REPORT

Inter-laboratory comparison on indoor radon measurements under field conditions

J.L. Gutierrez-Villanueva, C. Sainz Fernandez, I. Fuente Merino,
L. Quindos Lopez, and L.S. Quindos Poncela

23rd January 2015

Laboratorio de Radiactividad Ambiental

Contents

List of Tables

List of Figures

1 Introduction

The new Basic Safety Standards (BSS) [1] for protection against the dangers arising from exposure to ionising radiation were issued in January 2014. The subject matter of the proposed directive is to establish a Community framework for the basic safety standards for the protection of the health of the people. In particular, the Directive applies to the management of existing exposure situations, including the exposure of members of the public to indoor radon, the external exposure from building materials and cases of lasting exposure resulting from the after-effects of an emergency or a past activity. The Annex XVIII of the document summarizes the list of items to be covered in the national action plan to manage long-term risks from radon exposures. Radon gas is the biggest contributor to the total amount of radioactive dose for the general public. However, the legislation in differs among countires; from obligatory control of radon gas in countries such as the Republic of Ireland, the Nordic countries and the Czech Republic, to recommended monitoring in countries such as Spain or Italy as an example.

Application of the new European Directive will require competent measurement services in all member states. Thus it is very important to assess that values provided by different laboratories are accurate. One of the most common ways to assure the quality of the results of laboratories is by means of inter-laboratory comparisons carried out by approved services of reference laboratories. Here we can cite those inter-comparison exercises done annually by Bundesamt für Strahlenschutz (BfS) in Germany and Health Protection Agency (HPA) in United Kingdom both on the measurement of radon gas.

Inter-laboratory exercises are a very important tool for measurement services and laboratories in order to detect potential problems and perform rectifications as well as to provide calibrations for instruments using international standards. The common scenario for the typical inter-comparison exercise is the exposure of the instrument to a reference atmosphere of the parameter to control (i.e. radon gas) under temperature, humidity and atmospheric pressure stable conditions. However as we know, these are not the common situations we can find in a normal dwelling when measuring radon gas. Hence the existence of facilities to test instruments for the measurement of radon gas under changing conditions of meteorological parameters becomes necessary.

The Radon group from University of Cantabria in Spain has established a site where the values of natural radioactivity are high enough to test instruments and detectors under typically variations of temperature, humidity and atmospheric pressure which we can find in occupancy places (dwellings and working places). Such a place is located in an old uranium mine site in which was held the first inter-comparison exercise under field conditions in May 2011 [2, 3]. A total number of 41 laboratories from different European countries took part in the activities involving the measurement of radon gas and external gamma radiation. The Radon Group organized a new inter-laboratory performance exercise to measure radon indoors exposure in a place with changing parameters of temperature, pressure and humidity in June 2013. This report shows the results of the inter-comparison as well as discussions of the achieved results.

2 Participants

The Laboratory of Natural Radiation located in Saelices el Chico (Salamanca, Spain) hosted the inter-laboratory exercise. The next golden sponsors of the laboratory agreed to fund this inter-laboratory comparison:

- Landauer Nordic (Uppsala, Sweden)
- MI.am (Fabiano di Rivergaro, Italy)
- Radosys (Budapest, Hungary)
- SARAD (Dresden, Germany)

The golden sponsors are leading companies on radon issue in Europe and they provide measurement services for radon indoors using passive detectors. Most of the participants in this exercise are customers of the companies. The full list of participants in the inter-laboratory comparison is described in Table 1.

Table 1: List of participants

Participant	Country	E-mail
A.P.P.A. (AGENZIA PROVINCIALE PER LA PROTEZIONE DELL'AMBIENTE) S.L.C. (SETTORE LABORATORIO E CONTROLLI)	Italy	mauro.bonomi@provincia.tn.it stefano.pegoretti@provincia.tn.it
ARPACAL	Italy	s.procopio@arpacal.it
ARPA FVG	Italy	silvia.pividore@arpa.fvg
ARTA Abruzzo	Italy	l.carnesale@artaabruzzo.it s.palermi@artaabruzzo.it
EUROPEAN COMMISSION Joint Research Centre (Nuclear decommissioning Unit Radiation Protection Sector Dosimetry Service)	Italy	Gianfranco.minchillo@ec.europa.eu Daniele.giuffrida@ec.europa.eu
FGM AMBIENTE	Italy	luisa.salvatori@gmail.com
Hainaut Vigilance Sanitaire	Belgium	marie_alice.cailleaux@hainaut.be
ISPRA	Italy	giancarlo.torri@isprambiente.it annamaria.sotgiu@isprambiente.it
Laboratório de Radioactividade Natural Universidade de Coimbra	Portugal	apereira@dct.uc.pt
Landauer Nordic	Sweden	Karl.Nilsson@landauernordic.se
MI.AM SRL	Italy	info@miam.it
Unitat de Física de les Radiacions, Universitat Autònoma de Barcelona	Spain	Victoria.moreno@uab.cat
Universidad de Extremadura	Spain	jdltp@unex.es
Universidad de Santiago de Compostela	Spain	juanm.barros@usc.es joaquin.peon@usc.es
Università del Salento Servizio di Prevenzione e Protezione	Italy	manuel.fernandez@unisalento.it
University of Cantabria	Spain	laruc@unican.es
Radosys	Hungary	ehulber@radosys.com
Regional Agency for Ligurian Environmental Protection ARPA GENOVA	Italy	silvio.incardone@arpal.gov.it massimo.bussallino@arpal.gov.it
Track Analysis Systems Ltd	UK	maria@tasl.co.uk

Laboratories come from seven European countries (Belgium, Hungary, Italy, Portugal, Spain, Sweden and the UK) and 19 institutions (universities, research institutes, public bodies and private companies). Some parties sent more than one set of radon detectors and only one laboratory did not report results. In this report, participants are nameless and the results are identified by a unique alphanumeric code (IFC13_ij, where ij is a 2-digit number) in order to preserve the confidentiality of the laboratory. In some cases, the same laboratory participates with more than one series of detectors. This is identify as IFC13_ijX where X is a letter (A, B, C, D or E). Exception is made for laboratory IFC13_07A and IFC13_07B where the two codes are two different laboratories.

3 Description of the facilities

The laboratory is located in a site where the values of natural radioactivity allow testing instruments and detectors under typically variations of temperature, pressure and atmospheric pressure. These are conditions which we can find in occupancy places (dwellings and working places). The premises are located in an old uranium mine site and held the first inter-comparison exercise under field conditions in May 2011 [2].

The mine site was shut down in 2004 and since then, the restoration process has been taking place. During these activities, one of the buildings used for monitoring activities in the mine was chosen to become a Laboratory of Natural Radiation (LNR) in order to be used for the calibration and testing of instruments and detectors for the measurement of natural radiation. The Radon Group in collaboration with ENUSA and the Spanish Nuclear Safety Council (CSN) was in charge of the activities of adaptation of this building to the new situation. Radon concentrations and external gamma radiation are subjected to daily variations due to changes in environmental conditions. Thus, the laboratory of natural radiation is the perfect place for the performance of experiments devoted to the analysis of environmental radioactivity as well as a location for testing instruments specialized on the measurement of natural radiation. Figure 1 shows a general view of the main building of LNR.

The building is a two-storey house with four rooms in the ground floor. There is one room in the ground floor used for radon in water calibration purposes. There is another room with 30 working spaces for participants in

Figure 1: The laboratory of Natural Radiation (LNR) located in the facilities of ENUSA uranium mine in Saelices el Chico (Salamanca, Spain)

the exercises and two more spaces designed as radon chambers. One of these chambers has an artificial ventilation system installed. Both radon chambers have the same volume and the radon source comes from underground soil. Therefore, this source is of natural origin and it is affected by external meteorological parameters (temperature, humidity, pressure) as we observe in Figure 2.

The upper floor of the building consists of a conference hall and a big room which can also be used as radon chamber for studying very low exposures (radon concentrations are usually within the range 200 - 100 Bq m^{-3}). This room has also a ventilation system to reduce radon levels if required.

4 Parameters of the exercise

The inter-laboratory exercise consisted on the exposure of radon passive detectors to a radon atmosphere in a room (approximately 45 m^3 volume). As

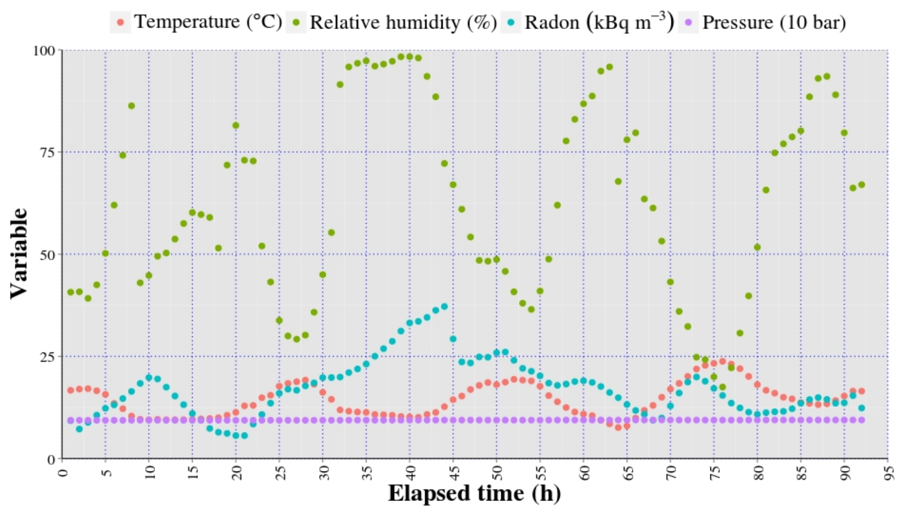

Figure 2: Graphical view of external parameters (temperature, relative humidity and pressure) the LNR premises

we explained before, this room is affected by daily variations of temperature, humidity and pressure. Therefore we try to simulate the same conditions as one can expect in a real occupancy place (either workplaces or dwellings). The inter-comparison was carried out from 17th to 20th July 2013, summer season on the locations. Given that, the changes on temperature can be high (10 - 15 ^{0}C in a 24-hour period), being the rest of parameters quite stable. Radon gas comes from underground soil of the building which has high content on radium and uranium.

4.1 Reference values

Aiming to obtain a reference value to be used for analysis the results of participants, we used Radon Scout monitors installed in different points inside the room. These are semiconductor detectors which can detect the alpha particles emitted by radon decay daughters (^{218}Po and ^{214}Po) with a sensitivity of 1.8 cpm at 1000 Bq m^{-3}. All these monitors are traceable to ATMOS 12 [4] which in turn is traceable to Physikalisch - Technische Bundesanstalt (PTB) in Germany. The measurement range is from 0 to 10 MBq m^{-3} and they also provide extra information on temperature and humidity [5]. We selected an integration time of 1 hour. Figure 3 shows the position of the radon monitors used in the inter-comparison.

Figure 3: Position of radon Scout monitors used during the inter-laboratory exercise to obtain a reference level of radon exposure

We tested the homogeneity of radon gas concentration in the room by means of a very simple statistical analysis of the obtained data. Each monitor provided 91 values of radon exposure and we have compared the results of the six devices to find out whether we can assume that all monitors have the same response to the radon concentration. In addition to that, we can check that radon concentration is constant in all points of the room. This is very important due to the large number of passive detectors exposed during the exercise. The room is not big and we must allocate the detectors in different points of the exposure area.

First, we can pay attention to the the box plot of the results corresponding to six monitors showed in Figure 4. The horizontal line through the box indicates the median or second quartile. Looking into the boxes' size of the six devices we observe the interquartile range is quite similar and thus, the expected variability of the data is similar in all cases. Also, the boundaries of the boxes (1st and 3rd) quartiles respectively correspond to comparable values. We can see that there are some outliers registered by the radon Scouts but only in the case of high radon concentrations. These can be related to peaks on the radon exposures in the room. However we cannot identify outliers for low concentrations.

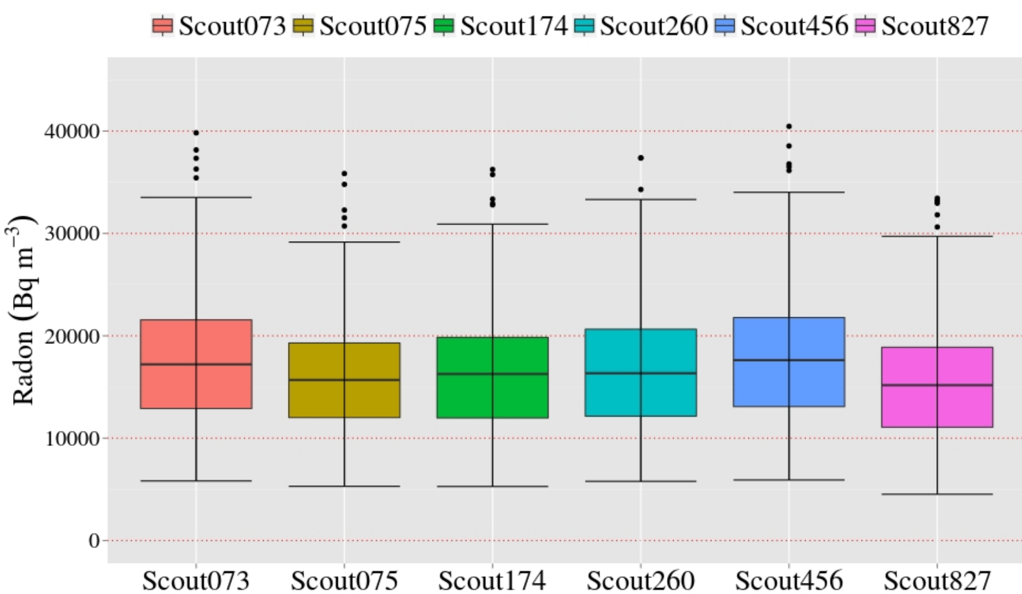

Figure 4: Exploratory graph showing results of six radon monitors installed in the inter-comparison's room

Now we can analyse if the time series data of the six radon Scouts are comparable or not. From Figure 4 it seems reasonable that this assumption is correct. As we can expect, the radon distribution registered by the measurement equipments is log-normal in all of them (p-values ranging from 0.288 to 0.5362). We performed a non-parametric statistical test (Kruskal-Wallis) and we concluded that there is no statiscal evidence to suggest differences exist among the radon distributions of the six radon Scouts installed in the room used during the inter-comparison. Also, the Fligner-Killeen test of homogeneity of variances shows that variances are similar in all the six radon monitors used as reference.

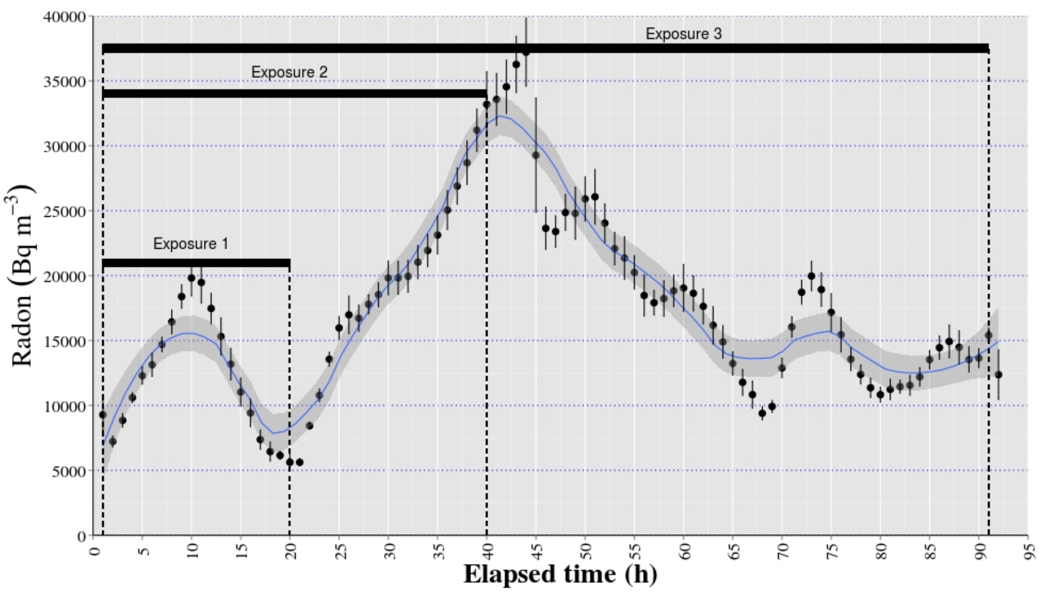

Figure 5: Radon concentration in the room during the exercise. Grey colour represents polynomical smooth of the time series

We have calculated the mean value every hour considering the six monitors and the result is considered to be the reference exposure level for analysing data provided by participants. Figure 5 represents the variation on the radon concentration during the exercise. If we look at this figure, we note big changes on radon concentration in the room during the entire exercise. We also observe that the individual uncertainties of data are low (between 5 and 15 %). The minimum value of radon concentration was 5626 Bq m^{-3} and the maximum was 37204 Bq m^{-3}. Meanwhile, the three exposures to be considered represent non constant radon concentration (see Table 2 to observe the reference values considered during the exercise). This is exactly one of the objectives of the inter-laboratory comparison: to test the response of radon passive detectors under real conditions of changes on radon activity concentrations one can find in a real occupancy building.

As we can notice, the parameters of this type of inter-comparison are very different from those normally used for testing radon detectors. In reference laboratories, detectors are exposed to constant radon values and it is not common to perform low radon exposures.

Table 2: Reference values for the exposures considered in the inter-laboratory comparison

Exposure	**Start**	**Stop**	**Time (h)**	**Exposure (kBq m^{-3} h)**	**Uncertainty (kBq m^{-3} h)**
1	15:10 (17/06/2013)	11:00 (18/06/2013)	20	242	38
2	15:10 (17/06/2013)	10:30 (19/06/2013)	43	742	99
3	15:10 (17/06/2013)	09:45 (21/06/2013)	91	1573	214

4.2 Conditions of detectors

All participants delivered detectors some weeks before starting the inter-comparison but not all travelled inside radon-proof bags. Each exposure consisted on 10 radon detectors and 5 detectors were used as transits. The measurement devices started the three exposures altogether and they were removed in groups of tens as exposures ended. Figure 6 shows how radon detectors were situated inside the room used for radon exposures. After moving detector from the exposure room, we waited for a minimum of two hours for degassing. Then, we packed detectors in aluminium holders and sent them back to participants for analysis. We requested laboratories to submit results in terms of radon exposure values including transits. Every participant received an individual sheet with their own data and the result obtained in the three exposures. We want to remark here that some participants delayed long time the results submission which is one of the impediments to produce this report earlier.

5 Results and discussion

As we explained in previous section, we requested participants to submit their results in terms of radon exposure for the three types of situations together with uncertainties and transit values. We also asked for information on the type of detector used, such as detector material, total detector size, detector thickness, use and type of filter, half time for diffusion and measuring range of the exposure to radon. Unfortunately not all participants sent back this

Figure 6: View of position of radon detectors inside the intercomparison room

information and we cannot make a proper analysis of the results based on this information. Thus, the results and their discussion are based only on the numerical values reported. We have calculated the mean and standard deviation of the three exposures and we have also used the recommended parameters by ISO for standardizing the results of the three exposures [6]. These parameters together with their description are:

1. Percent difference

$$PD = \frac{Exp_{lab} - Exp_{ref}}{Exp_{ref}} \cdot 100\% \tag{1}$$

2. E_n number

$$E_n = \frac{Exp_{lab} - Exp_{ref}}{\sqrt{SD_{lab}^2 + SD_{ref}^2}} \tag{2}$$

3. *z-score*

$$z - score = \frac{Exp_{lab} - Exp_{ref}}{SD_{lab}} \tag{3}$$

4. MES

$$MES[\%] = \sqrt{PD^2 + PER^2}, \tag{4}$$

   where $PER = \frac{SD_{lab}}{Exp_{ref}} \cdot 100$

5. REF

$$REF = \frac{Exp_{lab}}{Exp_{ref}} \tag{5}$$

Tables 3, 4 and 5 in Appendix A show the results for each exposure applying the parameters described before.

We begin the analysis of the results firstly looking into the distribution of submitted values per participant in all the three exposures[1]. Figure 7 shows the histograms of these distribution and we observe in all cases that data are normally distributed. This finding is also confirmed by means of Shapiro-Wilk normality test reporting p-values in all cases bigger than $\alpha = 0.05$. Hence it makes sense to use mean values and standard deviations for each of the exposures to compare results between laboratories.

Now we will analyse each exposure. First of all, laboratories obtained in the lowest exposure a mean value of 303 kBq m^{-3} h (with standard deviation of 53 kBq m^{-3} h) which is 25 % higher than the reference value for this exposure. Figure 8 shows in a graph the individual results with standards deviations compared with the reference value.

It is important to remark that, in this exposure, that most of the laboratories give results around mean value of all participants except 6 of them. If we compare results with reference value, only 6 sets of detectors obtained a mean

[1] We have used R software to perform the statistical analysis of this report [7]

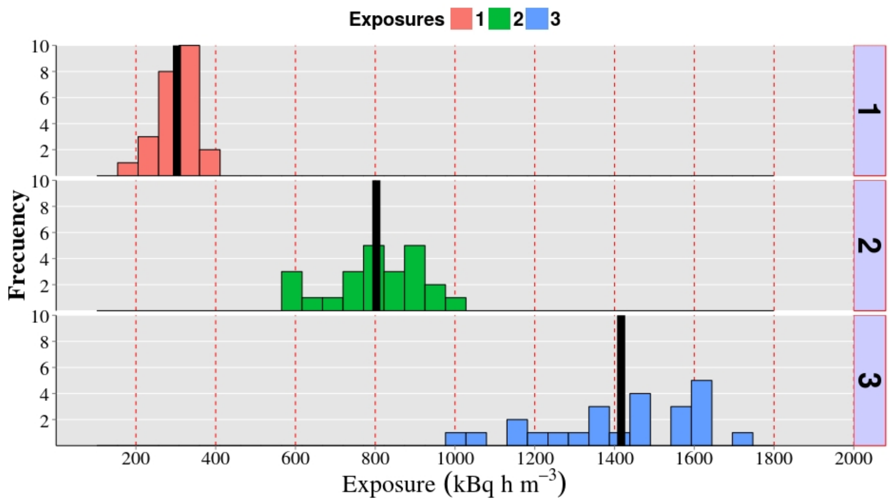

Figure 7: Histograms representing distribution of submitted results in each of the three exposures. Black lines represent mean values

value for this exposure which falls within the shadowed area around reference value, and it corresponds with 32 % of the laboratories. Also, the reference value for the low exposure has the biggest uncertainty of the three exposures. These two factors illustrate the difficulty to measure with accuracy and precision low radon exposures and, therefore, low radon concentrations.

The second radon exposure is represented on Figure 9. This exposure is considered as medium exposure and corresponds to a radon concentration of approximately 340 Bq m^{-3} during 3-month period. In this case, the difference between mean values of participants and reference parameter is much lower (8 %) which is a quite acceptable outcome. Nevertheless, we can observe a trend on the participants to provide systematically larger values than the reference one. As well as for exposure 1, laboratories labelled as IFC13_06 and IFC13_20A present a big standard deviation on their results.

Finally Figure 10 offers a view of the results in the inter-laboratory comparison for the highest radon exposure. We can look at the figure and realize that most of the laboratories offer a good agreement with the reference level. The difference between mean value reported by participants (with standard deviation of 195 kBq m^{-3} h) and the reference value is approximately 9 %. However, if we take into account the bound marked by one standard

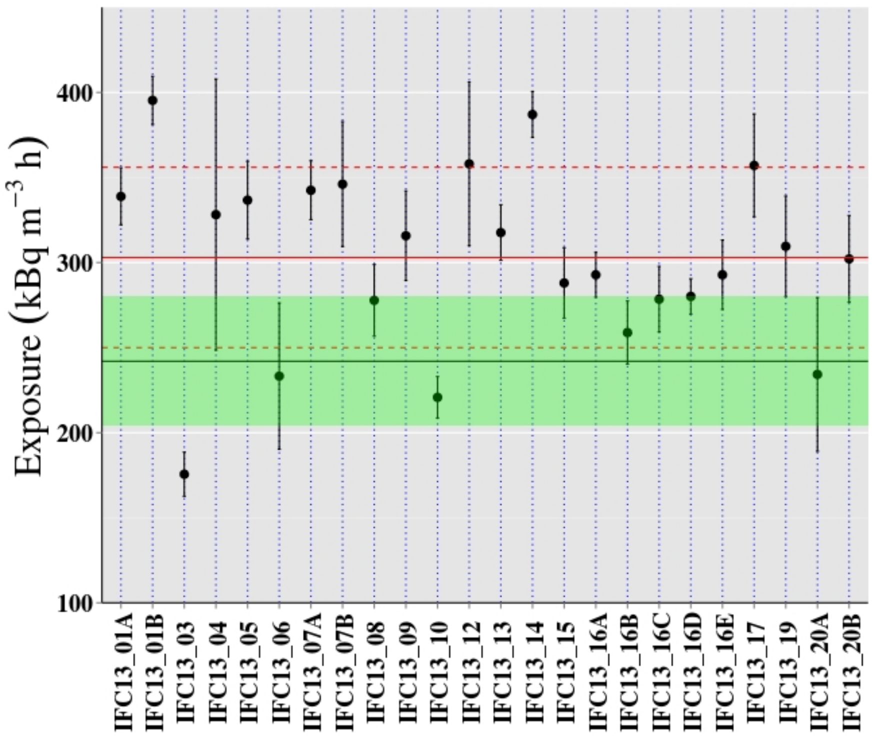

Figure 8: Results of exposure 1. Horizontal black line represents the the reference value and red line the mean of the participants. The shadowed area in green represents the uncertainty around the reference value. Red dashed lines are one standard deviation up and down mean value of participants

deviation from mean value, the difference is negligible. It is noteworthy to examine the range of the results. In addition we can note that there is 70 % difference between minimum and maximum value reported and nearly all laboratories offer small standard deviations respecting their mean values.

It is interesting to look into the possible reasons for the differences between results and the value we consider as a reference. We must remember the most common sources of uncertainty when dealing with radon passive measurements are [8, 9, 10]:

- Uncertainties during counting process of etched track detectors associated with repeatability

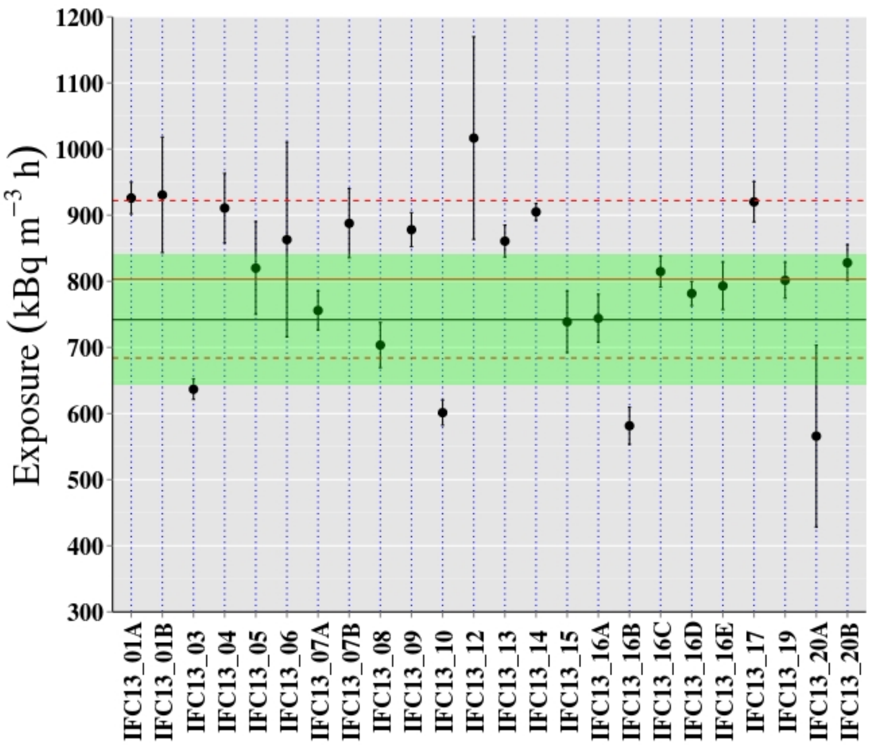

Figure 9: Graph showing values reported by participants for exposure 2. Black and red lines correspond to the reference value and mean value of participants respectively. The shadowed area in green represents the uncertainty around the reference value. Dashed red lines are one standard deviation (119 kBq m^{-3} h) from that mean value

- Variations on the material of detectors from the same batch which affect to the sensitivity of chips
- Effects of ageing fading on detectors

We have performed a list of results based on one scheme modified from that one proposed by PHE[2] (Public Health England, UK) in 2011. Our scheme combines the bias error of the laboratory compared with reference value and the precision error the laboratory has based on the repeatability of the results. To do this, we use the parameter defined as MES in equation

[2]Former HPA (Health Protection Agency, UK)

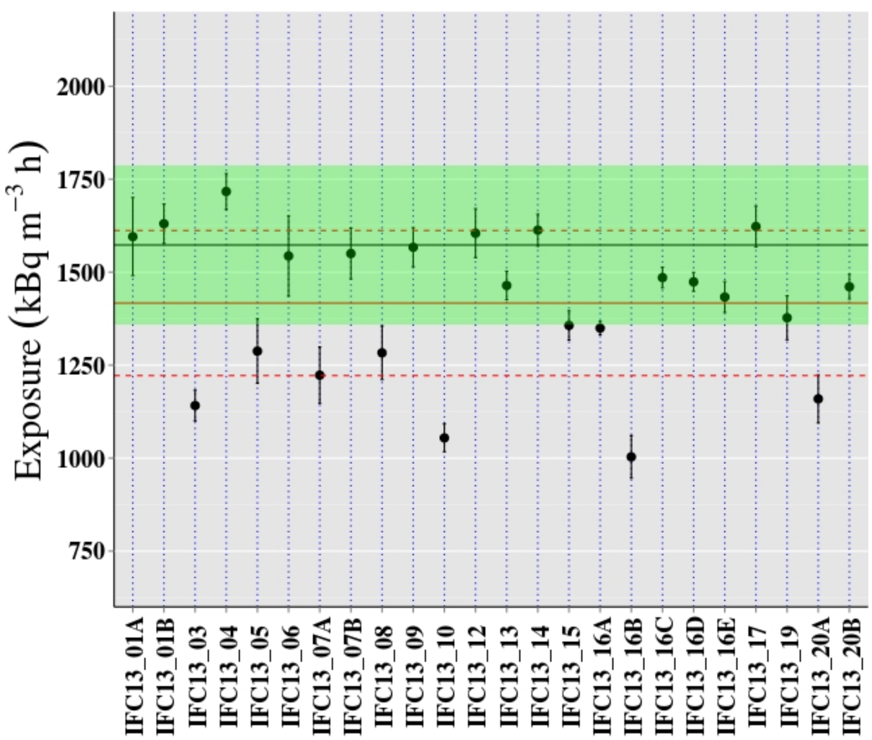

Figure 10: Results corresponding to the highest radon exposure. The shadowed area in green represents the uncertainty around the reference value. Black and red lines have the same meaning as in previous figures

4. So, we have listed the laboratories using the next criteria and the results are included on Table 6 (Appendix B). This table does not pretend to rank participants. Even more it aims to serve as a tool which can help them to investigate their own results.

- Category A: MES <20 %
- Category B: MES ≥20 % and < 35 %
- Category C: MES ≥35 % and < 50 %
- Category D: MES ≥50 %

We can conclude from that table that the measure of low radon exposures in quite complicated. Only 20 % of the participants obtained results within category A. Also, as the radon exposure increases, the results improve. There are no laboratories with a value of MES larger than 50 % nor in medium or highest exposure. For the case of exposure 3, all results belong to category A or B except for one case.

The last part of the analysis consists on the evaluation of the results between laboratories by means of Mandel's h statistic [11, 12] and Youden graph [13, 11]. Figure 11 represents Mandel's h statistic calculated for all laboratories and exposures. If we have n participants in an inter-laboratory test and each laboratory reports X_i as the mean value for a certain reference level, then $\bar{X}$ is the mean value of all results. Therefore, Mandel's h statistic is calculated for each laboratory as follows:

$$h_i = \frac{X_i - \bar{X}}{S}, i = 1 \dots n \tag{6}$$

We suppose that the random variables X_i are independent are normally distributed. This is the case of an inter-laboratory comparison. Also, we have shown that the results in our inter-comparison are normally distributed for the three exposures. In equation (6) S is:

$$S^2 = \frac{Q}{n-1}, \tag{7}$$

and

$$Q = \sum_{i=1}^{n} \left(X_i - \bar{X}\right)^2 \tag{8}$$

Mandel's h statistic is an index which permits the evaluation of the between-laboratories consistency. We can see in a graph the standardised bias obtained by one particular laboratory and the mean value of the rest of participants in a particular reference level. We can also define critical confidence levels from this statistic. Figure 11 shows the inter-laboratory data grouped by laboratory and gives a view of the laboratory bias and relative precision in the three radon exposures. Looking into this figure, we notice that 6 laboratories have a trend to give lower values than the whole group and particularly three of them, identified as IFC13_03, IFC13_10 and IFC13_20A have a response significantly lower than the group in all exposures. The situation for the laboratories giving higher values is always within the interval corresponding to 1 % confidence level.

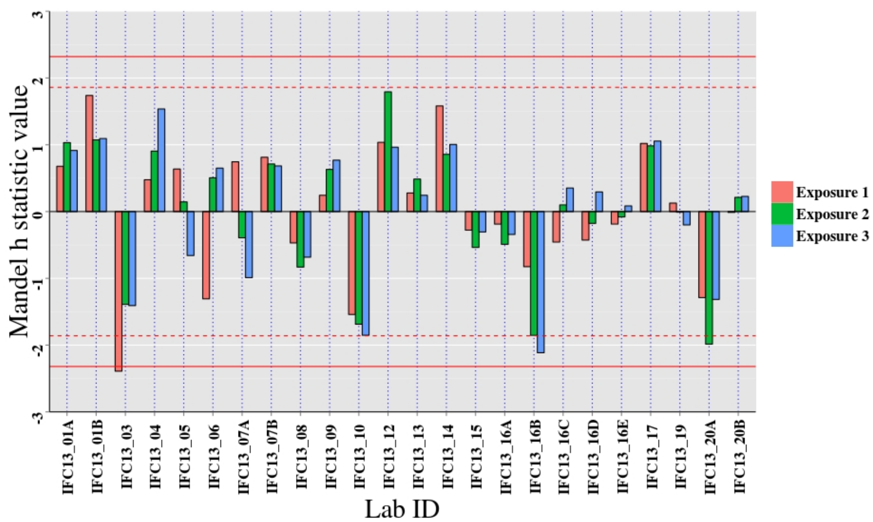

Figure 11: Mandel's h statistic for the three radon exposures. Red line represents 5 % confidence level and dashed line 1 %.

We have explored the results between laboratories by means of the Mandel's h statistic. However, we are also very interested on determining the performance of each participant with a reference value of the parameter radon exposure. To do this, we could use the parameter known as *z-score* defined in equation 3. This way to test performance is widespread used. Nevertheless, it is possible to check out how laboratories achieve results using a graphical tool called Youden plot. In this graph, we represent pairs of values corresponding to the results of the same participant in two levels of the studied level of the parameter. Each plot is divided in four quadrants being the circle around the centre of the plot a representation of the 95 % confidence level around this centre. If there would be only random errors, we would expect to find a cloud of points homogeneously distributed around the center. Upper right and lower left quadrants represent laboratories which with systematically higher or lower values than the rest. We can interpret this finding as sources of systematic errors in the participants.

Figures 12, 13 and 14 show the Youden graphs of participants compared by pairs of the level of radon exposure. The graphs are an adaptation of the original concept of Youden graph since we have standardised the results by analysing the differences with the median values for each exposure. We can observe that when we compare exposures 2 and 3 (figure 14), some laboratories systematically give results higher or lower than the reference value. On the contrary, comparing exposures 1 and 2 and 1 and 3 the majority of the participants are within the 95 % confidence level circle.

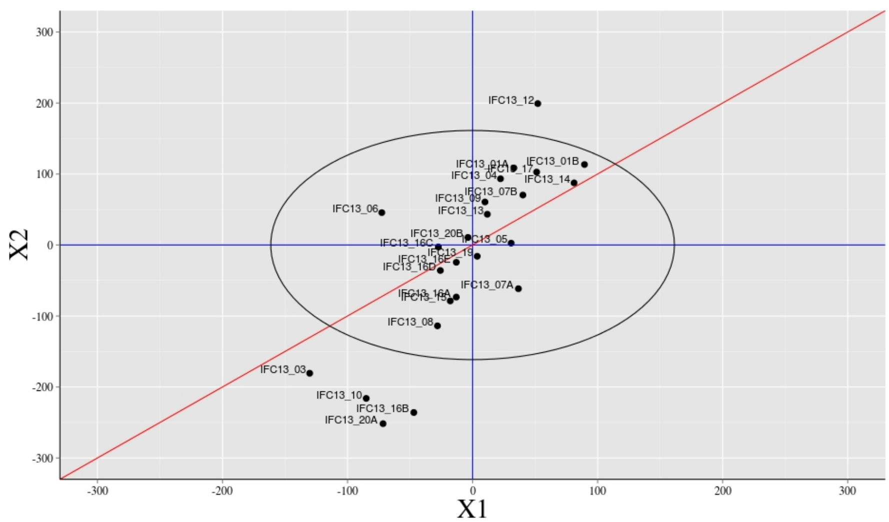

Figure 12: Youden graph comparing results of exposures 1 and 2

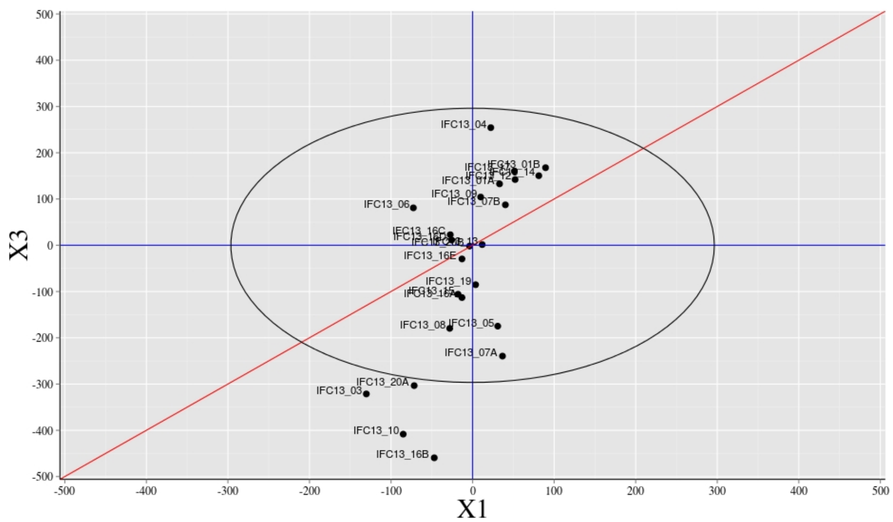

Figure 13: Youden graph comparing results of exposures 1 and 3

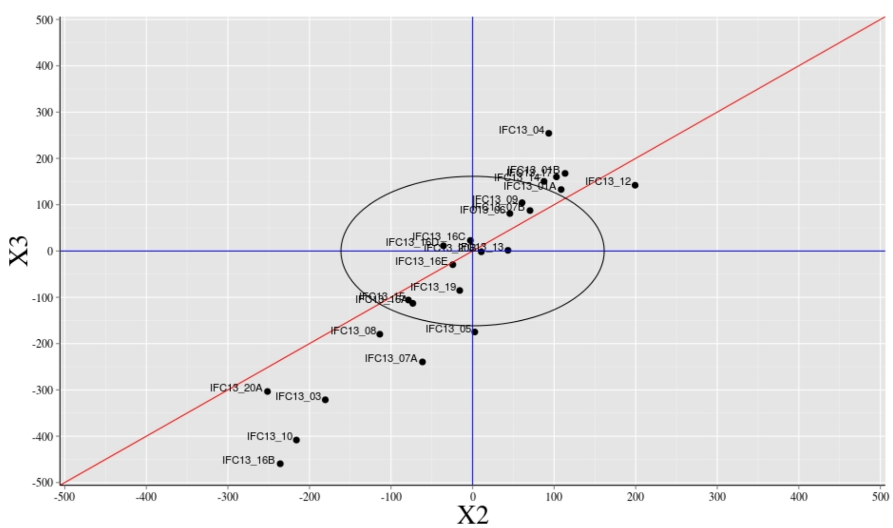

Figure 14: Youden graph comparing results of exposures 2 and 3

6 Conclusions

We have performed an inter-laboratory exercise with the participation of 19 institutions coming from different EU countries. Participants submitted a total number of 24 detector series which represents a good number of participants to carry out an acceptable inter-laboratory exercise. After a detailed analysis of the data, we can conclude the next important outcomes from this experience:

- The results of participants are comparable in all exposures and there are not outliers except for the case of the lowest exposure where one laboratory has reported an anomalously lower value than the group.

- We have shown in this exercise the importance of carrying out inter-laboratory comparisons *in situ* where radon concentrations can change dramatically in a short period of time. Some of the discrepancies observed in the data could be due to problems with the reading systems of track-etched detectors. Therefore, both type of inter-comparisons, constant values of radon exposures and changing values, are needed to assess a good performance of the measurement laboratories.

- Low exposures are complicated to measure due to the large uncertainties observed. This is a problem when laboratories have to measure low radon concentrations.

- Some laboratories seem to have problem with systematic errors which can be attributed to several reasons and they will require internal further evaluation.

7 Acknowledgements

We would like to say thanks and express our gratitude to the National Uranium Company of Spain (ENUSA) for its interest over a long period of time on natural radioactivity and the activities of the Radon Group (University of Cantabria, Spain). We want to pay homage to the staff of the facilities located at ENUSA in Saelices el Chico (Salamanca, Spain).

We also extend our acknowledgement to the Spanish Nuclear Safety Council (CSN) for its support in the activities of the radon group throughout the years.

Special mention is for the Golden Sponsors of the Laboratory of Natural Radiation: Landauer Nordic, Mi.am, Radosys and SARAD. This interlaboratory exercise and the activities at LNR would have not been possible without their support.

The last but not least expression of gratitude is for the participants of the exercise and especially their patience waiting for this report.

We come to the end in this section by saying thanks to the rest of LaRUC's staff involved in this exercise: Jorge Quindos Lopez, Enrique Fernandez Lopez, Santiago Celaya González, Sara Eva Casal Ordas and Alicia Fernández.

Appendix A: Summary of results per exposure

Table 3: Results of inter-laboratory test on radon indoors for exposure 1

LabID	Mean	SD	REF	PD	z-score	E_n	MES
IFC13_01A	338.90	16.76	1.40	40.04	5.78	2.33	40.13
IFC13_01B	395.35	14.12	1.63	63.37	10.86	3.78	63.41
IFC13_03	175.60	12.96	0.73	−27.44	−5.12	−1.65	27.54
IFC13_04	328.17	79.69	1.36	35.61	1.08	0.98	36.07
IFC13_05	336.70	22.84	1.39	39.13	4.15	2.14	39.25
IFC13_06	233.26	43.02	0.96	−3.61	−0.20	−0.15	5.55
IFC13_07A	342.52	17.34	1.42	41.54	5.80	2.41	41.62
IFC13_07B	346.08	36.63	1.43	43.01	2.84	1.97	43.19
IFC13_08	277.80	21.04	1.15	14.79	1.70	0.82	15.08
IFC13_09	315.78	26.28	1.30	30.49	2.81	1.60	30.66
IFC13_10	220.80	12.19	0.91	−8.76	−1.74	−0.53	9.04
IFC13_12	358.00	48.04	1.48	47.93	2.41	1.89	48.14
IFC13_13	317.64	16.31	1.31	31.26	4.64	1.83	31.37
IFC13_14	387.04	13.49	1.60	59.93	10.75	3.60	59.98
IFC13_15	288.01	20.70	1.19	19.01	2.22	1.06	19.24
IFC13_16A	292.81	13.10	1.21	21.00	3.88	1.26	21.12
IFC13_16B	258.88	18.55	1.07	6.97	0.91	0.40	7.50
IFC13_16C	278.50	19.26	1.15	15.08	1.90	0.86	15.34
IFC13_16D	280.10	10.38	1.16	15.74	3.67	0.97	15.88
IFC13_16E	292.84	20.37	1.21	21.01	2.50	1.18	21.21
IFC13_17	357.09	30.17	1.48	47.56	3.81	2.37	47.69
IFC13_19	309.57	29.47	1.28	27.92	2.29	1.41	28.14
IFC13_20A	234.25	45.15	0.97	−3.20	−0.17	−0.13	5.38
IFC13_20B	302.18	25.51	1.25	24.87	2.36	1.31	25.08

Table 4: Results of inter-laboratory test on radon indoors for exposure 2

LabID	Mean	SD	REF	PD	z-score	E_n	MES
IFC13_01A	926.00	23.83	1.25	24.80	7.72	1.81	24.86
IFC13_01B	930.80	87.32	1.25	25.44	2.16	1.43	25.67
IFC13_03	636.80	15.37	0.86	−14.18	−6.85	−1.05	14.25
IFC13_04	910.82	52.67	1.23	22.75	3.20	1.51	22.91
IFC13_05	820.10	70.12	1.11	10.53	1.11	0.64	10.97
IFC13_06	863.07	147.28	1.16	16.32	0.82	0.68	16.91
IFC13_07A	755.92	29.46	1.02	1.88	0.47	0.13	2.74
IFC13_07B	887.80	52.31	1.20	19.65	2.79	1.30	19.83
IFC13_08	703.60	34.20	0.95	−5.18	−1.12	−0.37	5.60
IFC13_09	878.10	25.66	1.18	18.34	5.30	1.33	18.44
IFC13_10	601.40	19.07	0.81	−18.95	−7.37	−1.39	19.02
IFC13_12	1016.67	153.26	1.37	37.02	1.79	1.51	37.30
IFC13_13	860.80	24.23	1.16	16.01	4.90	1.17	16.11
IFC13_14	904.99	12.86	1.22	21.97	12.68	1.63	22.01
IFC13_15	738.69	46.19	1.00	−0.45	−0.07	−0.03	2.53
IFC13_16A	744.13	36.32	1.00	0.29	0.06	0.02	2.23
IFC13_16B	581.54	27.96	0.78	−21.62	−5.74	−1.56	21.71
IFC13_16C	814.70	23.26	1.10	9.80	3.13	0.71	9.96
IFC13_16D	781.60	18.14	1.05	5.34	2.18	0.39	5.56
IFC13_16E	793.14	35.84	1.07	6.89	1.43	0.49	7.23
IFC13_17	920.22	30.47	1.24	24.02	5.85	1.72	24.10
IFC13_19	801.60	27.17	1.08	8.03	2.19	0.58	8.26
IFC13_20A	565.89	137.41	0.76	−23.73	−1.28	−1.04	24.12
IFC13_20B	828.11	27.18	1.12	11.61	3.17	0.84	11.76

Table 5: Results of inter-laboratory test on radon indoors for exposure 3

LabID	Mean	SD	REF	PD	z-score	E_n	MES
IFC13_01A	1595.52	105.16	1.01	1.43	0.21	0.09	2.96
IFC13_01B	1630.44	52.77	1.04	3.65	1.09	0.26	4.09
IFC13_03	1141.40	40.99	0.73	−27.44	−10.53	−1.98	27.49
IFC13_04	1717.02	48.17	1.09	9.16	2.99	0.66	9.32
IFC13_05	1287.90	86.79	0.82	−18.12	−3.28	−1.23	18.28
IFC13_06	1543.65	107.77	0.98	−1.87	−0.27	−0.12	3.21
IFC13_07A	1223.20	75.62	0.78	−22.24	−4.63	−1.54	22.35
IFC13_07B	1550.20	68.35	0.99	−1.45	−0.33	−0.10	2.54
IFC13_08	1283.10	71.82	0.82	−18.43	−4.04	−1.28	18.55
IFC13_09	1567.05	52.45	1.00	−0.38	−0.11	−0.03	1.86
IFC13_10	1054.50	37.29	0.67	−32.96	−13.90	−2.39	33.00
IFC13_12	1604.89	65.90	1.02	2.03	0.48	0.14	2.88
IFC13_13	1464.27	38.17	0.93	−6.91	−2.85	−0.50	7.09
IFC13_14	1613.18	43.15	1.03	2.55	0.93	0.18	3.04
IFC13_15	1356.89	39.47	0.86	−13.74	−5.47	−0.99	13.83
IFC13_16A	1349.74	18.08	0.86	−14.19	−12.35	−1.04	14.23
IFC13_16B	1003.32	56.82	0.64	−36.22	−10.03	−2.57	36.27
IFC13_16C	1485.56	27.80	0.94	−5.56	−3.15	−0.41	5.72
IFC13_16D	1474.10	25.18	0.94	−6.29	−3.93	−0.46	6.41
IFC13_16E	1433.23	41.37	0.91	−8.89	−3.38	−0.64	9.03
IFC13_17	1622.87	54.78	1.03	3.17	0.91	0.23	3.68
IFC13_19	1377.50	59.19	0.88	−12.43	−3.30	−0.88	12.58
IFC13_20A	1159.39	64.49	0.74	−26.29	−6.41	−1.85	26.37
IFC13_20B	1461.02	33.13	0.93	−7.12	−3.38	−0.52	7.27

Appendix B: Laboratories' self-evaluation

Table 6: Self-evaluation of laboratories

LabID	Exposure 1	Exposure 2	Exposure 3
IFC13_01A	C	B	A
IFC13_01B	D	B	A
IFC13_03	B	A	B
IFC13_04	C	B	A
IFC13_05	C	A	A
IFC13_06	A	A	A
IFC13_07A	C	A	B
IFC13_07B	C	A	A
IFC13_08	A	A	A
IFC13_09	B	A	A
IFC13_10	A	A	B
IFC13_12	C	C	A
IFC13_13	B	A	A
IFC13_14	D	B	A
IFC13_15	A	A	A
IFC13_16A	B	A	A
IFC13_16B	A	B	C
IFC13_16C	A	A	A
IFC13_16D	A	A	A
IFC13_16E	B	A	A
IFC13_17	C	B	A
IFC13_19	B	A	A
IFC13_20A	A	B	B
IFC13_20B	B	A	A

Bibliography

[1] Council of the European Union. Directive 2013/59/euratom of 5 december 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, 2014.

[2] J.L. Gutierrez-Villanueva, C. Sainz Fernandez, I. Fuente Merino, L. Quindos Lopez, J. Quindos Lopez, A. Fernandez Villar, S.E. Casal Ordas, D. Lopez Abascal, D. Arteche Laso, E. Fernandez Lopez, and L.S. Quindos Poncela. *International intercomparison exercise on natural radiation measurements under field conditions.* PUbliCan Ediciones Universidad de Cantabria, 2012.

[3] C. Sainz-Fernandez, A. Fernandez-Villar, I. Fuente-Merino, J. L. Gutierrez-Villanueva, J. L. Martin-Matarranz, M. Garcia-Talavera, S. Casal-Ordas, and L. S. Quindos-Poncela. The spanish indoor radon mapping strategy. *Radiation Protection Dosimetry*, 162(1-2):58–62, Nov 2014.

[4] LaRUC. Traceability report radon scouts monitors. Technical report, University of Cantabria, 2012.

[5] Radon scout - radonmonitor for indoor measurements. `http://www.sarad.de`. Accessed: 2014-12-17.

[6] ISO 17043: Conformity assessment – general requirements for proficiency testing, 2010.

[7] R Core Team. *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing, Vienna, Austria, 2013. ISBN 3-900051-07-0.

[8] Z. . Ibrahimi, C. B. Howarth, and J. C. H. Miles. Sources of error in etched-track radon measurements and a review of passive detectors using results from a series of radon intercomparisons. *Radiation Measurements*, 44(9-10):750–754, OCT-NOV 2009.

[9] O. Hanley, J. L. Gutierrez-Villanueva, L. Currivan, and D. Pollard. Assessment of the uncertainties in the radiological protection institute of Ireland (RPII) radon measurements service. *Journal of environmental radioactivity*, 99(10):1578–1582, OCT 2008 2008.

[10] G. D. Hardcastle and J. C. H. Miles. Ageing and fading of alpha particle tracks in cr-39 exposed to air. *Radiation Protection Dosimetry*, 67(4):295–298, 1996 1996.

[11] Yvan Vander Heyden and Johanna Smeyers-Verbeke. Set-up and evaluation of interlaboratory studies. *Journal of Chromatography a*, 1158(1-2):158–167, JUL 27 2007.

[12] Peter-T Wilrich. Critical values of mandel's h and k, the grubbs and the cochran test statistic. *Asta-Advances in Statistical Analysis*, 97(1):1–10, JAN 2013 2013.

[13] G. B. Wu and H. Meng. Application and improvement of the youden analysis in the intercomparison between flowmeter calibration facilities. *Flow Measurement and Instrumentation*, 7(1):19–24, MAR 1996.