Results of the 2012 HPA Intercomparison of Passive Radon Detectors

Z Daraktchieva, C B Howarth and R Algar

ABSTRACT

In total, 35 laboratories from 13 countries, took part in the 2012 HPA Intercomparison. Some laboratories submitted more than one set of detectors, so 41 sets of detectors were exposed together in the radon chamber. The detectors were exposed to five different radon concentrations in the range of 50 kBq m^{-3} h to 2500 kBq m^{-3} h. After the exposures the detectors were returned to the originating laboratories for processing. Each participant was asked to return results for each detector in terms of kBq m^{-3} h exposure of radon. In total, 34 laboratories reported results for 41 sets. The measurement error, introduced in 2011, was used to evaluate the performance for each exposure separately.

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EXECUTIVE SUMMARY

Radon is the largest and most variable contributor of radiation dose to the general population. For more than twenty years countries in Europe and elsewhere have carried out surveys in order to determine both individual and average exposures and identify where excessive exposures might occur. Most of these measurements have been carried out using passive etched track radon detectors exposed for periods of months. Activated charcoal and electret radon detectors have also been used, mainly for shorter term measurements. In addition, all three types of detector are used for experimental and research work.

Intercomparisons provide information about the accuracy of measurements. By allowing different detectors to be compared side by side an objective assessment of the accuracy of measurements can be made. The results of intercomparisons have been used by individual laboratories to identify and rectify problems, as well as providing calibrations for the detectors traceable to international standards.

The Centre for Radiation, Chemical and Environmental Hazards of the Public Health England (PHE-CRCE) carries out international intercomparisons of passive radon detectors each year. In this intercomparison laboratories were invited to submit sets of detectors which were randomised into six groups at PHE-CRCE. Five of these groups were exposed in the PHE-CRCE radon chamber to five different radon concentrations in the range of 50 kBq m^{-3} h to 2500 kBq m^{-3} h and the sixth group were used to determine transit exposures. Detectors were then returned to the laboratories who were asked to report the integrated exposure result for each detector. Laboratories are not informed of the details of the exposures or which detectors were in which group until all results have been submitted.

This report considers the results for the intercomparison carried out in 2012, for which a total of 35 laboratories from 13 countries submitted 42 sets of detectors. Analysis of the results allows each exposure group in each set to be ranked from A (best) to E (worst). All types of detector whether etched track, charcoal or electret can be found in each class, demonstrating the point that in measuring radon stringent quality assurance is vital irrespective of the measured technique.

International passive radon detector intercomparisons remain popular, with 8 new laboratories joining in 2012. It is intended to continue these exercises on an annual basis as long as demand for them continues.

CONTENTS

1 INTRODUCTION

Passive radon detectors have been employed for years for integrated measurements of radon concentrations using a variety of detectors designs.

Passive detectors employing plastic as the detector material are called etched track detectors. The alpha particles from the decay products of radon damage the surface of the plastic material and produce tiny tracks. These tracks are made visible by chemical or electrochemical etching. The most popular etched track materials are cellulose nitrate (LR-115), polycarbonate (Makrofol) and polyallyl diglycol carbonate (CR-39). There are two types of etched track detectors: open (the material is exposed to the ambient atmosphere) and closed (the material is enclosed in a container). The open etched track detectors record alpha particles originated from radon decay products and from all radon isotopes. Also, the equilibrium factor F should be taken into account to estimate the alphas only from radon-222 decay. The closed etched track detectors allow only radon to diffuse into the closed chamber and, therefore, exclude ambient radon daughters.

Activated charcoal detectors and electrets chambers do not rely on etched tracks. The charcoal detectors rely on retaining adsorbed radon for measurement in the laboratory. Electret radon detectors consist of an air chamber above an electret. Ionisation of air in the chamber by radon gradually discharges the electret. Measurement of the charge on the electret by the laboratory before and after exposure to radon allows the average radon concentrations during exposure to be calculated.

Although the passive radon detector technology is quite simple to produce and process, there are sources of errors that should be monitored closely. Therefore regular checks are needed against reference exposures in relevant radon exposure facilities. The laboratory intercomparison programme has been intended to provide participants with a routine benchmark performance standard, developed with broad international participation following standard and agreed test and interpretation protocols. The Intercomparison programme was established by NRPB in 1982 and has operated regularly since then.

2 LABORATORY EXPOSURE AND MEASUREMENT FACILITIES

HPA maintains a 43 m^3 walk-in radon chamber. The chamber is of the static type: radon is continuously released inside the chamber by radon sources, so there is no air flow into it . All of the exposures in this intercomparison were carried out in this chamber.
The chamber contains a radon atmosphere which can be varied from around 200 Bq m^{-3} to 8000 Bq m^{-3}, depending on the use of various dry Ra-226 sources. In 2010 the radon chamber was fully refurbished and upgraded with a new aerosol generator. Table 1 shows the parameters measured and controlled in the chamber. An equilibrium factor (F) of about 0.4 between radon and its decay products was maintained for the five laboratory exposures during the intercomparison.

The radon concentration in the chamber was continuously monitored using an ATMOS 12 ionisation chamber. From May 2011 the monitoring of the radon concentration inside the chamber was optimised by introducing an Alphaguard ionisation chamber as a second primary instrument. A daily cross calibration between the Atmos12 DPX and Alphaguard was carried out throughout the intercomparison exercise. Both instruments are calibrated regularly using a radon gas source supplied by Physikalisch Technische Bundesanstalt (PTB), Germany.

During exposures radon decay products were sampled approximately five times per day onto a Millipore AA filter and their concentrations determined using an alpha spectrometry system. All chamber monitored data was automatically transferred to a database. Radon and radon decay product exposures were calculated later.

3 LOGISTICAL ARRANGEMENT

In 2011 the format of the inter-laboratory comparison of passive radon detectors was modified as described in Daraktchieva et al. 2012.

Operational procedures and equipment are described fully in the reports of previous intercomparisons (Howarth 2009).

In total, 35 laboratories from 13 countries, took part in the 2012 HPA Intercomparison. Some laboratories submitted more than one set of detectors, so 42 sets of detectors were exposed side by side in the radon chamber. After the end of exposures the detectors were returned to the originating laboratories for processing. Each participant was asked to return results for each detector in terms of kBq m-3 h exposure of radon. In total, 34 laboratories reported results for 41 sets. Participants did not know which detectors were exposed together. The exposures given in the intercomparison were not calculated until the results for the deadline for return of all results had been passed. The exposure durations and magnitudes are given in Table 1.

4 EXPOSURES

The radon exposures were carried out in the radon exposure chamber at PHE-RPD. The appropriate conditions were obtained in the chamber before introducing the detectors.

The exposures are summarised in Tables 1. For charcoal detectors the exposures are given in Table 5. All exposures were carried out at the same equilibrium factor of about 0.4. The first exposure lasted 167.2 hours, the second exposure which was the longest was 532.05 hours, the third was 336.3 hours, the fourth which was the shortest lasted 29.88 hours and the fifth lasted 96.97 hours. The radon and EER concentrations during the exposures are shown in Figures 1–5. Because the exposures continued for longer than charcoal detectors are normally exposed, they were removed from the chamber after 2, 5 and 7 days and returned to the originating laboratory.

The radon concentration in the laboratory outside the exposure chamber was monitored during the exposures using an Alphaguard ionisation chamber. The daily average concentrations ranged from 21 to 35 Bq m^{-3}, with an overall average of 28 Bq m^{-3}. The estimated additional exposure of the detectors caused by leaving them exposed in the laboratory for 3 days to allow radon to diffuse out of them was less than 1% of the exposure in the chamber in all cases and was neglected.

5 RANKING SCHEME

The ranking scheme introduced in 2011 was based on the following parameters: % biased error, which measures the bias of the measurement; % precision error, which measures the precision of the measurement and % measurement error, which took into account their combined effect. This year % biased error was calculated taking into account its sign- positive or negative. The parameters are given below:

$$\% \, Biased \; error = \frac{Measured \; Mean - Reference \; Value}{Reference \; Value} \times 100$$

where the reference value is the reference radon exposure,

$$\% \, Precision \; error = \frac{Standard \; Deviation}{Measured \; Mean} \times 100$$

$$\% \text{ Measurement error}=\sqrt[2]{\%Biased \; error^2 + \%Precision \; error^2}$$

Since the percentage measurement error combines the biased error and precision error, a result can have low measurement error only if both bias and precision errors are low. In 2011 a new ranking scheme was introduced which evaluates the performance for each exposure separately. Each laboratory can achieve five ranks, i.e. one rank for each exposure.

The ranks based on the measurement error are:

- If the measurement error is < 10% the rank is A
- If the measurement error is between ≤10% and < 20% the rank is B
- If the measurement error is between ≤20% and < 30% the rank is C
- If the measurement error is between ≤30% and < 40% the rank is D
- If the measurement error is between ≤40% and < 50% the rank is E
- If the measurement error is ≥50% and < 100% the rank is F

6 RESULTS AND DISCUSSION

The results reported by customers are given in Table 2 and Table 6 (for charcoal detectors). In these tables, “Mean” is the mean result of ten (five for electrets and charcoal) exposed detectors after subtracting the mean transit exposure. “1SD” is the standard deviation of ten (five for electrets and charcoal) reported results. Results for % Biased error, % Precision error and % Measurement error are provided as well.

The mean results and their standard deviations, as reported by participants, are depicted in Figures 6-10. The analysis showed that the distributions of reported results were nearly normal for all five exposures. The mean, μ, and standard deviation, σ, of all reported results, calculated for each exposure, are given in Table 3.

The mean of all transit exposures is 22 kBq m^{-3} h (see Figure 11). Only three laboratories reported the transit exposure above 50 kBq m^{-3} h.

The new ranking scheme based on measurement error is given in Table 4. The exposures are shown in the headings of the columns of Table 4. The laboratories are sorted according to the ranks from A to F, from left to right. The position of the laboratories in the table reflects the ranks of the different exposures and should not be interpreted as a criterion of their total performance. The results in the table are informative and can be used by laboratories to review their procedures and to identify problems at different exposures. The characteristics of the detectors such as material, detector holder design, detector type and material supplier are provided in Table 4.

Three laboratories achieved a ranking of five ‘A’s meaning that they have less than 10 % measurement error for all five exposures. Six other laboratories have four ‘A’s and one ‘B’s in exposure 4. This shows that these laboratories perform less well in the low exposure measurements. The lowest exposure, as in the previous year, was the most difficult to measure with only 6 laboratories managing to achieve A. One factor that may contribute to the deterioration of precision for the low exposure range is the etched track material background, which can vary significantly from batch to batch and even from sheet to sheet of the same batch. Therefore the inaccurate estimation of the background can lead to either positive or negative bias of the result in the low exposure. One other laboratory had a ranking of five ‘A’s and one ‘B’s in exposure 5. The exposure 2 and exposure 3 were measured with the greatest precision – 26 and 24 laboratories achieved ‘A’, respectively. The proportion of sets achieving ranks ‘A’s, ‘B’s, ‘C’s, ‘D’s, ‘E’s and ‘F’s is given in Figure 12.

It should be noted (see Table 4) that laboratories participating with the same type of detectors and detector material can achieve quite different ranks from five ‘A’s to five ‘C’s which reflects each laboratory’s own Quality Assurance (QA) protocols.

Typical sources of errors for etch track detectors (Ibrahimi et al. 2009 and Hanley et al. 2008) are:

- variations of the etched track material (thickness, background)
- variation in the etching process (etching time, mixture, concentration)
- variation of the automatic track counting system (various track reading parameters)

- variation in the linearity of response (change in the parameters of the linearity curve for different sheets/ batches)
- variation of sensitivity due to chemical change of the etch track material-ageing and fading (Hardcastle and Miles 1996).

Therefore constant monitoring of detectors performance and strict QA protocols should be put in place to identify the above sources of errors.

The results reported by customers using charcoal detectors are given in Table 6 and the ranks for these exposures are given in Table 7.

7 CONCLUSION

In total, 35 laboratories from 13 countries participated in the 2012 HPA Intercomparison. The five rank exposure scheme, introduced in 2011, was used to evaluate the performance of the detectors across the range of exposures.

8 ACKNOWLEDGEMENTS

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10 LIST OF PARTICIPANTS

Contact person	Organisation	Country
Cailleaux Marie-Alice	Province du Hainaut – Hainaut Vigilance Sanitaire	Belgium
Dr. Nivaldo Carlos da Silva	Brazilian Commission for Nuclear Energy - CNEN	Brazil
Renato Falcomer	Health Canada National radon Laboratory	Canada
Fred Sarradin	Dosirad	France
Pierre Filleul	L.E.D.-ALGADE	France
Alexandre Berland	Pearl-SAS, (Pôle d' Expertise et d' Analyse Radioactivité Limousin)	France
Maria Kolovou	Department of Environmental Radioactivity - GEAEC	Greece
Eric Hülber	Radosys Ltd.	Hungary
Mr M Murray	RPII	Ireland
David Doyle	Alpharadon Teo	Ireland
Dr. Luca Verdi	Agenzia Provinciale per l'Ambiente	Italy
Chiaberto Enrico	ARPA Piemonte	Italy
Elena Caldonetto	ARPAV	Italy
Massimo Calamosca	ENEA – IRP - DOS	Italy
Dr G Torri	ISPRA - Servizio Misure Radiometriche	Italy
Dr L Baldassarre	L.B. Servizi per le Aziende s.r.l.	Italy
Dr Marta Rossetti	U-Series Srl	Italy
Massimo Moroni	RadonLab	Italy
Paola Gozzelino	TOINTECH S.r.l.	Italy
Aleksandar Birovljev	Radonlab Ltd	Norway
Trine Kolstad	NRPA	Norway
Victòria Moreno Baltà	Universitat Autònoma de Barcelona	Spain
Prof Jose Ferrero Calabuig	Laboratorio de Radiactividad Ambiental, Universitat de Valencia	Spain
Marianne Hallengren	Independia Control AB	Sweden
Dr Tryggve Rönnqvist	Landauer Nordic AB	Sweden
Frej Kullman	MRM Konsult AB	Sweden
Per-Arne Svanberg	PASELA miljosupport ab	Sweden
Prof. Gilbert Jönsson	RADONANALYS GJAB	Sweden
Kıymet Gökhan	SANAEM	Turkey
Berna Ataksor	CNAEM	Turkey

Contact person	Organisation	Country
Darren Langridge	DRPS Radiological Protection Services	UK
Dr Phil Gilvin	HPA Personal Monitoring Services	UK
Fero Ibrahimi	HPA Radon Dosimetry Service	UK
Simon Crust	Kingston University - School of Geography, Geology & Environment	UK
Maria Hansen	Track Analysis Systems Ltd	UK

11 TABLES AND FIGURES

TABLE 1 Exposure durations and magnitudes excluding exposures for charcoal detectors

Exposure	1	2	3	4	5
Duration (h)	167.2	532.05	336.3	29.88	96.97
Radon exposure (kBq m^{-3} h)	717	2385	1487	138	438
Uncertainty (%) at 68% CL	3.0	3.0	3.0	3.0	3.0
EER exposure (kBq m^{-3} h)	301	1002	625	57	184
Uncertainty (%) at 68% CL	7.0	7.0	7.0	7.0	7.0
F	0.42	0.42	0.42	0.41	0.42

Notes to Tables 1

EER is equilibrium equivalent of radon.

F is equilibrium factor.

CL is the confidence level.

Notes to Tables 2 and 4

Due to an administrative error, the results for exposure group 2 of set 14 -1 are based on nine detectors.

TABLE 2 Analysis of all reported results

	EXPOSURE 1 717 (kBq m-3 h)					EXPOSURE 2 2385 (kBq m-3 h)				
SET ID	Mean (kBq m-3 h)	1SD (kBq m-3 h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m-3 h)	1SD (kBq m-3 h)	% Biased error	% Precis on error	% Measur ement error
1-1	803.1	15.9	12.0	2.0	12.2	2658	60.7	11.4	2.3	11.7
1-2	778.2	34.7	8.5	4.5	9.6	2405.5	110.2	0.9	4.6	4.7
7-1	735.8	29.7	2.6	4.0	4.8	2293.1	71.1	-3.9	3.1	4.9
7-2	720.9	25.7	0.5	3.6	3.6	2295.2	45.7	-3.8	2.0	4.3
12-1	811.6	19.8	13.2	2.4	13.4	2642.6	28.1	10.8	1.1	10.9
13-1	701.4	21.3	-2.2	3.0	3.7	2279	50.8	-4.4	2.2	5.0
14-1	731	23.7	2.0	3.2	3.8	2369	82.3	-0.7	3.5	3.5
16-1	822.2	33.6	14.7	4.1	15.2	2476.8	69.5	3.8	2.8	4.8
16-2	813.9	58.7	13.5	7.2	15.3	2404	57	0.8	2.4	2.5
19-1	794.9	20.6	10.9	2.6	11.2	2442.5	113.1	2.4	4.6	5.2
20-1	723.1	29.3	0.9	4.1	4.1	2405.6	97.3	0.9	4.0	4.1
23-1	567.4	38	-20.9	6.7	21.9	1817.1	63.8	-23.8	3.5	24.1
25-1	713.9	37.7	-0.4	5.3	5.3	2637.2	82.2	10.6	3.1	11.0
25-2	723.9	67.5	1.0	9.3	9.4	2589.9	226	8.6	8.7	12.2
28-1	730.6	51.1	1.9	7.0	7.2	2362.9	82.4	-0.9	3.5	3.6
30-1	866	173.6	20.8	20.0	28.9	2539.4	308.4	6.5	12.1	13.8
32-1	756.5	22.3	5.5	2.9	6.2	2441.8	87.8	2.4	3.6	4.3
40-1	892.7	44	24.5	4.9	25.0	3325.7	264.6	39.4	8.0	40.2
45-1	670.8	111.7	-6.4	16.7	17.9	2454.8	164.3	2.9	6.7	7.3
94-1	770.8	68.2	7.5	8.8	11.6	2414.6	60.5	1.2	2.5	2.8
122-1	794.7	25.4	10.8	3.2	11.3	2587.7	70.6	8.5	2.7	8.9
122-2	807.6	20.1	12.6	2.5	12.9	2648.5	47.7	11.0	1.8	11.2
125-1	876.2	93.8	22.2	10.7	24.6	2367.3	50.2	-0.7	2.1	2.2

	EXPOSURE 1 (continued) 717 (kBq m^{-3} h)					EXPOSURE 2 (continued) 2385(kBq m^{-3} h)				
SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error
125-2	841.3	64	17.3	7.6	18.9	2342.5	71.2	-1.8	3.0	3.5
129-1	701.2	45.1	-2.2	6.4	6.8	2367.9	41	-0.7	1.7	1.9
141-1	782.9	33.7	9.2	4.3	10.1	2520.2	30.3	5.7	1.2	5.8
160-1	733.1	30.5	2.2	4.2	4.7	2296.7	72	-3.7	3.1	4.9
161-1	673.6	85.5	-6.1	12.7	14.1	2145.1	69.5	-10.1	3.2	10.6
163-1	855.6	59.4	19.3	6.9	20.5	2456.8	3.1	3.0	0.1	3.0
168-1	862.9	54.5	20.3	6.3	21.3	2478.8	77.6	3.9	3.1	5.0
171-1	1041	171.6	45.2	16.5	48.1	3218.5	211.1	34.9	6.6	35.6
172-1	1004.3	22.6	40.1	2.3	40.1	3107.7	88.7	30.3	2.9	30.4
173-1	764.1	38.9	6.6	5.1	8.3	2397.3	61.4	0.5	2.6	2.6
174-1	755.5	53.9	5.4	7.1	8.9	2639.4	231.5	10.7	8.8	13.8
175-1	1003.1	300.3	39.9	29.9	49.9	3131.7	77.1	31.3	2.5	31.4
177-1	696.4	35.7	-2.9	5.1	5.9	2220	76.8	-6.9	3.5	7.7
177-2	647.1	69	-9.7	10.7	14.4	2209.8	103.7	-7.3	4.7	8.7
178-1	695.9	23.4	-2.9	3.4	4.5	2326.9	63.6	-2.4	2.7	3.7
179-1	792.2	36.4	10.5	4.6	11.5	2559.1	39.1	7.3	1.5	7.5
180-1	553.5	50.1	-22.8	9.1	24.5	1599	149.8	-33.0	9.4	34.3

	EXPOSURE 3 1487 (kBq m^{-3} h)					EXPOSURE 4 138 (kBq m^{-3} h)				
SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error
1-1	1636.2	26.5	10.0	1.6	10.2	160.0	16.1	15.9	10.1	18.9
1-2	1566.6	40.8	5.4	2.6	6.0	156.1	11.8	13.1	7.6	15.1
7-1	1323.7	463	-11.0	35.0	36.7	147.3	14	6.7	9.5	11.7
7-2	1415.1	76.4	-4.8	5.4	7.2	136.8	20.2	-0.9	14.8	14.8
12-1	1665.8	32.2	12.0	1.9	12.2	158.1	4.1	14.6	2.6	14.8
13-1	1427.0	43.3	-4.0	3.0	5.0	132.3	9	-4.1	6.8	8.0
14-1	1493.7	47.8	0.5	3.2	3.2	144.2	14.7	4.5	10.2	11.1
16-1	1596.1	48.8	7.3	3.1	7.9	170.7	10.3	23.7	6.0	24.5
16-2	1583.5	41.8	6.5	2.6	7.0	170.0	20	23.2	11.8	26.0
19-1	1580.0	66.2	6.3	4.2	7.5	152.5	17.8	10.5	11.7	15.7
20-1	1456.7	60	-2.0	4.1	4.6	125.2	17.4	-9.3	13.9	16.7
23-1	1150.9	56.1	-22.6	4.9	23.1	104.4	7.5	-24.3	7.2	25.4
25-1	1538.6	65.9	3.5	4.3	5.5	137.2	14.7	-0.6	10.7	10.7
25-2	1615.1	186	8.6	11.5	14.4	140.5	16.8	1.8	12.0	12.1
28-1	1535.3	114	3.2	7.4	8.1	184.7	75.3	33.8	40.8	53.0
30-1	1680.1	227.6	13.0	13.5	18.8	178.4	23.2	29.3	13.0	32.0
32-1	1552.2	56	4.4	3.6	5.7	146.8	12.1	6.4	8.2	10.4
40-1	1840.4	326.3	23.8	17.7	29.7	166.5	17.2	20.7	10.3	23.1
45-1	1538.3	117.9	3.4	7.7	8.4	153.0	17.4	10.9	11.4	15.7
94-1	1536.4	76.2	3.3	5.0	6.0	188.6	34	36.7	18.0	40.9
122-1	1624.2	43.6	9.2	2.7	9.6	155.6	4.9	12.8	3.1	13.1
122-2	1647.0	36.7	10.8	2.2	11.0	147.5	6.7	6.9	4.5	8.2
125-1	1597.0	102.5	7.4	6.4	9.8	168.2	30.5	21.9	18.1	28.4

	EXPOSURE 3 (continued) 1487 (kBq m^{-3} h)					EXPOSURE 4 (continued) 138 (kBq m^{-3} h)				
SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error
125-2	1624.4	39.8	9.2	2.5	9.6	143.7	31.6	4.1	22.0	22.4
129-1	1477.7	36.8	-0.6	2.5	2.6	126.6	12.6	-8.3	10.0	12.9
141-1	1602.3	50	7.8	3.1	8.4	151.8	8	10.0	5.3	11.3
160-1	1417.3	49.6	-4.7	3.5	5.8	140.6	10.8	1.9	7.7	7.9
161-1	1353.5	91.2	-9.0	6.7	11.2	122.0	20.4	-11.6	16.7	20.3
163-1	1668.8	79.2	12.2	4.7	13.1	146.6	11.7	6.2	8.0	10.1
168-1	1628.5	69	9.5	4.2	10.4	195.8	38.6	41.9	19.7	46.3
171-1	2139.2	132	43.9	6.2	44.3	145.3	27.1	5.3	18.7	19.4
172-1	2184.6	35.1	46.9	1.6	46.9	240.7	14.7	74.4	6.1	74.7
173-1	1551.6	60.2	4.3	3.9	5.8	146.9	18.3	6.4	12.5	14.0
174-1	1558.7	88.8	4.8	5.7	7.5	152.3	22.2	10.4	14.6	17.9
175-1	2111.0	137.9	42.0	6.5	42.5	260.8	62	89.0	23.8	92.1
177-1	1368.9	48.2	-7.9	3.5	8.7	140.7	12.2	2.0	8.7	8.9
177-2	1328.4	73.1	-10.7	5.5	12.0	129.3	6.1	-6.3	4.7	7.9
178-1	1417.7	23.2	-4.7	1.6	4.9	134.4	11.8	-2.6	8.8	9.2
179-1	1589.0	44.8	6.9	2.8	7.4	160.6	9.2	16.4	5.7	17.3
180-1	1059.3	58.9	-28.8	5.6	29.3	107.0	19.8	-22.5	18.5	29.1

	EXPOSURE 5 438 (kBq m^{-3} h)					TRANSIT CONTROLS	
SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
1-1	467.1	16.3	6.6	3.5	7.5	23.2	13.9
1-2	466.8	16.6	6.6	3.6	7.5	27.9	15.6
7-1	456.1	14.5	4.1	3.2	5.2	18.6	11.5
7-2	446.1	22.5	1.8	5.0	5.4	20.4	11.3
12-1	475	14.6	8.4	3.1	9.0	11.6	1.8
13-1	432.7	12.9	-1.2	3.0	3.2	2.4	2.6
14-1	438.4	33.6	0.1	7.7	7.7	3.6	3.7
16-1	490.3	34.3	11.9	7.0	13.8	27.3	6.1
16-2	497.7	37.8	13.6	7.6	15.6	30.5	10.5
19-1	476.8	14.7	8.9	3.1	9.4	18	7.9
20-1	410.8	34.7	-6.2	8.4	10.5	6.6	9.0
23-1	338.8	20.1	-22.6	5.9	23.4	12.7	6.3
25-1	414.2	22.9	-5.4	5.5	7.8	6	0.0
25-2	441.5	51.2	0.8	11.6	11.6	10	0.0
28-1	473.9	90.6	8.2	19.1	20.8	53.7	14.5
30-1	554.2	55.8	26.5	10.1	28.4	19.2	10.2
32-1	458.1	13.7	4.6	3.0	5.5	13.9	7.2
40-1	510.1	18.3	16.5	3.6	16.8	18.9	5.1
45-1	434.2	39.9	-0.9	9.2	9.2	18.9	3.6
94-1	462.3	35.5	5.5	7.7	9.5	51.5	9.8
122-1	475.4	12.6	8.5	2.7	8.9	17.5	2.2
122-2	493.6	13	12.7	2.6	13.0	19.4	1.9
125-1	497.8	42.9	13.7	8.6	16.1	30.5	5.4

	EXPOSURE 5 (continued) 438 (kBq m^{-3} h)					TRANSIT CONTROLS (continued)	
SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
125-2	549.2	46.5	25.4	8.5	26.8	28.1	6.8
129-1	427.1	17.7	-2.5	4.1	4.8	20.8	14.5
141-1	476.2	19.7	8.7	4.1	9.7	29.1	4.6
160-1	432.2	10.2	-1.3	2.4	2.7	21.7	4.4
161-1	422.1	36.5	-3.6	8.6	9.4	29.8	10.4
163-1	461.8	37	5.4	8.0	9.7	79.2	18.2
168-1	529.2	38.5	20.8	7.3	22.1	23.8	15.2
171-1	522.2	63.5	19.2	12.2	22.7	17.8	9.3
172-1	621	34.7	41.8	5.6	42.2	22.8	7.8
173-1	450.1	23.1	2.8	5.1	5.8	0	0.0
174-1	490.4	67.1	12.0	13.7	18.2	8.9	12.3
175-1	655.1	65	49.6	9.9	50.5	38.9	18.4
177-1	397.8	18.1	-9.2	4.6	10.2	2.7	1.9
177-2	386.3	28.9	-11.8	7.5	14.0	6.8	5.5
178-1	408.7	22.4	-6.7	5.5	8.6	26.5	3.2
179-1	467.8	16.4	6.8	3.5	7.7	25.7	3.2
180-1	346.5	28.7	-20.9	8.3	22.5	19.5	5.4

TABLE 3 Analysis of all reported results given in Table 2

Reference exposures	Mean μ of all reported results, (kBq m^{-3} h)	Standard deviation σ of all reported results (kBq m^{-3} h)
Exposure 1 717 (kBq m^{-3} h)	775.3	102.2
Exposure 2 2385 (kBq m^{-3} h)	2471.9	319.7
Exposure 3 1487 (kBq m^{-3} h)	1567.0	220.1
Exposure 4 138 (kBq m^{-3} h)	154.2	29.9
Exposure 5 438 (kBq m^{-3} h)	466.4	61.5

TABLE 4 New ranking scheme based on the measurement error

SET ID	Rank EXPOSURE 4 138 (kBq m^{-3} h)	Rank EXPOSURE 5 438 (kBq m^{-3} h)	Rank EXPOSURE 1 717 (kBq m^{-3} h)	Rank EXPOSURE 3 1487 (kBq m^{-3} h)	Rank EXPOSURE 2 2385 (kBq m^{-3} h)	Detector Type	Filter	Holder	Detector material	Detector material supplier
13-1	A	A	A	A	A	Closed		NRPB/SSI	CR-39	Intercast
160-1	A	A	A	A	A	Closed		NRPB/SSI	CR-39	TASL
178-1	A	A	A	A	A	Closed		NRPB/SSI	CR-39	TASL
177-1	A	B	A	A	A	Closed		TASL	CR-39	TASL
177-2	A	B	B	B	A	Closed		TASL	CR-39	TASL
122-2	A	B	B	B	B	Closed		TASL	CR-39	TASL
1-2	B	A	A	A	A	Closed		NRPB/SSI	CR-39	Mi-Net
7-2	B	A	A	A	A	Closed		TASL	CR-39	TASL
14-1	B	A	A	A	A	Closed		NRPB/SSI	CR-39	TASL
32-1	B	A	A	A	A	Closed		NRPB/SSI	CR-39	TASL
129-1	B	A	A	A	A	Closed		Own	CR-39	Intercast
173-1	B	A	A	A	A	Closed		TASL	CR-39	TASL
25-1	B	A	A	A	B	Open		Dosirad	LR115	Dosirad
7-1	B	A	A	D	A	Closed		TASL	CR-39	TASL
19-1	B	A	B	A	A	Closed		ARPA	CR-39	Intercast
45-1	B	A	B	A	A	Closed		Own	LR115	-
122-1	B	A	B	A	A	Closed		TASL	CR-39	TASL
141-1	B	A	B	A	A	Closed		TASL	CR-39	TASL
179-1	B	A	B	A	A	Closed		TASL	CR-39	TASL

TABLE 4 (continue) New ranking scheme based on the measurement error

SET ID	Rank EXPOSURE 4 138 (kBq m^{-3} h)	Rank EXPOSURE 5 438 (kBq m^{-3} h)	Rank EXPOSURE 1 717 (kBq m^{-3} h)	Rank EXPOSURE 3 1487 (kBq m^{-3} h)	Rank EXPOSURE 2 2385 (kBq m^{-3} h)	Detector Type	Filter	Holder	Detector material	Detector material supplier
1-1	B	A	B	B	B	Closed		NRPB/SSI	CR-39	TASL
12-1	B	A	B	B	B	Closed	Yes	NRPB/SSI	CR-39	-
163-1	B	A	C	B	A	Closed		Eperm S	Electret	N/A
20-1	B	B	A	A	A	Closed		TASL	CR-39	TASL
174-1	B	B	A	A	B	Closed		TASL	CR-39	TASL
25-2	B	B	A	B	B	Open		Dosirad	LR115	Dosirad
171-1	B	C	E	E	D	Closed		Own	LR115	-
161-1	C	A	B	B	B	Closed	Yes	Radosys	CR-39	Radosys
16-1	C	B	B	A	A	Closed	Yes	Radosys	CR-39	Radosys
16-2	C	B	B	A	A	Closed	Yes	Radosys	CR-39	Radosys
125-1	C	B	C	A	A	Closed	Yes	Radosys	CR-39	Radosys
40-1	C	B	C	C	E	Closed		NRPB/SSI	CR-39	Mi-Net
125-2	C	C	B	A	A	Closed	Yes	Radosys	CR-39	Radosys
23-1	C	C	C	C	C	Closed		RPII	CR-39	TASL
180-1	C	C	C	C	D	Closed	Yes	Radosys	CR-39	Radosys
30-1	D	C	C	B	B	Closed		KfK FN	Makrofol	KIT
94-1	E	A	B	A	A	Closed		Own	CR-39	-
168-1	E	C	C	B	A	Closed		NRPB/SSI	CR-39	TASL
28-1	F	C	A	A	A	Closed	Yes	Radosys	CR-39	Radosys
172-1	F	E	E	E	D	Closed	Yes	Radosys	CR-39	Radosys
175-1	F	F	E	E	D	Closed	Yes	Radosys	CR-39	Radosys

TABLE 5 Exposure durations and magnitudes for charcoal detectors

Exposure	1	2	3
Duration (h)	114.23	48.58	168.05
Radon exposure (kBq m^{-3} h)	492	207	734
Uncertainty (%) at 68% CL	3.0	3.0	3.0
EER exposure (kBq m^{-3} h)	207	87	308
Uncertainty (%) at 68% CL	7.0	7.0	7.0
F	0.42	0.42	0.42

TABLE 6 Analysis of results with charcoal detectors

SET ID	Mean (kBq m^{-3} h)	1SD (kBq m^{-3} h)	% Biased error	% Precision error	% Measurement error
			EXPOSURE 1 492 (kBq m^{-3} h)		
176-1	592.7	157.4	20.5	26.6	33.5
			EXPOSURE 2 207 (kBq m^{-3} h)		
176-1	186.4	6.9	-10.0	3.7	10.6
			EXPOSURE 3 734 (kBq m^{-3} h)		
176-1	186.4	6.9	-10.0	3.7	10.6

TABLE 7 New ranking scheme based on the measurement error for charcoal detectors

SET ID	Rank EXPOSURE 1 207 (kBq m^{-3} h)	Rank EXPOSURE 2 492 (kBq m^{-3} h)	Rank EXPOSURE 3 734 (kBq m^{-3} h)	Detector Type	Filter	Holder	Detector material	Detector material supplier
176-1	B	D	C				charcoal	

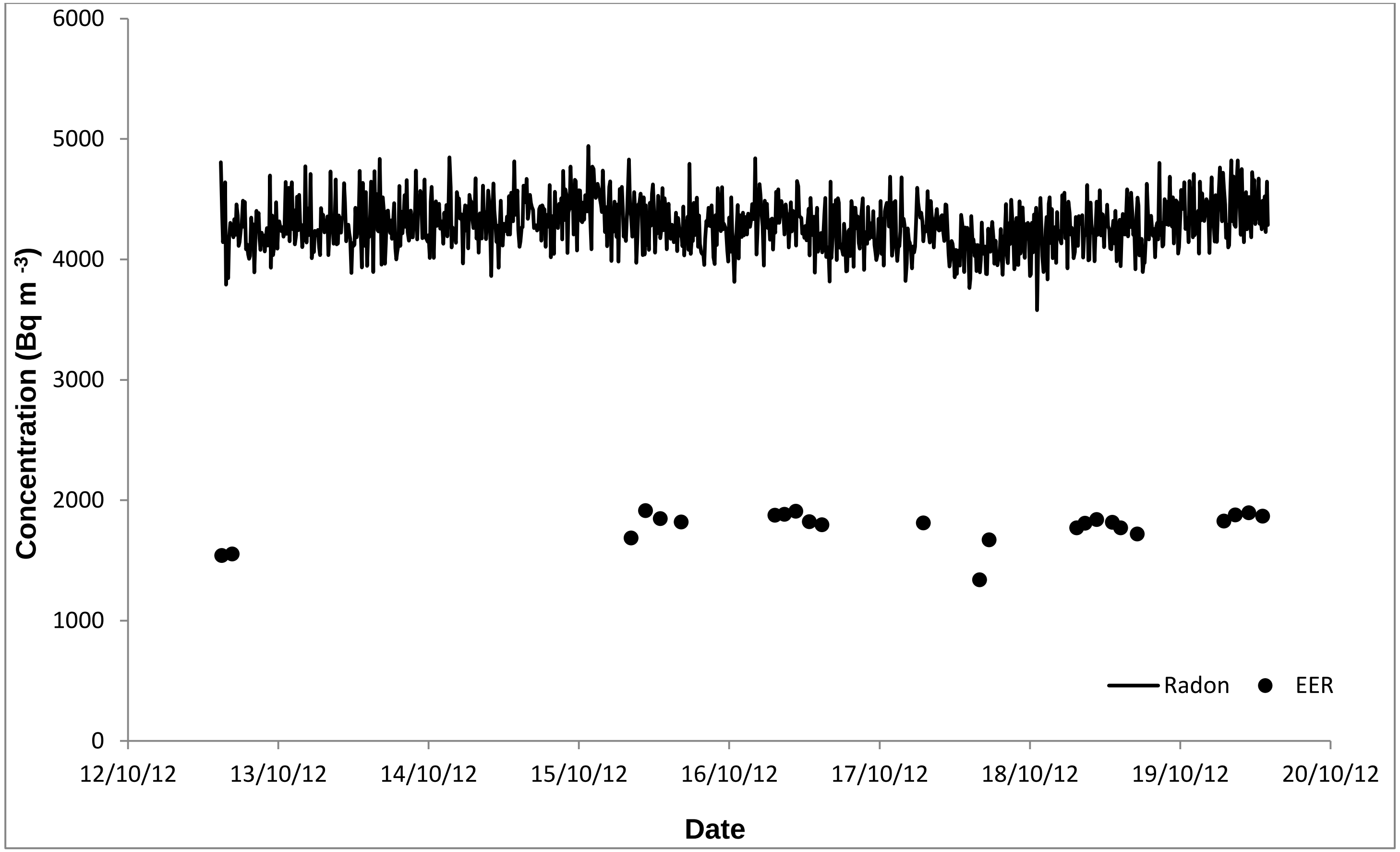

FIGURE 1 Radon and EER concentrations exposure 1

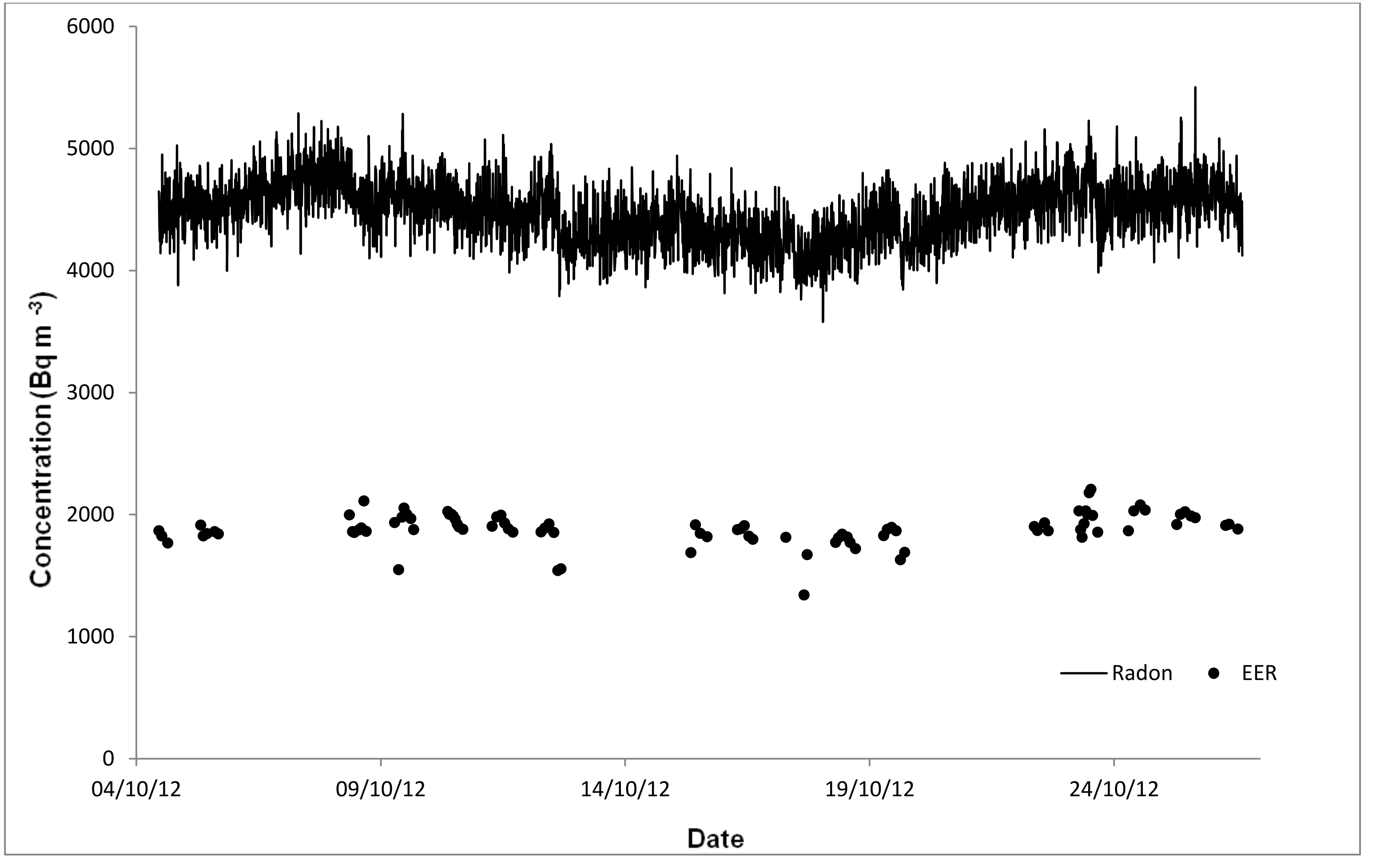

FIGURE 2 Radon and EER concentrations exposure 2

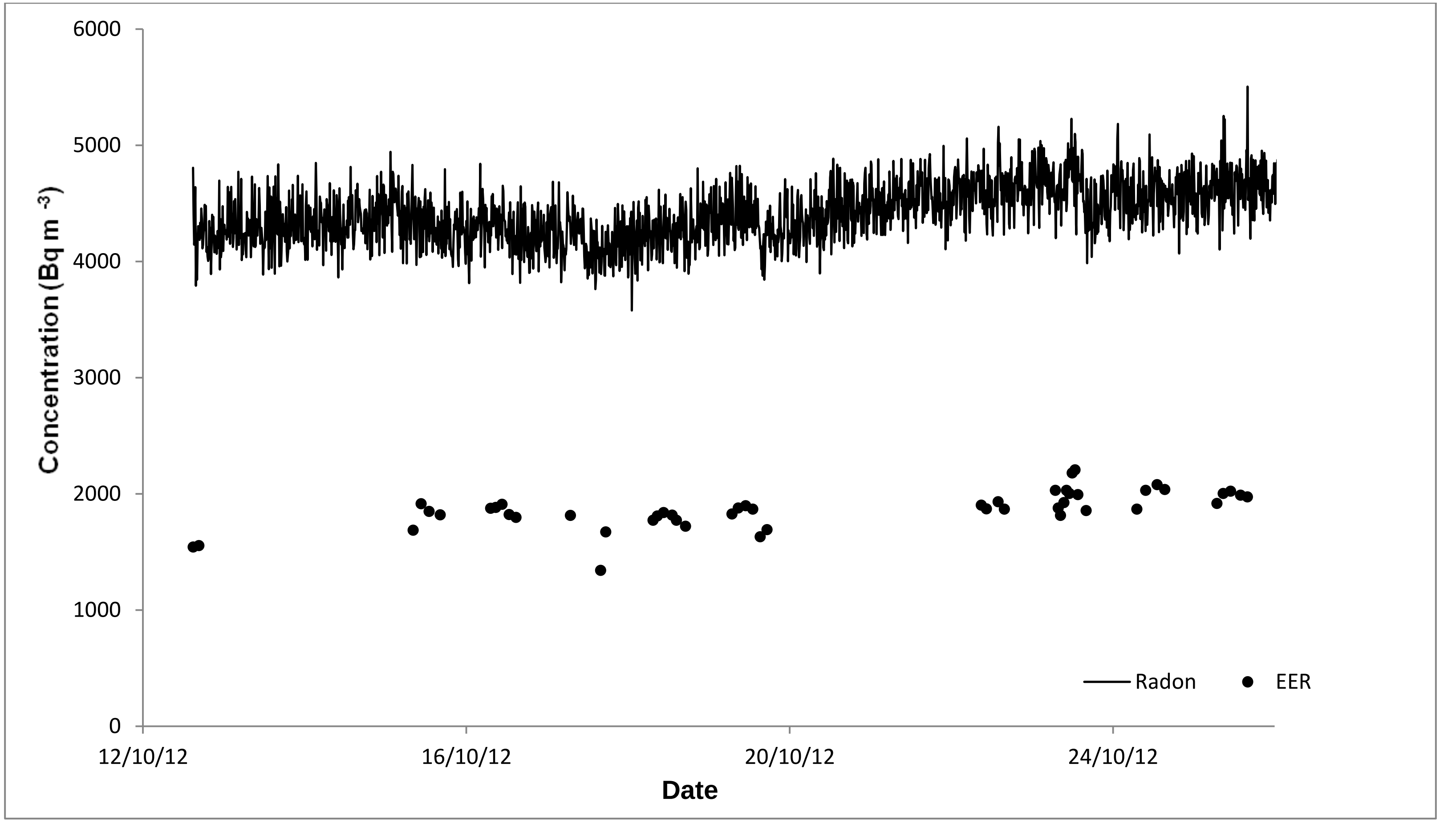

FIGURE 3 Radon and EER concentrations exposure 3

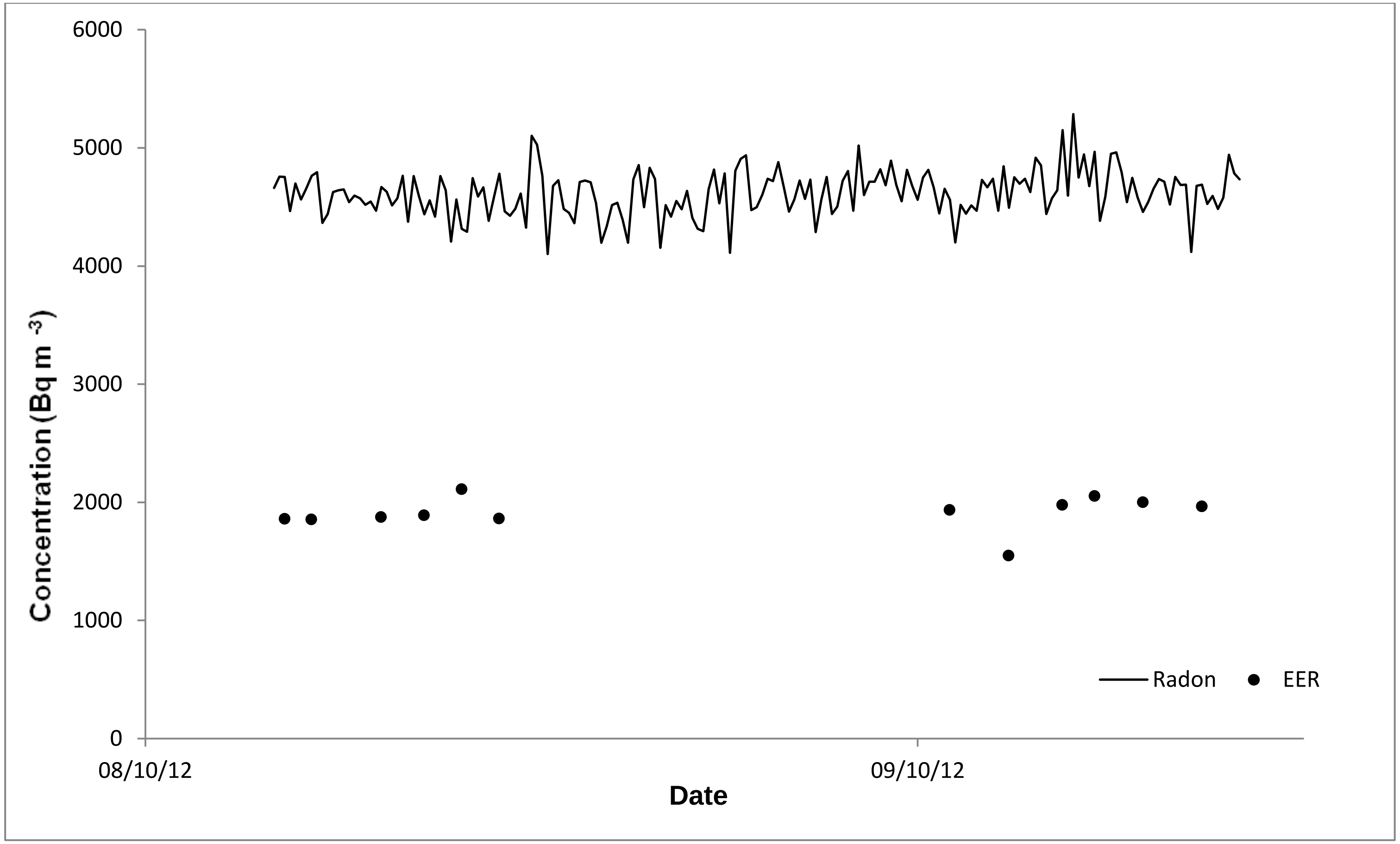

FIGURE 4 Radon and EER concentrations exposure 4

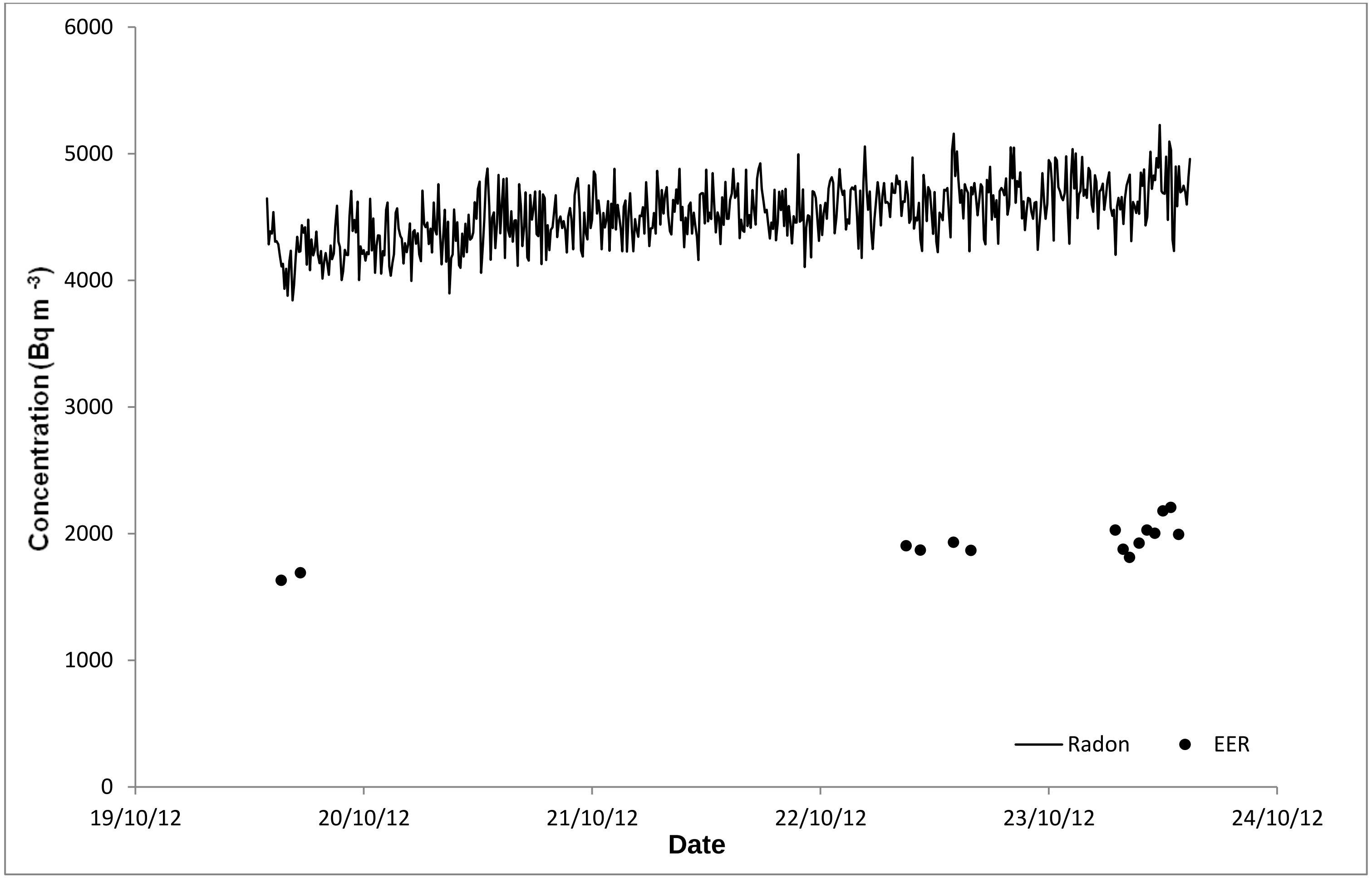

FIGURE 5 Radon and EER concentrations exposure 5

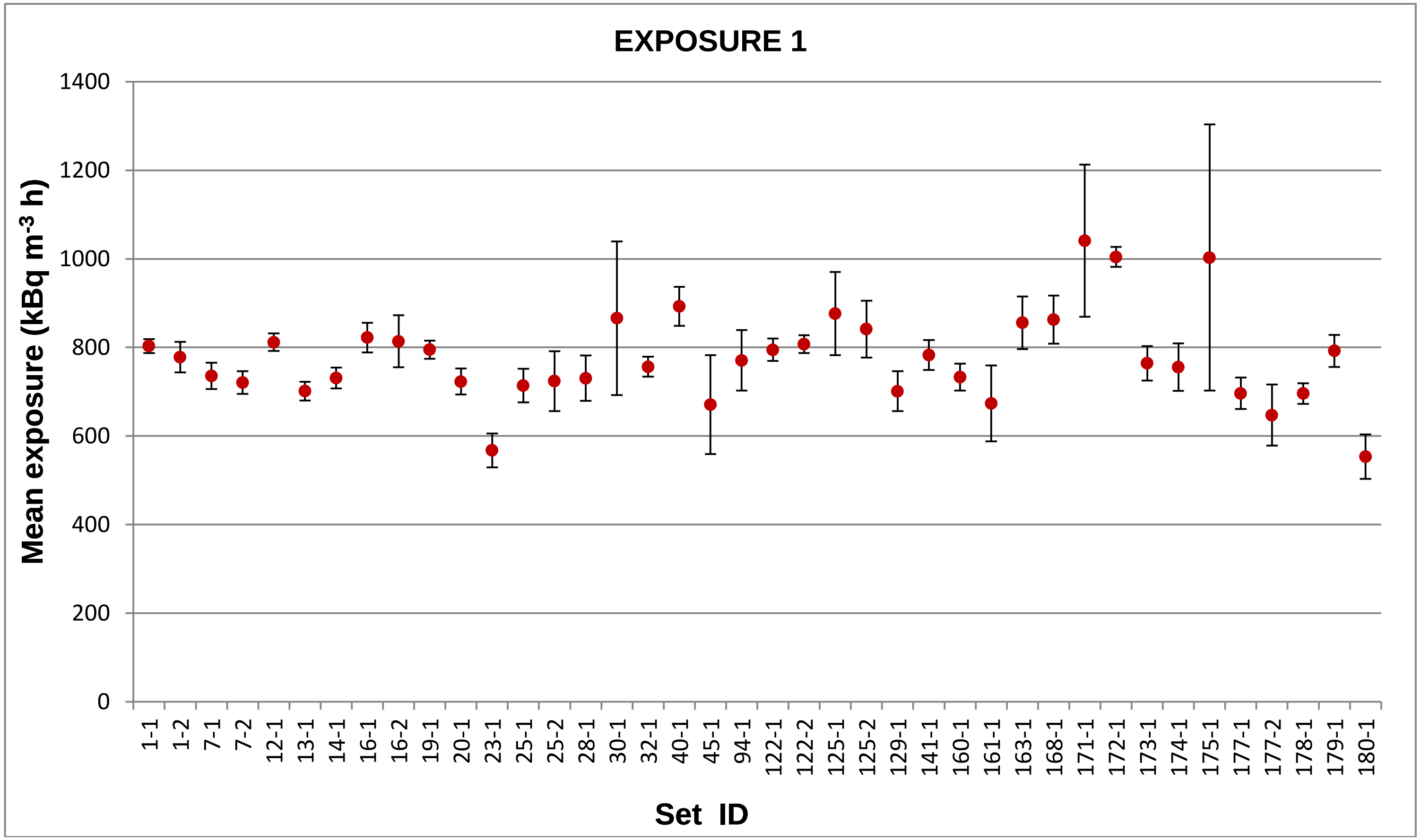

FIGURE 6 Results as reported by participants for exposure 1

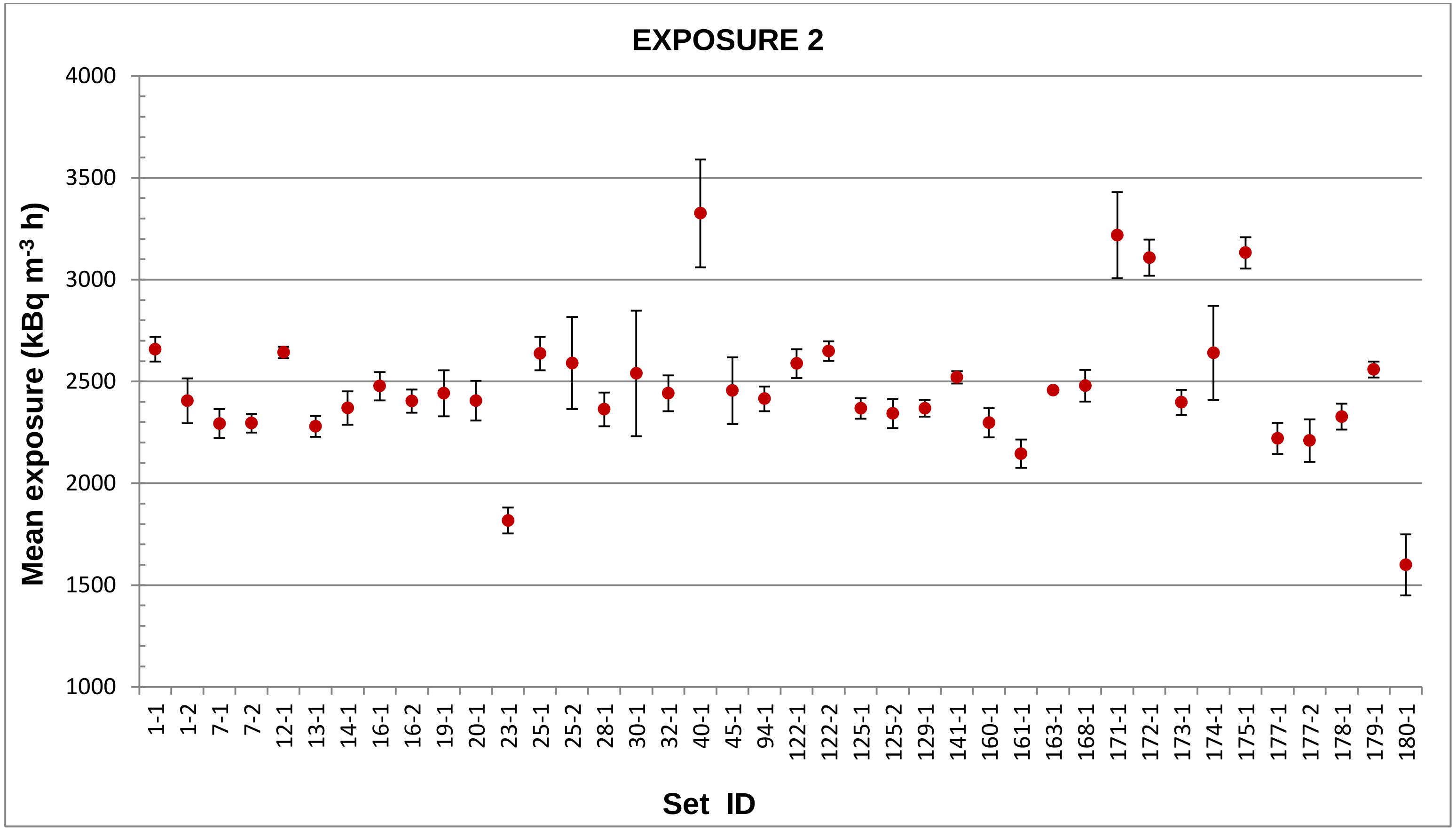

FIGURE 7 Results as reported by participants for exposure 2

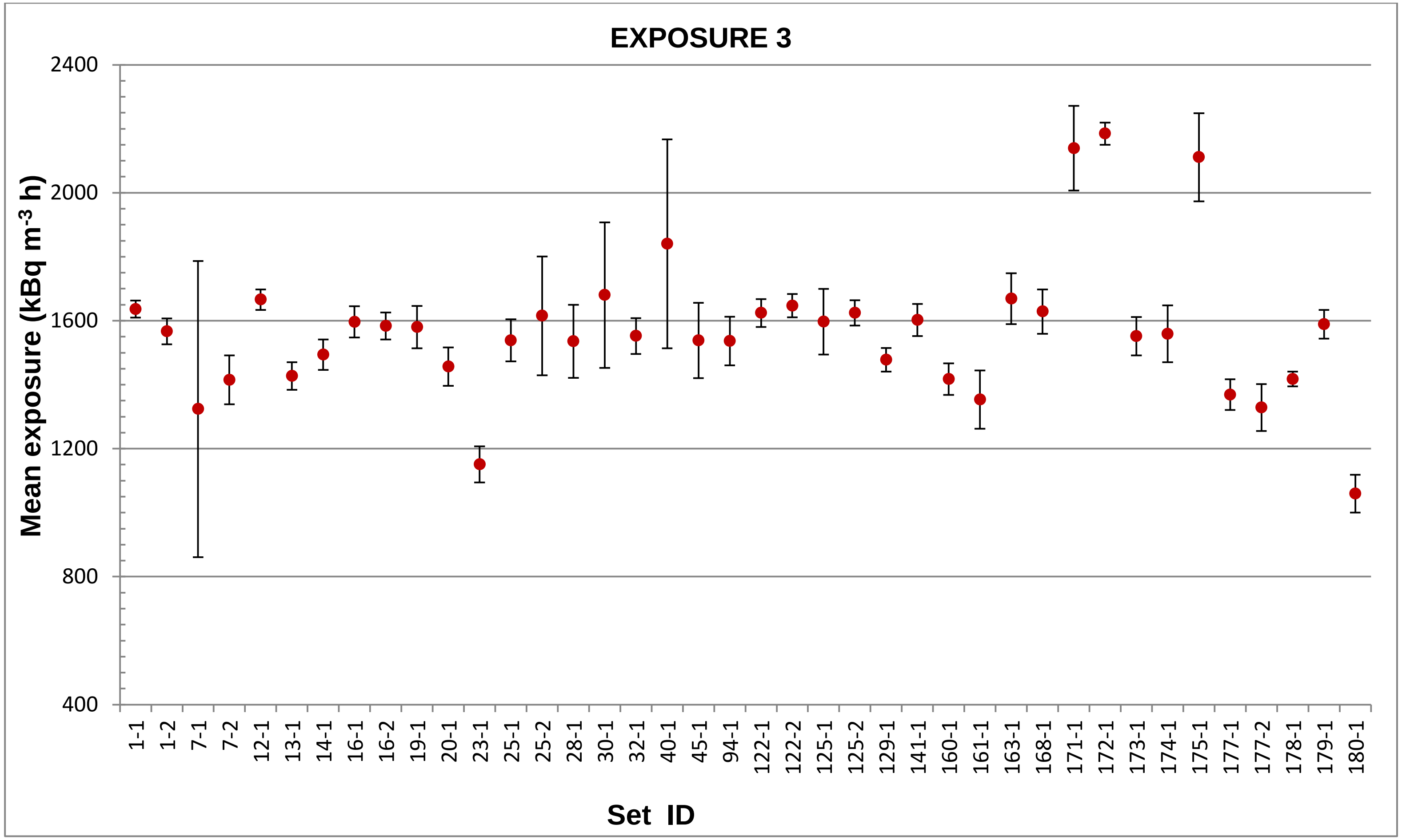

FIGURE 8 Results as reported by participants for exposure 3

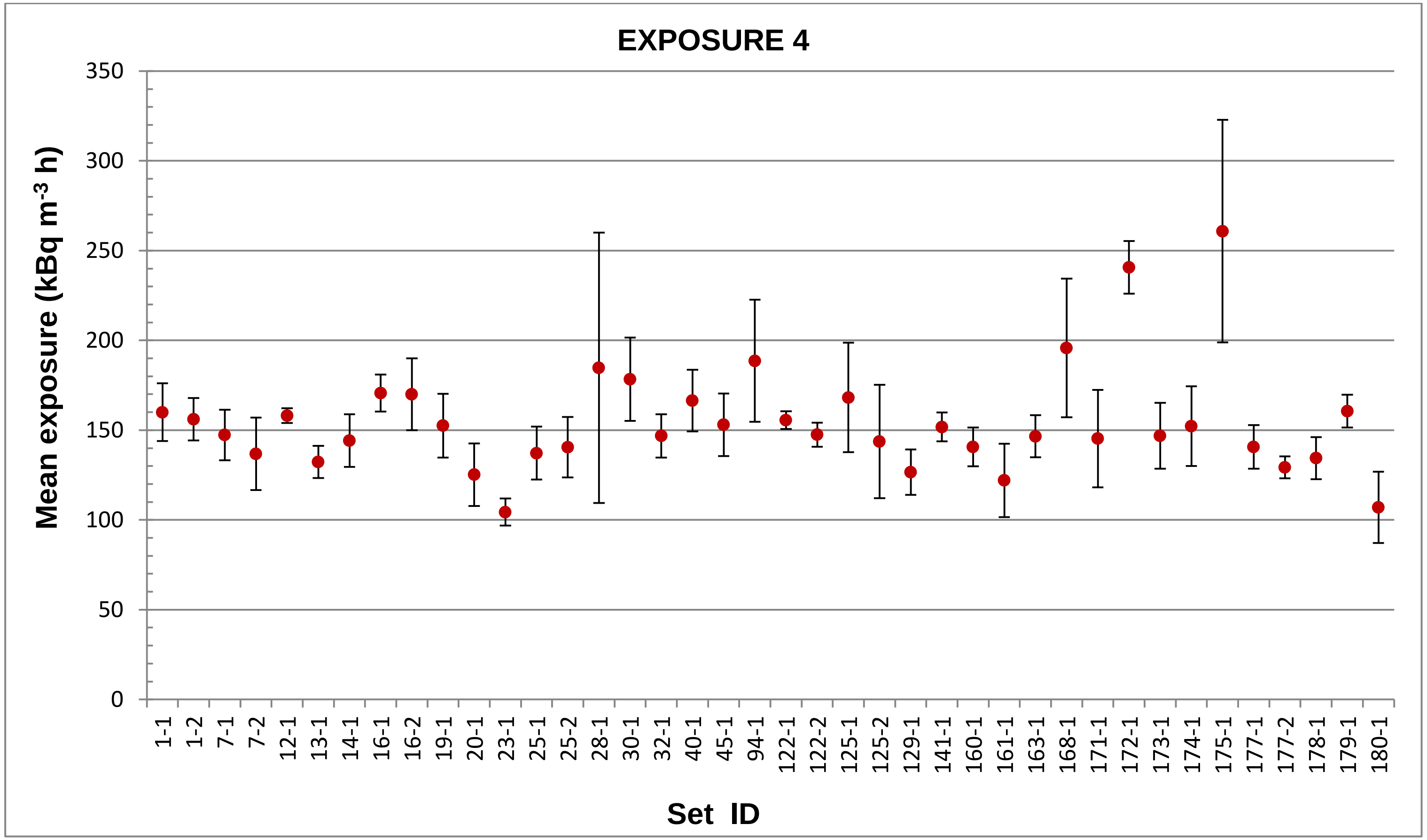

FIGURE 9 Results as reported by participants for exposure 4

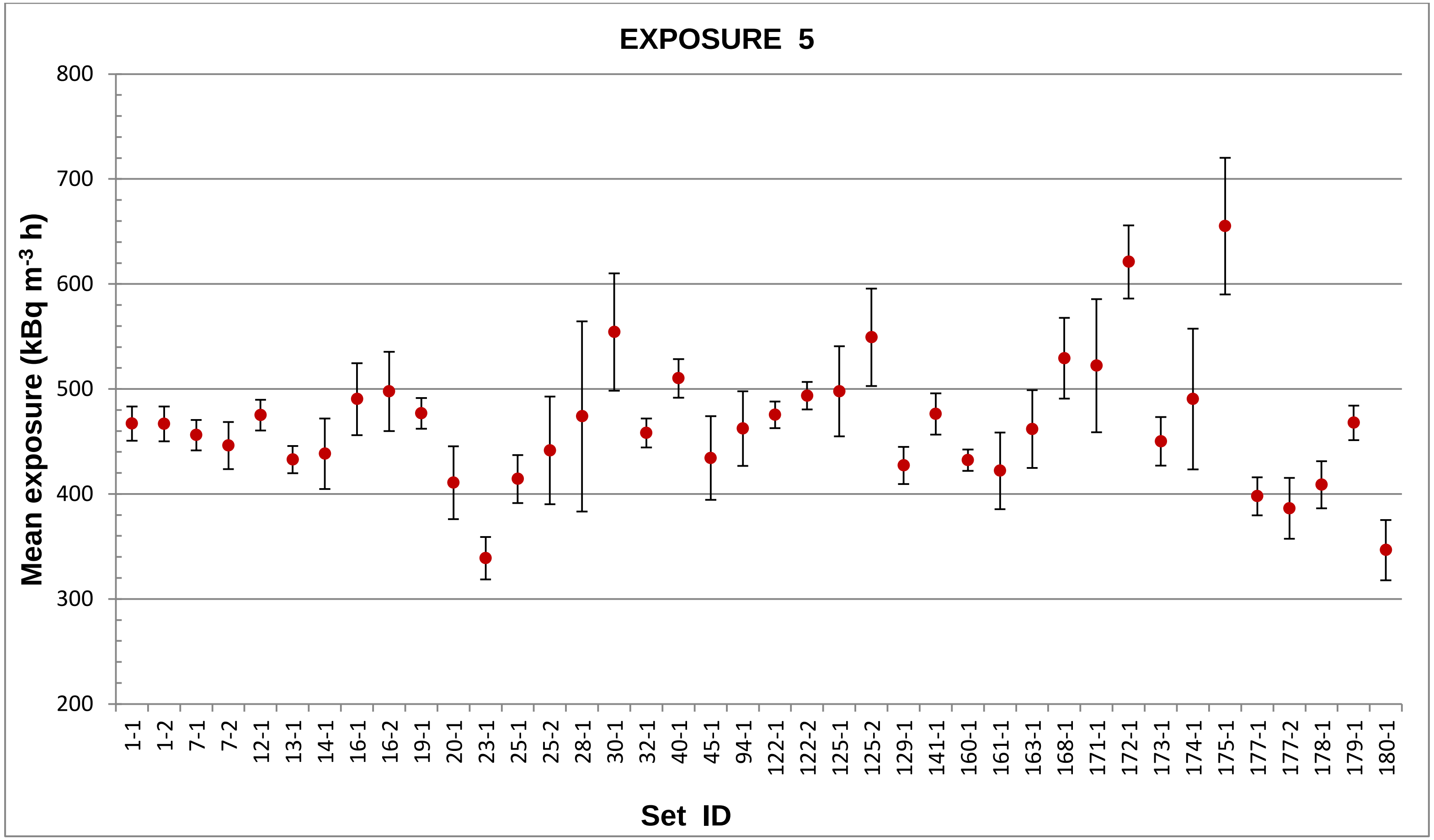

FIGURE 10 Results as reported by participants for exposure 5

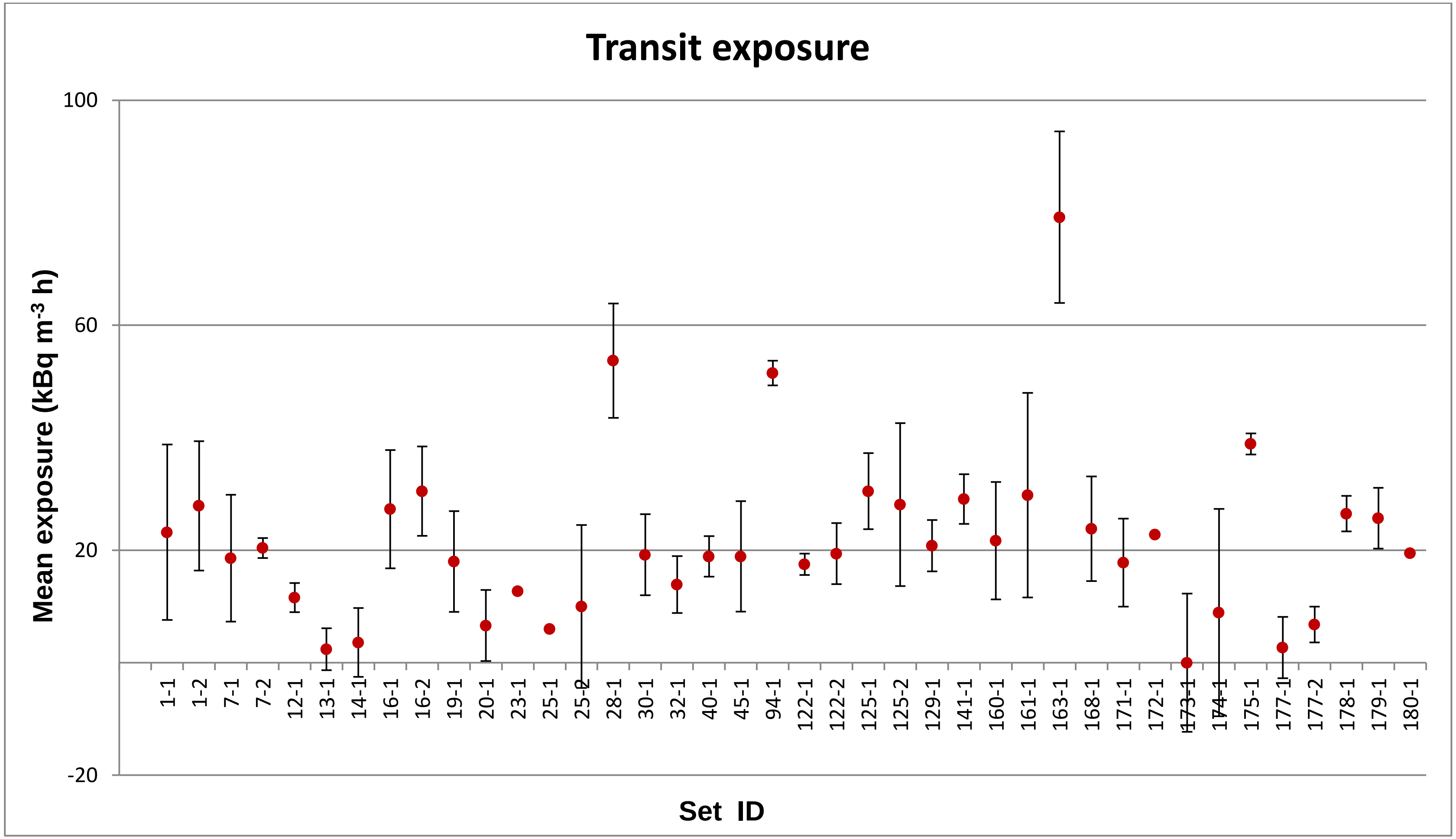

FIGURE 11 Results as reported by participants for transit exposure

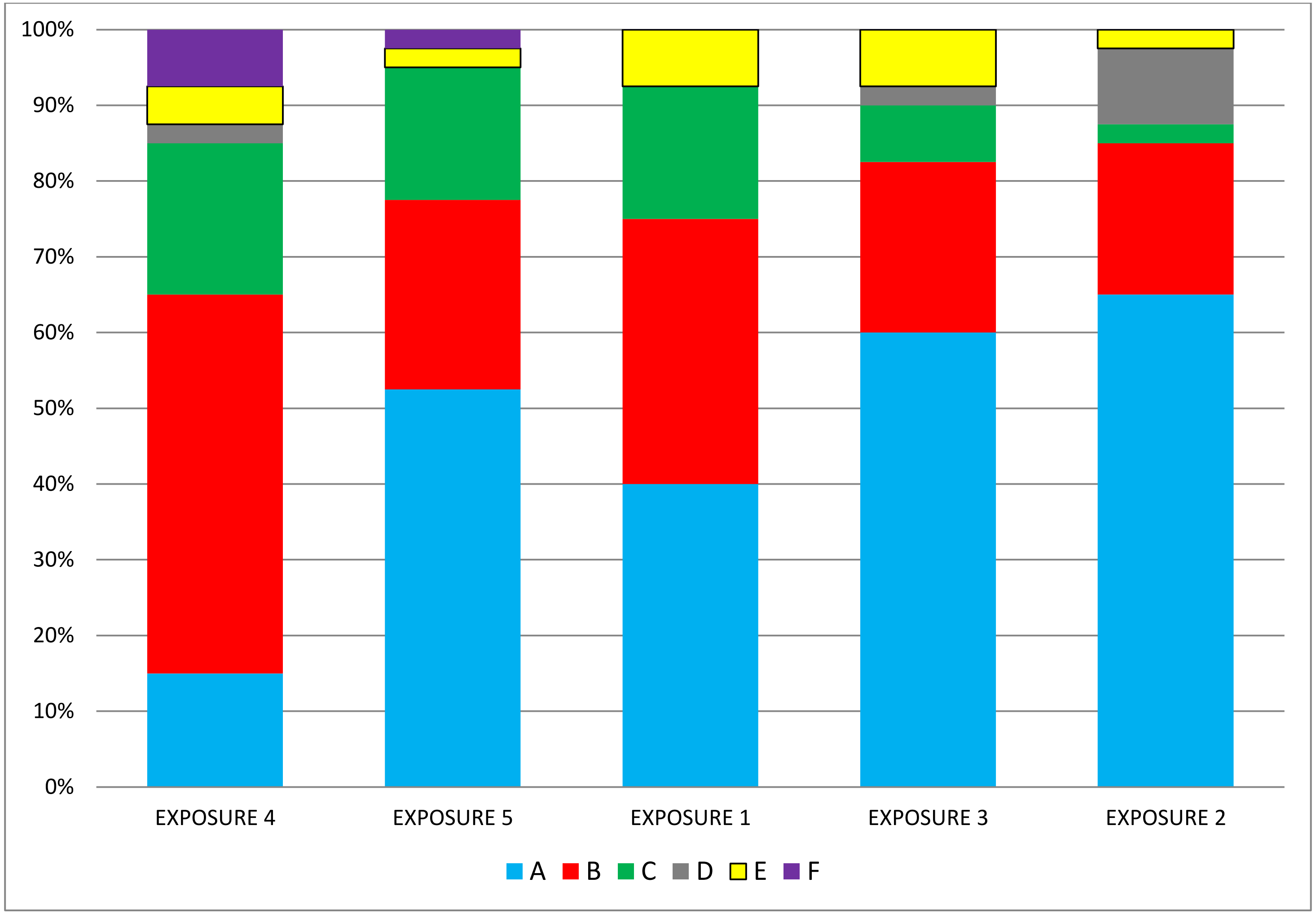

FIGURE 12 Proportions of sets achieving different ranks in each exposure