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Results of the 2012 HPA Intercomparison of Passive Radon Detectors

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Results of the 2012 HPA Intercomparison of Passive Radon Detectors

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ABSTRACT

In total, 35 laboratories from 13 countries, took part in the 2012 HPA intercomparison of passive radon detectors. Some laboratories submitted more than one set of detectors, so 42 sets of detectors were exposed together in the radon chamber. Results for 41 sets were reported by 34 laboratories.

The detectors were exposed to five different radon concentrations ranging from 50 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 exposure to radon. The parameter called 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 20 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 their detectors traceable to international standards.

The Centre for Radiation, Chemical and Environmental Hazards of Public Health England (CRCE), formerly part of the Health Protection Agency, carries out international intercomparisons of passive radon detectors each year. For this intercomparison laboratories were invited to submit sets of detectors that were randomised into six groups at CRCE. Five of these groups were exposed in the CRCE radon chamber to five different radon concentrations ranging from 50 to 2500 kBq m^{-3} h and the sixth group was used to determine transit exposures. The detectors were then returned to the laboratories who were asked to report the integrated exposure result for each detector. The laboratories were not informed of the details of the exposures or which detectors were in which group until all the results had 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 eight 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 detector designs.

Passive detectors employing plastic as the detector material are called etched track detectors, because 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 plastic 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 from radon-222 decay only. The closed etched track detectors allow only radon to diffuse into the closed chamber and therefore exclude entry of ambient radon decay products.

Activated charcoal detectors and electret chambers do not rely upon etched tracks. The charcoal detectors rely upon 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 concentration 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 designed 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 the (then) National Radiological Protection Board (NRPB) in 1982 and has operated regularly since then.

2 LABORATORY EXPOSURE AND MEASUREMENT FACILITIES

CRCE 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 to 8000 Bq m^{-3}, depending on the use of various dry radium-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 monitoring of the radon concentration inside the chamber

was optimised by introducing an Alphaguard ionisation chamber as a second primary transfer standard. 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 subsequently.

3 LOGISTICAL ARRANGEMENTS

In 2011 the format of the interlaboratory comparison of passive radon detectors was modified as described by Daraktchieva et al (2012). Operational procedures and equipment have been described fully in the reports on 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 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 exposure to 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.

One set of charcoal detectors was submitted this year. Each exposure group was returned immediately after exposure to the laboratory for analysis.

4 EXPOSURES

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

The exposures are summarised in Table 1. For charcoal detectors the exposures are given in Table 2. All exposures were carried out at the same equilibrium factor of about 0.4. 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, these detectors were removed from the chamber after 2, 5 and 7 days and returned to the originating laboratory straight away.

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 three days to allow radon to diffuse out of them was less than 1% of the exposure in the chamber in all cases and the values were neglected for the purpose of calculating the reference exposures. The transit detectors were used to monitor the transit exposure.

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 takes into account their combined effect. The measured mean is obtained by subtracting the mean transit exposure from the mean reported exposure. This year % biased error was calculated taking into account its sign – positive or negative. The parameters are given below:

$$\%\ \text{biased error} = \frac{\text{Measured mean} - \text{Reference value}}{\text{Reference value}} \times 100$$

where the reference value is the reference radon exposure,

$$\%\ \text{precision error} = \frac{\text{Standard deviation}}{\text{Measured mean}} \times 100$$

$$\%\ \text{measurement error} = \sqrt[2]{\%\ \text{biased error}^2 + \%\ \text{precision error}^2}$$

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, ie one rank for each exposure.

The ranks based on the measurement error are:

a If the measurement error is <10% the rank is A

b If the measurement error is between ≤10% and <20% the rank is B

c If the measurement error is between ≤20% and <30% the rank is C

d If the measurement error is between ≤30% and <40% the rank is D

e If the measurement error is between ≤40% and <50% the rank is E

f If the measurement error is ≥50% and <100% the rank is F

6 RESULTS AND DISCUSSION

The results reported by the laboratories are given in Table 3. Table 4 gives the results for charcoal detectors. In these tables, the ‘Mean’ is the mean result of ten exposed detectors (five for electrets and five for charcoal) after subtracting the mean transit exposure. The standard deviation, ‘1 SD’, is for ten reported results (again, five for electrets and five for charcoal). 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 reported results were nearly normally distributed

for all five exposures. The mean, μ, and standard deviation, σ, of all reported results, calculated for each exposure, are given in Table 5.

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 6. The exposures are shown in the headings of the columns of Table 6. 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 6.

Three laboratories achieved a ranking of five As meaning that they have a measurement error of under 10% for every exposure. Six other laboratories have four As and one Bs 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 six 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 background can lead to either positive or negative bias of the result in the low exposure. One other laboratory had a ranking of five As and one B in exposure 5. Exposure 2 and exposure 3 were measured with the greatest precision – for which 26 and 24 laboratories achieved A, respectively. The proportion of sets achieving ranks A, B, C, D, E and F is given in Figure 12.

It should be noted (see Table 6) that laboratories participating with the same type of detectors and detector material can achieve quite different ranks from five As to five Cs, 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:

a Variations of the etched track material (thickness, background)

b Variation in the etching process (etching time, mixture, concentration)

c Variation of the automatic track counting system (various track reading parameters)

d Variation in the linearity of response (change in the parameters of the linearity curve for different sheets/ batches).

e Variation of sensitivity due to chemical change of the etch track material-ageing and fading (Hardcastle and Miles, 1996)

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

The results reported by customers using charcoal detectors are given in Table 4 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 of passive radon detectors. 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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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, equilibrium factor	0.42	0.42	0.42	0.41	0.42

Notes
EER is equilibrium equivalent of radon.
CL is the confidence level.

TABLE 2 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, equilibrium factor	0.42	0.42	0.42

TABLE 3 Analysis of all reported results

Exposure 1 717 kBq m^{-3} h

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	803.1	15.9	12.0	2.0	12.2
1-2	778.2	34.7	8.5	4.5	9.6
7-1	735.8	29.7	2.6	4.0	4.8
7-2	720.9	25.7	0.5	3.6	3.6
12-1	811.6	19.8	13.2	2.4	13.4
13-1	701.4	21.3	–2.2	3.0	3.7
14-1	731.0	23.7	2.0	3.2	3.8
16-1	822.2	33.6	14.7	4.1	15.2
16-2	813.9	58.7	13.5	7.2	15.3
19-1	794.9	20.6	10.9	2.6	11.2
20-1	723.1	29.3	0.9	4.1	4.1
23-1	567.4	38.0	–20.9	6.7	21.9
25-1	713.9	37.7	–0.4	5.3	5.3
25-2	723.9	67.5	1.0	9.3	9.4
28-1	730.6	51.1	1.9	7.0	7.2
30-1	866.0	173.6	20.8	20.0	28.9
32-1	756.5	22.3	5.5	2.9	6.2
40-1	892.7	44.0	24.5	4.9	25.0
45-1	670.8	111.7	–6.4	16.7	17.9
94-1	770.8	68.2	7.5	8.8	11.6
122-1	794.7	25.4	10.8	3.2	11.3
122-2	807.6	20.1	12.6	2.5	12.9
125-1	876.2	93.8	22.2	10.7	24.6
125-2	841.3	64.0	17.3	7.6	18.9
129-1	701.2	45.1	–2.2	6.4	6.8
141-1	782.9	33.7	9.2	4.3	10.1
160-1	733.1	30.5	2.2	4.2	4.7
161-1	673.6	85.5	–6.1	12.7	14.1
163-1	855.6	59.4	19.3	6.9	20.5
168-1	862.9	54.5	20.3	6.3	21.3
171-1	1041.0	171.6	45.2	16.5	48.1
172-1	1004.3	22.6	40.1	2.3	40.1
173-1	764.1	38.9	6.6	5.1	8.3
174-1	755.5	53.9	5.4	7.1	8.9
175-1	1003.1	300.3	39.9	29.9	49.9
177-1	696.4	35.7	–2.9	5.1	5.9
177-2	647.1	69.0	–9.7	10.7	14.4
178-1	695.9	23.4	–2.9	3.4	4.5
179-1	792.2	36.4	10.5	4.6	11.5
180-1	553.5	50.1	–22.8	9.1	24.5

TABLE 3 Analysis of all reported results *(continued)*

Exposure 2 2385 kBq m^{-3} h

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	2658.0	60.7	11.4	2.3	11.7
1-2	2405.5	110.2	0.9	4.6	4.7
7-1	2293.1	71.1	–3.9	3.1	4.9
7-2	2295.2	45.7	–3.8	2.0	4.3
12-1	2642.6	28.1	10.8	1.1	10.9
13-1	2279.0	50.8	–4.4	2.2	5.0
14-1*	2369.0	82.3	–0.7	3.5	3.5
16-1	2476.8	69.5	3.8	2.8	4.8
16-2	2404.0	57.0	0.8	2.4	2.5
19-1	2442.5	113.1	2.4	4.6	5.2
20-1	2405.6	97.3	0.9	4.0	4.1
23-1	1817.1	63.8	–23.8	3.5	24.1
25-1	2637.2	82.2	10.6	3.1	11.0
25-2	2589.9	226	8.6	8.7	12.2
28-1	2362.9	82.4	–0.9	3.5	3.6
30-1	2539.4	308.4	6.5	12.1	13.8
32-1	2441.8	87.8	2.4	3.6	4.3
40-1	3325.7	264.6	39.4	8.0	40.2
45-1	2454.8	164.3	2.9	6.7	7.3
94-1	2414.6	60.5	1.2	2.5	2.8
122-1	2587.7	70.6	8.5	2.7	8.9
122-2	2648.5	47.7	11.0	1.8	11.2
125-1	2367.3	50.2	–0.7	2.1	2.2
125-2	2342.5	71.2	–1.8	3.0	3.5
129-1	2367.9	41.0	–0.7	1.7	1.9
141-1	2520.2	30.3	5.7	1.2	5.8
160-1	2296.7	72.0	–3.7	3.1	4.9
161-1	2145.1	69.5	–10.1	3.2	10.6
163-1	2456.8	3.1	3.0	0.1	3.0
168-1	2478.8	77.6	3.9	3.1	5.0
171-1	3218.5	211.1	34.9	6.6	35.6
172-1	3107.7	88.7	30.3	2.9	30.4
173-1	2397.3	61.4	0.5	2.6	2.6
174-1	2639.4	231.5	10.7	8.8	13.8
175-1	3131.7	77.1	31.3	2.5	31.4
177-1	2220.0	76.8	–6.9	3.5	7.7
177-2	2209.8	103.7	–7.3	4.7	8.7
178-1	2326.9	63.6	–2.4	2.7	3.7
179-1	2559.1	39.1	7.3	1.5	7.5
180-1	1599.0	149.8	–33.0	9.4	34.3

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

TABLE 3 Analysis of all reported results *(continued)*

Exposure 3 1487 kBq m^{-3} h

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	1636.2	26.5	10.0	1.6	10.2
1-2	1566.6	40.8	5.4	2.6	6.0
7-1	1323.7	463.0	–11.0	35.0	36.7
7-2	1415.1	76.4	–4.8	5.4	7.2
12-1	1665.8	32.2	12.0	1.9	12.2
13-1	1427.0	43.3	–4.0	3.0	5.0
14-1	1493.7	47.8	0.5	3.2	3.2
16-1	1596.1	48.8	7.3	3.1	7.9
16-2	1583.5	41.8	6.5	2.6	7.0
19-1	1580.0	66.2	6.3	4.2	7.5
20-1	1456.7	60.0	–2.0	4.1	4.6
23-1	1150.9	56.1	–22.6	4.9	23.1
25-1	1538.6	65.9	3.5	4.3	5.5
25-2	1615.1	186.0	8.6	11.5	14.4
28-1	1535.3	114.0	3.2	7.4	8.1
30-1	1680.1	227.6	13.0	13.5	18.8
32-1	1552.2	56.0	4.4	3.6	5.7
40-1	1840.4	326.3	23.8	17.7	29.7
45-1	1538.3	117.9	3.4	7.7	8.4
94-1	1536.4	76.2	3.3	5.0	6.0
122-1	1624.2	43.6	9.2	2.7	9.6
122-2	1647.0	36.7	10.8	2.2	11.0
125-1	1597.0	102.5	7.4	6.4	9.8
125-2	1624.4	39.8	9.2	2.5	9.6
129-1	1477.7	36.8	–0.6	2.5	2.6
141-1	1602.3	50.0	7.8	3.1	8.4
160-1	1417.3	49.6	–4.7	3.5	5.8
161-1	1353.5	91.2	–9.0	6.7	11.2
163-1	1668.8	79.2	12.2	4.7	13.1
168-1	1628.5	69.0	9.5	4.2	10.4
171-1	2139.2	132.0	43.9	6.2	44.3
172-1	2184.6	35.1	46.9	1.6	46.9
173-1	1551.6	60.2	4.3	3.9	5.8
174-1	1558.7	88.8	4.8	5.7	7.5
175-1	2111.0	137.9	42.0	6.5	42.5
177-1	1368.9	48.2	–7.9	3.5	8.7
177-2	1328.4	73.1	–10.7	5.5	12.0
178-1	1417.7	23.2	–4.7	1.6	4.9
179-1	1589.0	44.8	6.9	2.8	7.4
180-1	1059.3	58.9	–28.8	5.6	29.3

TABLE 3 Analysis of all reported results *(continued)*

Exposure 4 138 kBq m^{-3} h

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	160.0	16.1	15.9	10.1	18.9
1-2	156.1	11.8	13.1	7.6	15.1
7-1	147.3	14	6.7	9.5	11.7
7-2	136.8	20.2	–0.9	14.8	14.8
12-1	158.1	4.1	14.6	2.6	14.8
13-1	132.3	9.0	–4.1	6.8	8.0
14-1	144.2	14.7	4.5	10.2	11.1
16-1	170.7	10.3	23.7	6.0	24.5
16-2	170.0	20.0	23.2	11.8	26.0
19-1	152.5	17.8	10.5	11.7	15.7
20-1	125.2	17.4	–9.3	13.9	16.7
23-1	104.4	7.5	–24.3	7.2	25.4
25-1	137.2	14.7	–0.6	10.7	10.7
25-2	140.5	16.8	1.8	12.0	12.1
28-1	184.7	75.3	33.8	40.8	53.0
30-1	178.4	23.2	29.3	13.0	32.0
32-1	146.8	12.1	6.4	8.2	10.4
40-1	166.5	17.2	20.7	10.3	23.1
45-1	153.0	17.4	10.9	11.4	15.7
94-1	188.6	34.0	36.7	18.0	40.9
122-1	155.6	4.9	12.8	3.1	13.1
122-2	147.5	6.7	6.9	4.5	8.2
125-1	168.2	30.5	21.9	18.1	28.4
125-2	143.7	31.6	4.1	22.0	22.4
129-1	126.6	12.6	–8.3	10.0	12.9
141-1	151.8	8.0	10.0	5.3	11.3
160-1	140.6	10.8	1.9	7.7	7.9
161-1	122.0	20.4	–11.6	16.7	20.3
163-1	146.6	11.7	6.2	8.0	10.1
168-1	195.8	38.6	41.9	19.7	46.3
171-1	145.3	27.1	5.3	18.7	19.4
172-1	240.7	14.7	74.4	6.1	74.7
173-1	146.9	18.3	6.4	12.5	14.0
174-1	152.3	22.2	10.4	14.6	17.9
175-1	260.8	62.0	89.0	23.8	92.1
177-1	140.7	12.2	2.0	8.7	8.9
177-2	129.3	6.1	–6.3	4.7	7.9
178-1	134.4	11.8	–2.6	8.8	9.2
179-1	160.6	9.2	16.4	5.7	17.3
180-1	107.0	19.8	–22.5	18.5	29.1

TABLE 3 Analysis of all reported results *(continued)*

Exposure 5 438 kBq m^{-3} h

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	467.1	16.3	6.6	3.5	7.5
1-2	466.8	16.6	6.6	3.6	7.5
7-1	456.1	14.5	4.1	3.2	5.2
7-2	446.1	22.5	1.8	5.0	5.4
12-1	475.0	14.6	8.4	3.1	9.0
13-1	432.7	12.9	–1.2	3.0	3.2
14-1	438.4	33.6	0.1	7.7	7.7
16-1	490.3	34.3	11.9	7.0	13.8
16-2	497.7	37.8	13.6	7.6	15.6
19-1	476.8	14.7	8.9	3.1	9.4
20-1	410.8	34.7	–6.2	8.4	10.5
23-1	338.8	20.1	–22.6	5.9	23.4
25-1	414.2	22.9	–5.4	5.5	7.8
25-2	441.5	51.2	0.8	11.6	11.6
28-1	473.9	90.6	8.2	19.1	20.8
30-1	554.2	55.8	26.5	10.1	28.4
32-1	458.1	13.7	4.6	3.0	5.5
40-1	510.1	18.3	16.5	3.6	16.8
45-1	434.2	39.9	–0.9	9.2	9.2
94-1	462.3	35.5	5.5	7.7	9.5
122-1	475.4	12.6	8.5	2.7	8.9
122-2	493.6	13.0	12.7	2.6	13.0
125-1	497.8	42.9	13.7	8.6	16.1
125-2	549.2	46.5	25.4	8.5	26.8
129-1	427.1	17.7	–2.5	4.1	4.8
141-1	476.2	19.7	8.7	4.1	9.7
160-1	432.2	10.2	–1.3	2.4	2.7
161-1	422.1	36.5	–3.6	8.6	9.4
163-1	461.8	37.0	5.4	8.0	9.7
168-1	529.2	38.5	20.8	7.3	22.1
171-1	522.2	63.5	19.2	12.2	22.7
172-1	621.0	34.7	41.8	5.6	42.2
173-1	450.1	23.1	2.8	5.1	5.8
174-1	490.4	67.1	12.0	13.7	18.2
175-1	655.1	65.0	49.6	9.9	50.5
177-1	397.8	18.1	–9.2	4.6	10.2
177-2	386.3	28.9	–11.8	7.5	14.0
178-1	408.7	22.4	–6.7	5.5	8.6
179-1	467.8	16.4	6.8	3.5	7.7
180-1	346.5	28.7	–20.9	8.3	22.5

TABLE 3 Analysis of all reported results *(continued)*

Transit controls

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
1-1	23.2	13.9	122-1	17.5	2.2
1-2	27.9	15.6	122-2	19.4	1.9
7-1	18.6	11.5	125-1	30.5	5.4
7-2	20.4	11.3	125-2	28.1	6.8
12-1	11.6	1.8	129-1	20.8	14.5
13-1	2.4	2.6	141-1	29.1	4.6
14-1	3.6	3.7	160-1	21.7	4.4
16-1	27.3	6.1	161-1	29.8	10.4
16-2	30.5	10.5	163-1	79.2	18.2
19-1	18.0	7.9	168-1	23.8	15.2
20-1	6.6	9.0	171-1	17.8	9.3
23-1	12.7	6.3	172-1	22.8	7.8
25-1	6.0	0.0	173-1	0.0	0.0
25-2	10.0	0.0	174-1	8.9	12.3
28-1	53.7	14.5	175-1	38.9	18.4
30-1	19.2	10.2	177-1	2.7	1.9
32-1	13.9	7.2	177-2	6.8	5.5
40-1	18.9	5.1	178-1	26.5	3.2
45-1	18.9	3.6	179-1	25.7	3.2
94-1	51.5	9.8	180-1	19.5	5.4

TABLE 4 Analysis of results with charcoal detectors

Exposure	Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1 (492 kBq m^{-3} h)	176-1	592.7	157.4	20.5	26.6	33.5
2 (207 kBq m^{-3} h)	176-1	186.4	6.9	–10.0	3.7	10.6
3 (734 kBq m^{-3} h)	176-1	787.4	201	7.3	25.5	26.5

TABLE 5 Analysis of all reported results given in Table 3

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

TABLE 6 New ranking scheme based on the measurement error

	Rank exposure									
	4	5	1	3	2					
Set ID	138 kBq m^{-3} h	438 kBq m^{-3} h	717 kBq m^{-3} h	1487 kBq m^{-3}	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
1-1	B	A	B	B	B	Closed		NRPB/SSI	CR-39	TASL

	Rank exposure									
	4	5	1	3	2					
Set ID	138 kBq m^{-3} h	438 kBq m^{-3} h	717 kBq m^{-3} h	1487 kBq m^{-3}	2385 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
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	Closed		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		NRPB/SSI	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

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

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

	Rank exposure							
	1	2	3					
Set ID	492 kBq m^{-3} h	207 kBq m^{-3} h	734 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
176-1	D	B	C				Charcoal	

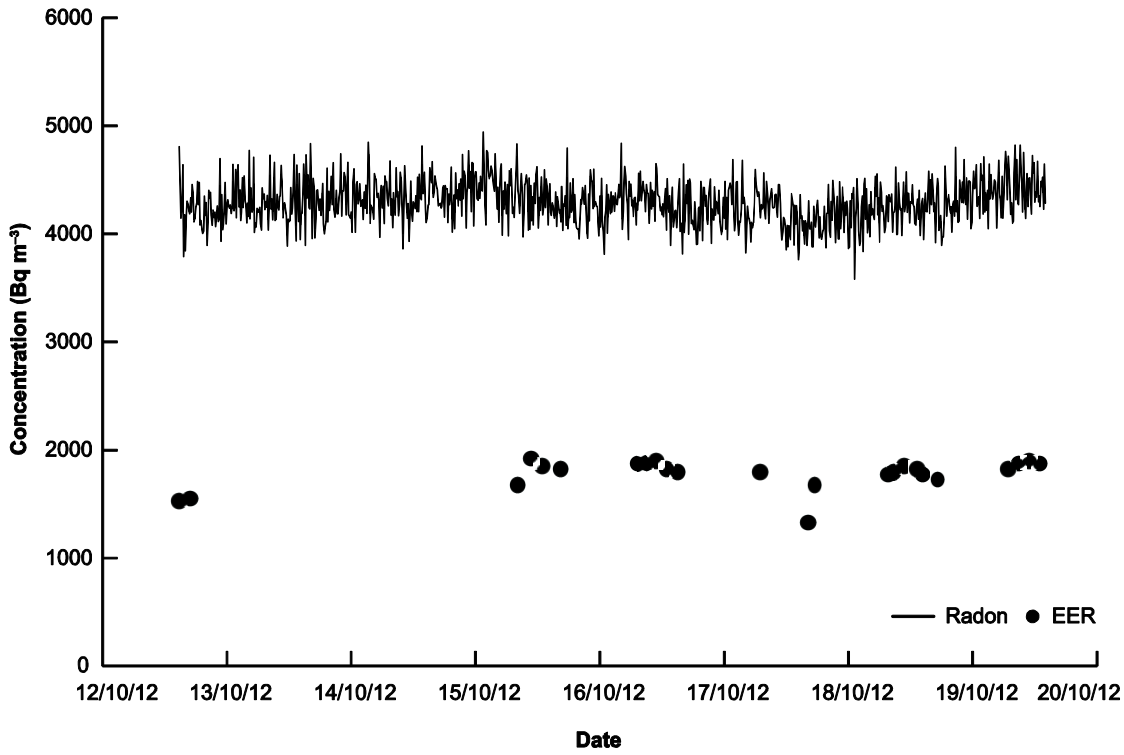

FIGURE 1 Radon and EER concentrations for exposure 1

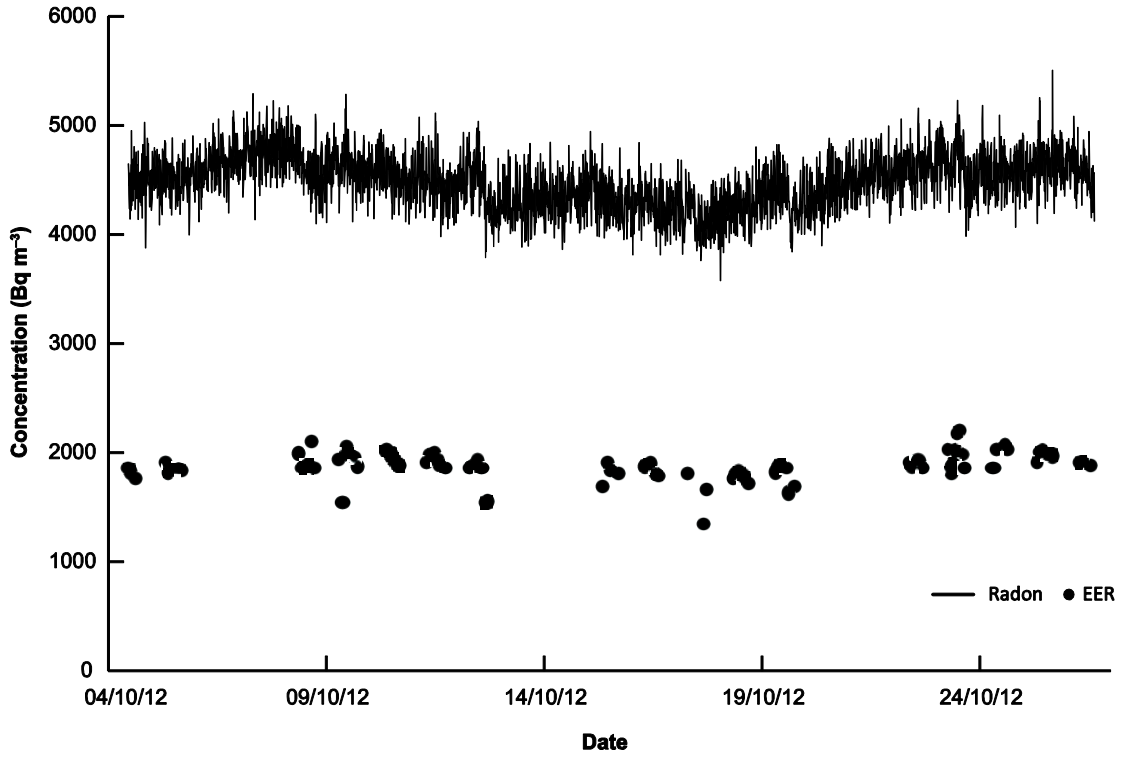

FIGURE 2 Radon and EER concentrations for exposure 2

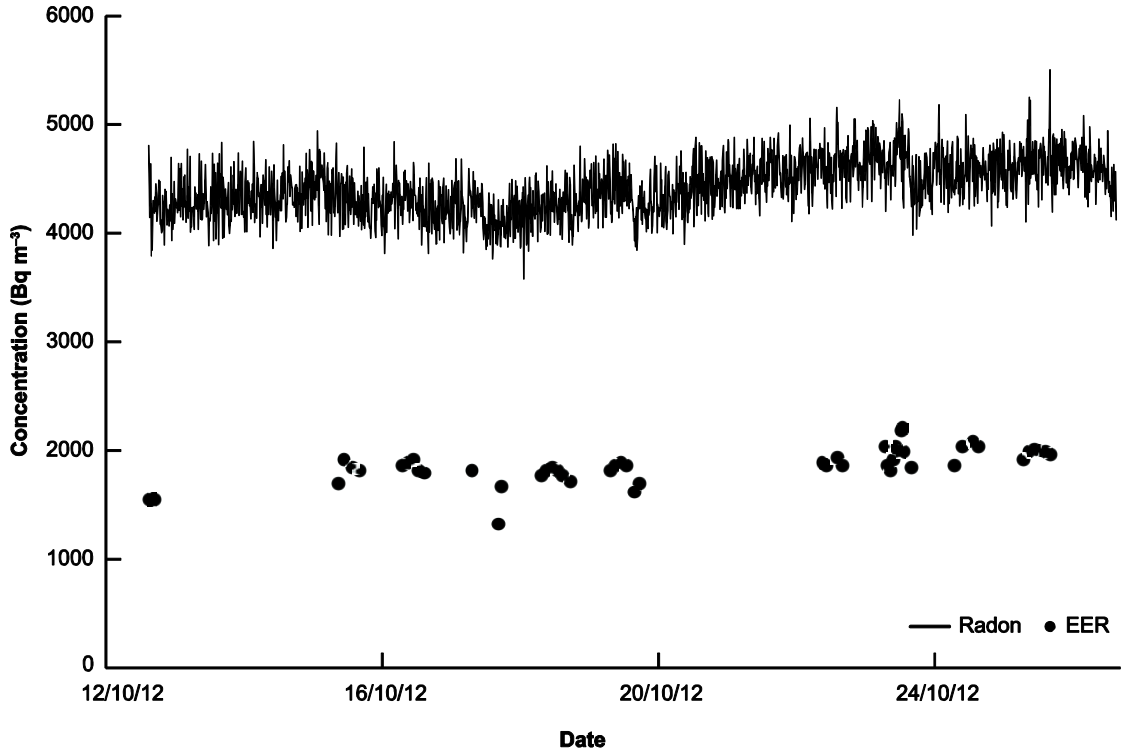

FIGURE 3 Radon and EER concentrations for exposure 3

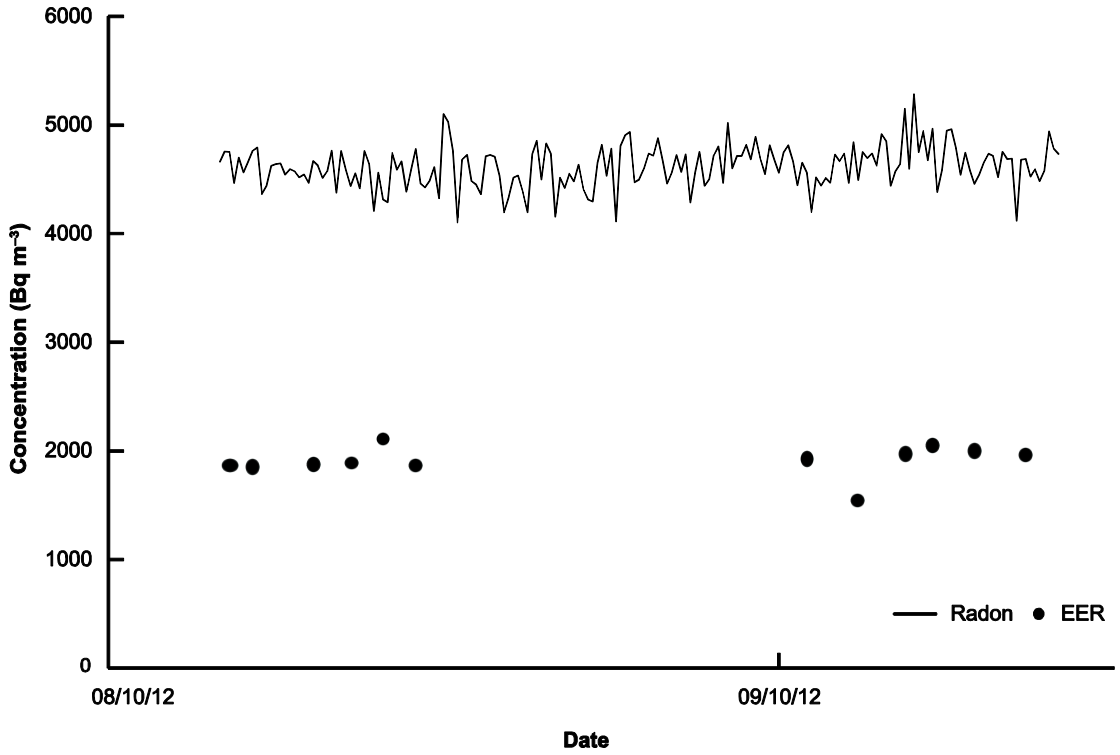

FIGURE 4 Radon and EER concentrations for exposure 4

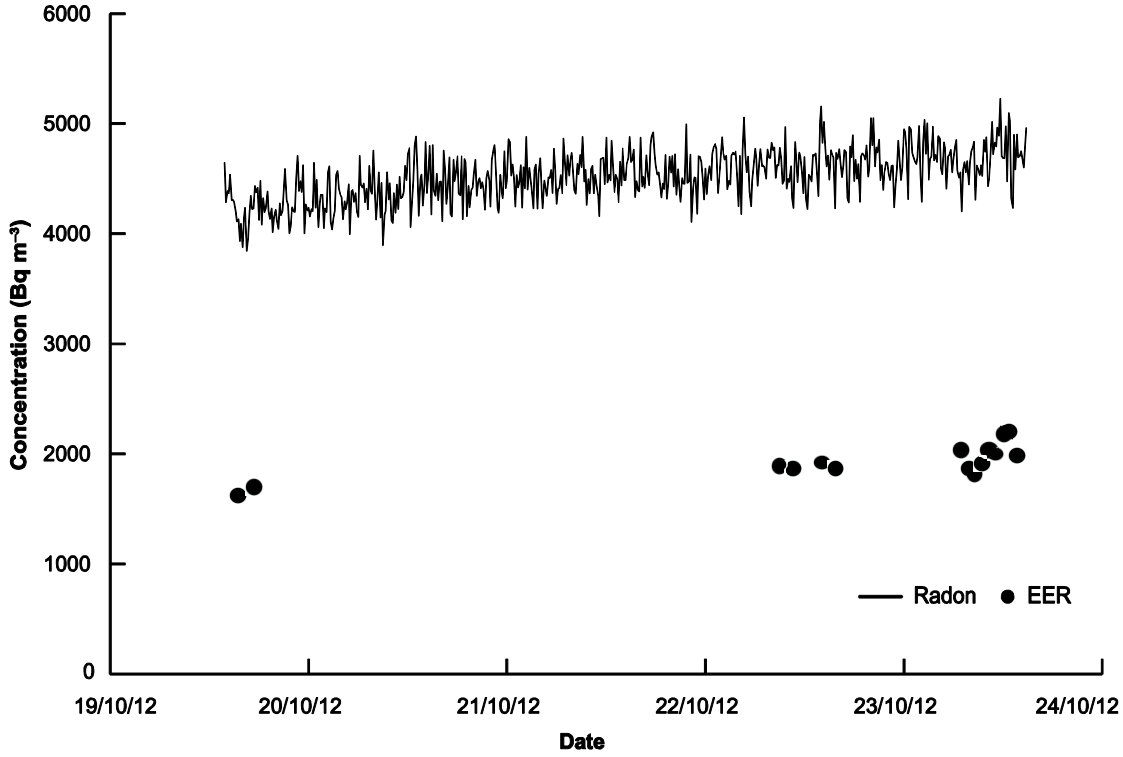

FIGURE 5 Radon and EER concentrations for exposure 5

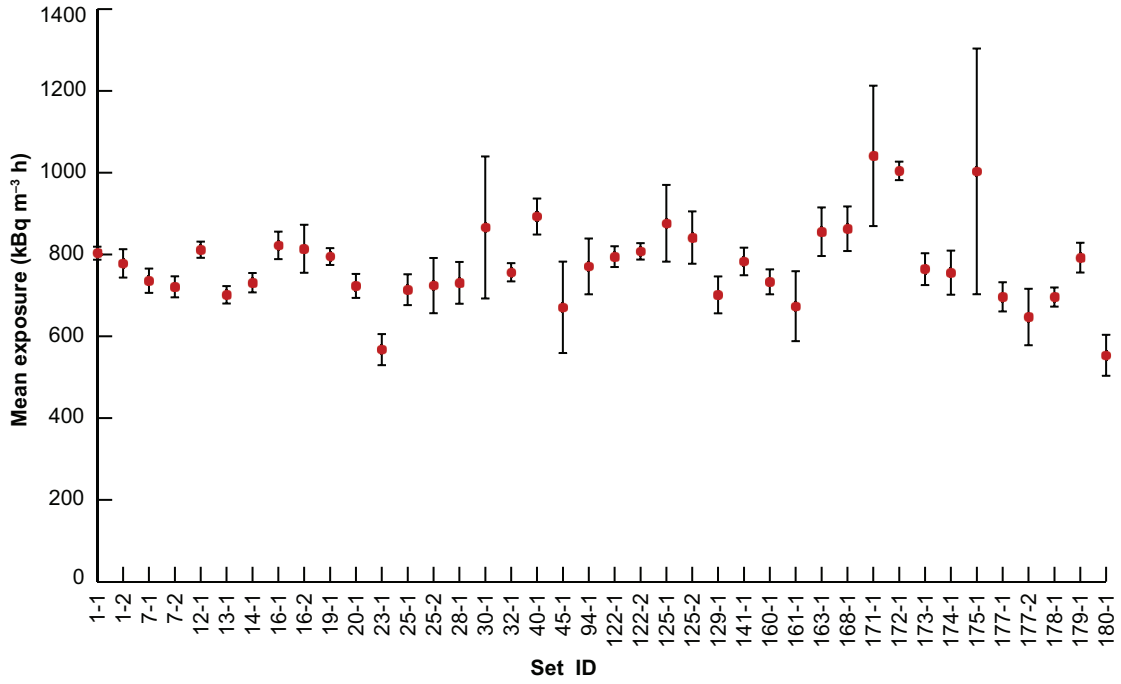

FIGURE 6 Results as reported by participants for exposure 1

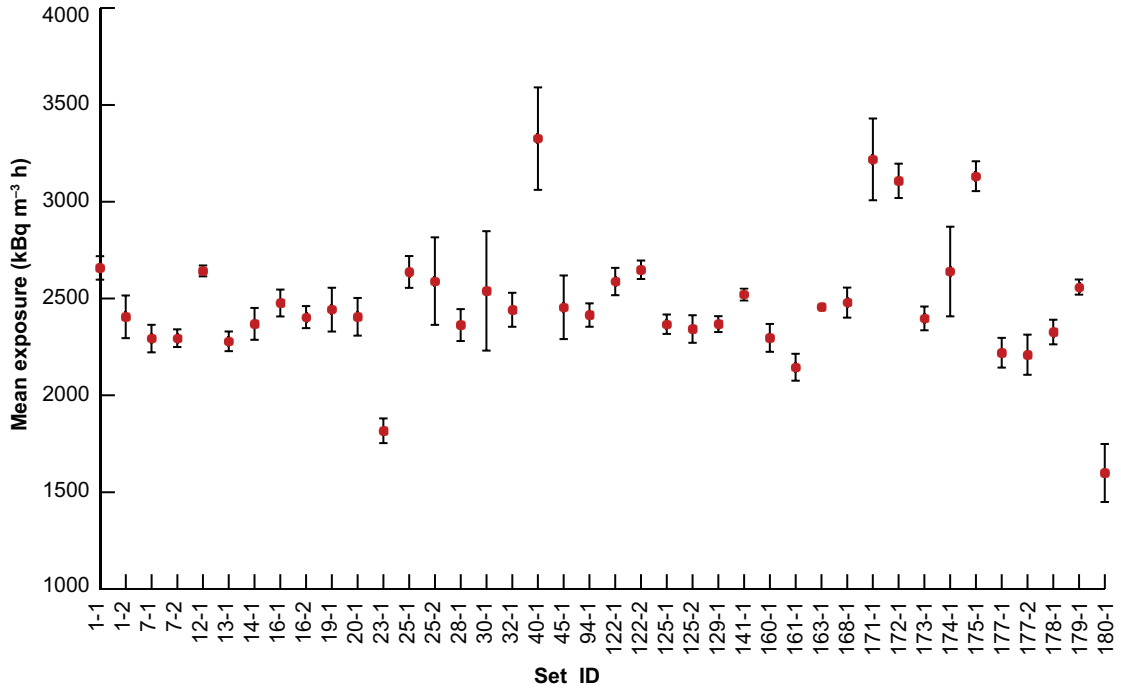

FIGURE 7 Results as reported by participants for exposure 2

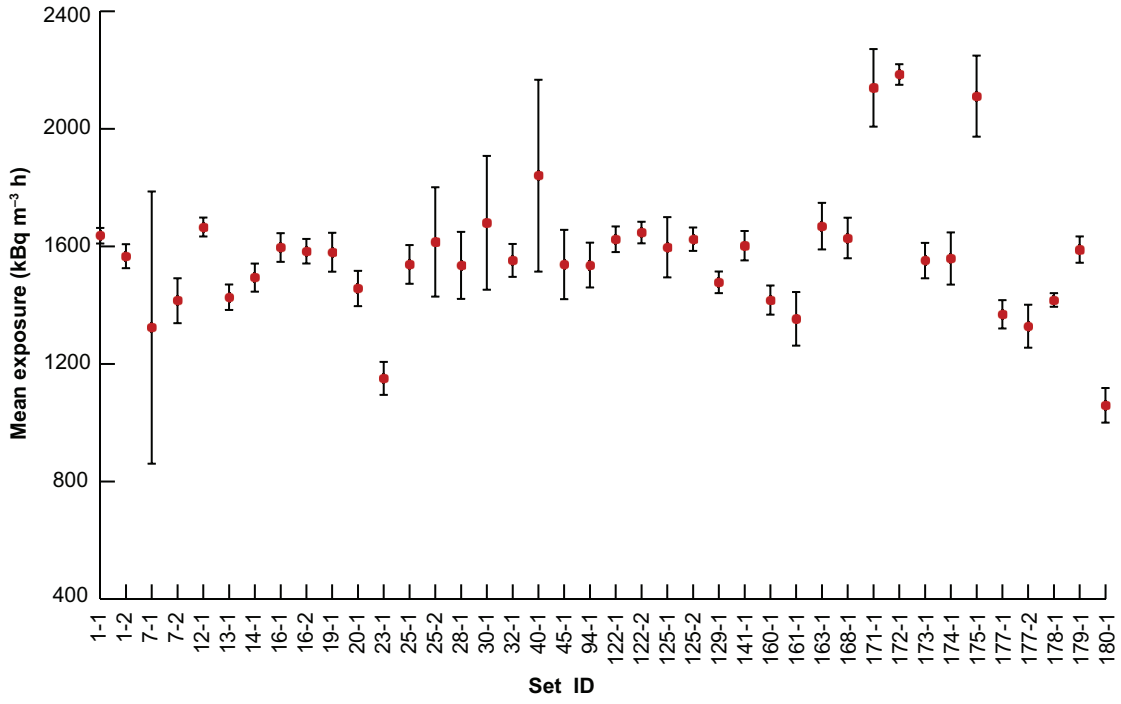

FIGURE 8 Results as reported by participants for exposure 3

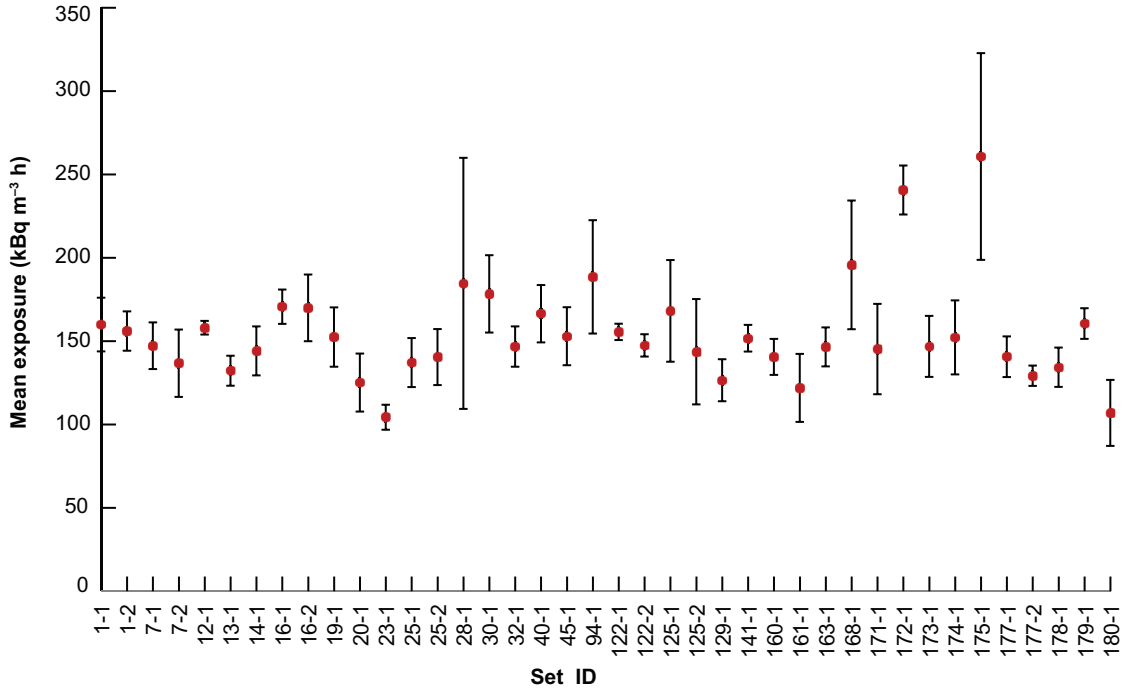

FIGURE 9 Results as reported by participants for exposure 4

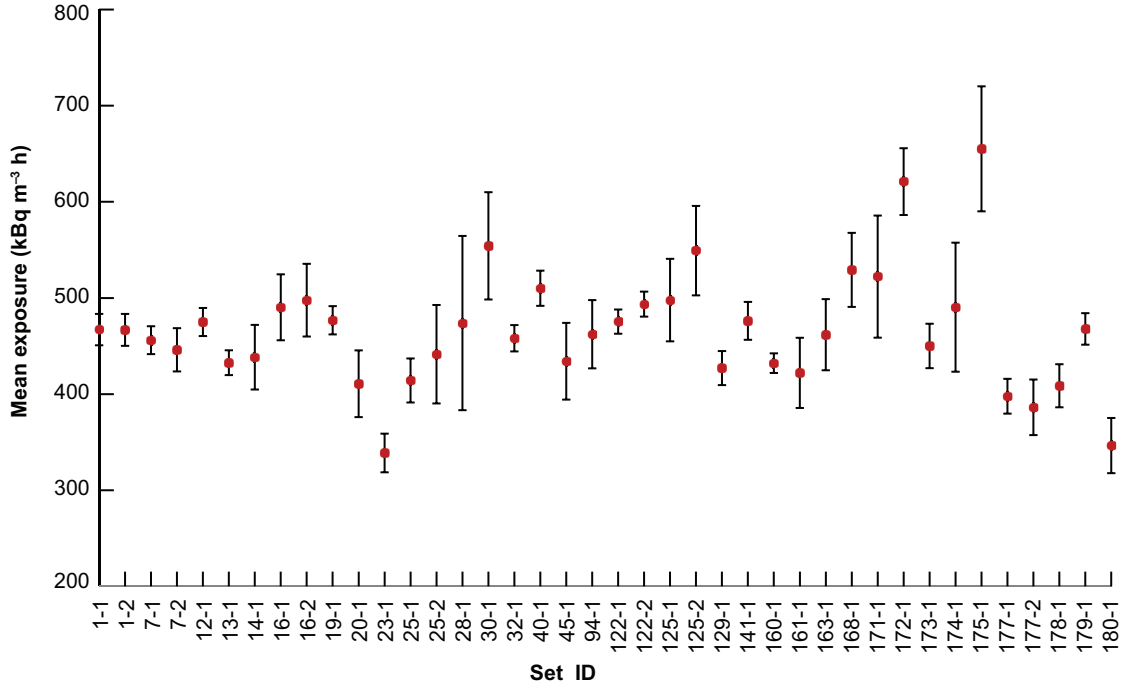

FIGURE 10 Results as reported by participants for exposure 5

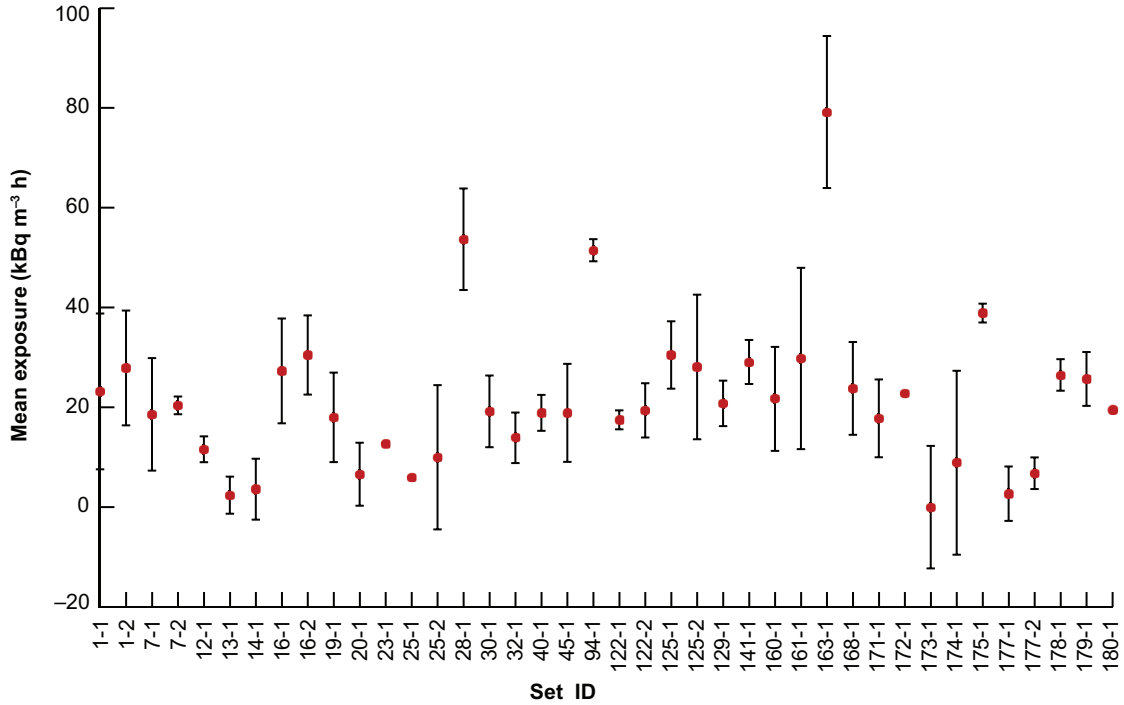

FIGURE 11 Results as reported by participants for transit exposure

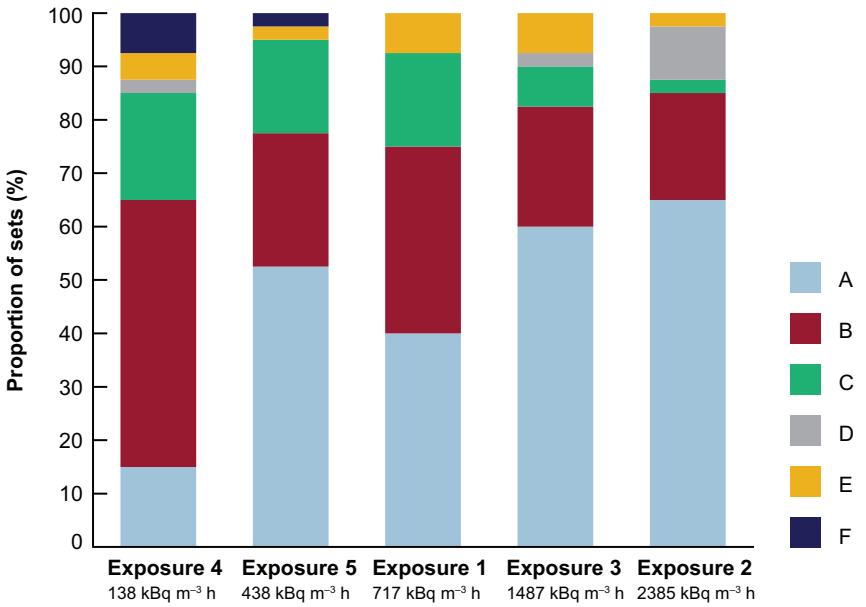

FIGURE 12 Proportions of sets achieving different ranks for each exposure