Intercomparison of indoor radon and geogenic radon measurements under field conditions

WP3: Comparison and harmonisation of radon measurement methodologies in Europe

Task 3.3: Intercomparisons of indoor radon and geogenic radon measurements under field conditions

Activities: A3.3.1 to A3.3.4

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CONTENTS

1 Introduction

This report describes the activities carried out within Task 3.3 “Intercomparison of indoor radon and geogenic radon measurements under field conditions” of the MetroRADON project. The aim is to provide a direct comparison between different methodologies and to identify physical reasons for possible inconsistencies, particularly related to sampling and measurement techniques. Three different comparison exercises were performed under field conditions in order to identify physical reasons for possible inconsistencies, particularly related to sampling and measurement techniques. The main exercise was the comparison of indoor radon gas measurements performed with passive detectors, giving an integrated measurement over time, and active monitors, continuously monitoring radon concentration. A series of geogenic radon measurements, such as radon exhalation rate from soil and radon concentration in soil gas, was also conducted.

This intercomparison exercise was organized by the University of Cantabria (UC) with the support of the Joint Research Centre (JRC).

The radon intercomparison measurements were held from 5-8November 2018 in the Laboratory of Natural Radiation (LNR) located at the facilities of the former uranium mine managed by the Spanish National Uranium Company ENUSA (Address: Ctra. Ciudad Rodrigo - Lumbrales, km 7. 37592 Saelices el Chico, Salamanca, Spain).

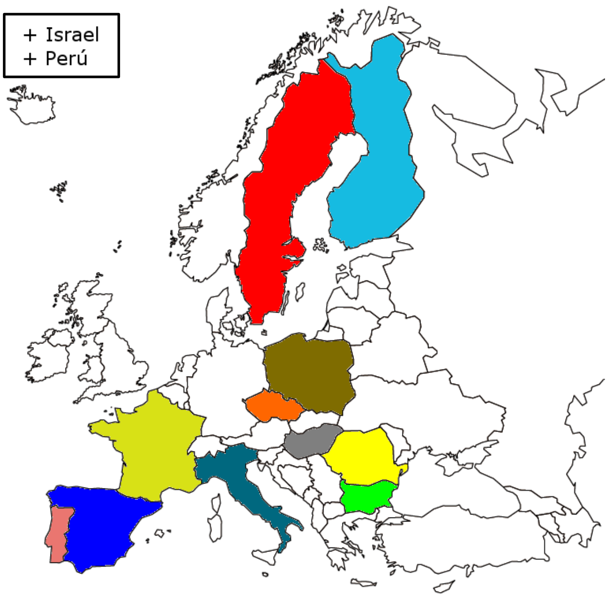

Fig. 1. Participants from the coloured European countries as well as Israel and Peru participated in the intercomparison.

1.1 Participants

The number of participants was limited to 20 due to operational reasons. All participants took part in the exercise related to radon in air measurements, whereas exhalation from soil and radon in soil measurements were performed by 3 and 5 participants, respectively. The questionnaire sent to participants to request their contact information and participation details is shown in Appendix II. The list of participants is given in Table 1. There is no correlation between this table and the code assigned to each participant in the results section. Fig. 1 shows coloured European countries of participants.

Table 1. Participants in the intercomparison sorted by alphabetical order.

Acronym	**Institution**	**Country**
CIEMAT	Centro de investigaciones energéticas, medioambientales y tecnológicas	Spain
CLOR	Central Laboratory for Radiological Protection	Poland
ENEA	ENEA Radon Service	Italy
INAIL	Italian National Institute for Insurance against Accidents at work	Italy
IRSN	Institut de Radioprotection et de Sûreté Nucléaire	France
JRC	Joint Research Centre	Italy
LaRUC (UC)	Laboratory of environmental radioactivity, University of Cantabria	Spain
LRAB - UEX	LRAB - Universidad de Extremadura	Spain
LRG	Laboratorio de Radón de Galicia	Spain
LRN-UC	Laboratorio de Radioatividade Natural - Universidade de Coimbra	Portugal
NRCN	Nuclear Research Center Negev	Israel
PUCP	Pontificia Universidad Católica Del Perú	Peru
RADONOVA	Radonova Laboratories AB	Sweden
Radosys	Radosys / Radosys Atlantic	Portugal/Hungary
RERA-CIEMAT	Centro de investigaciones energéticas, medioambientales y tecnológicas	Spain
STUK	Radiation and Nuclear Safety Authority	Finland
SUBG	Sofia University "St. Kliment Ohridski"	Bulgaria
SUJCHBO	National Institut for NBC Protection	Czech Republic
TR	TECNO RAD s.u.r.l.	Italy
UBB	Babes-Bolyai University	Romania

1.2 Site Description

The intercomparison was carried out in the former uranium mine managed by the Spanish National Uranium Company ENUSA. The reclamation of the uranium mining operations (exploited from 1972 to 2000) and the dismantling of the uranium concentrate factory started in 2001. The purpose of this reclamation is to try to restore the affected natural space and to recover it to its original state, with radiological and environmental conditions returning to those existing before the mining operations. One of the buildings was chosen to house the Laboratory of Natural Radiation (LNR) for calibration and testing of instruments and detectors for the measurement of natural radiation (see Fig. 2).

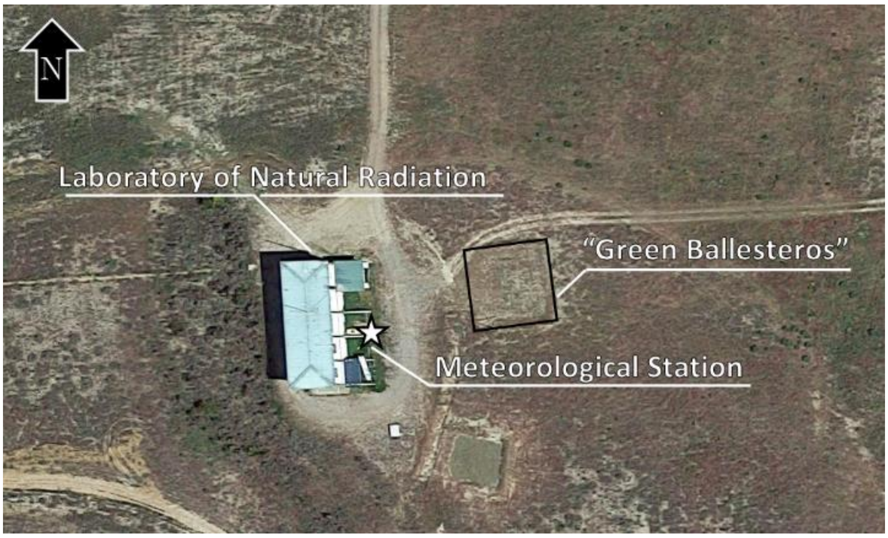

Fig. 2. Aerial view of LNR and surroundings where the intercomparison was developed.

This place has been used to carry out interlaboratory exercises both measuring radon concentration and gamma dose rate under natural environmental fluctuations. The high radioactive content in the soil along with the environmental conditions make this location a suitable place to conduct these kind of activities.

The LNR (see Fig. 3) has two floors; the first floor is used as a conference hall and multi-purpose room. The ground floor has two spaces designed as radon chambers (Room1 and Room2) with approximately 45 m^3 volume each. Room1 has no direct connection to the exterior while Room2 has an artificial ventilation system installed. The radon source is the uranium mine underground soil which has a high radium content.

In the east part of the LNR a meteorological station is set up to monitor environmental conditions. The datalogger, which has temperature and humidity sensors, is connected wirelessly to the station from the Room1.

Fig. 3. Laboratory of Natural Radiation seen from both sides.

Outside of LNR there is a place called “Green Ballesteros”, where a 5×5 m^2 and 1.5 m deep hole was dug out and filled with homogeneous soil with low radioactive content (^{226}Ra concentration about 43 ± 10 Bq/kg and gamma dose rate around 110 ± 5 nGy/h at 1 m height). The main radon source of this area is the original underlying soil.

Fig. 4. “Green Ballesteros” view and in the background the LNR.

The radon in air comparison exercise was developed inside Room1 of LNR, while the radon exhalation from soil and radon in soil activities were performed in the location called “Green Ballesteros”. Additionally, a place close to the uranium mine entrance was used to compare the radon in soil measurements, hereinafter named “Offices site”.

2 Methods

2.1 Activities

Radon in air exposure has been evaluated using passive detectors and active monitors inside Room1 of the Laboratory of Natural Radiation (LNR). Two exposures have been planned taking into account the natural radon evolution during those days. The devices were placed in Room1 on the 5 December 2018 and were taken off on 6 and 8 December 2018 for the first and second exposure, respectively, according to schedule shown in Table 2.

Table 2. Start and end dates for each exposure ((UTC+01:00) Brussels, Copenhagen, Madrid, Paris).

	Start date	**End date**
1^{st} exposure E1:	05/11/2018 12:00	06/11/2018 1:00
2^{nd} exposure E2:	05/11/2018 12:00	08/11/2018 10:00

Each participation with passive detectors requires a number of 30 units: 10 detectors for the first exposure, 10 for the second exposure and 10 transit detectors.

A total of 23 groups of passive detectors and 22 active monitors were exposed in Room1 of the Laboratory of Natural Radiation (see Fig. 5). For the second exposure E2 there are four results that are not reported due to various problems indicated by the participants.

Fig. 5. Radon devices inside Room1 (LRN).

There are several types of devices used by the participants. Passive detectors are made by different materials and/or use various technologies such as CR-39, LR 155, electret ion chambers, etc. Other procedures were implemented, e.g. using DVDs half made of polycarbonate (used as a solid state track detector) and polycarbonate foils used as a radon absorber. The features of diffusion chambers, holders, material quality and manufactures were diverse too. The overall characteristics given by participants are shown in Table 3.

Table 3. Passive detector features provided by the participants.

Detector	Diffusion chamber
CR-39 RSKS 100 mm^2 (Radosys)	Diameter 26 mm, height 55 mm 29 cm^3 volume
CR-39 24.7×36.7×1.40 (mm) (Mi-Net)	ENEA patent
CR-39 Radout 25×25×1.5 (mm) (Mi.am)	Diameter 50 mm, height 20 mm
CR-39 TASTRAK 13×37×1 (mm) (Tasl)	Diameter 58 mm, height 20 mm NRPB/SSI
CR-39 Duotrack (Radonova)	Diameter 58 mm, height 40 mm
CR-39 Radtrak2 (Radonova)	Diameter 58 mm, height 20 mm NRPB/SSI
CR-39 Rapidos (Radonova)	Diameter 58 mm, height 40 mm
ST Electret Teflon (E-PERM)	L-OO Chamber 58 mL
ST Electret Teflon (E-PERM)	S Chamber 210 mL
LR-115 type2 400 mm^2 (DOSIRAD)	Diameter 60.4 mm, height 27.6 mm Own design
LR-115 (KODAK) RAMARN device 0.012 mm film of cellulose nitrate, and coated on 0.1 mm thick polyester base	Polypropylene chamber 700 cm^3 volume
Makrofol 75.7 mm^2 STUK design “Radonpurkki”	Diameter 20 mm, height 71 mm 79 cm^3 volume
DVD half made of polycarbonate and two thin Makrofol N foils	Thin CD case

In this intercomparison different active monitors were used with various operation modes and features as shown in Table 4. This information has been obtained from the manufacturer’s technical specifications.

Table 4. Active monitor features used in the intercomparison.

Monitor	Detection technology	Sensitivity (cpm at 1 kBq m^{-3})
AlphaGUARD	Ionisation chamber	50
ATMOS12 DPX	Ionisation chamber	20
SARAD EQF 3120	Silicon detector	7
Radon Scout	Silicon detector	1.8
Radon Scout Home	PIN photo diode	0.1

The organizers introduced/removed the passive detectors and active monitors from Room1. After each exposure, passive detectors were stored in a low radon concentration area. After two days, they were sealed in radon proof aluminium bags in order to allow a proper degassing. Active monitors were stopped and turned off at the end of the second exposure.

Transit detectors were stored in their original bags until the end of the second exposure. Afterwards, they were sealed in radon proof aluminium bags in order to simulate the exposed detectors conditions.

Participants have provided the exposure value and its uncertainty for each passive detector and the declared value for the first and second exposure period expressed in kBq m^{-3} h. In the case of active monitors, the overall exposure for each period was given; the individual radon concentration every hour was also included. The template for reporting results is shown in Appendix III.

For radon exhalation rate and radon in soil measurements two different points were available at the site of the intercomparison: the area “Green Ballesteros” and the “Offices site”. In the “Offices site” only radon in soil activity measurements were carried out. For these exercises, the measurements were conducted in situ and each participant used their own measuring system and sampling materials.

Participants have provided the exhalation rate value and its uncertainty for “Green Ballesteros” expressed in Bq m^{-2} h^{-1}. Radon in soil measurements were given for “Green Ballesteros” and “Offices site” expressed in kBq m^{-3}. Results template is shown in Appendix III.

Results provided by participants have been coded in order to maintain their anonymity. Such codification follows the rule:

LxxTn

where

xx is the number assigned to each participant from 01 to 20,

T is the type of measurement, **A**: radon in air with active monitor, **P**: radon in air with passive detectors, **E**: radon exhalation rate from soil, **S**: radon in soil,

n is the correlative number for more than one kind of measurements group.

2.2 Data Analysis

The determination of the assigned value and its standard uncertainty for each radon in air exposure have been obtained by using consensus value from participant results applying an iterative algorithm according to ISO 13528:2015. This algorithm considers the results of all participants and relocates the extreme values within the interval of acceptable deviation.

An outliers study has been applied in order to know the extreme values. The outlier values were found from the boxplot representation and the interquartile analysis. In this case an outlier is defined as a data point that is located 1.5 times the interquartile range (IQR) above the upper quartile and below the lower quartile. The interquartile range is defined as the difference between the third quartile (75th percentile) and the first quartile (25th percentile): IQR = (Q_3-Q_1).

The robust average and robust standard deviation denoted by E_{ref} and s^* have been calculated using "Algorithm A" taken from ISO 13528:2015:

There are p items of results denoted as:

$$E_i = E_1 , E_2 , E_3, \dots , E_p$$

Calculate initial values for E_{ref} and s^* as:

$$E_{ref} = \text{median of } E_i$$

$$s^* = 1.485 \text{ median of } |E_i - E_{ref}|$$

Update the values of E_{ref} and s^* as follows. Calculate:

$$\delta = 1.5\ s^*$$

$$E_i^* = \begin{cases} E_{ref} - \delta & \text{when} \quad E_i < E_{ref} - \delta \\ E_{ref} + \delta & \text{when} \quad E_i > E_{ref} + \delta \\ E_i & \text{otherwise} \end{cases}$$

Calculate the new values of E_{ref} and s^* from:

$$E_{ref} = \text{ mean of } E_i^*$$
$$s^* = 1.134 \cdot \text{SD } (E_i^*)$$

The robust estimates E_{ref} and s^* are derived by an iterative calculation, i.e. by updating the values of E_{ref} and s^* several times until the process converges.

Once the robust average and robust standard deviation have been calculated for each exposure period, the standard uncertainty of the assigned value may be estimated as:

$$u(E_{ref}) = 1.25\frac{s^*}{\sqrt{p}} \quad (1)$$

The indexes used to analyse the participants' results are the relative percentage difference *D*(%), the Zeta score (ζ) and the z-score (z).

The relative percentage difference *D*(%) has been introduced to quantify the difference between the participant's result and the reference value obtained as consensus. Therefore:

$$D_i(\%) = 100 \cdot \frac{E_i - E_{ref}}{E_{ref}} \quad (2)$$

where E_i is the exposure result i given by the participant.

The Zeta score (ζ) is a statistical index used to compare intercomparison results where the uncertainty in the measurement result is included. It is given by the following equation:

$$\zeta_i = \frac{E_i - E_{ref}}{\sqrt{u^2(E_i) + u^2(E_{ref})}} \quad (3)$$

being $u(E_i)$ the participant's own estimate the standard uncertainty of its result.

The z-score (z) index is calculated as follows:

$$z_i = \frac{E_i - E_{ref}}{\sigma_p} \quad (4)$$

where σ_p is the standard deviation for the intercomparison assessment estimated as 20% of reference value for the first exposure and 10% of reference value for the second one. This parameter should meet the following criterion: $u(E_{ref}) < 0.3\,\sigma_p$.

These indexes are interpreted as follow:

$|\zeta|; |z| \leq 2.0$ result is considered satisfactory

$2.0 < |\zeta|; |z| < 3.0$ result is considered to give a problem

$|\zeta|; |z| \geq 3.0$ is considered not satisfactory

The Zeta score (ζ) is used together with z-score (z) as an aid for improving the performance of participants. If a participant obtains a z-score higher than the critical value of 3.0, they may find it valuable to reassess their procedure with the subsequent uncertainty evaluation for that procedure. If the participant's ζ score also exceeds the critical value of 3.0, it implies that the participant's uncertainty evaluation does not include all significant sources of uncertainty. However, if a participant obtains a z-score ≥ 3.0 but a ζ score ≤ 2.0, this demonstrates that the participant may have assessed the uncertainty of their results accurately but that their results do not meet the performance expected for the proficiency testing scheme. The interpretation guidelines are shown in Table 5.

Table 5. Summary of guidelines to understand ζ and z scores.

ζ score	z-score	Action to take
Satisfactory	Satisfactory	Participant's result is good. No action is required.
Not satisfactory	Satisfactory	Participant's claimed uncertainty is too low, but the result fulfils the intercomparison requirements.
Satisfactory	Not Satisfactory	Participant's uncertainty assessment is accurate but the results do not fulfil the intercomparison requirements.
Not Satisfactory	Not Satisfactory	Participant's result is biased in excess. A complete revaluation should be performed.

In case of geogenic radon measurements, exhalation rate and radon in soil measurements, the methodology to assess the results is different due to the low number of results reported and the high dispersion of them. Descriptive statistics are applied and the claimed value is considered acceptable if it is within the interval defined by the mean value ± its standard deviation. In this case the analysis is not the same as radon in air activity due to the reasons mentioned.

3 Results

3.1 Environmental conditions

Below the environmental conditions in Room1 and outside during the intercomparison exercise are presented. Fig. 6 graphically shows the variation of internal and external environmental parameters, temperature and relative humidity. Table 6 gives the mean and extreme values. It is observed that the variation of temperature in Room1 is quite stable, with an absolute difference of 1 ºC, while this difference outside is about 10 ºC. Atmospheric pressure average inside Room1 was 935 ± 5 hPa with an absolute variation of 14 hPa.

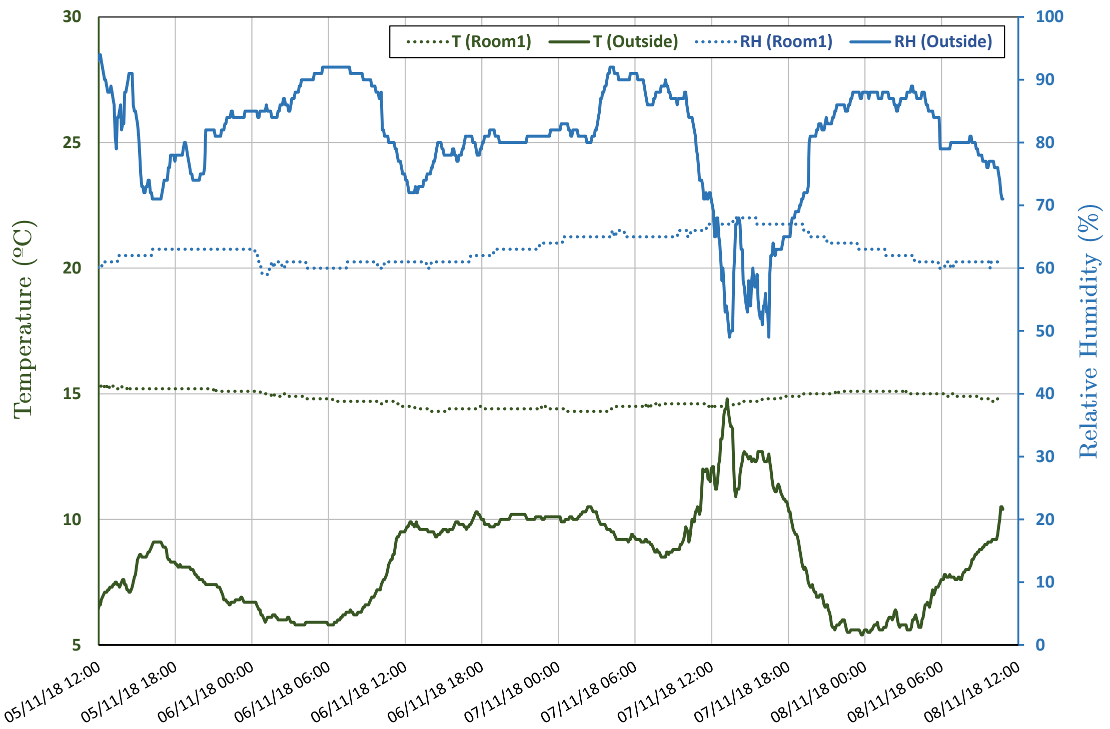

Fig. 6. Temperature (green) and relative humidity (blue) variation in Room1 (dotted line) and outside (solid line) during the intercomparison exercise. Measurements are taken every five minutes.

Table 6. Temperature and humidity conditions in Room1 and outside LNR.

	Room1	Outside
T_{mean} (ºC)	14.8 ± 0.3	8.1 ± 2.0
T_{min} (ºC)	14.3 ± 0.1	5.3 ± 0.1
T_{max} (ºC)	15.3 ± 0.1	14.8 ± 0.1
RH_{mean} (%)	63 ± 2	82 ± 9
RH_{min} (%)	57 ± 1	49 ± 1
RH_{max} (%)	68 ± 1	95 ± 1

The weather during the intercomparison exercise was rainy. On 4 November it started to rain and it continued until the 8 November. The amount of precipitation is shown in Fig. 7. Rain has a special interest in geogenic measurements because it could significantly modify the mobility of radon in the soil.

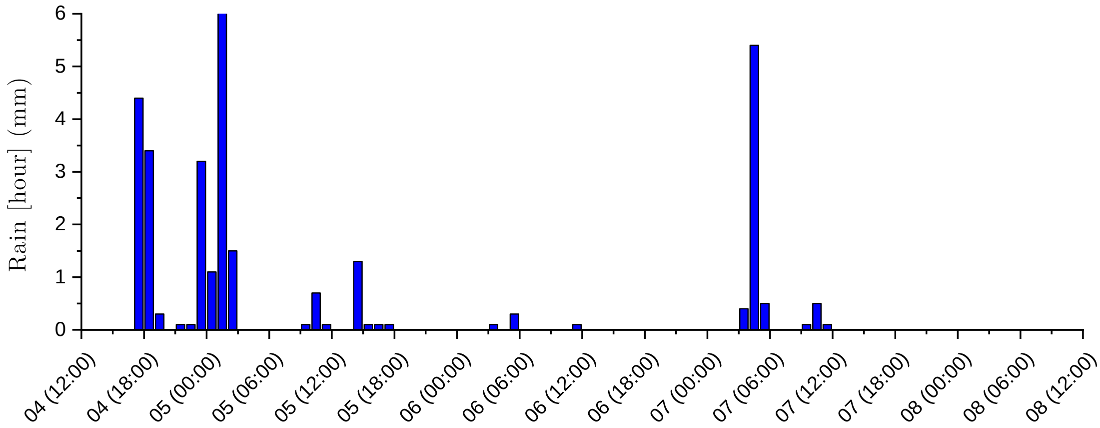

Fig. 7. Rain accumulated every hour expressed in mm from the 4 November 2018 to 8 November 2018.

3.2 Radon in air

In this subsection the radon in air exposure results are analysed. Participants submitted one exposure result together with its uncertainty per group of passive detectors and/or active monitor for the first exposure E1 and for the second exposure E2.

Appendix I contains the numerical results submitted by the participants for each exposure and the indexes used to assess their performance.

The variation of radon concentration in Room1 shows a big range of values, with levels from approximately 0.5 to 30 kBq/m^3. As an example, the radon concentration measurements of Laboratory of environmental radioactivity, University of Cantabria (LaRUC), taken by the device AlphaGUARD (S/N AG000032), are shown in Fig. 8.

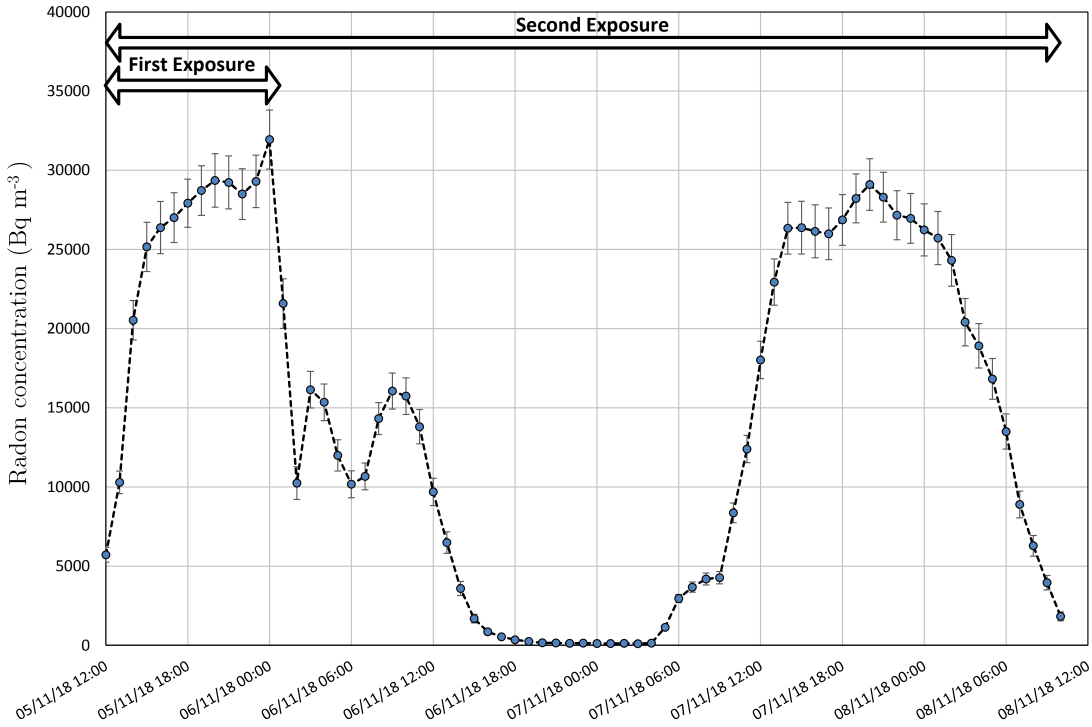

Fig. 8. Radon concentration in Room1 during the intercomparison exercise according to LaRUC. Data is displayed every hourly.

The assigned values used as reference for each exposure period are derived from a weighted average of participants' results applying the iterative algorithm described above according to ISO 13528:2015. Table 7 shows the robust average E_{ref}, the robust standard deviation s^*, the standard uncertainty $u(E_{ref})$, the number of results p and the standard deviation for the intercomparison assessment σ_p estimated as 20% of reference value for the first exposure and 10% of reference value for the second one. This parameter meets the criterion: $u(E_{ref}) < 0.3\ \sigma_p$.

Table 7. Reference parameters of the first exposure E1 and second exposure E2 expressed in kBq m^{-3} h obtained from participant results according to ISO 13528:2015. p is the dimensionless number of results.

	E_{ref}	$u(E_{ref})$	σ_p	s^*	p
1st exposure E1:	356	8	71	43	45
2nd exposure E2:	1014	13	101	68	41

As mentioned before, outliers have been identified using a bloxplot diagram (Fig. 9). The corresponding codes are displayed in Table 8. There are no statistical differences between the reference exposure value calculated taking into account the total amount of results and the one calculated without considering outliers. Therefore all the results have been considered to calculate the reference values.

Table 8. Results considered outliers from the interquartile analysis.

	Laboratory code				
1st exposure E1:	L01P2	L01P3	L02P1	L02P2	L16P1
2nd exposure E2:	L03P1	L16P1	L19P1	L20A3	

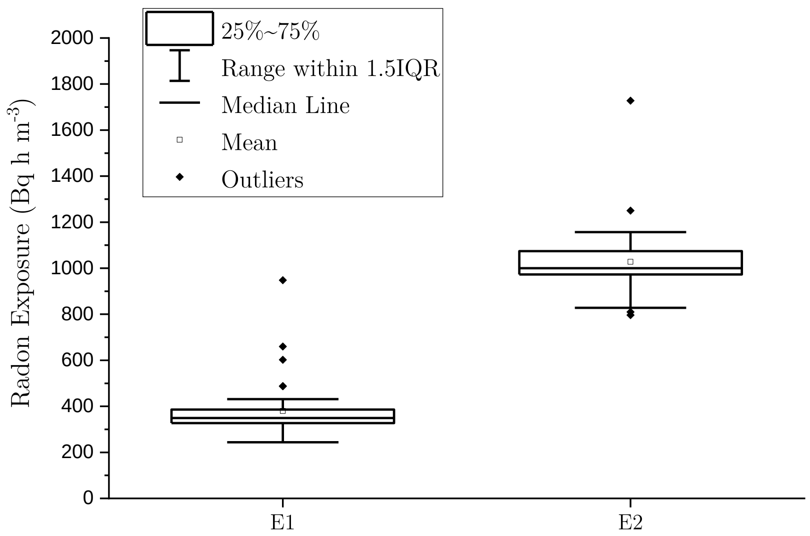

Fig. 9. Boxplot diagram of the participant's results for exposures E1 and E2.

Participant's results for the first radon in air exposure are given in Fig. 10. Each value is presented with its uncertainty (k = 1). The solid line represents the reference value obtained through consensus (356 kBq m^{-3} h) and the dashed lines denote the standard deviation for the inter-laboratory assessment estimated as 20% of the reference value. Fig. 11 shows the results for the second exposure, with the reference value of 1014 kBq m^{-3} h indicated with a solid line. In this case the dashed lines represent the 10% of that reference value.

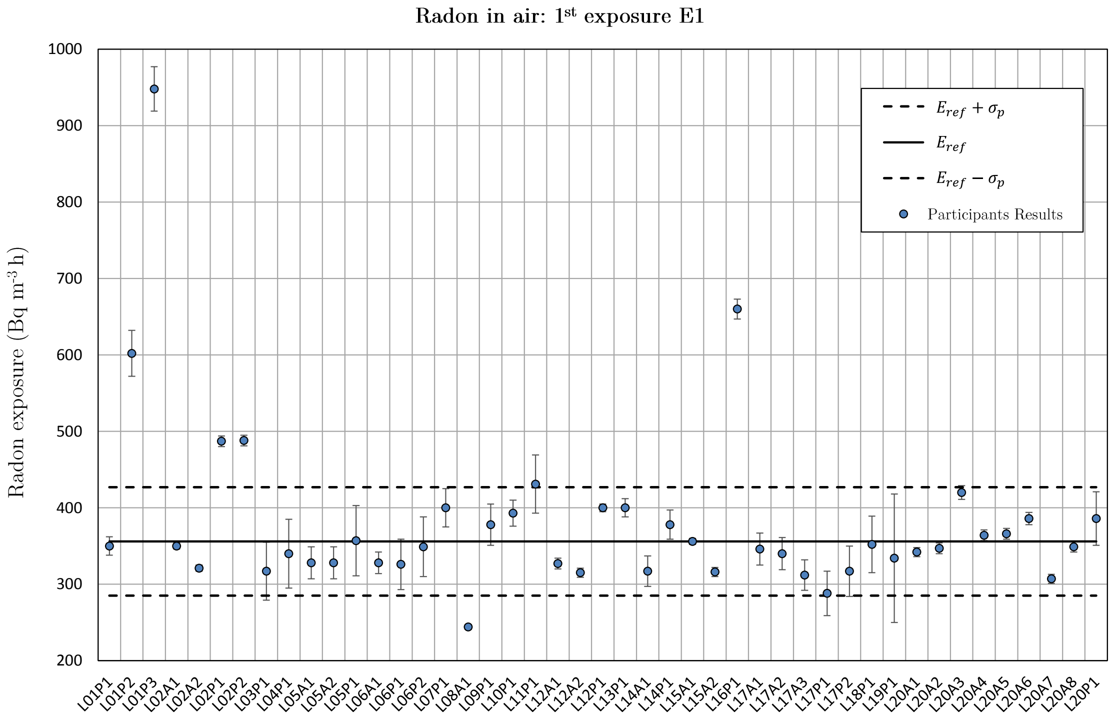

Fig. 10. Participant's results for the first exposure E1 with its associated uncertainty ($k = 1$). Exposure reference value is shown with a solid line and the standard deviation $\sigma_p = 0.2E_{ref}$ with dashed lines.

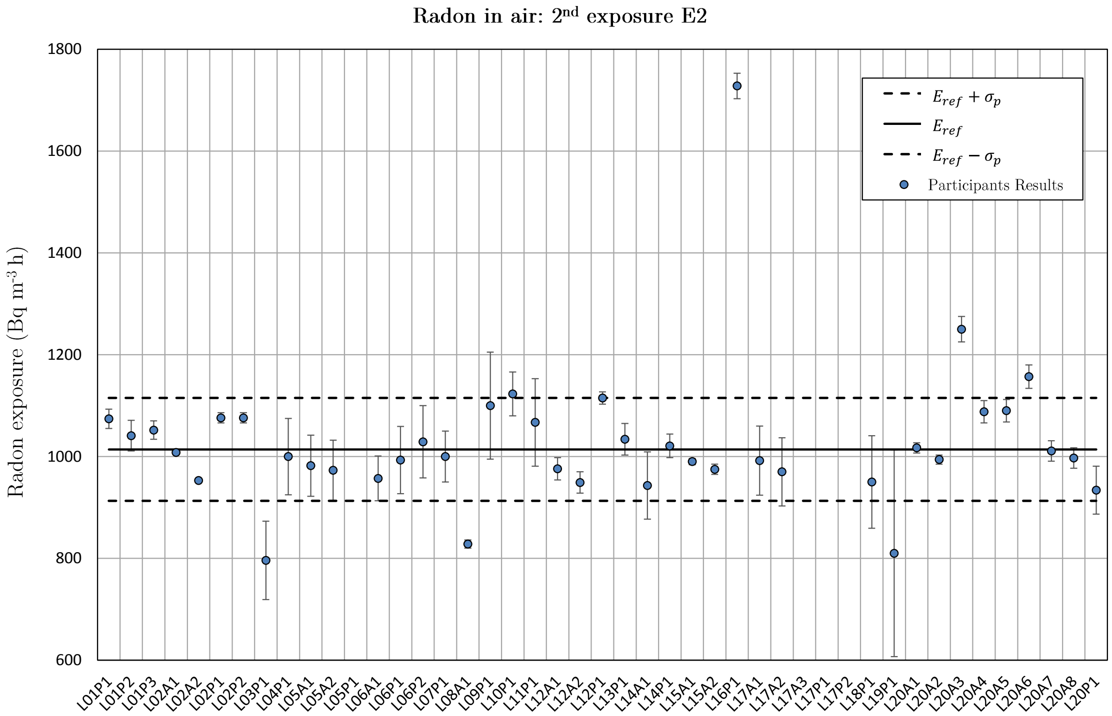

Fig. 11. Participant's results for the second exposure E2 with its associated uncertainty ($k = 1$). Exposure reference value is shown with a solid line and the standard deviation $\sigma_p = 0.1E_{ref}$ with dashed lines.

About 80% of the results presented in Fig. 10 and Fig. 11 are within the interval defined by the exposure reference value E_{ref} and the standard deviation σ_p established as 20% and 10% for the first and the second exposure, respectively. The relative difference $D(\%)$ between each single value and the reference is shown in Fig. 12. The anomalous values shown in Table 8 are clearly out of those intervals.

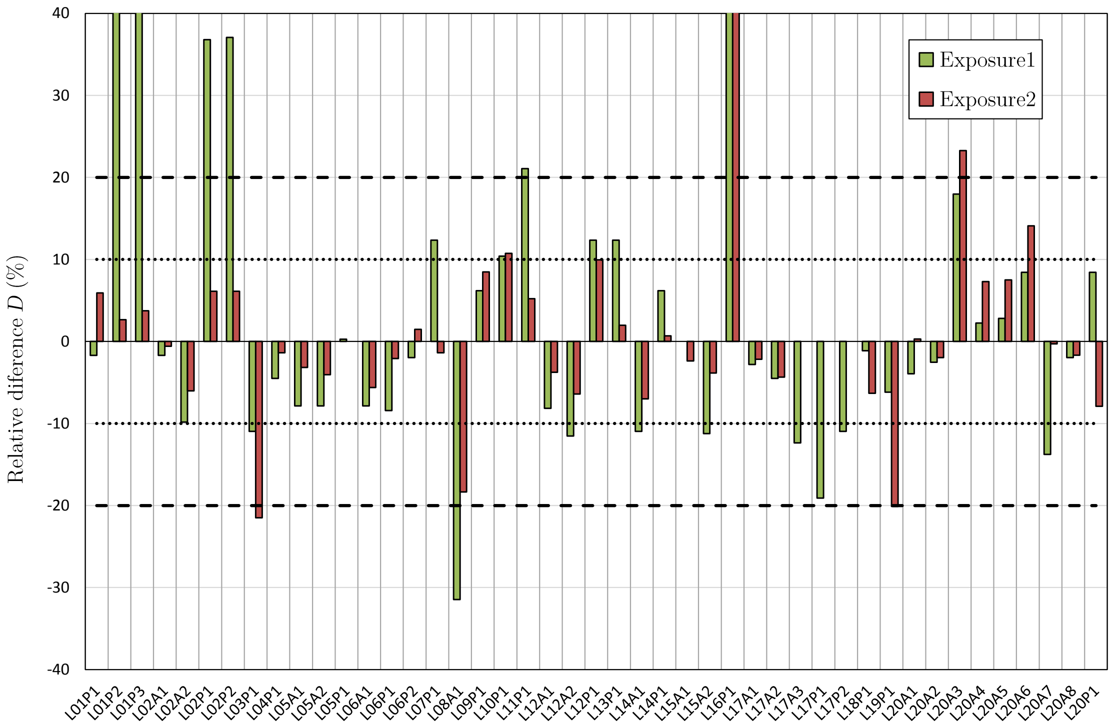

Fig. 12. Relative difference of participant's results to the mean value for the first and second exposure. Intervals established for the first exposure (± 10%) and second exposure (± 20%) are indicated.

Below it is shown the graphical representation of indexes used to assess the participant's results. In some cases the value is out of scale in order to improve the graph view. Numerical results are collected in Appendix I. In addition, Table 9 shows the percentage of results that are within the limits for each index. For the relative difference, the percentage of results within 10% and 20% of reference exposure in each case is presented.

The overall performance of results given by z-score is satisfactory, about 90% of results have a value lower than 2.0 for both exposures. Only the results of three cases have a z-score value above 3.0 for the first exposure and one result for the second exposure period. Regarding the Zeta score, about 60% of results are satisfactory ($|\ \zeta\ | \leq 2.0$), however, 29% of results for the first exposure and 20% for the second exposure period are not satisfactory, with a Zeta score $|\ \zeta\ | \geq 3.0$.

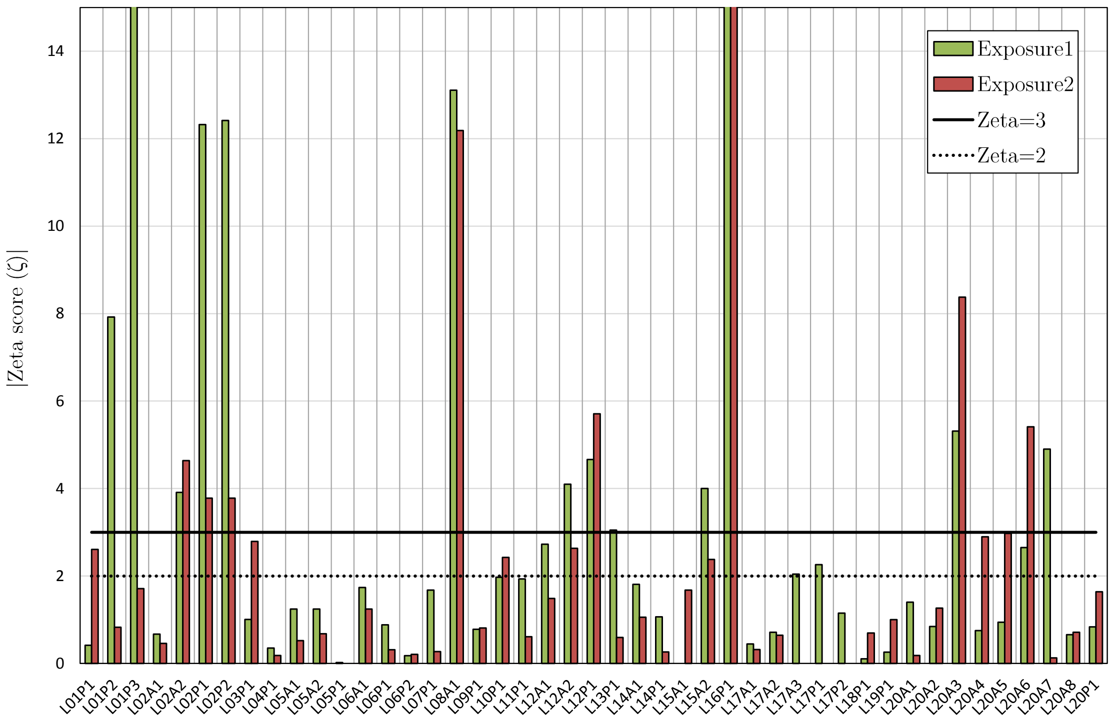

Fig. 13. Absolute values of Zeta score for the first and second exposure.

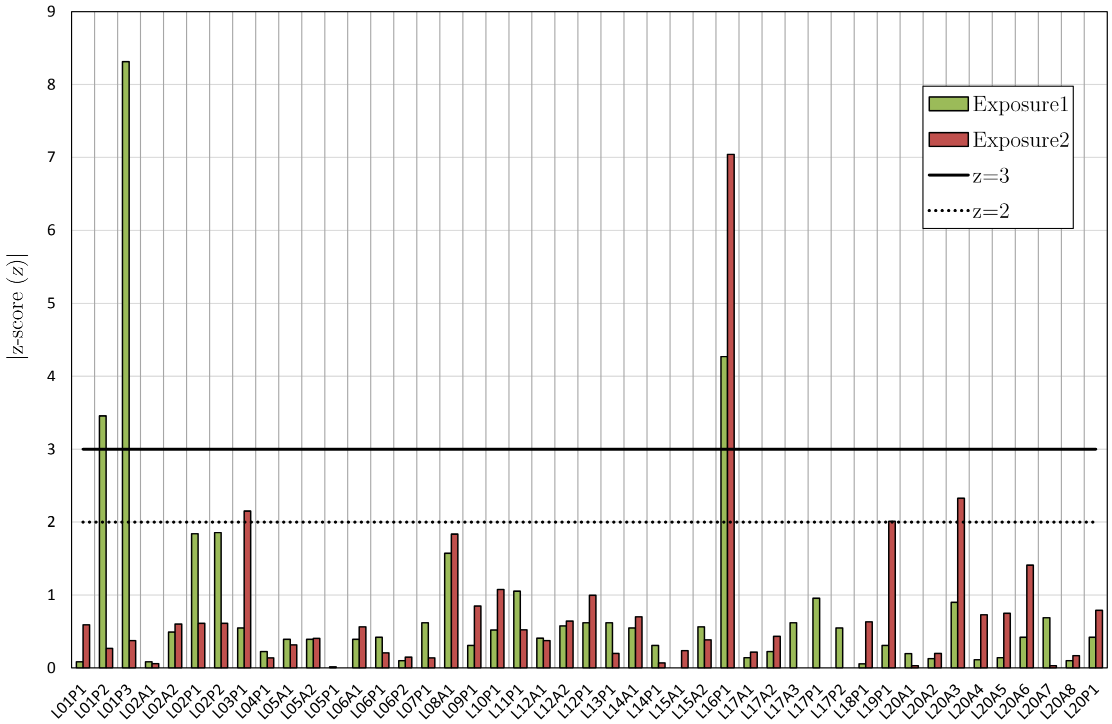

Fig. 14. Absolute values of z-score for the first and second exposure.

Table 9. Percentage of results that are within the limits for Zeta score (ζ) and z-score (z).

	Results of E1 (%)	Results of E2 (%)
$\lvert D(\%)\rvert \leq 10\%$	56	83
$\lvert D(\%)\rvert \leq 20\%$	84	90
$\lvert \zeta \rvert \leq 2.0$	62	63
$2.0 < \lvert \zeta \rvert < 3.0$	9	17
$\lvert \zeta \rvert \geq 3.0$	29	20
$\lvert z \rvert \leq 2.0$	93	90
$2.0 < \lvert z \rvert < 3.0$	0	7
$\lvert z \rvert \geq 3.0$	7	2

3.3 Exhalation from soil

In this subsection the results for exhalation rate measurements are presented. Participants submitted one single value with its uncertainty for the exhalation rate expressed in Bq m^{-2} h^{-1} in "Green Ballesteros". There were 3 participants who used their own methodology in situ, all different from each other.

Due to the different methodologies involved, the measurements were not carried out at the same time. Participant L03 used absorption in polycarbonate, which is a cumulative measurement, with a duration of two days. Participant L17 used the accumulation method with a radon monitor with a sampling time of approximately one hour. This method provides a discrete value of exhalation. In case of participant L20, the measurements were performed using the absorption in activated charcoal canisters during 24 hours one week later due to logistics problems. Results, dates and methodologies are shown in Table 10.

Table 10. Radon exhalation J and its uncertainty $u(J)$ performed in the indicated date with the methodology used by each participant to conduct the test in the "Green Ballesteros".

Code	J (Bq m^{-2} h^{-1})	$u(J)$ (Bq m^{-2} h^{-1})	Date (2018)	Methodology
L03E1	361	33	5 Nov 15:30 to 7 Nov 13:30	Gradient method with polycarbonate foils
L17E1	14719	1939	6 Nov 15:30 (approx. 1 hour.)	Accumulation method
L20E1	35100	8200	15 Nov 10:00 to 16 Nov 10:00	Absorption in activated charcoal collector

The large differences in the obtained results require some explanation. Although the measurements are very few to draw definitive conclusions, still some consideration can be made. As can be seen in Table 10, measurements L03E1 and L17E1 overlap in time, but they differ in two orders of magnitude. However, the first method is cumulative, while the second is discrete. During the period of these measurements, the weather was mostly rainy and windy and the soil was soaked, which would impede the exhalation. Due to the windy weather, there were some cloudless and sunny time windows and the discrete measurement L17E1 was carried out in such a window (see Fig. 15). The sun would dry the soil and lead to an increase in the radon exhalation, which could be a possible explanation for the observed difference between the results of the two measurements.

On the other hand, the two cumulative measurements L03E1 and L20E1 could not be compared directly, as they were carried out at different times. The weather was dry and sunny in the week of the L20E1 measurement, in contrast to the weather during the L03E1 measurement. Although no definitive conclusions can be drawn, these results indicate the significant effect of the weather on the radon exhalation rate, which deserves a more thorough study.

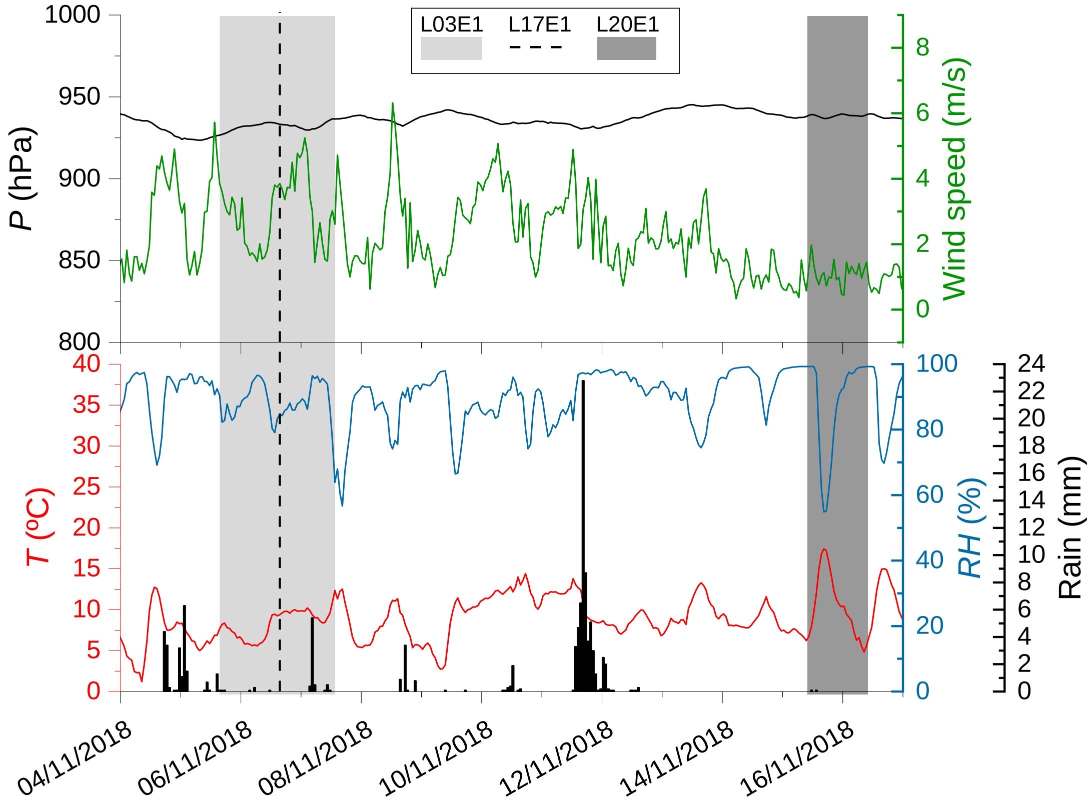

Fig. 15. Environmental conditions during the exhalation rate activity displayed every hour. Shaded areas correspond to the cumulative measurements (light grey L03E1; dark grey L20E1), and dashed line to L17E1 discrete measurement.

It is observed that there is a great difference between the results. The standard deviation (SD) is as big as the mean value (see Table 11).

Table 11. Descriptive statistics of radon exhalation results expressed in Bq m^{-2} h^{-1}.

	"Green Ballesteros"
Mean	16727
Median	14719
SD	17456
p	3

3.4 Radon in soil

Radon in soil measurements were carried out in the "Green Ballesteros" area and at "Offices site" on 6 November 2018. Table 12 gives the results and the methodology applied. Descriptive statistics for each case are shown in Table 13. It is observed that the dispersion of results is acceptable in case of "Green Ballesteros", with a standard deviation of about 14% of the mean value. However, the "Offices site" results show great differences. Graphical representation of radon in soil measurements performed in "Green Ballesteros" is shown in Fig. 16.

Table 12. Radon concentration in soil C_{soil} and its uncertainty $u(C_{soil})$ with the methodology used by each participant to conduct the measurements in "Green Ballesteros" and at the "Offices site".

	"Green Ballesteros"		"Offices site"		
Code	C_{soil} (kBq m^{-3})	$u(C_{soil})$ (kBq m^{-3})	C_{soil} (kBq m^{-3})	$u(C_{soil})$ (kBq m^{-3})	Methodology
L03S1	602	57			Absorption in polycarbonate foils
L10S1	546	143	6.3	3.3	Continuous monitoring
L13S1	789	74			Etched track detectors
L17S1	894	37	994	40	Continuous monitoring
L20S1	840	140	20	12	Grab sampling in ionization chamber plus measure with electrometer

Table 13. Descriptive statistics of radon in soil results expressed in kBq m^{-3}.

	"Green Ballesteros"	"Offices site"
Mean	734	340
Median	840	20
SD	152	566
p	5	3

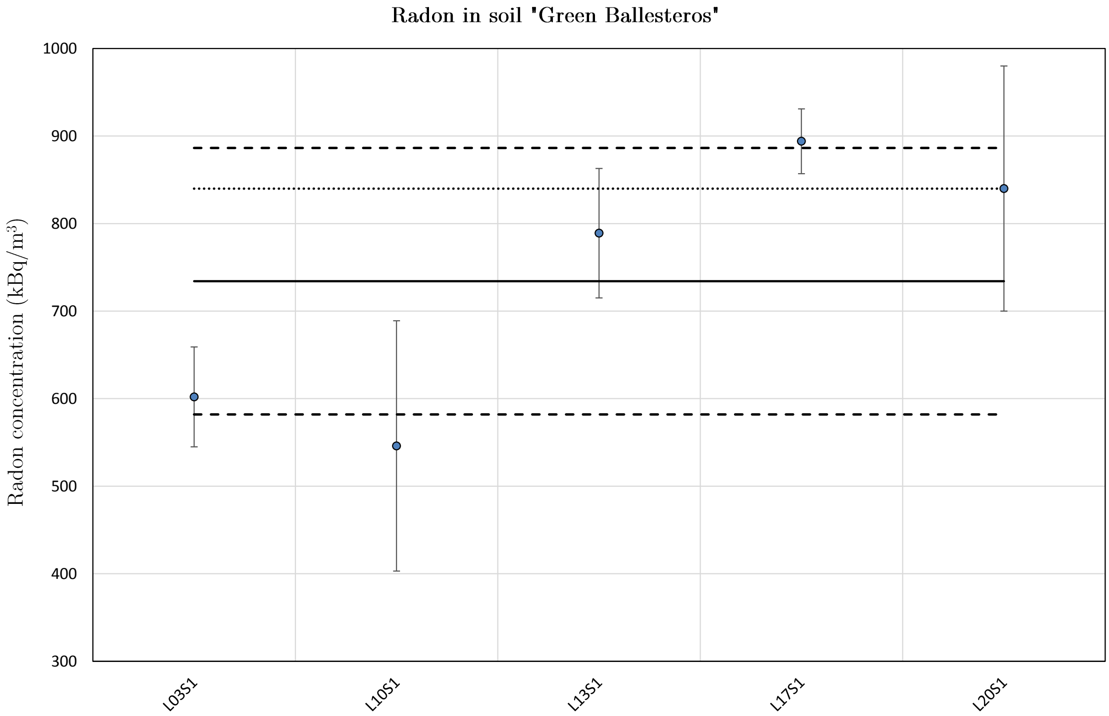

Fig. 16. Radon in soil results with its associated uncertainty ($k = 1$) in "Green Ballesteros". The solid line denotes the mean value, the dotted line the median and the dashed lines denote the standard deviation from the mean.

4 Conclusions

An inter-laboratory exercise of indoor radon and geogenic radon measurements under field conditions has been carried out in the Laboratory of Natural Radiation (LNR) between 5 and 8 December 2018. The facility is located in the former uranium mine managed by the Spanish National Uranium Company ENUSA (Saelices el Chico, Salamanca, Spain). Radon in air measurements were assessed from two exposure periods, while the geogenic radon parameters were evaluated from radon exhalation from soil and radon concentration in soil gas measurements.

Radon in air reference values for each exposure were obtained through consensus from participant's results applying an iterative algorithm according to ISO 13528:2015. The indexes used to analyse the participants results are relative percentage difference $D(\%)$, Zeta score (ζ) and z-score (z).

Over 80% of the results for radon in air exposure are within the interval defined by the reference value and the standard deviation, established as 20% and 10% for the first and the second exposure respectively. The exercise was successful, taking into account the large number of different devices used, especially in passive detectors where holder materials, diffusion chamber volume, detectors area or detection principle were diverse.

Five results of the first exposure are considered outliers. All of them are passive detectors and are overestimating the exposure from approximately 40% to 160%. Such deviations could be related with the degassing time of detector holder materials. Radon could get adsorbed in it for a long time so even after two days, when the detectors were put in radon proof bags and sealed. A further difficulty in this intercomparison exercise is that the exposures are reached in a short time period with high radon concentrations in air. At the end of the first exposure period there was a radon concentration in air around 30 kBq m^{-3} which can cause the holder degassing problem previously mentioned. In case of the second exposure, the radon concentration was under 2 kBq m^{-3} at the end of that period, therefore reducing the exposure increase due to the possible effect of adsorption and degassing.

Most z-score results are satisfactory, about 90% of the results have a value lower than 2 for both exposures. Only the results for three cases for the first exposure and one result for the second exposure period are not satisfactory, with z-score values higher than 3.0.

Regarding the Zeta score, about 60 % of results are satisfactory ($|\zeta| \leq 2.0$), however, 29% of results for the first exposure and 20% for the second exposure period are not satisfactory, with a Zeta score $|\zeta| \geq 3.0$.

Every participant has assessed their own results and revaluated their method if it necessary according to the indexes obtained.

Radon exhalation measurements were carried out in “Green Ballesteros” only by three participants. The participants did not perform the measurements during the same time due to the different methodologies involved. The weather in each case was different which could explain the widespread of results.

L03E1 and L17E1 measurements overlapped in time, but they differ in two orders of magnitude. Participant L03 used absorption in polycarbonate, which is a cumulative measurement, with a duration of two days. Participant L17 used an accumulation method with a radon monitor with a sampling time of approximately one hour. This method provides a discrete value of exhalation. On the other hand, participant L20 performed the measurements using the absorption in activated charcoal canisters during 24 hours, however the measurements were performed one week later.

During the first period of measurements, L03E1 and L17E1, the weather was mostly rainy and the soil was soaked, which would impede the exhalation. The discrete measurement L17E1 was carried out in a sunny period, the temperature raised and the relative humidity decreased. The sun would dry the soil and lead to an increase in the radon exhalation. This effect could be a possible explanation for the observed difference between the results of the two measurements. In the week of the L20E1 measurement, which is the highest value of exhalation rate, the weather was dry and sunny, in contrast to the weather during the other measurements.

Therefore, a consensus value for radon exhalation rate cannot be obtained due to the dispersion of the results. Results indicate a significant effect of the weather on the radon exhalation rate, which deserves a more thorough study.

Radon in soil measurements were carried out in “Green Ballesteros” by 5 participants and, additionally, in “Offices site” by 3 participants. Results in “Green Ballesteros” are approx. between 550 and 900 kBq m^{-3}. All participants provided acceptable values taking into account the arithmetic mean value and its standard deviation. This fact could be explained due to the homogeneity of the area. The observed differences agree with the typical spatial variability of radon in soil measurements. On the other hand, the lack of homogeneity in the “Offices site” provides an extremely high dispersion of results. Homogeneity and a historical data collection are necessary to carry out an intercomparison of geogenic radon measurements with such a low number of participants.

Appendix I: Radon in air exposure results

This appendix contains the results submitted by the participants for each exposure and the indexes used to assess their performance.

Table 14. Participant's results and their statistical indexes, relative percentage difference *D*(%), Zeta score (ζ) and z-score for the **first exposure E1**.

Code	E1 (kBq m^{-3} h)	*u* (E1) (*k*=1) (kBq m^{-3} h)	*D*(%)	ζ score	z-score
L01P1	350	12	-1.7	-0.4	-0.1
L01P2	602	30	69.1	7.9	3.5
L01P3	948	29	166.3	19.7	8.3
L02A1	350	4	-1.7	-0.7	-0.1
L02A2	321	4	-9.8	-3.9	-0.5
L02P1	487	7	36.8	12.3	1.8
L02P2	488	7	37.1	12.4	1.9
L03P1	317	38	-11.0	-1.0	-0.5
L04P1	340	45	-4.5	-0.4	-0.2
L05A1	328	21	-7.9	-1.2	-0.4
L05A2	328	21	-7.9	-1.2	-0.4
L05P1	357	46	0.3	0.0	0.0
L06A1	328	14	-7.9	-1.7	-0.4
L06P1	326	33	-8.4	-0.9	-0.4
L06P2	349	39	-2.0	-0.2	-0.1
L07P1	400	25	12.4	1.7	0.6
L08A1	244	3	-31.5	-13.1	-1.6
L09P1	378	27	6.2	0.8	0.3
L10P1	393	17	10.4	2.0	0.5
L11P1	431	38	21.1	1.9	1.1
L12A1	327	7	-8.1	-2.7	-0.4
L12A2	315	6	-11.5	-4.1	-0.6
L12P1	400	5	12.4	4.7	0.6
L13P1	400	12	12.4	3.1	0.6
L14A1	317	20	-11.0	-1.8	-0.5
L14P1	378	19	6.2	1.1	0.3
L15A1	356	4	0.0	0.0	0.0
L15A2	316	6	-11.2	-4.0	-0.6
L16P1	660	13	85.4	19.9	4.3
L17A1	346	21	-2.8	-0.4	-0.1
L17A2	340	21	-4.5	-0.7	-0.2
L17A3	312	20	-12.4	-2.0	-0.6

Code	E1 (kBq m^{-3} h)	u (E1) (k=1) (kBq m^{-3} h)	D(%)	ζ score	z-score
L17P1	288	29	-19.1	-2.3	-1.0
L17P2	317	33	-11.0	-1.1	-0.5
L18P1	352	37	-1.1	-0.1	-0.1
L19P1	334	84	-6.2	-0.3	-0.3
L20A1	342	6	-3.9	-1.4	-0.2
L20A2	347	7	-2.5	-0.8	-0.1
L20A3	420	9	18.0	5.3	0.9
L20A4	364	7	2.2	0.8	0.1
L20A5	366	7	2.8	0.9	0.1
L20A6	386	8	8.4	2.7	0.4
L20A7	307	6	-13.8	-4.9	-0.7
L20A8	349	7	-2.0	-0.7	-0.1
L20P1	386	35	8.4	0.8	0.4

Table 15. Participant's results and their statistical indexes, relative percentage difference D(%), Zeta score (ζ) and z-score for the **second exposure E2**.

Code	E2 (kBq m^{-3} h)	u (E2) (k=1) (kBq m^{-3} h)	D(%)	ζ score	z-score
L01P1	1074	19	5.9	2.6	0.6
L01P2	1041	30	2.7	0.8	0.3
L01P3	1052	18	3.7	1.7	0.4
L02A1	1008	2	-0.6	-0.5	-0.1
L02A2	953	2	-6.0	-4.6	-0.6
L02P1	1076	10	6.1	3.8	0.6
L02P2	1076	10	6.1	3.8	0.6
L03P1	796	77	-21.5	-2.8	-2.1
L04P1	1000	75	-1.4	-0.2	-0.1
L05A1	982	60	-3.2	-0.5	-0.3
L05A2	973	59	-4.0	-0.7	-0.4
L06A1	957	44	-5.6	-1.2	-0.6
L06P1	993	66	-2.1	-0.3	-0.2
L06P2	1029	71	1.5	0.2	0.1
L07P1	1000	50	-1.4	-0.3	-0.1
L08A1	828	8	-18.3	-12.2	-1.8
L09P1	1100	105	8.5	0.8	0.8
L10P1	1123	43	10.7	2.4	1.1
L11P1	1067	86	5.2	0.6	0.5

Code	E2 (kBq m^{-3} h)	*u* (E2) (*k*=1) (kBq m^{-3} h)	*D*(%)	ζ score	z-score
L12A1	976	22	-3.7	-1.5	-0.4
L12A2	949	21	-6.4	-2.6	-0.6
L12P1	1115	12	10.0	5.7	1.0
L13P1	1034	31	2.0	0.6	0.2
L14A1	943	66	-7.0	-1.1	-0.7
L14P1	1021	23	0.7	0.3	0.1
L15A1	990	6	-2.4	-1.7	-0.2
L15A2	975	10	-3.8	-2.4	-0.4
L16P1	1728	25	70.4	25.3	7.0
L17A1	992	68	-2.2	-0.3	-0.2
L17A2	970	67	-4.3	-0.6	-0.4
L18P1	950	91	-6.3	-0.7	-0.6
L19P1	810	203	-20.1	-1.0	-2.0
L20A1	1017	10	0.3	0.2	0.0
L20A2	994	9	-2.0	-1.3	-0.2
L20A3	1250	25	23.3	8.4	2.3
L20A4	1088	22	7.3	2.9	0.7
L20A5	1090	22	7.5	3.0	0.7
L20A6	1157	23	14.1	5.4	1.4
L20A7	1011	20	-0.3	-0.1	0.0
L20A8	997	20	-1.7	-0.7	-0.2
L20P1	934	47	-7.9	-1.6	-0.8

Appendix II: Questionnaire sent to participants

LaRUC
Laboratorio de Radiactividad Ambiental

MetroRADON

MetroRADON: Intercomparison on indoor radon at LNR

November 5th - 8th, 2018

Saelices el Chico (Salamanca, Spain)

► Participant information

Organization name: Acronym:

Address:

Country:

Contact person:

E-mail:

Phone number:

► Activities

Indicate in what activities you are going to participate ("Yes" or "No")

Radon in air with PASSIVE detectors:

Radon in air with ACTIVE monitors:

Radon in soil:

Radon Exhalation from soil:

► Additional information:

How many people are going to attend the intercomparison?[1] :

Indicate the name of the attendees[2]:

Are you going to send the Passive detectors and Active monitors by mail? [3]:

[1] Attendance is mandatory for radon in soil and exhalation activities

[2] Send by E-mail the ID card scanning of every attendee to manage the access to the facilities

[3] If so, they have to be in LaRUC facilities before October, 31th.

More information and shipping address:

LaRUC, Facultad de Medicina
C/Cardenal Herrera Oria s/n 39011 Santander,
University of Cantabria
Spain
E-mail: daniel.rabago@unican.es / laruc@unican.es
(Phone: +34 942 20 22 07)

Appendix III: Results Template

		1st Exposure (kBq h m^{-3})		2nd Exposure (kBq h m^{-3})	
Device	S/N	Value	Uncertainty	Value	Uncertainty

		Date	C (Bq m^{-3})	u(C) (Bq m^{-3})
2nd Exposure	1st Exposure	05/11/2018 12:00		
		05/11/2018 13:00		
		05/11/2018 14:00		
		05/11/2018 15:00		
		05/11/2018 16:00		
		05/11/2018 17:00		
		05/11/2018 18:00		
		05/11/2018 19:00		
		05/11/2018 20:00		
		05/11/2018 21:00		
		05/11/2018 22:00		
		05/11/2018 23:00		
		06/11/2018 0:00		
		06/11/2018 1:00		
		06/11/2018 2:00		
		06/11/2018 3:00		
		06/11/2018 4:00		
		06/11/2018 5:00		
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		08/11/2018 4:00		
		08/11/2018 5:00		
		08/11/2018 6:00		
		08/11/2018 7:00		
		08/11/2018 8:00		
		08/11/2018 9:00		
		08/11/2018 10:00		

1st Exposure (kBq h m^{-3})			2nd Exposure (kBq h m^{-3})		
Detector code	Value	Uncertainty	Detector code	Value	Uncertainty

	Overall Results (kBq h m^{-3})	
	Value	Uncertainty
1st Exposure		
2nd Exposure		

Brief description of detector: (kind of detector, chamber volume)	

	Radon in soil concentration (kBq m^{-3})	
Location	Value	Uncertainty
"Green Ballesteros" (next to the LNR)		
Offices site		

	Radon Exhalation (Bq m^{-2} h^{-1})	
Location	Value	Uncertainty
"Green Ballesteros" (next to the LNR)		

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