European Commission

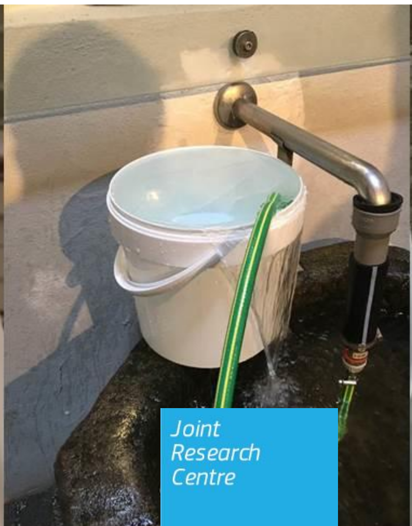
JRC TECHNICAL REPORTS

Performance evaluation report of the REM 2018 radon-in-water proficiency test

Viktor Jobbágy, Mikael Hult

Limited distribution

2019




Joint Research Centre

Contact information
Name: Viktor Jobbágy
Address: European Commission, Joint Research Centre, Retieseweg 111, 2440 Geel, Belgium
Email: Viktor.JOBBAGY@ec.europa.eu
Tel.: +32 (0)14 571 251

JRC Science Hub
https://ec.europa.eu/jrc

JRC116812

Geel: European Commission, 2019

How to cite this report: Jobbágy V., Hult M., *Performance evaluation report of the REM 2018 radon-in-water proficiency test*, European Commission, Geel, 2019, JRC116812

Contents

Foreword

This report focuses on the performance evaluation of the REM2018 radon-in-water proficiency test. It provides an overview of the exercise including the final reference values and the key scores of the participants. A second technical report will be issued later where more details on the material characterization, scores, information on the participants` organization and applied methods will be described.

The REM 2018 proficiency test was performed within the institutional programme of Directorate G (Nuclear Safety and Security) and described in the JRC-Work Package SELMER (Support to European Member States Measuring Environmental Radioactivity in the JRC-Project SARA (Science Applications of Radionuclides and Actinide materials). It is conducted in support of DG ENER and its work in implementing Articles 35 and 39 of the Euratom Treaty.

Acknowledgements

Thanks are due to all the 101 participant laboratories because this work was possible only with their active collaboration (listed in Annex 1).

This proficiency test exercise would not have been completed without the commitment and kind cooperation of the following Austrian colleagues:

- Valeria Gruber, Dietmar Roth, Stefan Willnauer, Markus Bernreiter, Viktoria Schauer and Wolfgang Ringer from the Austrian Agency for Health and Food Safety (AGES).

The following organizations for technical cooperation:

- SCK•CEN (Belgian Nuclear Research Centre in Mol, Belgium)
- Silesian Centre for Environmental Radioactivity at GIG (Katowice-Poland)

Thanks are due to the following JRC colleagues for supporting the PT exercise:

- Heiko Stroh and Gerd Marissens from JRC-Geel, Unit G.2 RN team for their commitment during sampling, logistics,
- Members of the advisory group (Head of Unit ad interim: Arjan Plompen, 17043 Quality management: Petya Malo, Project Leader: Mikael Hult, Statistical advisor: Stefaan Pommè, Jan Paepen, External advisor: Piotr Robouch from JRC-Geel Directorate F.5 Food & Feed Compliance Unit),
- Radionuclide Metrology team in JRC-Geel Unit G.2. Standards for Nuclear Safety, Security and Safeguards,
- Giovani Kerckhove and Thomas Linsinger JRC-Geel, Directorate F.6 Reference Materials Unit for providing temporary storage rooms,
- JRC-Geel Directorate R.6 Resource Management Geel, Central Store staff: Pascal Vergucht, Sigrid Beutels, Ellen Weckx.

Authors

Viktor Jobbágy, Mikael Hult

1 Introduction

This report gives an overview of the Europe-wide proficiency test on radon-in-water organised by the European Commission's Joint Research Centre in Geel, Belgium (JRC-Geel), "REM2018". The focus of this report is to provide the reference values and the evaluation of the participants' performances. A second technical report will be produced that will describe more in-depth this exercise and provide more technical and evaluation/analysis details.

The REM 2018 radon-in-water PT was requested by the EU member states` Euratom article 35/36 experts with the approval of the European Commission's Directorate-General for Energy (DG ENER). This European scale PT was meant to underpin the new EURATOM Drinking Water Directive (E-DWD)[1].

The G.2 unit of JRC-Geel organizes regular proficiency tests (PTs) of radiological analyses of drinking water and other matrices on the request of DG ENER. This is in support of the Euratom Treaty Article 35 (and 39) and the aim is to check comparability of these measurement results and verification of data submitted to the EC by EU Member States (following Article 36). These PTs are usually linked to a European legal document or directive related to radioactivity in environmental matrices or food/feed. One of the fundamental EU directives in this field is the Euratom-Drinking Water Directive or E-DWD (EURATOM, 2013), which covers several naturally occurring radionuclides including ^{222}Rn (radon). The other radon isotopes, like thoron (^{220}Rn) and actinon (^{219}Rn), are excluded from the directive and consequently also from this report due to their short half-life and limited impact on human health.

Radon-in-water analysis is one of the most frequently used radiological monitoring methods because the techniques are relatively simple, straightforward and provide reliable data (Jobbágy, 2017). Despite this fact, very few international PTs have been organized in Europe since the publication of the E-DWD (Neznal et al., 2014; Björklöf et al., 2015; Björklöf et al., 2017, Celaya González et al., 2018). The main reason is that there are a lot of practical problems in implementing such PTs and intercomparisons (Jobbágy el al., 2018; Jobbágy el al., 2019) linked to e.g. (i) the short-half-life, 3.8 d (ii) the fact that radon is an inert gas that easily escapes the sample and (iii) the problems of producing large numbers of homogeneous samples. Further shortcomings of past PTs were related to the lack of metrological traceability, and to missing or incomplete material homogeneity and stability studies. Our aim was to address these shortcomings by providing homogeneous high-quality interference-free material, metrologically traceable reference values, and a transport chain free of radon-loss from sampling till analysis.

From quality assurance point of view, the REM 2018 PT was performed in compliance with ISO 35 Guide (2017), ISO 17043 (2010) and ISO 13528 (2015) standards on characterization of reference materials, organizing proficiency tests and performance assessments, respectively.

[1] Council Directive 2013/51/EURATOM of 22 October 2013 Laying Down Requirements for the Protection of the Health of the General Public with Regard to Radioactive Substances in Water Intended for Human Consumption.

1.1 Responsibilities and roles

The REM 2018 radon-in-water PT was organized by: European Commission, Joint Research Centre (JRC-Geel), Retieseweg 111, B-2440 Geel, Belgium.

The communication between the organizer and the participants was mainly done via the following functional mailbox:

JRC-GEE-REM-COMPARISONS@ec.europa.eu.

The responsibilities amongst the involved staff of the organizer:

- Viktor Jobbágy: PT coordinator, sampling, logistics, LSC analysis, reporting.
- Mikael Hult: team leader and quality control.
- Petya Malo: logistics assistant, administration, quality management.
- Heiko Stroh: sampling, logistics, gamma-ray spectrometry analysis.
- Gerd Marissens: sampling, logistics.
- Katarzyna Sobiech-Matura, Jan Paepen, Raf Van Ammel: quality assurance and logistics.
- Jan Paepen: data validation.
- Advisory group members (Arjan Plompen: Head of Unit ad interim, Petya Malo: 17043 Quality management, Mikael Hult: Team Leader, Jan Paepen, Stefaan Pommè: Statistical advisors, Piotr Robouch: External advisor).

1.2 Collaborating partners

JRC-Geel collaborated with external expert institutes in the field. The main contact person and the name of each collaborating institute are listed below:

- Valeria Gruber: Austrian Agency for Health and Food Safety (AGES) in Linz, Austria.
- Michel Bruggeman: SCK•CEN (Belgian Nuclear Research Centre in Mol, Belgium)
- Stanisław Chałupnik: Silesian Centre for Environmental Radioactivity (Katowice-Poland)

AGES in Austria iactively contributed to the REM 2018 PT by enabling access to the water source, collecting PT material, performing preliminary material characterization, carrying out some of the logistics tasks and giving technical support throughout the PT. The measurement results from SCK•CEN and the Silesian Centre for Environmental Radioactivity were used to verify the JRC measurement results.

1.3 Participating organizations, participation fee

As it was announced in 2018, the participation was public but preference was given to the environmental radioactivity monitoring laboratories nominated by the EU member states` Euratom article 35/36 contact points and authorities. In total 101 expert organizations from all over Europe participated in the PT (from 26 EU countries and 6 non-EU countries). In addition to the registered organizations, there were further participation requests in e-mails. Unfortunately, these requests were rejected because they were received after the registration deadline, shortly before the sampling.

Eight participants were outside the European Union (but all H2020 associated countries), while 93 were within the European Union. The full list of participants with their affiliations is presented in Annex 1.

Participation in this PT was free of charge. All costs regarding the PT organization were covered by the PT organizer JRC-Geel, except the sample analysis related costs.

1.4 Timeline and announcements

The REM 2018 PT exercise had the following tentative planning introduced in Table 1.

Table 1. Time-line of the radon-in-water REM 2018 PT exercise.

13 July 2018	JRC-Geel contacted national authorities, laboratories requesting nominations and expression of interest
3 September 2018	Invitation letter sent to the nominated/interested organizations
14 September 2018	Registration deadline
18 October 2018	PT material shipment to participants
14 Nov 2018	Laboratories` results and questionnaire submission deadline
14 Dec 2018	Preliminary results to participants
30 April 2019	Final report

Source: JRC

The list of announcements and communication documents are presented in Annex 2.

1.5 PT materials and logistics

Since it was difficult to get suitable water samples close to JRC-Geel (Jobbágy, 2017) for the PT, it was necessary to contact external experts for help. A natural spring water was used as PT material and the material was named "JRC-W1". It was selected on a basis of previous experimental investigations and the JRC pilot-proficiency test (Jobbágy et al., 2019) organized in the first half of 2018. This PT material had elevated ^{222}Rn massic activity, a low ^{226}Ra massic activity and generally complying with our basic requirements towards suitable radon-in-water PT materials. If a PT provider would like to use natural waters, not only will the water need to contain relatively high radon-concentration but homogeneity within the individual PT samples and stability have to be assured and proven. Participants should be able to measure it before it decays to low-levels of activity since ^{222}Rn half-life is only 3.8232 (8) days (Bé et al., 2008). The PT sample's ^{226}Ra massic activity proved to be below the minimum detectable massic activity (<1 Bq/kg) of the gamma-ray spectrometry system used for reference value determination. It could be concluded that there was no interference linked to any presence of dissolved ^{226}Ra.

For sampling, an immersion/overflow technique was used where a hose was connected through an in-house made adapter to the outlet of the spring/well water as shown in Figure 1. On the other side of the adapter, a long plastic tube was connected and led into a 15 L bucket. This bucket was first filled with water and then allowed to have a continuous overflow of water. Then, a sampling bottle was immersed into the fully filled bucket followed by inserting the plastic tube to the bottom of the sampling bottle. The bottle was flushed with three bottle-volumes of water before closing it with its cap still underwater. The sampling time of each bottle was registered. After filling, each bottle was wiped dry carefully with towels and paper tissues. There was approximately 1 L of water in each bottle, which was expected to be sufficient for the requested analyses. More sampling procedures can be found in details in the corresponding ISO standards (ISO 5667-1, 2006; ISO 5667-3, 2012; ISO 13164-1, 2013). By default, only one sampling bottle was assigned to each participant. However, the PT coordinator gave the opportunity to the labs to send their own sampling bottles if it was requested. It was not allowed to send liquid scintillation vials with cocktails because JRC-Geel experienced some difficulties with shipping LSC cocktails. According to European regulations (EC No. 1272/2008), they are classified as hazardous materials (chemicals). In the pilot-PT, it was also observed that some of the LSC vials were leaking during the transport to JRC-Geel. The decision to abandon the shipping of LSC vials was also taken from environmental protection point of view to avoid accidental contamination of the natural water sources.

Figure 1. Sampling arrangement at the Austrian sampling site.

Source: JRC

The water temperature at the source was (9.5 ± 0.5) °C and the flow rate of the water was found to be between 6-8 L/min. It was not possible to regulate the flow rate but a special sampling adapter was applied to reduce bubble formation. The total duration of sampling lasted approximately 4 hours and covered 1440-1920 L of water of which 170-172 L was collected in 175 individual sampling bottles including different size of sampling bottles for the proficiency test participants.

The samples were distributed by a logistics company. In general, the samples arrived to the participant organizations` shipping addresses within 1-7 days but there were some delays due to customs procedure outside the EU area or to internal reasons (the sample was received by the organization logistics/storage service but the laboratory personnel only received the sample after a few days).

To avoid bias from systematic errors, samples assigned to different studies were selected according to a random stratified selection strategy using Sample Number Assignment Program (SNAPP) developed and validated at JRC-Geel.

In total, there were 160 individual PT items in glass bottles per sampling site (Figure 2) used in the following ways.

- 107 to participants
- 11 samples in sampling bottles provided by certain participants,
- 10 to homogeneity study
- 10 to reference value determination
- 5 to stability study
- 28 back-ups.

Figure 2. PT test samples for homogeneity and reference measurements.

Source: JRC

1.6 Packaging and sample preparation for shipment

Special precautions were taken to protect the water samples and ensure that the PT material arrived to the participants safely. Therefore, robust physical and thermal resistant transport boxes were used from EXAM packaging (model: HIGH-Q Pack 20L). They are insulated containers moulded in technical polyurethane foam accommodated in water-resistant cardboard. These transport boxes can keep the products at low temperature, below 10 °C, from 1 day up to 5 days using pre-chilled cooling elements with non-toxic liquid. To confirm that the PT samples were not exposed to any extreme temperature, thermo-buttons were placed into each transport box next to the samples. These thermo-buttons logged the temperature profile with 15 minutes frequency during shipment until they were returned to the PT coordinator. A typical temperature profile during sample transport is presented in Annex 15.

The glass sampling bottles containing the water samples were put into a protective bubble foil layer or bubble foil envelop. Transport arrangement in a transport box is illustrated in Figure 3.

Figure 3. Interior view of six transport boxes whilst being prepared for shipment.

Source: JRC

Each package shipped to participants contained the following items:

- PT material (1 L glass bottle) sealed in a plastic bag and wrapped in bubble foil,
- an accompanying letter,
- blue cooling elements (12-18 units),
- a thermo-button (electronic temperature logger) in a plastic bag and
- the Sample receipt form.

Upon arrival of this package, the participants were requested to send back immediately the *Sample receipt form (Annex 2)* by e-mail and the thermo-button in an envelope to the PT coordinator.

Participants were instructed to store their samples in a dark place maximum at room temperature (preferably below) but well above 0 C. Before the analysis, the PT coordinator recommended to store the sample bottle at room temperature until it reached thermal equilibrium with its environment.

Samples arrived to the participants without any major problems. Only few participants commented the presence of a small volume (approximately 1 mL) of water in the protective plastic bag. This could be explained by condensed humidity on the cooled sampling.

1.7 Reporting of the results

The reporting of laboratory results was done via the JRC online reporting tool. Participants were also requested to fill in an online questionnaire about their organization and technical details of the methods used. The links were sent via e-mail to the participants.

Participants were asked to submit their results via the following weblink using the personalized password key provided to each participant:

https://web.jrc.ec.europa.eu/ilcReportingWeb

Participants had the opportunity to report results obtained by different methods (LSC, γ-ray spectrometry, emanometry, other methods) following the organizer`s instructions:

- One measurement result/mean value per technique (massic activity in Bq/kg),
- Associated combined uncertainty with coverage factor of k = 1,
- the applied measurement technique.

The reference date for JRC-W1 was 18 October 2018 (Thursday). The exact reference date and times were communicated after shipping the samples and they were given as Coordinated Universal Time (UTC) (Annex 14.). In addition, each participant received information on the exact minute his/her sample was collected.

For calculations, we recommended to use the data provided by the Decay Data Evaluation Project (DDEP) at:

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

The current ^{222}Rn half-life is 3.8232 (8) days (Bé et al., 2008).

The organizer pointed out to the participants that they needed to check their calculations and report before submitting the results because it was not possible to accept modifications after the reporting deadline.

1.8 Questionnaire

Participants were asked to fill in a questionnaire which was composed of four main parts concerning the information on the laboratory, experience, technical details on measurement methods, feedback. In the technical section, participants were requested to answer ten brief questions. Information in the questionnaire was essential in order to evaluate the results of the proficiency test. The questionnaire was available on the EU-Survey website via the following link:

https://ec.europa.eu/eusurvey/runner/REM_2018_PT_radon-in-water

1.9 Data treatment

Each laboratory's results were treated with confidentiality; identities were and will be kept anonymous and will not be disclosed to third parties. However, the results and performance of each nominated laboratory will be made available to its national representative(s) (the nominating authority) and to the relevant services of the European Commission at Directorate General for Energy as was communicated in the invitation e-mail (Annex 2).

In order to comply with the European regulation on the General Data Protection Regulation (GDPR), we asked for the participants` consent/approval to be able to list the organization and the name of the contact person in the final report.

Participants could express their consent by sending us an e-mail with the following statement:

"Hereby, I [give / DO NOT give] (delete as necessary) my consent to have my name and the name of my organisation listed in the final report of the Rem 2018 Radon-in-Water PT organised by JRC-Geel."

However, we decided to include the name of the organizations only.

2 Material characterization

Determination of ^{222}Rn in water samples for the reference value assignment, homogeneity and stability studies was done at JRC-Geel by using standard analytical methods (ISO 13164-2:2013: Water quality - Radon-222 - Part 2: Test method using gamma-ray spectrometry; ISO 13164-4:2015: Water quality Radon-222 - Part 4. Test method using two-phase liquid scintillation counting) more details will be provided in the JRC technical report.

2.1 Homogeneity study

Homogeneity and stability studies were performed and evaluated according to ISO 13528 (2015). The reference value of a comparison material is assumed to be valid for the whole batch at the level of subsample with a minimum mass or volume (approximately 10 g). Therefore, between-bottle homogeneity in the radionuclide concentration increases the uncertainty of the corresponding reference value.

2.2 Stability study

According to the ISO 17043 and ISO 13528 standards, uncertainty can get contributions from two types of stability. The first one is uncertainty due to the short-term stability of the samples which is related to sample transport (i.e. transport between the PT provider and the participants). The second type of uncertainty arising from the long-term stability of the samples is linked to sample storage.

Table 2. Summary of short and long term stability tests. Data includes the total number of measurements taken in the covered period, the deviation of experimental half-life from the literature value and the deviation of radon-222 massic activity from the reference value.

Measurement data per bottle	Covered period	Average deviation from half-life	Average deviation from reference value
33-107	19/10/2018-02/12/2018 (half-life) 19/10/2018-16/11/2018 (ref. value)	0.4 %	2.0 %

Source: JRC

The average deviation of the individual results of the stability study from the reference value was found to be < 1.0 %. However, we decided to use the highest uncertainty value from the stability study for the reference value uncertainty.

2.3 Establishing reference values

For the radon-in-water PT samples, uncertainties from the long-term stability (u_{lts}) and short term stability due to transport conditions (u_{sts}) were included as a sum of the two components. Moreover, an extra uncertainty component related to sampling (u_{smpl}) was also introduced due to the possible interferences during sampling and as it is required by ISO 17025.

The combined uncertainty of the reference value (u_{ref}) can be given as

$$u_{ref} = k \times \sqrt{u_{char}^2 + u_{bb}^2 + u_{sts}^2 + u_{lts}^2 + u_{smpl}^2} \quad (3)$$

where

-k: coverage factor (k=1) at ~ 68% confidence interval

-u_{char}: combined standard uncertainty from the characterisation study,

-u_{bb}: uncertainty from the massic activity between bottles of the same batch,

-u_{sts}: uncertainty due to the short-term stability of the samples (related to transport),

-u_{lts}: uncertainty due to the long-term stability of the samples (longer than the duration of the comparison-exercise).

The reference values of massic activity for the ^{222}Rn are presented in Table 3 and their uncertainty components are presented in Table 4.

Table 3. The reference ^{222}Rn massic activity values (A_{ref}) in the REM 2018 proficiency test samples with their combined standard uncertainties (u_{ref}) with a coverage factor *k* = 1.

Sample code	^{222}Rn massic activity	Reference date
JRC-W1	(318 ± 16) Bq/kg	18 October 2018

Source: JRC

Table 4. The relative uncertainty of the reference values ($u_{ref,}$ k = 1) and their contributions from the characterisation study u_{char} and the relative homogeneity contributions u_{bb}.

PT sample	u_{char}	u_{bb}	u_{sts}+u_{lts}	u_{smpl}	$\boldsymbol{u_{ref}}$
JRC-W1	2.6 %	1.0 %	2.0 %	3.5 %	**4.9 %**

Source: JRC

3 Reported results

From the 101 participating laboratories, 28 participants used multiple methods (Table 5). Therefore, in total 135 measurement results were reported.

Table 5. Overview on the number of participants and reported results for JRC-W1 PT samples.

Registered participants	Participants reported	Results submitted	Filled in the questionnaire
101	101	135	97

Source: JRC

The participants were requested to submit their results together with their combined standard uncertainties (coverage factor k = 1). If the reported coverage factor differed from 1 then we recalculated the uncertainties for k = 1.

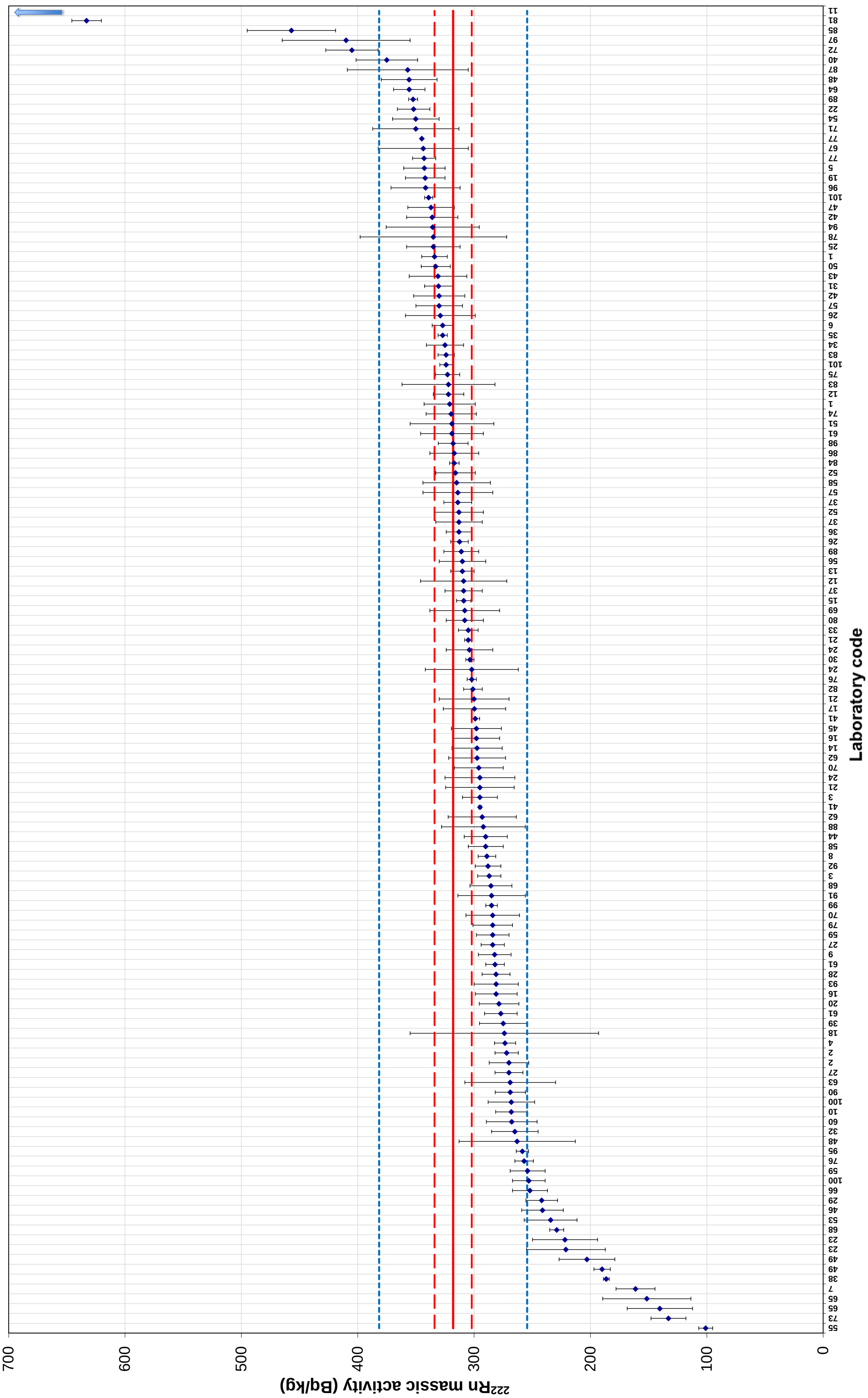
The participants' results and their scoring using percentage difference from the reference value, z-score, ζ(zeta)-score according to ISO 13528:2015 are collected in the table in Annex 3. It is also indicated in Annex 4 if a laboratory used an ISO 17025 accredited method and followed a standard method whenever it was possible to take this information from the questionnaires. The spread of measurement results were also checked on the basis of use of the ISO standard methods.

The detailed numerical measurement results as reported by the participants, further information on accreditation and standard methods can be found in Annex 3-4. Measurement results sorted on the basis of measurement techniques and use of a standard method are presented in Annex 5.

The reported ^{222}Rn massic activities in Bq/kg with their corresponding combined standard uncertainties (k = 1) are plotted in ascending order for the JRC-W1 sample in Figure 4.

The solid red line indicates the reference ^{222}Rn massic activity (A_{ref}). The dashed red lines show the combined standard uncertainties (u_{ref}, k = 1) of the reference values. Blue dashed lines represent the reference range within **the standard deviation for proficiency assessment (σ_{PT}) which was set to 20 %**. The participants' identification numbers are indicated with the results.

Figure 4. The range of ^{222}Rn massic activity measurement results reported by participants with combined standard uncertainties (k = 1) for JRC-W1 sample. Solid red line: reference ^{222}Rn massic activity (A_{ref}). The red dashed lines: the uncertainty of the reference value (u_{ref}). Blue dashed lines: acceptance range (A_{ref} ± 20 %).



Source: JRC

4 Scores, evaluation and comparison of results

The participants` results were evaluated with respect to the reference values using percentage difference from the reference value, z-score, zeta-score according to ISO 13528:2015. Therefore, a well-founded estimate of the uncertainty of the reported results was required from each participating laboratory. The participants` numerical scores (percentage difference, z and zeta score) are given in Annex 3 plotted in Figure 5-6.

4.1 Standard deviation for proficiency assessment (σ_{PT})

The standard deviation for proficiency assessment (σ_{PT}) was initially set to 15 % but the PT organizer decided to change it because an additional component related to adsorption of radon decay progenies to the sampling bottle was suggested by Cassette (2019) and Mitev (2019) during the follow-up JRC workshop held in Geel between 26-29 March 2019. This can affect the GS measurement results as it changes the measurement geometry and efficiency in case of efficiency transfer calibration. The detection efficiency would be underestimated thus consequently the reference values may be overestimated. Since the PT organizer could not confirm these findings yet, the reference value did not change on this ground but **the standard deviation for proficiency assessment (σ_{PT}) was increased to 20 %** to compensate for this.

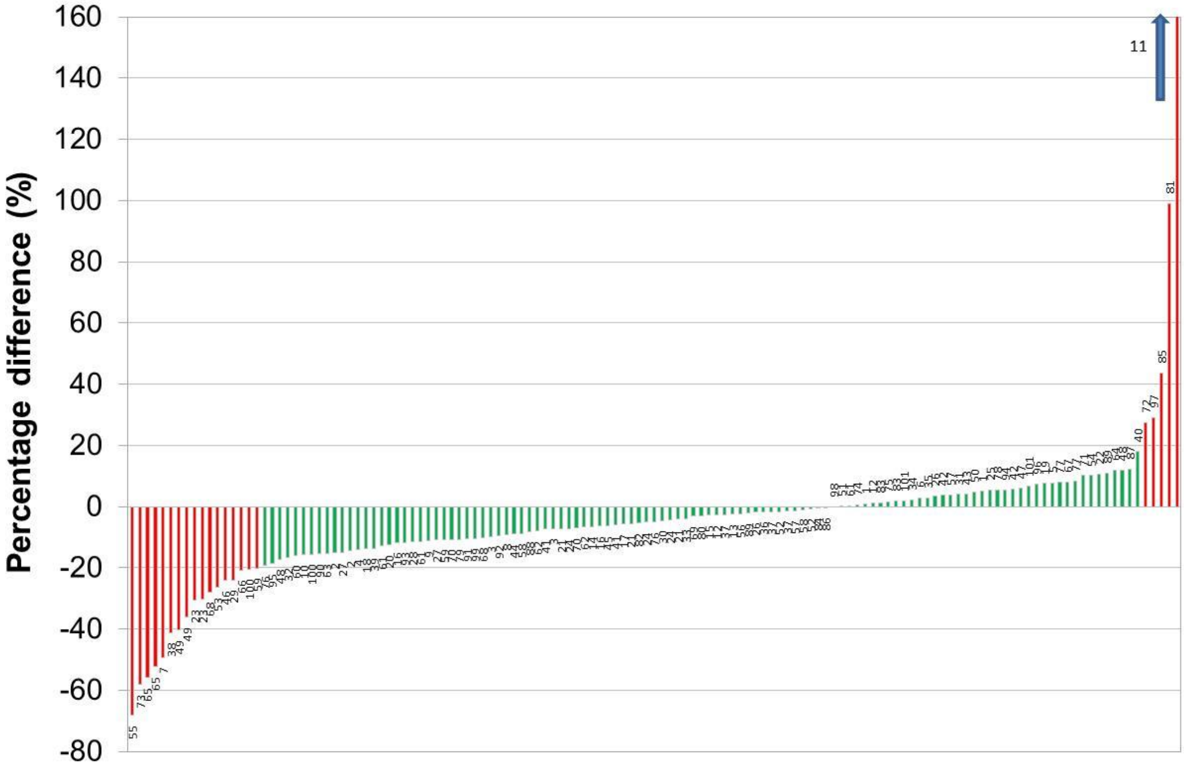
4.2 Percentage difference (%)

The percentage differences are plotted in ascending order in a deviation chart, where too low or too high measurement values become more visible (Figure 5). For the environmental radioactivity measurements the criterion of ± 10-30 % difference from the reference value is usually used but on the basis of our experience on previous radon-in-water PTs, 20 % can be sufficient.

The majority of the measurements obtained satisfactory results having 84 % of the measurement results were acceptable. Nevertheless approximately 16 % of the results (22 out of 135 measurement results) deviated more than 20 % from the reference values. There was one outlying measurement result (ID 11) which is indicted by the blue arrow symbol. It is also visible that the averages of the submitted results are lower than the reference value.

There are 9 (22.5 %), 3 (11.1 %) and 9 (13.2 %) measurement results outside the standard deviation of the proficiency test (σ_{PT}) in case of emanometry, gamma-ray spectrometry and liquid scintillation counting respectively.

Figure 5. Participants` percentage differences for JRC-W1 sample plotted in ascending order. Green colour indicates results within the ± 20 % difference from the reference value, red colour indicates outside this range. The participants` identification numbers are indicated on the horizontal axis.



Source: JRC

4.3 Z and zeta (ζ) scores

The interpretation of the z and ζ scores is done according to ISO 13528:2015. The following scores and colour codes are used in Figure 6 and the Table 6 in Annex 3:

- |score| ≤ 2 satisfactory performance (green),
- 2 < |score| < 3 questionable performance (orange),
- |score| ≥ 3 unsatisfactory performance (red).

The z scores compare the participant's deviation from the assigned value with the standard deviation for proficiency test assessment (σ_{PT}) used as common quality criterion.

The ζ scores state whether the laboratory's result agrees with the assigned value within the respective uncertainty. An unsatisfactory ζ score can either be caused by an inappropriate estimation of the concentration, or of its measurement uncertainty, or both.

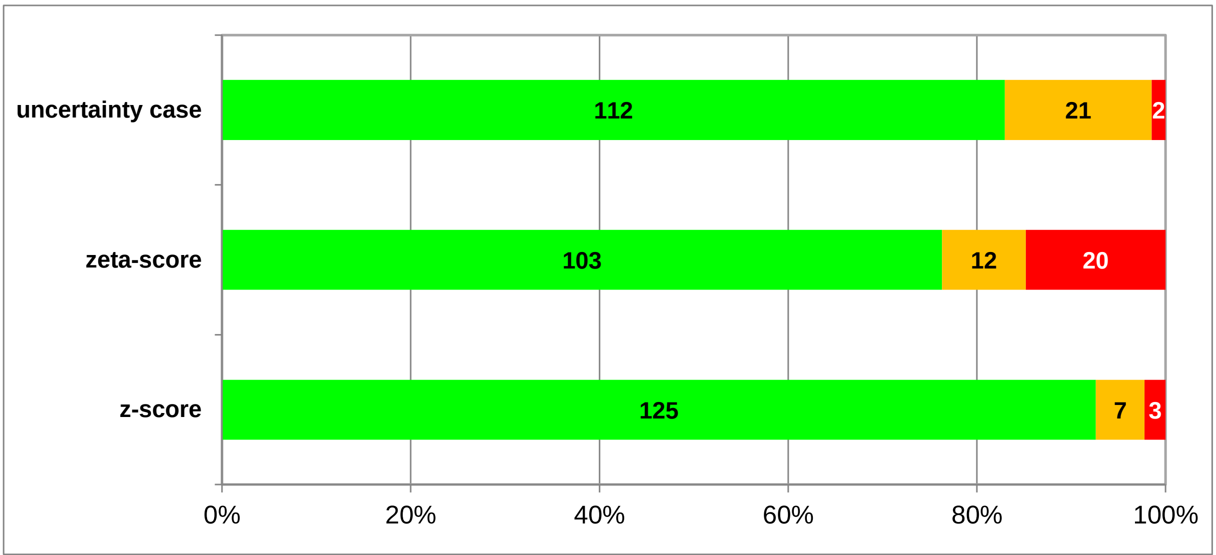
4.4 Uncertainties

Participants had to submit their results together with their combined uncertainties (coverage factor k = 1). If the reported coverage factor differed from 1 then we recalculated the uncertainties for k = 1. Furthermore, participants were requested to provide information on their typical uncertainty budget. Although 97 participants submitted the questionnaire only 61 (63 %) from them filled in the uncertainty budget.

The standard measurement uncertainty from a laboratory $u(A_i)$ is most likely to fall in a range between a minimum and a maximum allowed uncertainty (case a": $u_{min} \leq u(A_i) \leq u_{max}$). u_{min} is set to the standard uncertainties of the assigned values $u(A_{ref})$ excluding the uncertainty from sampling and stability study; $u(A_{ref})$ = 2.8 %. In general, it is unlikely that a laboratory carrying out the analysis on a routine basis would determine the measurand with (much) smaller measurement uncertainty than the expert laboratories which establish the assigned value or the uncertainty of available calibration standards. u_{max} is set to the standard deviation accepted for the PT assessment (σ_{PT} = 20 %).

- case "a" (green colour in Figure 6): $u(A_{ref}) \leq u(A_i) \leq \sigma_{PT}$,
- case "b" (orange colour in Figure 6): If $u(A_i) < u(A_{ref})$; the laboratory may have underestimated its measurement uncertainty,
- case "c" (red colour in Figure 6): If $u(A_i) > \sigma_{pt}$; the laboratory may have overestimated its measurement uncertainty.

Figure 6. Number of measurement results as a function of uncertainty cases, zeta-scores and z-sores.



Note: green colour indicates acceptable results, orange indicates warning sign, and red colour indicates unacceptable results for z and zeta (ζ) scores. Uncertainty cases: case "a" in green, case "b" in orange, case "c" in red.

Source: JRC

It may be stated that the uncertainty budgets were correctly established for the majority of the submitted results. However they may be issues in case of 23 measurement results representing 17 % of the submitted results which has to be investigated by the participants.

It can be concluded that 93 % of the z-scores were acceptable. When the ζ scores are evaluated, the acceptable results dropped to approximately 76 % clearly indicating the problems linked to establishing realistic uncertainty budgets.

5 Summary and conclusions

A proficiency test on measurements of the massic activity of ^{222}Rn in drinking water was organised by JRC-Geel in October 2018. The proficiency test material with elevated ^{222}Rn massic activity was collected from a natural water source in Austria. The reference value traceable to SI units was established on the basis of the power moderated means of the HPGe gamma-ray spectrometry measurements.

5.1 Conclusions from performances

The participants were requested to treat and measure PT samples according to their routine procedures. Every participant submitted at least one measurement result, thirty participants submitted measurement results from more than one method.

The performance of the participating laboratories was evaluated with respect to the reference values using relative deviations, z-score, zeta-score.

The overall scores of 101 participating laboratories and the 135 measurement results were found to be satisfactory with few exceptions only. The submitted results with their combined uncertainties were within the pre-established criteria (σ_{PT} = 20 %) for 113 participants, only 1 outlier performance was identified from the Grubbs test which was from an LSC measurement. The reason for this might be that the participant had problems with the instrument which was out of order for some weeks. They were able to measure sample after few weeks of reception while their normal procedure includes measurement within 48 hours. Besides this, further possible calibration problems cannot be excluded as well.

The results were also evaluated on the basis of applied methods to check for method dependency. It was found that the majority of the participants' results (84%) were within the reference range, which was set to ± 20% of the reference value. However, when the uncertainty budget was evaluated then less acceptable scores were found: 103 measurement results out of 135 (76%) included proper uncertainty budget. Underperforming measurement methods need to be reviewed to reduce ^{222}Rn loss during manipulation. Furthermore, calibration procedures and uncertainty budgets should be also re-evaluated at the participants.

It can be concluded that each of the three applied methods (emanomery, gamma-ray spectrometry and liquid scintillation counting) seems to be adequate for radon activity measurements in waters. In addition, all the three seem to be relatively well controlled in the laboratories. The only bigger concern affecting the measurement results the most is that radon can be lost during sample preparation leading to reported values that have a somewhat negative bias.

5.2 Sources of interferences

There are some potential sources of interferences mentioned by the participants and the PT organizer as well (Jobbágy et al., 2019).

- Bubble formation in the sampling container,
- Additional pouring/sample transfer,
- From elevated radon background in the laboratory,
- Adsorption of radon daughters on the surface of the glass bottle (Cassette, 2019; Mitev, 2019).

5.3 Reported impacts of this PT

Some participants could already use the results or the materials to improve the quality and reliability of laboratory practice.

- interesting and educating PT exercise for a "new in the field" participant,
- Bottles were useful, new procedure is adopted to that geometry,
- PT was useful regarding the QA system and accreditation procedure.

5.4 Future JRC actions

Repetition of this PT can be considered if requested by the member state laboratories, Euratom 35/36 experts and the European Commission's Directorate-General for Energy (DG ENER).

It is planned to organize a radon-in-water sampling PT in the future but it has to be further discussed within the European Commission and the Euratom article 35/36 experts.

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List of abbreviations and definitions

Activity concentration*	Activity per unit volume
AGES	Austrian Agency for Health and Food Safety
A_{lab}	mean laboratory result of massic activity
A_{ref}	reference value of massic activity
BIPM	Bureau International des Poids et Mesures
D (%)	Percentage deviation between the reported and the reference massic activity
DDEP	Decay Data Evaluation Project
DG ENER	European Commission’s Directorate-General for Energy
EURATOM	European Atomic Energy Community
GUM	Guide to the Expression of Uncertainty in Measurement
HPGe	high-purity germanium detector
ILC	interlaboratory comparison
ISO	International Organization for Standardization
k	coverage factor according to GUM
LSC	liquid scintillation counting
Massic activity*	Activity per unit mass
MS	member states of the European Union
PT	proficiency test
SI	Système International d'Unités, International System of Units
SIR	Système International de Référence, International Reference System for radionuclides
U	expanded uncertainty according to GUM
u	standard uncertainty according to GUM
u_c	combined standard uncertainty according to GUM
U_{lab}	expanded uncertainty of average laboratory result
U_{ref}	expanded uncertainty of reference value
UTC	Coordinated Universal Time; time standard
σ_{PT}	the standard deviation for proficiency assessment

(*) In this report, the matrix was water, which has a density very close to 1. Although we clearly distinguish between massic activity (Bq/kg) and activity concentration (Bq/L), their numerical value would be almost identical.

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Annex 1. List of participating laboratories

AUSTRIA

AGES - Austrian Agency for Health and Food Safety, Vienna

AGES - Austrian Agency for Health and Food Safety, Radon and Radioecology
Linz

BELGIUM

Institute for radioelements (IRE ELiT), Radioactivity Measurements Lab
Fleurus

FANC, Surveillance of the territory, Brussels

SCK•CEN, Low radioactivity measurements, Mol

BOSNIA - HERZEGOVINA

Institute for Public Health of Federation of Bosnia and Herzegovina
Radiation Protection Center, Sarajevo

BULGARIA

National Center of Radiobiology and Radiation Protection
Public Exposure Monitoring Lab, Sofia

Sofia University "St. Kliment Ohridski", Atomic Physics
Sofia

DIAL Ltd, Buhovo

Executive Environment Agency, Radioactivity Measurement Labo
Sofia

Institute of Soil Science, Agrotechnologies and Plant Protection "N. Poushkarov"
Isotope laboratory, Sofia

CROATIA

J. J. Strossmayer University of Osijek, Department of Physics
Osijek

Ruđer Bošković Institute, Zagreb

CYPRUS

University of Cyprus, Chemistry,Nicosia

Radiation Inspection and Control Service, Department of Labour Inspection
Nicosia

CZECH REPUBLIC

National Radiation Protection Institute (Státní ústav radiační ochrany)
Radiochemie, Ostrava 3

National Radiation Protection Institute, Branch in Hradec Kralove
Hradec Kralove

ESTONIA

Environmental Board, Radiation Safety Department, Tallinn

FINLAND

Radiation and Nuclear Safety Authority (STUK), Helsinki

FRANCE

CEA/LIST, LNHB, CE-Saclay, Gif sur Yvette cedex

IRSN, PSE-ENV / SAME, Le Vesinet

PearL, Limoges

GERMANY

Federal Office for Radiation Protection, Rad. Protection & Environment, Berlin

CVUA Freiburg, 12.1 Radioactivity Lab, Freiburg

Federal Institute of Hydrology, G4, Koblenz

GREECE

Greek Atomic Energy Commission, Environmental Radioactivity, Attiki

National Technical University of Athens, Nuclear Engineering Department
Athens

HUNGARY

RadiÖko Kft., Veszprém

University of Pannonia, Institute of Radiochemistry and Radioecology
Veszprém

National Public Health Institute, Dept. of Radobiology & Radiohygiene
Budapest

MECSEKÉRC, Radiometriai laboratórium, Kővágószőlős

National Food Chain Safety Office, Radioanalytical Reference Lab, Budapest

Hydrosys Labor Kft.,Budapest

ICELAND

Icelandic Radiation Safety Authority, Reykjavik

IRELAND

Environmental Protection Agency, ORM, Dublin

ITALY

ARPACAL, Dipartimento Reggio Calabria, Reggio Calabria

L.B. Servizi per le Aziende srl, Rome

Istituto Zooprofilattico Sperimentale della Puglia e della Basilicata
Chimica - CRN-Radioattività, Foggia

Istituto Superiore di Sanità, CNPRFC, Roma

ARPA Lazio, Viterbo

ARPA Valle d'Aosta, Saint Christophe

National Research Council (CNR) / Sapienza - University of Rome, Rome

ARPAV, Dip. Reg. Laboratori – CRR, Verona

Arpa Sicilia, Catania

ARPA Piemonte, Ivrea

MI.AM SRL, Piacenza

ARPA Marche - Dipartimento Prov.le di Ancona, U.O. Radioattività Ambientale
Ancona

ARPACAL, Catanzaro - Physics lab, Catanzaro

APPA TN - Local Environmental Protection Agency, Settore Laboratorio, Trento

Agenzia Provinciale per l'Ambiente Bolzano, Laboratorio di chimica fisica, Bolzano

ARPA Puglia, U.O.S. Polo R. I., Bari

Agenzia Regionale per la Tutela Ambientale ARTA Abruzzo
Laboratorio Fisica ambientale, Pescara

ARPA Umbria, Servizio Radiazioni Ionizzanti, Perugia

ARPAE Emilia Romagna, CTR Radioattività ambientale, Piacenza

Università "Roma Tre", Dipartimento di Scienze, Roma

ARPA Sicilia, Palermo

LATVIA

Latvian Environment, Geology and Meteorology Centre Laboratory, Riga

LITHUANIA

Radiation Protection Centre of expertise and exposure monitoring, Vilnius

LUXEMBOURG

Ministry of Health, Radioprotection, Luxembourg

NETHERLANDS

Rijkswaterstaat, CIV Laboratory, Lelystad

NORWAY

The Norwegian Radiation Protection Authority, Østerås

POLAND

Silesian Centre for Environmental Radioactivity, Katowice

AGH University of Science and Technology, Geophysics, Krakow

Technical University of Lodz, Institute of Applied Radiation, Lodz

Institute of Nuclear Physics PAN, LER Lab. of Radiometric Expert, Kraków

National Centre for Nuclear Research, LPD, Otwock

Central Laboratory for Radiological Protection, Warsaw

PORTUGAL

Instituto Superior Técnico/Laboratório de Proteção e Segurança Radiológica
Bobadela LRS

ROMANIA

Cosma Constantin Radon Laboratory, Cluj-Napoca

SERBIA

University of Novi Sad, Faculty of Sciences, Department of Physics, Novi Sad

Vinca Institute of Nuclear Sciences, Radiation and Envir.Protection, Belgrade

SLOVAKIA

Regional Public Health Organisation, Radiation Protection, Kosice

Regional Public Health Authority in Banska Bystrica, Radiation Protection
Banska Bystrica

Public Health Authority of the Slovak Republic, Radiation Protection
Bratislava

Water Research Institute, Radiochemistry, Bratislava

SLOVENIA

ZVD Zavod za Varstvo pri Delu D. O. O., CFM, Ljubljana Polje

Jožef Stefan Institute, Environmental Sciences, Ljubljana

SPAIN

Institut Tecniques Energetiques, Universitat Politècnica de Catalunya, Barcelona

University of Extremadura, Lab Environmental Radioactivit, LARUEX-Faculty of Veterinary, Caceres

University of Granada, Inorganic Chemistry, Radiochemistry Environmental
Laboratory Faculty of Sciences Granada

CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
Medioambiente, Madrid

Universidad del Pais Vasco, Ing. Nuclear y Mec. Fluidos, Bilbao

Universitat Politecnica de Valencia, Lab. Radiactividad Ambiental, Valencia

University of Zaragoza, Faculty of Sciences, Theoretical Physics. Nuclear A
Zaragoza

CEDEX, Área Aplicaciones Isotópicas, Madrid

Universitat Rovira i Virgili - Unitat de Radioquimica Ambiental i Sanitaria
URAIS, Consorci d'Aigues de Tarragona, L'Ampolla

LARUC (University of Cantabria), Faculty of Medicine, Santander

Universidad de Valencia, Laboratorio de Radiactividad Ambiental,
Burjassot (Valencia)

ETSI Caminos, Canales y Puertos. UPM, Laboratorio Nuclear, Madrid

Universitat de Barelona, Lab. Radiologia Ambiental, Barcelona

University of Extremadura, Physics, Badajoz

SWEDEN

SYNLAB Analytics and Services, Linköping

Uppsala Vatten och Avfall AB, Vattenlaboratoriet, Uppsala

Eurofins Environment Testing Sweden AB, Lidköping

Radonova Laboratories AB, Uppsala

SWITZERLAND

Federal Office of Public Health, Str/URA, Bern

UKRAINE

SE "The O.M.Marzeev Institute of Public Health NAMSU", Kyiv

UHMI, Environmental Rad.Monitoring, Kyiv

UK

Public Health England, RHED CRCE Glasgow, Glasgow

SOCOTEC UK Limited, Nuclear Chemistry, Didcot

South West Water Ltd, DWS Science and Water Quality, Exeter

Annex 2. List of announcements and communication with participants

- Nomination request, e-mail, invitation letter: Ref. Ares(2018)3738457 - 13/07/2018
- Invitation letter: Ref. Ares(2018)4511844 - 03/09/2018
- Registration instructions: Ref. Ares(2018)4511844 - 03/09/2018
- Reporting instructions: Ref. Ares(2018)4956535 - 27/09/2018
- Sample accompanying letter: JRC.G.2/VJ/Ares(2018)4956535
- Sample receipt form: Ref. Ares(2018)4956535 - 27/09/2018
- Communication on preliminary results: Ref. Ares(2018)6449519-14/12/2018

Annex 3. Summary table on participants` scores

Table 6. Participants` results and their scores as percentage difference (D%), z-score, ζ(zeta)-score for JRC-W1 sample. ^{222}Rn massic activity values (A_{ref}) with their combined standard uncertainties (u_{ref}) with a coverage factor k = 1.

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
1	321	22	0.9	0.05	0.11	Liquid-scint. counting
1	334	11	5.0	0.25	0.82	Direct gamma-spec.
2	270	17	-15.1	-0.75	-2.06	Liquid-scint. counting
2	272	10	-14.5	-0.72	-2.44	Direct gamma-spec.
3	287	10	-9.7	-0.49	-1.64	Liquid-scint. counting
3	295	15	-7.2	-0.36	-1.05	Direct gamma-spec.
4	273.4	9.1	-14.0	-0.70	-2.42	Liquid-scint. counting
5	342.7	17.8	7.8	0.39	1.03	AlphaGUARD + AquaKIT
6	327	9	2.8	0.14	0.49	Liquid-scint. counting
7	161.3	16.8	-49.3	-2.46	-6.75	Emanometry
8	289	7.54	-9.1	-0.46	-1.64	Liquid-scint. counting
9	282.3	14.1	-11.2	-0.56	-1.67	Emanometry
10	268	13.5	-15.7	-0.79	-2.39	Direct gamma-spec.
11	2757.41	523.905	767.1	38.36	4.65	Liquid-scint. counting
12	309	37.1	-2.8	-0.14	-0.22	Electret Ion Chamber (EIC) technology
12	322	13.1	1.3	0.06	0.19	Direct gamma-spec.
13	310	10	-2.5	-0.13	-0.42	Liquid-scint. counting
14	297.44	21.61	-6.5	-0.32	-0.76	Emanometry

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
15	308.9	6.2	-2.9	-0.14	-0.53	Liquid-scint. counting
16	281	18	-11.6	-0.58	-1.54	Gamma spectrometry with NaI(Tl), water transfered from glass to plastic bottles
16	298	20	-6.3	-0.31	-0.78	Gamma spectrometry with NaI(Tl), own bottles
17	299.7	26.8	-5.8	-0.29	-0.59	Liquid-scint. counting
18	274	81	-13.8	-0.69	-0.53	Radon monitor-Rad7
19	342	17	7.5	0.38	1.03	Liquid-scint. counting
20	278.56	17.01	-12.4	-0.62	-1.69	Liquid-scint. counting
21	295	29.5	-7.2	-0.36	-0.69	Liquid-scint. counting
21	300	30	-5.7	-0.28	-0.53	Liquid-scint. counting
21	305	3.2	-4.1	-0.20	-0.80	Emanometry
22	352	14	10.7	0.53	1.60	Liquid-scint. counting
23	221.11	33.82	-30.5	-1.52	-2.59	Liquid-scint. counting
23	221.87	27.94	-30.2	-1.51	-2.99	Emanometry
24	295	30	-7.2	-0.36	-0.68	alphaguard measurement
24	302	40	-5.0	-0.25	-0.37	Direct gamma-spec.
24	304	20	-4.4	-0.22	-0.55	Liquid-scint. counting
25	335	23	5.3	0.27	0.61	Emanometry
26	312.5	7.5	-1.7	-0.09	-0.31	Direct gamma-spec.
26	329	30	3.5	0.17	0.32	Emanometry

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
27	270	12	-15.1	-0.75	-2.40	LSC in organic LS scintilation coctail (3 sample 3 measurements each average)
27	284	10	-10.7	-0.53	-1.80	LSC in water miscible LS scintilation coctail (3 sample 3 measurements each average)
28	281.13	12.03	-11.6	-0.58	-1.84	Liquid-scint. counting
29	241.9	13.6	-23.9	-1.20	-3.62	Alfa counting, RAD7 + BigBottle System (soda bottles)
30	303.6	3.5	-4.5	-0.23	-0.88	Liquid-scint. counting
31	330.6	12	4.0	0.20	0.63	Liquid-scint. counting
32	265	20	-16.7	-0.83	-2.07	Direct gamma-spec.
33	305	8.5	-4.1	-0.20	-0.72	Liquid-scint. counting
34	325	16	2.2	0.11	0.31	Emanometry
35	327	4	2.8	0.14	0.55	Liquid-scint. counting
36	313	11	-1.6	-0.08	-0.26	Direct gamma-spec.
37	309	16	-2.8	-0.14	-0.40	Liquid-scint. counting
37	313	20	-1.6	-0.08	-0.20	Emanometry
37	314	12	-1.3	-0.06	-0.20	Direct gamma-spec.
38	186.4	2.55	-41.4	-2.07	-8.12	Direct gamma-spec.
39	274.9	20.5	-13.6	-0.68	-1.66	Liquid-scint. counting

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
40	375	26.5	17.9	0.90	1.84	Liquid-scint. counting
41	294.9	1.2	-7.3	-0.36	-1.44	Liquid-scint. counting
41	298.9	3.7	-6.0	-0.30	-1.16	Liquid-scint. counting
42	330	22	3.8	0.19	0.44	Emanometry
42	336	22	5.7	0.28	0.66	Emanometry
43	331	24.8	4.1	0.20	0.44	Liquid-scint. counting
44	290	18.5	-8.8	-0.44	-1.14	Liquid-scint. counting
45	298	21.5	-6.3	-0.31	-0.75	Emanometry
46	241.2	17.9	-24.2	-1.21	-3.20	Liquid-scint. counting
47	337	20	6.0	0.30	0.74	Liquid-scint. counting
48	263	50	-17.3	-0.86	-1.05	Emanometry
48	355.8	24	11.9	0.59	1.31	Liquid-scint. counting
49	190	7	-40.3	-2.01	-7.33	Liquid-scint. counting
49	203	24	-36.2	-1.81	-3.99	Emanometry
50	333	12.5	4.7	0.24	0.74	Liquid-scint. counting
51	319	36	0.3	0.02	0.03	Liquid-scint. counting
52	313	21	-1.6	-0.08	-0.19	RAD7
52	316	17	-0.6	-0.03	-0.09	Liquid-scint. counting
53	234.22	22.72	-26.3	-1.32	-3.01	Emanometry
54	350.1	20	10.1	0.50	1.25	Liquid-scint. counting
55	101	6	-68.2	-3.41	-12.70	Emanometry
56	310	20	-2.5	-0.13	-0.31	Direct gamma-spec.
57	314	30	-1.3	-0.06	-0.12	Emanometry

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
57	330	20	3.8	0.19	0.47	Direct gamma-spec.
58	290	15	-8.8	-0.44	-1.28	Liquid-scint. counting
58	315	29	-0.9	-0.05	-0.09	Direct gamma-spec.
59	254	15	-20.1	-1.01	-2.92	Liquid-scint. counting
59	284	14	-10.7	-0.53	-1.60	Emanometry
60	267.68	21.79	-15.8	-0.79	-1.86	Emanometry
61	277	14	-12.9	-0.64	-1.93	Direct gamma-spec.
61	282	8	-11.3	-0.57	-2.01	Emanometry
61	319	27	0.3	0.02	0.03	Liquid-scint. counting
62	293	29.3	-7.9	-0.39	-0.75	AlphaGuard
62	297.4	24.45	-6.5	-0.32	-0.70	Liquid-scint. counting
63	269	39	-15.4	-0.77	-1.16	solid scintilation
64	355.69	13.5	11.9	0.59	1.80	Liquid-scint. counting
65	140.4	28.1	-55.8	-2.79	-5.49	Liquid-scint. counting
65	151.6	37.9	-52.3	-2.62	-4.04	Emanometry
66	252	15	-20.8	-1.04	-3.01	Direct gamma-spec.
67	343.7	38.7	8.1	0.40	0.61	Liquid-scint. counting
68	229	6	-28.0	-1.40	-5.21	Liquid-scint. counting
68	285.5	18	-10.2	-0.51	-1.35	Direct gamma-spec.
69	308	30	-3.1	-0.16	-0.29	Emanometry
70	284	23	-10.7	-0.53	-1.21	Direct gamma-spec.
70	296	21	-6.9	-0.35	-0.83	Liquid-scint. counting

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
71	350.088	37.033	10.1	0.50	0.80	Liquid-scint. counting
72	405	22.5	27.4	1.37	3.15	Liquid-scint. counting
73	133	15	-58.2	-2.91	-8.44	Emanometry
74	319.7	21.6	0.5	0.03	0.06	Liquid-scint. counting
75	322.8	10.46	1.5	0.08	0.25	Liquid-scint. counting
76	257	8	-19.2	-0.96	-3.41	Direct gamma-spec.
76	302	4	-5.0	-0.25	-0.97	Emanometry
77	342.94	9.935	7.8	0.39	1.32	Direct gamma-spec.
77	344.89	0.655	8.5	0.42	1.68	Liquid-scint. counting
78	335	63	5.3	0.27	0.26	Emanometry
79	284	17	-10.7	-0.53	-1.46	Liquid-scint. counting
80	308	16	-3.1	-0.16	-0.44	Direct gamma-spec.
81	633	12.7	99.1	4.95	15.42	Direct gamma-spec.
82	301	8	-5.3	-0.27	-0.95	Liquid-scint. counting
83	322	40	1.3	0.06	0.09	Emanometry
83	324	7	1.9	0.09	0.34	Liquid-scint. counting
84	317	4.1	-0.3	-0.02	-0.06	Liquid-scint. counting
85	457	38	43.7	2.19	3.37	Liquid-scint. counting
86	317	21	-0.3	-0.02	-0.04	Emanometry
87	357	52	12.2	0.61	0.71	Emanometry
88	292	36	-8.2	-0.41	-0.66	Liquid-scint. counting
89	311	15	-2.2	-0.11	-0.32	Direct gamma-spec.

Lab ID	Value (Bq/kg)	Uncertainty (Bq/kg;k=1)	D%	z score	ζ (zeta) score	Technique
89	352.4	3.9	10.8	0.54	2.09	Liquid-scint. counting
90	268.9	13	-15.4	-0.77	-2.38	Direct gamma-spec.
91	285	29	-10.4	-0.52	-1.00	Liquid-scint. counting
92	288	11	-9.4	-0.47	-1.55	Liquid-scint. counting
93	281	19	-11.6	-0.58	-1.49	Emanometry
94	335.6	40	5.5	0.28	0.41	Liquid-scint. counting
95	258.5	5.25	-18.7	-0.94	-3.53	Liquid-scint. counting
96	341.7	29.7	7.5	0.37	0.70	Emanometry
97	410	55	28.9	1.45	1.61	Liquid-scint. counting
98	318	12.8	0.0	0.00	0.00	Liquid-scint. counting
99	285	5	-10.4	-0.52	-1.97	Liquid-scint. counting
100	253	14	-20.4	-1.02	-3.06	Alpha Guard Pro 2000 professional radon monitor
100	268	20	-15.7	-0.79	-1.95	Direct gamma-spec.
101	324	5.5	1.9	0.09	0.35	Emanometry
101	339	3.5	6.6	0.33	1.28	Liquid-scint. counting

Source: JRC

Annex 4. Summary table on participants` accreditation and use of standards

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
1	Yes, accredited	Yes	ISO/IEC 17025	
2	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
3	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
4	No, not accredited	No		Other: In compliance with internally developed methodology
5	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	
6	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
7	No, not accredited	No		Other: Instruction Manual - Pylon Model WG-1001 - Vacuum water degassing system
8	Yes, accredited	Yes	ISO/IEC 17025;Other: ISO 14000	Other: E-R1:2011 (internal method)
9	No, not accredited	No		Other: No
10	No, not accredited	Yes	ISO/IEC 17025	

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
11	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
12	Yes, accredited	Yes	ISO/IEC 17025	Other: Gamma spectrometry: ASTM D7784-12; EIC: ISO 11665-4
13	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
14	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-3 Emanometry
15	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	Other: TDCR method (cf. Standardization of 222Rn by LSC and comparison with alpha and gamma spectrometry. P. Cassette et al., ARI 64(2006), 1465-1470
16	Yes, accredited	Yes	ISO/IEC 17025	Other: Czech standard ČSN 75 7624, part 6
17	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	Other: In house method T105-R-02-2013 " Determination of the activity of Radon 222Rn in water using liquid scintillation method"

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
19	Yes, accredited	Yes	ISO/IEC 17025	Other: Radon is measured in a homogeneous solution with a liquid scintillation spectrometer 1414 GuardianTM (PerkinElmer). The sample is prepared by adding 10 ml of water into a glass vial (equipped with a cap containing an aluminium foil) pre-filled with liquid scintillation cocktail Ultima GoldTM XR (PerkingElmer). The concentration of Rn-222 is calculated from the alpha spectrum in the window, which covers the most part of the alpha peaks. The alpha counting efficiency of radon in the selected alpha window is between 260 - 290%. Repeatability of the method is 4%.
20	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
21	No, not accredited	No		ISO 13164-3 Emanometry
22	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025;Other: ISO 14001	ISO 13164-4 Liquid scintillation counting

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
23	Yes, accredited	Yes	ISO/IEC 17025	Other: 1-Interlaboratory method for determination of Radon concentration in water samples by emanometry and pulse ionisation chamber; 2-Interlaboratory method for determination of Radon concentration in water samples by LSC with used of water miscible (one phase) coctail
24	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
25	No, not accredited	Yes	ISO 9000 series	ISO 13164-3 Emanometry
26	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-3 Emanometry
27	No, not accredited	No		
28	No, not accredited	Yes	ISO 9000 series	ISO 13164-4 Liquid scintillation counting
29	No, not accredited	No		Other: Our method has been cross-calibrated with other techniques (gamma ray-spectrometry). This results have been published in high-level journals
30	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
31	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
32	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
33	Yes, accredited	Yes	ISO/IEC 17025	Other: UNI 11261:2008
34	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-3 Emanometry
35	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
36	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
37	Yes, accredited;No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-3 Emanometry;ISO 13164-4 Liquid scintillation counting
38	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry
39	No, not accredited	Yes	ISO/IEC 17025	
40	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
41	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
42	No, not accredited	Yes	ISO 9000 series	ISO 13164-3 Emanometry
43	Yes, accredited	Yes	ISO/IEC 17025	Other:
44	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
45	No, not accredited	No		ISO 13164-3 Emanometry

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
46	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
47	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
48	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
49	No, not accredited	No		ISO 13164-3 Emanometry;ISO 13164-4 Liquid scintillation counting
50	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
51	No, not accredited	Yes	Other: ISO/IEC 17043 and ISO 13528 for proficiency testing, the other mentioned above are about to be implemented	ISO 13164-4 Liquid scintillation counting
52	Yes, accredited	Yes	ISO/IEC 17025	Other: EPA 913.0 and user manual RAD7
53	No, not accredited	No		
54	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	Other: ASTM_D5072D Standard Test Method for Radon in Drinking Water 2009.
55	Yes, accredited	Yes	ISO/IEC 17025	Other: STN 75 7615
56	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
57	Yes, accredited	Yes	ISO/IEC 17025	Other: IAEA TRS 295
	No, not accredited	Yes	ISO/IEC 17025	Other: method in development
58	Yes, accredited	Yes	ISO/IEC 17025	
60	No, not accredited	No		ISO 13164-3 Emanometry
61	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-3 Emanometry;ISO 13164-4 Liquid scintillation counting
62	No, not accredited	Yes	ISO/IEC 17025	
63	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	Other: solid scintillation
64	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
65	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
66	Yes, accredited	Yes	ISO/IEC 17025	Other: Analys av radon i vatten – metodbeskrivning, Strålsäkerhetsmyndigheten 2013
67	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
68	No, not accredited	Yes	ISO/IEC 17025	Other: mo dified EPA 913

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
69	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-3 Emanometry
70	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
71	Yes, accredited	Yes	ISO/IEC 17025;Other: Drinking Water Inspectorate	ISO 13164-4 Liquid scintillation counting
72	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
73	No, not accredited	No		ISO 13164-3 Emanometry;ISO 13164-4 Liquid scintillation counting
74	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
75	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
76	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	Other:
77	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting
78	No, not accredited	No		

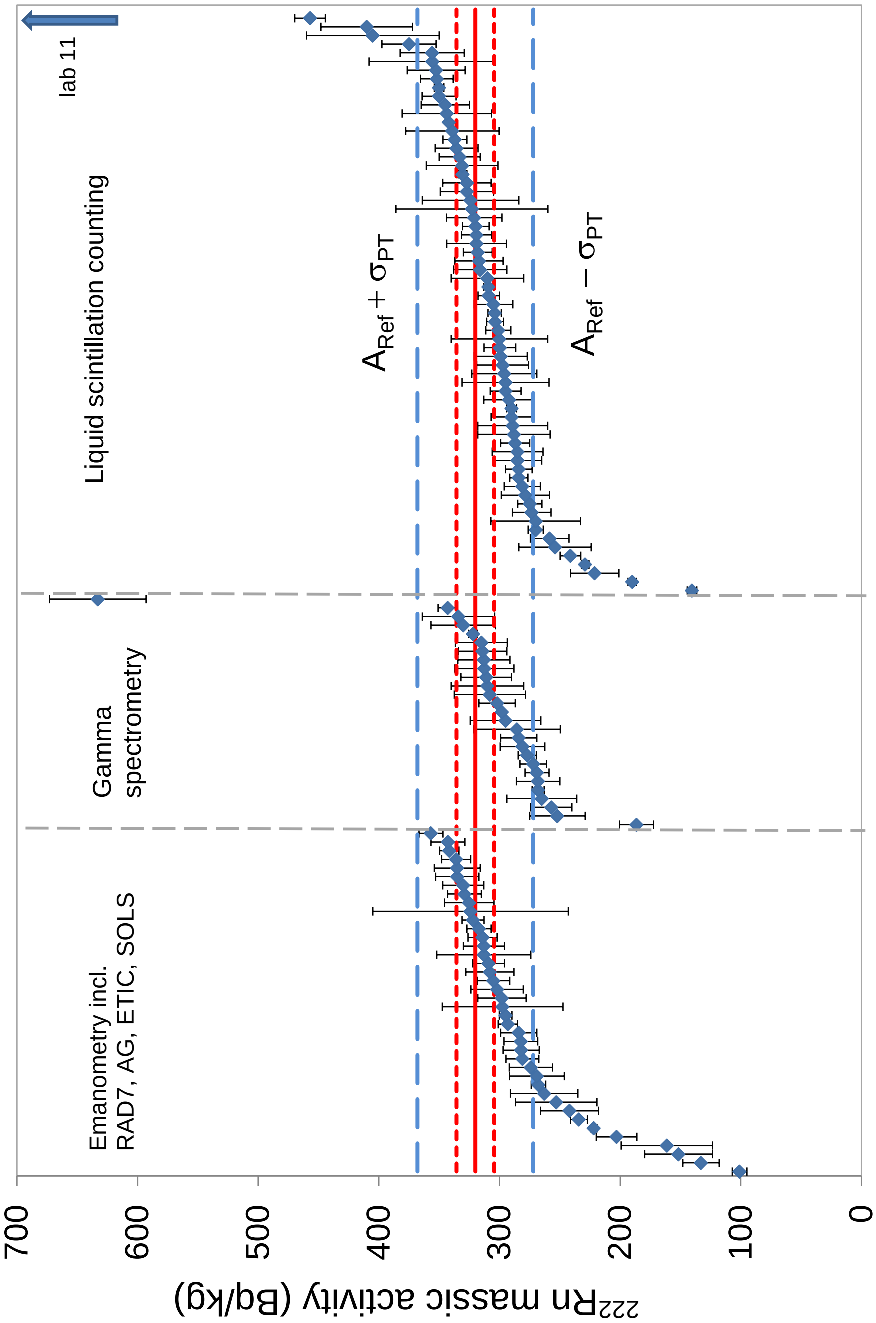
Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
79	No, not accredited	No		
80	Yes, accredited	Yes	ISO 9000 series;EN 45000 series;ISO/IEC 17025	Other: Gamma-ray spectrometry - own method described in Quality Manual
81	No, not accredited	No		Other: CSN 75 7624
82	Yes, accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
83	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
84	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
85	No, not accredited	Yes	ISO 9000 series;ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
86	Yes, accredited	Yes	ISO/IEC 17025;Other ISO 13164-3:2013	ISO 13164-3 Emanometry
87	No, not accredited	No		ISO 13164-3 Emanometry
88	Yes, accredited	Yes	ISO/IEC 17025	Other: Liquid scintillation spectrometry of two phase samples
89	No, not accredited	Yes	ISO/IEC 17025	ISO 13164-2 Gamma-ray spectrometry;ISO 13164-4 Liquid scintillation counting

Lab ID	Is your laboratory accredited for radon-in-water analysis according to ISO/IEC 17025?	Is your laboratory working according to a quality management system?	Select one or more	1. Did you perform the test in compliance with the following standards? (Select one or more) If other, please specify:
90	No, not accredited	Yes	ISO/IEC 17025	
91	No, not accredited	Yes	Other: DSTU ISO 10012:2005	Other: Homemade method based on the Doc 411-001 of the Hidex Oy
92	No, not accredited	Yes	ISO 9000 series	
94	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
95	No, not accredited	No		ISO 13164-4 Liquid scintillation counting
96	No, not accredited	No		ISO 13164-3 Emanometry
97	Yes, accredited	Yes	ISO/IEC 17025	ISO 13164-4 Liquid scintillation counting
99	No, not accredited	No		
100	Yes, accredited	Yes	ISO/IEC 17025	Other: Internal laboratory method
101	No, not accredited	Yes	ISO/IEC 17025	

Annex 5. Sorted results

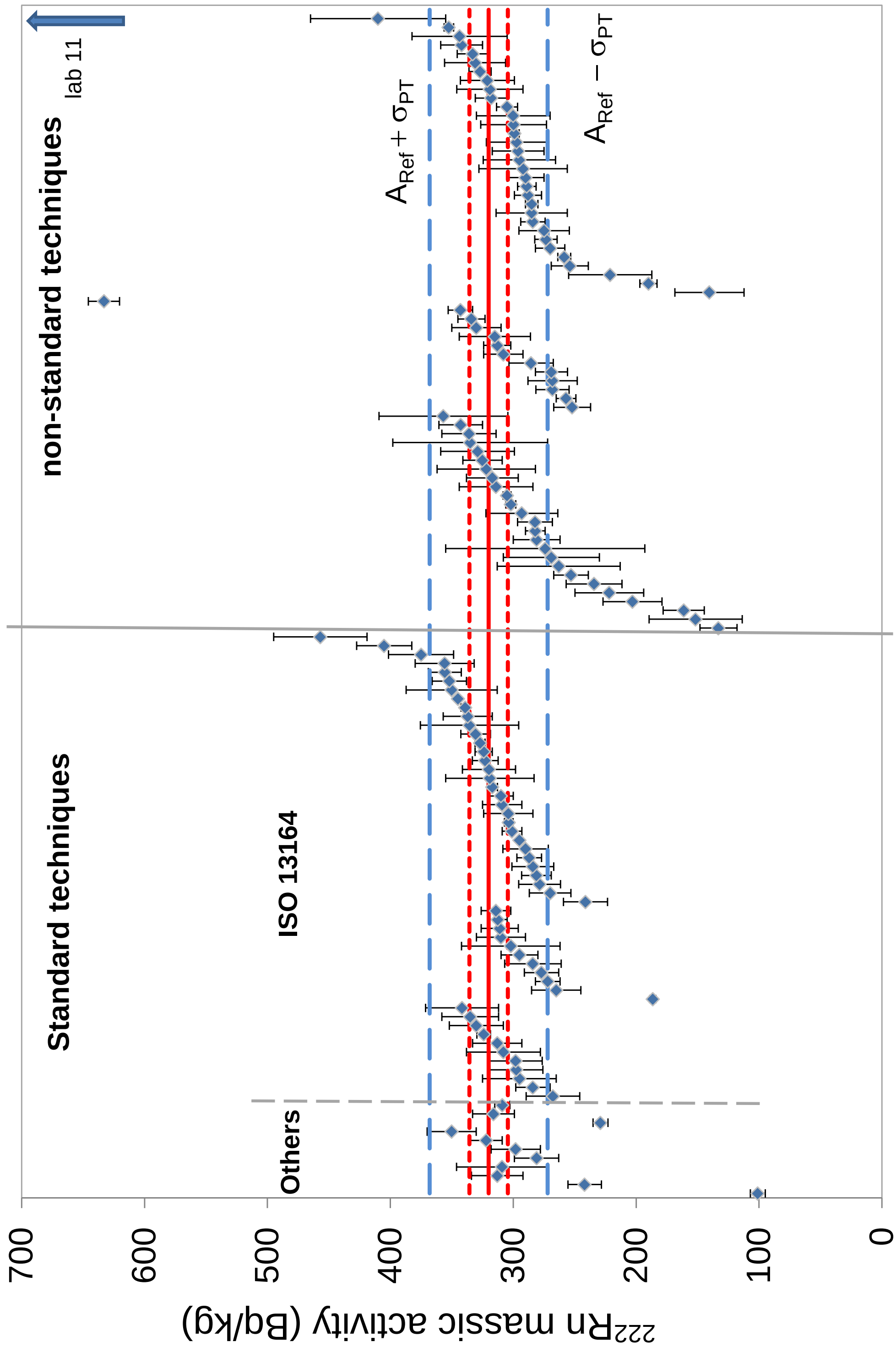
Results were sorted by counting technique and use of standard methods. The graphical evaluations are given in Figure 7-8. First, the results were sorted on the basis of the measurement methods used by participants.

Figure 7. Participants` results of ^{222}Rn massic activity with combined standard uncertainties (k = 1) separating curves depending on the measurement methods for JRC-W1 sample. The red dashed lines indicated the uncertainty of the reference value (solid red line).



Source: JRC

Figure 8. Participants`results sorted on the basis of application of a standard technique for JRC-W1 sample. The three curves under standard/non-standard techniques represent (from left) emanometry, GS and LSC.



Source: JRC

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