymo GmbH, previously Genitron GmbH, Germany) is portable, real-time ionization chamber type device with 0.56 litre of active volume. It can be used for laboratory and environmental radon measurements. The AlphaGUARD is recognized as one of the most used reference device for radon measurements because of its advantages, especially stability and low uncertainty. Simultaneously to radon it register air temperature (in the range from -10°C to $+50^{\circ}\text{C}$), air pressure (from 700 mbar to 1,100 mbar) and air humidity (from 0% to 95%). The important feature of the AlphaGUARD is its linear response from 2 Bq m^{-3} to 2 MBq m^{-3} of ^{222}Rn concentration declared by producer. The system linearity error is less than 3% and instrument calibration error is within $\pm 3\%$ (plus uncertainty of the primary standard). The AlphaGUARD can operate in four, user-selectable, measurement cycles: flow (1 and 10 min) and diffusion (10 and 60 min).³⁰⁾ A disadvantage of this device is that it detects alpha emitters without energy discrimination therefore the measurement of thoron is limited but possible using e.g. flow mode and decay chamber or recently updated AlphaGUARD version. The sensitivity and application of AlphaGUARD to thoron measurement was investigated by several experiments published elsewhere.^{31–33)}

ATMOS 12 (Gammadata, Sweden) is based on the pulsed ionization chamber technology for measuring radon in indoor air in the range from 1 to $100,000\text{ Bq m}^{-3}$. The detector chamber volume is 2 litres. It operate only in the flow mode with flow rate of 1 litre min^{-1} . The integration time can be chosen from 1 minute to 24 hours. The quoted accuracy $\pm 10\%$ at 800 Bq m^{-3} after 10 min.³⁴⁾

The reported uncertainty by NIRS, described as standard deviation of the measurement by reference device combined with calibration uncertainty and using the coverage factor $k = 1$, was in the range from 3% for high radon level ($8\text{--}10\text{ kBq m}^{-3}$) to 16% for lowest radon concentration ($0.9\text{--}1.1\text{ kBq m}^{-3}$).

The BfS expressed uncertainty as the expanded relative uncertainty of ^{222}Rn activity concentration resulting from standard uncertainty of the measurement multiplied by a factor $k = 2$ (95% confidence interval). The uncertainty was in the range from 7% for high radon level ($5\text{--}6\text{ kBq m}^{-3}$) to 12 for lowest concentration ($0.5\text{--}0.9\text{ kBq m}^{-3}$).

The SURO declares the overall uncertainty ($k = 1$) of each calibration point of radon activity concentration better than 5%.

The HPA (formerly NRPB) assumed the uncertainty to 3–5%. The uncertainty was estimated at 68% confidence level from the contributions on measurement with the ATMOS 12 instrument: volume of calibration vessel, counting statistics and radon gas source.

All laboratories used dry ^{226}Ra as the radon source. In three of the four radon chambers, environmental parameters like temperature and humidity could be controlled. Three radon chambers were equipped with aerosol generators and the equilibrium factor could be set; however, the range in the BfS and SURO chambers was wider than that at NIRS because of

the chamber operation mode could be static for the first two, but it was only dynamic for the NIRS radon chamber. In the dynamic mode radon was injected into the chamber with a controlled flow rate and it was removed from the chamber at the same time under the defined air exchange rate. In the static mode radon was injected in the loop-line (BfS) or the radon emanated from the source inside the chamber (PHE) without air exchange, i.e. the chamber was tightly closed and the reduction of radon concentration was driven only by radioactive decay. Moreover, the SURO radon chamber could be operated with the equilibrium factor ranging from ~ 0.01 to 0.95 for both dynamic and static modes.

Two institutes have carried out thoron intercomparison exercises. The NIRS and SURO chambers had similar volumes, but only the NIRS chamber had control of the relative humidity in the range from 5 to 60%. The humidity of the air in the chamber was controlled by injecting a mixture of the dry and humidified air obtained by bubbling deionized water.³⁵⁾ The SURO environmental parameters were assumed to be the same as the surroundings. Both institutes used the same device as the primary instrument for thoron determination, a RAD7 electronic radon and thoron detector with real-time monitoring and spectral analysis.³⁶⁾ NIRS also utilized a scintillation cell in the grab sampling mode as a back-up instrument. The thoron sources were different, NIRS used commercially available lantern mantles³⁷⁾ whereas the SURO system was based on the mixed radium and thorium emanation source produced as a prototype for SURO at the Czech Metrological Institute.

The uncertainty of measurement reported by NIRS is expressed as standard deviation of measurement by RAD7 with combination of the calibration uncertainty. The range of uncertainty during intercomparison was from 6% for high thoron concentration ($45\text{--}48\text{ kBq m}^{-3}$) to 16% for lowest thoron concentration ($3\text{--}6\text{ kBq m}^{-3}$).

Overall the uncertainty of each separately measured average values of thoron gas concentration represented by relative combined standard uncertainty for $k = 1$, the SURO declares better than 10%.³⁸⁾

Deeper investigation by the intercomparison of Atmos 12, RAD7 with other radon measurement devices and their application for measurement of indoor radon levels is described elsewhere.³⁹⁾

V RESULTS

General comments

Ranges of values obtained during intercomparison exercises are presented in **Table 3**. Exposures ranged from 40 (SURO) to $2,832\text{ (BfS) kBq h m}^{-3}$, which corresponded to the range from 5 to 320 Bq m^{-3} for one-year exposure (8,760 h). As mentioned earlier, two typical average values for the radon reference level have been recommended: 100 Bq m^{-3} by WHO and 300 Bq m^{-3} by EU Commission. It should be mentioned that 100 Bq m^{-3} equals the exposure of 876 kBq h m^{-3} whereas 300 Bq m^{-3} corresponds to $2,621\text{ kBq h m}^{-3}$.

Two institutes (NIRS and BfS) have been carrying out intercomparisons in an aerosol-free atmosphere.

Table 3 Ranges of values during intercomparisons.

Institution (references)	Concentration range [kBq m ⁻³]	Exposure duration [h]	Exposure [kBq h m ⁻³]	Temperature [°C]	Relative humidity [%]	Equilibrium factor, F [—]
Rn exercise						
NIRS ^{18, 20, 58, 59)}	0.92–9.88	47–119	93–1094	21.2–21.8	56.9–58.5	Not available
PHE ^{40, 41, 55, 60–62)}	1.76–8.69	29.88–532.05	138–2385	Not available	Not available	0.1–0.9
BfS ^{56, 63, 64)}	5.66–10.53	151.2–414.2	180–2832	24–25	19–31	Not available
SURO ^{23, 38)}	2.16–8.30	20–72.5	40–602	27.4–30.2	24.1–63.8	0.05–0.46
Tn exercise						
NIRS ^{18, 58)}	4.18–48.6	20–54	100–997	29.4–31.9	12.9–44.2	Not available
SURO ^{23, 38)}	4.12–25.5	2–25	8.24–637	24.1–26.8	< 5–12.1	< 0.05

In the SURO intercomparisons the F parameter was varied from 0.05 (radon only) to 0.46 (aerosols injected). A carnauba wax aerosol generator is used to maintain a higher aerosol concentration. On the other hand, to produce low equilibrium factor F, an electrostatic precipitator including fan is used. The F parameter was continuously measured by SURO reference monitor Frirta 4. The SURO calibration of Frirta 4 was compared to PTB, Germany, BfS, Germany and AMC-Kamenna (Authorized Metrological Centre), Czech Republic primary standards. The combined relative standards uncertainty ($k = 1$) should not exceed 10%.³⁸⁾

Recently PHE^{40, 41)} reported an equilibrium factor around 0.4 which is typical value for dwellings reported by UNSCEAR.⁴²⁾ Previously PHE intercomparisons had been conducted with F varied from 0.15 to 0.95. The method to obtain a high value of F in the chamber is similar to SURO method and based on growing of aerosols using aerosols generator. A low equilibrium factor was obtained by running an electrostatic precipitator to remove aerosols and decay products. By running the precipitator fan at low speed an intermediate equilibrium factor was obtained. The total ambient aerosol concentration and size distribution within the radon chamber were monitored using a TSI condensation nucleus counter system.⁴³⁾ Measurements were carried out twice a day during the exposures, each measurement consisting of four samples, the results being averaged.⁴⁴⁾ These average values were then used to calculate the aerosol size distribution using a program developed at NRPB (former name of HPA) based on the TWOMEY⁴⁵⁾ method. The reported by PHE (NRPB) uncertainty of radon decay product was 7%. The method of estimating this value was given by CLIFF.⁴⁶⁾

The lowest temperature was recorded for the NIRS radon chamber (21–22°C) and highest in the SURO (27–30°C).

The most stable value for relative humidity (RH) was reported for the NIRS radon chamber. In the four intercomparisons provided by NIRS the RH was set to around 57%. The widest range was registered in the SURO chamber (24 to 64%). The lowest value was 19% reported for the BfS chamber. The relative humidity was not shown in the PHE reports.

1. NIRS

For standardizing the results obtained for all the exposure conditions, the recommended parameters by ISO/IEC

17043: 2010 Conformity Assessment-General Requirements for Proficiency Testing Standard⁴⁷⁾ and by the National Association for Proficiency Testing⁴⁸⁾ were used and calculations were made with the following formulas.

$$PD [\%] = \frac{C_{\text{Lab}} - C_{\text{Ref}}}{C_{\text{Ref}}} \times 100\% \quad (\text{Eq. 1})$$

where:

C_{Lab} –The average radon or thoron concentration given by each laboratory,

C_{Ref} –The average radon or thoron concentration in radon or thoron chamber measured by reference device,

The percent difference (PD) performance statistic is simply the difference between a participant's test data and the reference value, divided by the reference value and multiplied by 100.

$$E_n = \frac{|C_{\text{Lab}} - C_{\text{Ref}}|}{\sqrt{u_{\text{Lab}}^2 + u_{\text{Ref}}^2}} \quad (\text{Eq. 2})$$

Where

u_{Lab} –The measurement uncertainty of radon or thoron concentration given by each laboratory.

u_{Ref} –The measurement uncertainty of radon or thoron concentration given by reference device.

E_n number performance level is normally determined as follows:

$$E_n \leq 1 = \text{satisfactory performance}$$

$$E_n > 1 = \text{unsatisfactory performance}$$

In order to allow comparisons between PHE and NIRS the PHE classification parameter, which is described later, was applied as given by the MES parameter. It is a combined uncertainty and composed of the PD parameter (accuracy of results) and the PER parameter (precision of measurements), and consequently it is low only if both parameters are low.

The MES is calculated by the following equations

$$MES [\%] = \sqrt{PD^2 + PER^2} \quad (\text{Eq. 3})$$

where PER (percentage precision error) is defined by Eq. (4):

$$PER = \frac{u_{\text{Lab}}}{C_{\text{Ref}}} \times 100\%. \quad (\text{Eq. 4})$$

The laboratories were categorized by the parameter PD

with “Category I” being in the range of $\pm 20\%$ from the value obtained by the reference instrument and “Category II” being outside this $\pm 20\%$ range. The 20% level was chosen based on the US EPA RPP (Radon Proficiency Program) requirement and statistical approach described by FRIEDMANN.⁴⁹⁾ The EPA RPP requires individuals to pass a radon monitors performance test to provide measurement results within 25% of an EPA values.²⁴⁾ The other study showed that it was well chosen value considering field radon concentration variability and the statistical radiobiological risk uncertainty.⁵⁰⁾

Furthermore, two additional parameters (*REF* and *z-score*) were listed¹⁸⁾ and they were assessed based on the next formulas.

REF

$$REF = \frac{C_{Lab}}{C_{Ref}} \quad (\text{Eq. 5})$$

The ratio *REF* was defined in order to quantify the difference between observed value and reference value.

z-score

$$z\text{-score} = \frac{(C_{Lab} - C_{Ref})}{u_{Lab}} \quad (\text{Eq. 6})$$

A graphical way to evaluate the consistency of results and laboratories is therefore useful. NIRS implemented two methods recommended by ISO: Mandel's *h*-statistics⁵¹⁾ and the Youden plot.⁵²⁾ Outputs of graphical presentations can be find elsewhere.¹⁸⁾

2. PHE

The data evaluations were based on the ranking scheme that considered the following parameters: % *biased error*, which measures the bias of the measurement; % *precision error*, which measures precision of the measurement; and % *measurement error* which is the result of combination of % *biased error* and % *precision error*.

% *biased error*

$$= \frac{\text{Measured mean} - \text{Reference value}}{\text{Reference value}} \times 100 \quad (\text{Eq. 7})$$

$$\% \text{ precision error} = \frac{\text{Standard deviation}}{\text{Measured mean}} \times 100 \quad (\text{Eq. 8})$$

% *measurement error*

$$= \sqrt{\% \text{ biased error}^2 + \% \text{ precision error}^2} \quad (\text{Eq. 9})$$

The % *measurement error* (total budget uncertainty) is low when both % *biased error* and % *precision error* are low.⁴⁰⁾

3. SURO

The latest evaluation data by SURO³⁸⁾ were based on the following equations with statistical approach, i. e. *t*, *R* and *D*_%.

$$t = \frac{X - Y}{\sqrt{\left(\frac{S_x}{\sqrt{n}}\right)^2 + \left(\frac{S_y}{\sqrt{m}}\right)^2}} \quad (\text{Eq. 10})$$

$$R = \frac{X}{Y} \quad (\text{Eq. 11})$$

$$D_{\%} = \text{abs}(R - 1) \times 100 \quad (\text{Eq. 12})$$

X and *Y* are mean values reported by participants and the mean value obtained by the reference instrument, respectively. *S_x* and *S_y* are sample standard deviations given by participants and SURO, respectively. Parameters *n* and *m* are the corresponding sample sizes.

(Eq. 10) describes Welch's *t*-test statistic. In general, the Welch's *t*-test (or unequal variances *t*-test) is a two-sample location test, and is used to test the hypothesis that two populations have equal means.⁵³⁾ In this case it checks whether the response of the checked and reference instruments are not significantly different.

(Eq. 11) and (Eq. 12) quantify the observed difference between mean values of the reference and compared instruments.

In addition, SURO classified results by the *PD* rank; this is the percentage difference of a tested device value from the reference instrument value. The ranks had the ranges of $PD \leq 5\%$, $5\% < PD \leq 10\%$, $10\% < PD \leq 20\%$ and $PD > 20\%$ for exposures in the big chamber and $PD \leq 10\%$, $10\% < PD \leq 20\%$ and $PD > 20\%$ for exposures in the small chamber.

4. BFS

BfS results were based on parameters RSD (relative standard deviation of the measurement value in percent) and RERR (relative error of the measurement value from the reference value in percent) defined as follows:

$$RSD = \frac{\sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}}{\bar{x}} \times 100 \quad (\text{Eq. 13})$$

$$RERR = \frac{(\bar{x} - X)}{X} \times 100 \quad (\text{Eq. 14})$$

where *x_i* is the measurement value exposure given by participant for monitor *i*, *n* is the number of monitors, $\bar{x}$ is the participant arithmetic mean value of the exposure and *X* is the exposure value in the radon chamber measured by the reference instrument.⁶⁴⁾

VI SUMMARY

This review presented passive and active methods and results obtained by them in intercomparison exercises carried out periodically by three institutes in Europe and one in Japan.

The principle of the measurement exercises were all similar, but the environmental exposure conditions were slightly different. The radon concentrations were almost all in the same range: 1 to 10 kBq m⁻³ but there was a difference in the equilibrium factor.

Results were presented in the same form of output for two of the institutes as the ratio of the result given by the participant and the value by the reference instrument, named *REF* and *R* by NIRS and SURO, respectively.

The bias of the measurement was given by all laboratories as *PD* by NIRS, % *biased error* by PHE, *D%* by SURO and RERR by BfS.

In addition, the evaluation of results was presented in a graphical form by NIRS using Mandel's *h*-statistics and the Youden plot.

It seems that intercomparison plays a significant role in QA and QC programs, and it offers a way for participants to improve their radon and thoron measurement methods and evaluate their results in a better way.

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