UK Health Security Agency

Results of the 2021 intercomparison of passive radon detectors

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Executive summary

Radon is the largest and most variable contributor of radiation dose to the general population. For more than 30 years, countries in Europe and elsewhere have carried out measurement surveys in order to determine both individual and average exposures, and to 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 3 types of detector are used for experimental and research work.

Intercomparisons provide information about the accuracy and precision of measurements. By allowing different detectors to be compared side by side to reference radon exposures, an objective assessment 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. Laboratories are required to participate in “intralaboratory comparisons” to achieve accreditation under ISO/IEC 17025:2017 ‘General requirements for the competence of testing and calibration laboratories’.

The Radiation, Chemicals and Environmental Hazards Directorate (RCE) of the UK Health Security Agency (UKHSA), was formerly known as the Centre for Radiation, Chemical and Environmental Hazards (CRCE) of Public Health England (PHE). RCE carries out international intercomparisons of passive radon detectors each year. For this latest intercomparison, laboratories were invited to submit sets of etched track detectors, electret detectors and/or activated charcoal detectors, however, no activated charcoal detectors were submitted.

The sets of etched track and electret detectors were randomised into 6 groups at RCE. A total of 5 of these groups were exposed in the RCE radon chamber to radon gas exposures ranging from 170 kBq m^{-3} h to 2,600 kBq m^{-3} h; the 6th group was used to determine transit exposures. The detectors were then returned to the participating laboratories, which were asked to report the integrated radon gas exposure result for each detector. The laboratories were not informed of the details of the exposures, nor which detectors were in which group, until all the results had been submitted.

This report considers the results for the intercomparison carried out in 2021, for which a total of 30 laboratories from 12 countries submitted 36 sets of detectors. One laboratory was unable to process their exposed detectors due to staff shortages, so the report covers 29 laboratories and 35 sets of detectors from 12 countries. The 35 sets of detectors comprise 32 sets of etched track detectors and 3 sets of electret detectors. Analysis of the results allows each exposure group in each set to be classified from A (best) to F (worst).

Stringent quality assurance is vital, as is consideration of the equipment used and the measurement technique. Some laboratories reported their results to 1 or 2 decimal places – these results have been rounded to the nearest whole number for this report.

Introduction

Passive detectors, of varying designs, have been used for many years to make measurements of integrated radon exposures. The 3 most common methods are outlined below:

1. Etched track detectors are referred to as such because alpha particles from radon and its decay products damage the surface of the plastic detection medium, producing microscopic invisible tracks. These tracks are subsequently made visible by chemical or electrochemical etching. The most popular etched track materials are cellulose nitrate (LR-115), polycarbonate (Makrofol®) and polyallyl diglycol carbonate (PADC or CR-39™). In the open type of etched track detector, the plastic material is exposed to the ambient atmosphere and records alpha particles originating from radon decay products and from radon isotopes. For these open detectors, the radioactive decay equilibrium factor, *F*, for radon-222 (^{222}Rn) has to be taken into account to estimate the proportion of alpha particles that arise from ^{222}Rn decay. In the closed type, the detection material is enclosed in a chamber that excludes entry of ambient radon decay products and only allows entry of radon gas by diffusion. The response of closed detectors is not affected by the equilibrium factor (*F*).
2. Activated charcoal detectors work by retaining adsorbed radon in a charcoal volume. The radon is subsequently measured in the originating laboratory.
3. Electret 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 radon exposure allows the average radon concentration during exposure to be calculated. A filter in the chamber excludes radon decay products, so the response is unaffected by *F*.

Passive radon detectors are quite simple to produce and to process but are subject to various sources of error during production, storage and processing. It is therefore appropriate for laboratories that use these detectors to undertake regular checks against reference exposures carried out in relevant radon exposure facilities.

The present laboratory intercomparison programme was developed with broad international participation, following standard and agreed test and interpretation protocols. It has been designed to provide participants with a routine benchmark performance standard. The intercomparison programme was established by the National Radiological Protection Board (NRPB)[1], now the UKHSA Radiation, Chemical and Environmental Hazards Directorate (RCE), and has operated annually since 1982.

Operational procedures and equipment have been described previously (1).

[1] The NRPB was subsequently incorporated into the Health Protection Agency (HPA). On 1 April 2013 the HPA was abolished and its functions transferred to Public Health England (PHE). On 1 October 2021, PHE was abolished and its functions transferred to UK Health Security Agency.

Laboratory exposure and measurement facilities

The exposures in this intercomparison were carried out in the RCE radon chamber. This 43m^3 walk-in chamber is of the static type, in which radon is continually released from dry radium-226 (^{226}Ra) radon sources. There is no air flow through the chamber during operation.
The radon concentration in the chamber was continuously monitored using an ATMOS 12 DPX ionisation chamber and with an AlphaGUARD ionisation chamber as a secondary transfer standard. A daily cross-calibration between the ATMOS 12 DPX and AlphaGUARD was carried out throughout the intercomparison exercise. Both instruments are calibrated annually using a radon gas source, most recently supplied by Laboratoire National Henri Becquerel, France.

During the etched track and electret exposures, radon decay products were sampled approximately 4 times per weekday onto a Millipore AA filter and their concentrations determined using an alpha spectrometry system. All chamber-monitored data were automatically transferred to a database. Radon and radon decay product exposures were calculated subsequently.

Logistical arrangements

In total, 30 laboratories from 12 countries took part in the 2021 UKHSA intercomparison. Some laboratories submitted more than 1 set of detectors, so 36 sets of detectors were exposed in the radon chamber. Following exposure, the detectors were returned to the originating laboratories for processing.

One laboratory was unable to process their exposed detectors due to staff shortages, so this report covers 29 laboratories and 35 sets of detectors from 12 countries, as shown in Table 2. The 35 sets of detectors were 32 sets of etched track detectors and 3 sets of electret detectors. Participants were asked to return the result for each detector in terms of integrated exposure to radon. The participants were not told any details of the exposures delivered in the exercise until after the results had been received from all participating laboratories.

Radon exposures

Appropriate conditions for typical domestic radon exposure were established in the chamber before introducing the etched track and electret detectors. An equilibrium factor, *F*, of approximately 0.4 to 0.5 between the radon and its decay products was maintained in the chamber for all 5 etched track and electret detector intercomparison exposures.

The chamber exposures were calculated after the deadline for return of results by participants and are shown with exposure durations in Table 3. Radon and EER (equilibrium equivalent of radon) concentrations during the etched track and electret detector exposures are shown in Figures 1 to 5.

The radon concentration in the laboratory outside the exposure chamber was monitored during the exposures using an AlphaGUARD ionisation chamber. The laboratory daily average corrected concentrations ranged from 20 Bq m^{-3} to 61 Bq m^{-3}, with an overall average of 40 Bq m^{-3} The estimated additional exposure of the etched track and electret detectors caused by leaving them exposed in the laboratory for a minimum of 3 days to allow radon to diffuse out was less than 3% of the exposure in the chamber for the lowest exposure and less than 1% for the other exposures. This value was excluded for the purpose of calculating the reference exposures. Transit detectors were used to monitor radon exposures received in transit.

Performance classification scheme

A performance classification scheme was introduced in 2011 (2), based on the following parameters:

- percentage biased error which measures the bias of the measurement
- percentage precision error, which measures the precision of the measurement
- percentage 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. 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. Measurement errors are reflected as a performance classification from A (best) to F (worst) for each exposure separately. Each participating laboratory was assigned a classification, between A and F, for each exposure. The criteria for each of the classification groups are given below:

Table 1. Performance classification

Range of measurement error (%)	Performance classification
less than 10%	A
greater than or equal to 10% and less than 20%	B
greater than or equal to 20% and less than 30%	C
greater than or equal to 30% and less than 40%	D
greater than or equal to 40% and less than 50%	E
greater than or equal to 50%	F

Results and discussion

The results reported by the laboratories for the etched track and electret detectors are given in Tables 4.1 to 4.6. One of the participating laboratories was unable to analyse their exposed detectors, so the tables show the results for 29 laboratories and a total of 35 sets of detectors. In Tables 4.1 to 4.5, the 'mean' is the mean result of 10 exposed detectors (5 for electrets) after subtracting the mean transit exposure. The standard deviation, '1 SD', is for 10 reported results (5 for electrets). Results for % biased error, % precision error and % measurement error are also provided.

The mean results and their standard deviations, as reported by participants, are depicted in Figures 6 to 10; the reference exposures are indicated by dotted lines. The mean of all transit exposures is shown in Figure 11.

The mean and standard deviation of all reported results, calculated for each exposure, are given in Table 5. The distributions of the mean exposure results given in Table 5 are depicted in Figures 12 to 17. For Figures 12 to 16, the reference exposures are indicated by vertical dotted lines.

The characteristics of the detectors such as material, detector holder design, detector type and material supplier are provided in Table 6.

The mean of all transit exposures was 51 kBq m^{-3} h (Figure 11). Most of the reported transit exposures were below 30 kBq m^{-3} h, 11 reported transit exposures between 30 kBq m^{-3} h and 780 kBq m^{-3} h, and 10 of these were above 40 kBq m^{-3} h. This is a larger range of results than in 2020 (3) where 13 out of a total of 37 reported transit exposures were between 30 kBq m^{-3} h and 90 kBq m^{-3} h, of which 8 were above 40 kBq m^{-3} h.

The results, using the performance classification scheme, are given in Table 6. This table is sorted according to performance classification with the first order of sort being the lowest exposure. The position of a laboratory in the table reflects the performance classification 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 exposure levels.

Four laboratories achieved class A results for all 5 exposures in a set, meaning that they have a measurement error of under 10% for all 5 exposures. This is the same as in 2020.

Approximately 72% of all sets of detectors achieved class A for at least 3 exposures, which is an improvement from 2020, (3). For the lowest exposure measurement (173 kBq m^{-3} h), 17% of laboratories achieved class A, a decrease from 2020. For the second lowest exposure (553 kBq m^{-3} h), 57% of laboratories achieved class A, an improvement from 2020.
It should be noted that the laboratories participating with the same type of detectors and detector material can achieve quite different performance classifications, possibly reflecting each laboratory's own quality assurance (QA) protocols and staff experience.

In order to identify sources of errors, the laboratories should take into account changes in various parameters such as: calibration factor, sensitivity and background. Reviews of sources of errors for etched track detectors are given in (4), (5) and (6). Constant monitoring of detector performance and strict QA protocols should be established and maintained to identify and manage the above sources of errors.

The storage methods used by the laboratories were: freezer, fridge, nitrogen, radon-proof bags in a low radon store, and stored in a unit with filtered pressurised air. The majority of laboratories (21 out of 35 sets) use a freezer. The maximum storage time before use ranged from 2 months to 24 months or more. Most (22 out of 35) sets were sent using radon proof bags and had a transit exposure less than 50 Bq m^{-3}. Of the 5 sets sent using radon-proof bags where the transit exposure equalled or exceeded 50 Bq m^{-3}, 1 was due to a record-keeping error. Of the 7 sets not sent in radon-proof bags, only 1 set had a transit exposure above 40 Bq m^{-3} . This indicates that other factors apply – including etching methods and staff training. The proportion of sets achieving each performance classification (A to F) is given in Figure 18.

Conclusion

In total, 30 laboratories from 12 countries participated in the 2021 UKHSA intercomparison. One laboratory was unable to process their exposed detectors due to staff shortages, so this report is for 29 laboratories and 35 sets of detectors from 12 countries. The detectors were 32 sets of etched track detectors and 3 sets of electret detectors.

A 6-band (A to F) classification scheme was used to evaluate the performance of the detectors across a range of exposures. Four laboratories achieved 5 class A ratings, the same as in the 2020 intercomparison.

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Tables and figures

Table 2. Participating laboratories

Contact person	Organisation	Country
Nivaldo Carlos da Silva, Danila Carrijo S. Dias	LAPOC, CNEN	Brazil
Jussi-Pekka Laine	STUK	Finland
Roselyne Ameon	Algade	France
Nicolas Tharaud	Algade / Dosirad	France
David Delage	Pearl-SAS	France
Erik Hülber, Tímea Hülber	Radosys, Ltd.	Hungary
David Doyle	AlphaRadon Teo	Ireland
Enrico Chiaberto, Mauro Magnoni, Elena Serena	ARPA Piemonte	Italy
Dr. Massimo Faure Ragani	ARPA Valle D'Aosta	Italy
Dr. Silvia Penzo, Dr. Fabio Alessio Vittoria	ENEA Radon Service	Italy
Leandro Magro, Monica Buchetti, Anna Maria Sotgiu	ISIN	Italy
Christian Di Carlo, Francesco Bochicchio	Istituto Superiore di Sanità	Italy
Dr. Giacomo Zambelli / Dr. Tommaso Chioccini / Dr. Giulia Leardini	Lavoro e Ambiente s.r.l.	Italy
Leonardo Baldassarre, Oliviero Tito Sandri	L.B. Servizi per le Aziende s.r.l.	Italy
Ing. Gianluca Troiano	Niton Srl	Italy
Dr. Andrea Iannarone, Dr. Mattia Taroni, Dr. Giacomo Zambelli	Protex Italia Srl "A.Corberi"	Italy
Dr. Claudio Cazzato	Radongas srl	Italy
Serena Sanna	U-Series Srl	Italy
Dr. Giacomo Dalle Mulle	X-GAMMAGUARD di Laura Pini	Italy
Marielle LeComte, Karin Pier	Ministère de la Santé	Luxembourg
Trine Kolstad	DSA	Norway
Daniel Rábago, LaRUC	Laboratory of Environmental Radioactivity, University of Cantabria (LaRUC)	Spain
Hanna Malmström	Eurofins	Sweden

Contact person	Organisation	Country
Dr. Tryggve Rönnqvist	Radonova	Sweden
Denis Henshaw, Peter Fews	TASL / Radosure	United Kingdom
Julie Cowlin	Testair Ltd.	United Kingdom
Kinga Zmijewska, Richard Burkett	UKHSA Personal Dosimetry Service	United Kingdom
Dr. Jaroslaw Wasikiewicz	UKHSA Radon Dosimetry	United Kingdom
Frederick Stieff	Rad Elec Inc.	USA

Table 3. Exposure parameters – etched track and electret detectors

Exposure	1	2	3	4	5
Duration (h)	263.35	405.75	25.03	92.05	167.22
Radon exposure (kBq m^{-3} h)	1,599	2,548	173	553	1,023
Uncertainty (%) at 68% CL	3.0	3.0	3.0	3.0	3.0
EER exposure (kBq m^{-3} h)	624	1019	69	216	399
Uncertainty (%) at 68% CL	7.0	7.0	7.0	7.0	7.0
F, equilibrium factor	0.39	0.40	0.39	0.39	0.39

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

Table 4.1. Analysis of all reported results for etched track and electret detectors: Exposure 1, 1599 kBq m^{-3} h, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	1,552.2	49.4	-2.9	3.2	4.3
12-1	1,559.6	47.9	-2.5	3.1	3.9
13-1	1,511.4	45.0	-5.5	3.0	6.2
13-2	1,538.2	40.2	-3.8	2.6	4.6
16-1	1,604.4	81.5	0.3	5.1	5.1
19-1	1,529.3	82.8	-4.4	5.4	7.0
20-1	1,380.6	41.3	-13.7	3.0	14.0
21-1	1,560.6	45.3	-2.4	2.9	3.8
25-1	1,689.3	90.9	5.6	5.4	7.8
25-2	1,589.0	162.8	-0.6	10.2	10.3
32-1	1,704.2	25.4	6.6	1.5	6.7
40-1	1,278.2	255.8	-20.1	20.0	28.3
45-1	1,617.7	159.2	1.2	9.8	9.9
62-1	421.2	1,150.5	-73.7	273.1	282.9
90-1	1,795.8	61.4	12.3	3.4	12.8
136-1	1,695.3	45.4	6.0	2.7	6.6
136-2	1,758.6	100.1	10.0	5.7	11.5
141-1	1,609.6	17.2	0.7	1.1	1.3
141-2	1,730.8	36.9	8.2	2.1	8.5
153-1	1,424.0	27.8	-10.9	2.0	11.1
156-1	1,467.2	55.3	-8.2	3.8	9.1
160-1	1,661.8	85.9	3.9	5.2	6.5
163-1	1,521.3	43.5	-4.9	2.9	5.6
163-2	1,546.0	46.2	-3.3	3.0	4.5
177-1	1,689.6	79.8	5.7	4.7	7.4
178-1	1,744.2	9.8	9.1	0.6	9.1
186-1	1,490.4	55.5	-6.8	3.7	7.7
191-1	1,591.6	52.8	-0.5	3.3	3.3
196-1	1,978.0	66.4	23.7	3.4	23.9
197-1	1,437.0	72.6	-10.1	5.1	11.3
198-1	1,739.8	65.2	8.8	3.7	9.6
199-1	1,301.0	120.4	-18.6	9.3	20.8
200-1	1,437.0	70.9	-10.1	4.9	11.3
201-1	1,636.9	61.1	2.4	3.7	4.4
201-2	1,568.4	46.0	-1.9	2.9	3.5

Table 4.2. Analysis of all reported results for etched track and electret detectors: Exposure 2, 2548 kBq m^{-3} h, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	2,371.2	71.1	-6.9	3.0	7.6
12-1	2,505.7	86.4	-1.7	3.4	3.8
13-1	2,352.9	77.2	-7.7	3.3	8.3
13-2	2,294.4	47.0	-10.0	2.0	10.2
16-1	2,488.9	84.5	-2.3	3.4	4.1
19-1	2,530.2	108.4	-0.7	4.3	4.3
20-1	2,157.6	45.4	-15.3	2.1	15.5
21-1	2,521.3	203.7	-1.0	8.1	8.1
25-1	2,512.2	198.4	-1.4	7.9	8.0
25-2	2,755.0	344.0	8.1	12.5	14.9
32-1	2,730.6	22.5	7.2	0.8	7.2
40-1	2,123.5	326.6	-16.7	15.4	22.7
45-1	2,501.1	159.4	-1.8	6.4	6.6
62-1	183.2	1,027.9	-92.8	561.1	568.7
90-1	2,780.8	74.2	9.1	2.7	9.5
136-1	2,835.2	86.9	11.3	3.1	11.7
136-2	2,861.6	150.5	12.3	5.3	13.4
141-1	2,629.2	31.2	3.2	1.2	3.4
141-2	2,739.4	64.1	7.5	2.3	7.9
153-1	2,272.9	58.0	-10.8	2.6	11.1
156-1	2,240.2	48.4	-12.1	2.2	12.3
160-1	2,611.6	74.2	2.5	2.8	3.8
163-1	2,261.4	37.4	-11.2	1.7	11.4
163-2	2,265.4	55.9	-11.1	2.5	11.4
177-1	2,754.4	79.2	8.1	2.9	8.6
178-1	2,851.1	16.6	11.9	0.6	11.9
186-1	2,391.3	88.7	-6.1	3.7	7.2
191-1	2,554.2	119.2	0.2	4.7	4.7
196-1	3,040.2	73.4	19.3	2.4	19.5
197-1	2,228.6	60.1	-12.5	2.7	12.8
198-1	2,757.9	159.5	8.2	5.8	10.1
199-1	1,949.0	65.2	-23.5	3.3	23.7
200-1	2,121.0	581.8	-16.8	27.4	32.1
201-1	2,514.9	46.3	-1.3	1.8	2.3
201-2	2,443.8	73.5	-4.1	3.0	5.1

Table 4.3. Analysis of all reported results for etched track and electret detectors: Exposure 3, 173 kBq m^{-3} h, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	195.3	10.4	12.9	5.3	13.9
12-1	185.4	6.5	7.2	3.5	8.0
13-1	187.2	11.6	8.2	6.2	10.3
13-2	192.6	13.2	11.3	6.9	13.2
16-1	252.8	51.7	46.1	20.5	50.5
19-1	188.9	12.3	9.2	6.5	11.3
20-1	160.5	16.0	-7.2	10.0	12.3
21-1	201.1	25.6	16.2	12.7	20.6
25-1	159.9	19.3	-7.6	12.1	14.2
25-2	148.4	36.6	-14.2	24.7	28.5
32-1	174.5	4.8	0.9	2.8	2.9
40-1	156.0	29.1	-9.8	18.7	21.1
45-1	147.6	20.3	-14.7	13.8	20.1
62-1	1,001.3	1,008.9	478.8	100.8	489.3
90-1	192.8	5.8	11.4	3.0	11.8
136-1	217.9	17.9	26.0	8.2	27.2
136-2	328.4	344.6	89.8	104.9	138.1
141-1	189.7	2.3	9.7	1.2	9.7
141-2	187.6	4.9	8.4	2.6	8.8
153-1	187.3	24.2	8.3	12.9	15.3
156-1	191.7	24.9	10.8	13.0	16.9
160-1	211.6	54.9	22.3	25.9	34.2
163-1	206.5	17.8	19.4	8.6	21.2
163-2	200.8	27.3	16.1	13.6	21.0
177-1	197.9	17.2	14.4	8.7	16.8
178-1	194.8	2.6	12.6	1.3	12.7
186-1	167.3	8.6	-3.3	5.1	6.1
191-1	171.0	17.2	-1.2	10.1	10.1
196-1	227.8	13.2	31.7	5.8	32.2
197-1	179.7	15.7	3.9	8.7	9.6
198-1	189.3	16.3	9.4	8.6	12.8
199-1	132.0	55.5	-23.7	42.0	48.3
200-1	156.0	54.0	-9.8	34.6	36.0
201-1	194.9	10.9	12.7	5.6	13.8
201-2	214.6	29.2	24.0	13.6	27.6

Table 4.4. Analysis of all reported results for etched track and electret detectors: Exposure 4, 553 kBq m^{-3} h, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	555.3	19.6	0.4	3.5	3.6
12-1	524.9	17.3	-5.1	3.3	6.1
13-1	551.9	12.7	-0.2	2.3	2.3
13-2	569.7	22.6	3.0	4.0	5.0
16-1	610.5	132.6	10.4	21.7	24.1
19-1	563.7	32.0	1.9	5.7	6.0
20-1	497.6	13.6	-10.0	2.7	10.4
21-1	549.4	31.7	-0.7	5.8	5.8
25-1	555.1	45.0	0.4	8.1	8.1
25-2	553.1	118.1	0.0	21.4	21.4
32-1	642.2	173.8	16.1	27.1	31.5
40-1	500.4	76.0	-9.5	15.2	17.9
45-1	511.1	89.3	-7.6	17.5	19.0
62-1	317.3	923.0	-42.6	290.9	294.0
90-1	630.7	31.1	14.1	4.9	14.9
136-1	622.6	23.2	12.6	3.7	13.1
136-2	665.8	58.8	20.4	8.8	22.2
141-1	580.2	10.1	4.9	1.7	5.2
141-2	601.6	5.1	8.8	0.8	8.8
153-1	518.1	24.6	-6.3	4.7	7.9
156-1	554.4	21.4	0.3	3.9	3.9
160-1	574.8	54.9	3.9	9.6	10.3
163-1	577.3	13.8	4.4	2.4	5.0
163-2	582.4	32.3	5.3	5.5	7.7
177-1	597.7	29.3	8.1	4.9	9.5
178-1	594.8	5.2	7.6	0.9	7.6
186-1	514.8	23.0	-6.9	4.5	8.2
191-1	558.4	70.9	1.0	12.7	12.7
196-1	682.6	38.1	23.4	5.6	24.1
197-1	519.8	16.8	-6.0	3.2	6.8
198-1	595.7	23.8	7.7	4.0	8.7
199-1	466.0	120.1	-15.7	25.8	30.2
200-1	653.0	566.6	18.1	86.8	88.6
201-1	597.9	17.6	8.1	2.9	8.6
201-2	600.0	26.1	8.5	4.4	9.5

Table 4.5. Analysis of all reported results for etched track and electret detectors: Exposure 5, 1023 kBq m^{-3} h, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	993.0	22.7	-2.9	2.3	3.7
12-1	994.6	27.5	-2.8	2.8	3.9
13-1	972.2	27.8	-5.0	2.9	5.7
13-2	965.6	20.8	-5.6	2.2	6.0
16-1	991.7	152.0	-3.1	15.3	15.6
19-1	1,007.2	73.3	-1.5	7.3	7.4
20-1	896.3	27.9	-12.4	3.1	12.8
21-1	982.9	32.9	-3.9	3.3	5.2
25-1	1,048.3	53.1	2.5	5.1	5.6
25-2	1,040.1	179.5	1.7	17.3	17.3
32-1	1,067.3	171.9	4.3	16.1	16.7
40-1	878.9	112.3	-14.1	12.8	19.0
45-1	930.8	80.0	-9.0	8.6	12.5
62-1	365.3	1,187.4	-64.3	325.0	331.3
90-1	1,124.1	60.8	9.9	5.4	11.3
136-1	1,146.5	63.9	12.1	5.6	13.3
136-2	1,079.4	307.1	5.5	28.5	29.0
141-1	1,026.2	13.9	0.3	1.4	1.4
141-2	1,088.6	11.8	6.4	1.1	6.5
153-1	929.3	38.6	-9.2	4.2	10.1
156-1	953.2	44.0	-6.8	4.6	8.2
160-1	1,076.0	56.4	5.2	5.2	7.4
163-1	1,010.6	20.4	-1.2	2.0	2.4
163-2	997.8	29.4	-2.5	2.9	3.8
177-1	1,088.6	38.9	6.4	3.6	7.3
178-1	1,060.3	15.8	3.6	1.5	3.9
186-1	947.0	30.1	-7.4	3.2	8.1
191-1	1,021.9	53.7	-0.1	5.3	5.3
196-1	1,274.0	59.8	24.5	4.7	25.0
197-1	945.0	54.7	-7.6	5.8	9.6
198-1	1,080.5	60.5	5.6	5.6	7.9
199-1	792.0	99.2	-22.6	12.5	25.8
200-1	901.0	62.3	-11.9	6.9	13.8
201-1	1,039.4	25.0	1.6	2.4	2.9
201-2	1,018.0	51.8	-0.5	5.1	5.1

Table 4.6. Analysis of all reported results for etched track and electret detectors: Transit exposure, etched track and electret detectors

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
1-1	3.6	2.5
12-1	11.1	2.6
13-1	6.9	3.6
13-2	7.7	5.0
16-1	21.8	7.6
19-1	0.8	0.8
20-1	4.9	2.4
21-1	16.7	6.4
25-1	11.5	2.2
25-2	13.4	4.9
32-1	11.6	2.1
40-1	7.6	6.8
45-1	32.2	4.4
62-1	775.7	860.7
90-1	0.0	0.0
136-1	40.1	8.0
136-2	89.5	28.4
141-1	21.4	4.6
141-2	22.2	10.1
153-1	24.1	17.5
156-1	48.5	10.6
160-1	168.4	68.6
163-1	8.6	3.7
163-2	9.8	7.8
177-1	15.1	8.2
178-1	4.0	1.9
186-1	5.4	2.6
191-1	73.6	13.9
196-1	4.6	3.7
197-1	17.3	12.9
198-1	2.5	3.4
199-1	126.0	84.4
200-1	88.0	91.9
201-1	40.6	22.7
201-2	41.2	16.3

Table 5. Statistical analysis of all reported results given in Tables 4.1 to 4.5

Group	Exposure (kBq m^{-3} h)	Mean of all reported results (kBq m^{-3} h)	Standard deviation of all reported results (kBq m^{-3} h)
1	1,599	1,553.1	242.9
2	2,548	2,432.3	466.3
3	173	214.0	141.1
4	553	565.5	65.7
5	1,023	992.4	139.4

Table 6. Performance classification scheme based on measurement error

	Performance classification in each exposure									
	Exposure 3	**Exposure 4**	**Exposure 5**	**Exposure 1**	**Exposure 2**					
Set ID	173 kBq m^{-3} h	553 kBq m^{-3} h	1,023 kBq m^{-3} h	1,599 kBq m^{-3} h	2,548 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
12-1	A	A	A	A	A	Closed	Yes	Eurofins	CR-39	GM Scientific
141-1	A	A	A	A	A	Closed	No	Radosure	TASTRAK™	TASL
141-2	A	A	A	A	A	Electret	Yes	E-Perm	Electret	E-Perm
186-1	A	A	A	A	A	Closed	No	TASL	TASTRAK™ PADC	TASL
197-1	A	A	A	B	B	SSNTD	Yes	RSKS	CR-39	Radosys
32-1	A	D	B	A	A	Closed		NRPB/SSI (black)	CR-39/ PADC	TASL
1-1	B	A	A	A	A	Closed		NRPB	CR-39	MiNet (UK)
13-1	B	A	A	A	A	Radtrak 2	Yes	NRPB/SSI	CR-39	RTP
19-1	B	A	A	A	A	SSNTD	Yes	Radout™	CR-39	TASL
25-1	B	A	A	A	A	Kodalpha (open)	No	Algade	LR-115	Algade

Performance classification in each exposure										
	Exposure 3	Exposure 4	Exposure 5	Exposure 1	Exposure 2					
Set ID	173 kBq m^{-3} h	553 kBq m^{-3} h	1,023 kBq m^{-3} h	1,599 kBq m^{-3} h	2,548 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
177-1	B	A	A	A	A	Closed	No	TASL	CR-39	TASL
201-1	B	A	A	A	A	Closed	No	Miam - RadOut™	CR-39	RTP Company
13-2	B	A	A	A	B	Radtrak 3	Yes	Radtrak 3	CR-39	RTP Company
156-1	B	A	A	A	B	SSNTD	No	Radosys Ltd., Hungary	CR-39	Radosys Ltd., Hungary
178-1	B	A	A	A	B	Closed	No	TASL	CR-39	TASL
191-1	B	B	A	A	A	Passive SSNTD	No	RadOut™	PADC CR-39	TASL
198-1	B	A	A	A	B	SSNTD	Yes	Closed	TASTRAK™ CR-39	TASL
90-1	B	B	B	B	A	Electret Ion Chamber	Yes	N/A	N/A	Rad Elec
153-1	B	A	B	B	B	Closed	Yes	Radout™	CR-39	TASL
20-1	B	B	B	B	B	Etched track diffusion chamber	No	TASL	PADC	TASL
21-1	C	A	A	A	A	Closed with air gap	No	ENEA	CR-39	TASL

	Performance classification in each exposure									
	Exposure 3	**Exposure 4**	**Exposure 5**	**Exposure 1**	**Exposure 2**					
Set ID	173 kBq m^{-3} h	553 kBq m^{-3} h	1,023 kBq m^{-3} h	1,599 kBq m^{-3} h	2,548 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
201-2	C	A	A	A	A	Closed	No	Miam – RadOut™	CR-39	RTP Company
163-1	C	A	A	A	B	SSNTD	No	Cylinder	CR-39	TASL
163-2	C	A	A	A	B	Electret	No	SLT	Electret	Rad-Elec Inc.
45-1	C	B	B	A	A	Closed	Yes	DPR3	LR-115	Algade
136-1	C	B	B	A	B	Closed	No	NRPB/SSI	PADC	TASL
25-2	C	C	B	B	B	DPR (closed)	No	Algade	LR-115	Algade
40-1	C	B	B	C	C	SSNTD	No	NRPB – yellow	PADC	Mi-Net Technology Ltd., (Instrument Plastics)
160-1	D	B	A	A	A	Closed	No		CR-39	TASL
196-1	D	C	C	C	B	Closed	No	RadOut™	PADC CR-39	GM Scientific
200-1	D	F	B	B	D	Closed	No	Miam – RadOut™	PADC	GM Scientific
199-1	E	D	C	C	C	Closed	No	Miam – RadOut™	PADC	GM Scientific
16-1	F	C	B	A	A	RSK	No	Cylindrical	PADC	Radosys

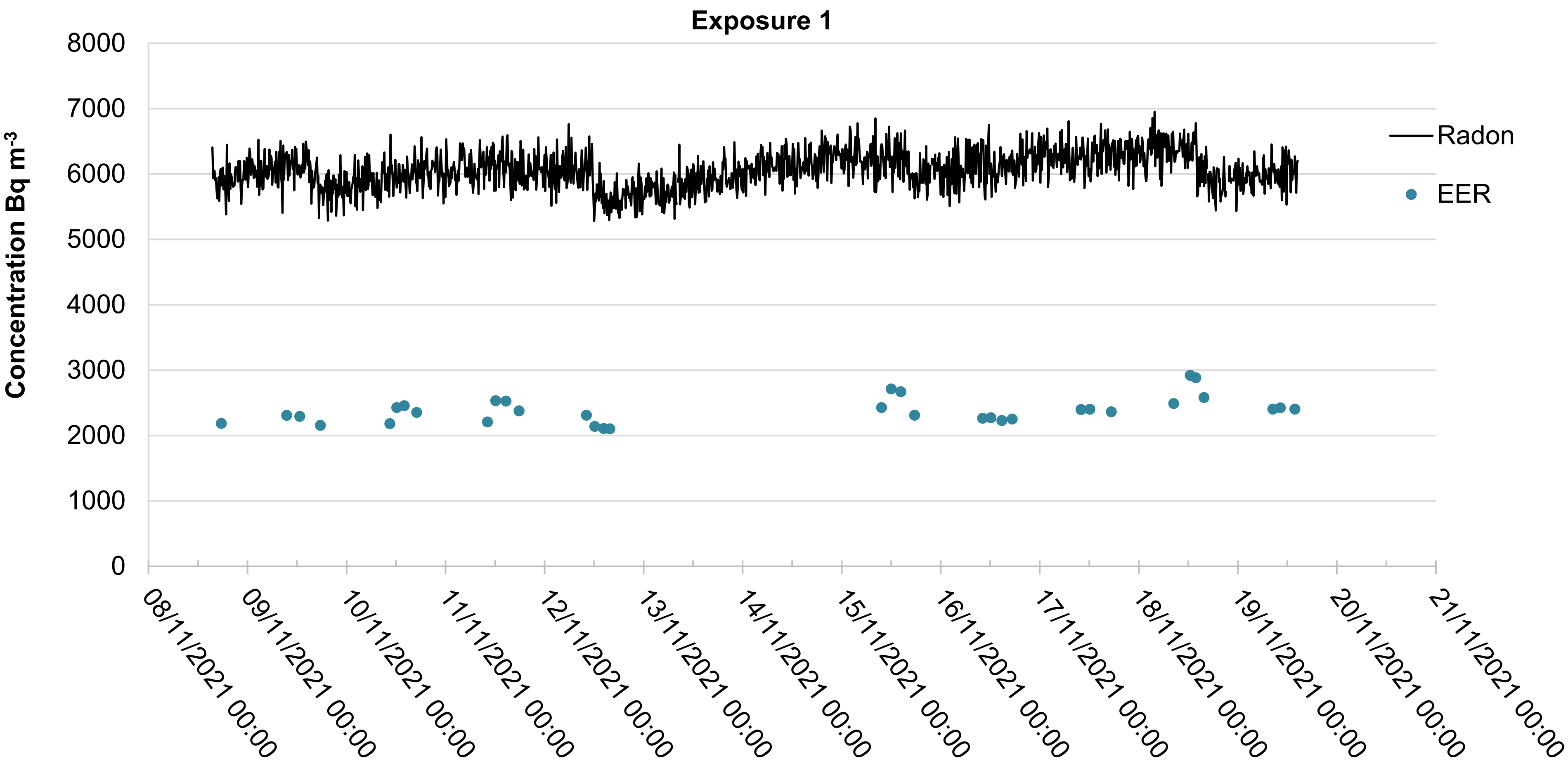
Performance classification in each exposure										
	Exposure 3	**Exposure 4**	**Exposure 5**	**Exposure 1**	**Exposure 2**					
Set ID	173 kBq m^{-3} h	553 kBq m^{-3} h	1,023 kBq m^{-3} h	1,599 kBq m^{-3} h	2,548 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
136-2[2]	F	C	C	B	B	Badge		In-house	PADC	TASL
62-1[3]	F	F	F	F	F	Closed	Yes (Mylar)	In-house	Makrofol®	Covestro

Notes to Table 6

[2] Set ID 136-2 – 2 of the detectors were not recorded correctly against their laboratory detector numbers. Without this error, the results would have been B B C C B.

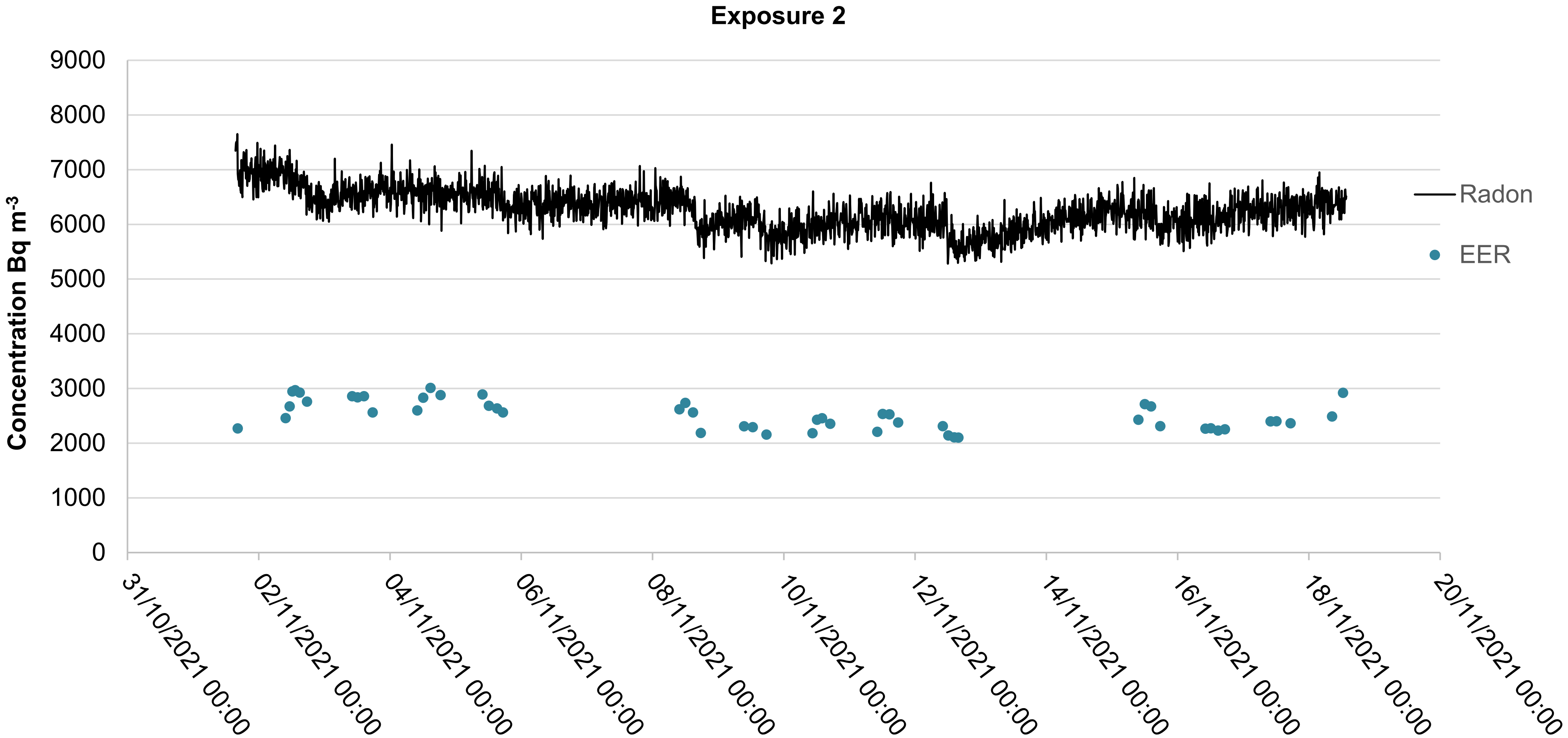
[3] Set ID 62-1 – there were errors in the record keeping – the UKHSA detector numbers were not recorded correctly against their laboratory detector numbers. Without this error, the results would have been B B C B B.

Figure 1. Radon and EER concentrations for exposure 1



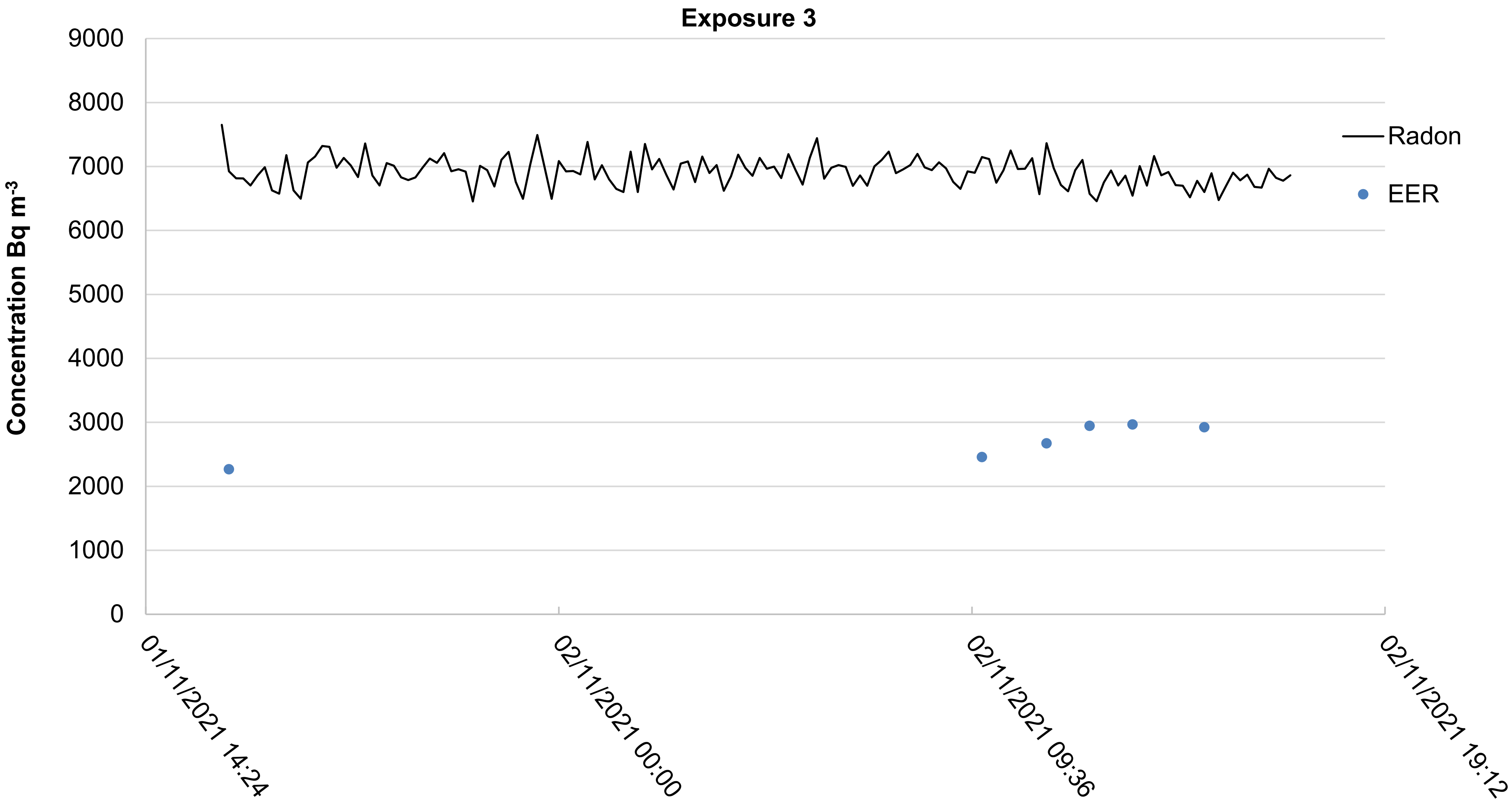
The above figure shows the fluctuation of radon concentration during exposure 1, which covers the period 8 November 2021 to 19 November 2021. The radon concentration hovered around 6,000 Bq m^{-3}. The EER values were between 2000 and 3000 Bq m^{-3}.

Figure 2. Radon and EER concentrations for exposure 2



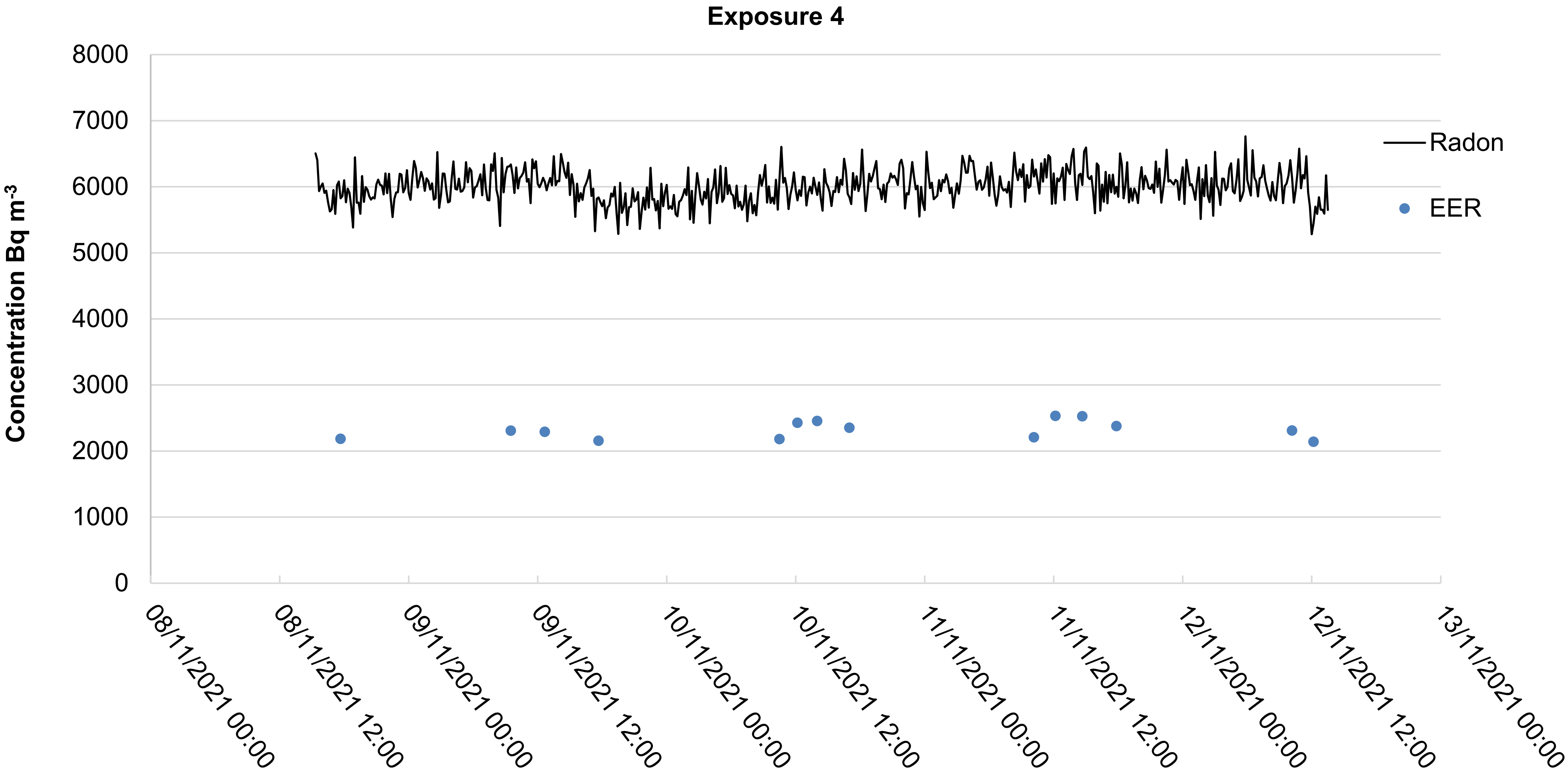
The above figure shows the fluctuation of radon concentration during exposure 2, which covers the period 1 November 2021 to 18 November 2021. The radon concentration began at over 7000 Bq m^{-3} and then hovered around 6,000 Bq m^{-3}. The EER values were between 2,000 and 3,000 Bq m^{-3}.

Figure 3. Radon and EER concentrations for exposure 3



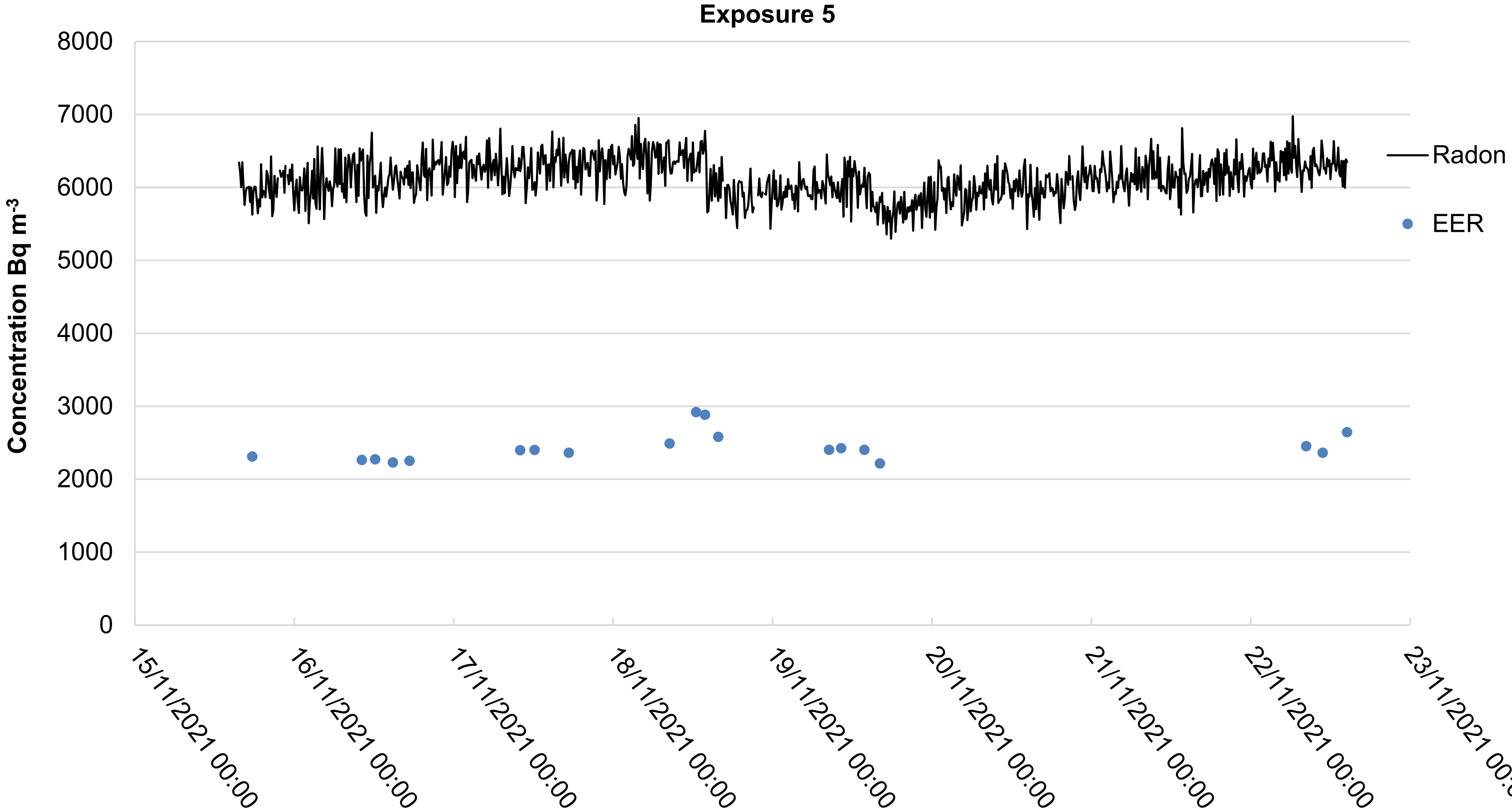
The above figure shows the fluctuation of radon concentration during exposure 3, which covers the period 1 November 2021 to 2 November 2021. The radon concentration began at over 7,000 Bq m^{-3} and then hovered around 7,000 Bq m^{-3}. The EER values were between 2,000 to 3,000 Bq m^{-3}.

Figure 4. Radon and EER concentrations for exposure 4



The above figure shows the fluctuation of radon concentration during exposure 4, which covers the period 08 November 2021 to 12 November 2021. The radon concentration hovered around 6,000 Bq m^{-3}. The EER values were between 2,000 to 3,000 Bq m^{-3}.

Figure 5. Radon and EER concentrations for exposure 5



The above figure shows the fluctuation of radon concentration during exposure 5 which covers the period 15 November 2021 to 22 November 2021. The radon concentration hovered around 6000 Bq m^{-3}. The EER values were between 2,000 to 3,000 Bq m^{-3}.

Figure 6. Results as reported by participants for exposure 1 - given in Table 4.1

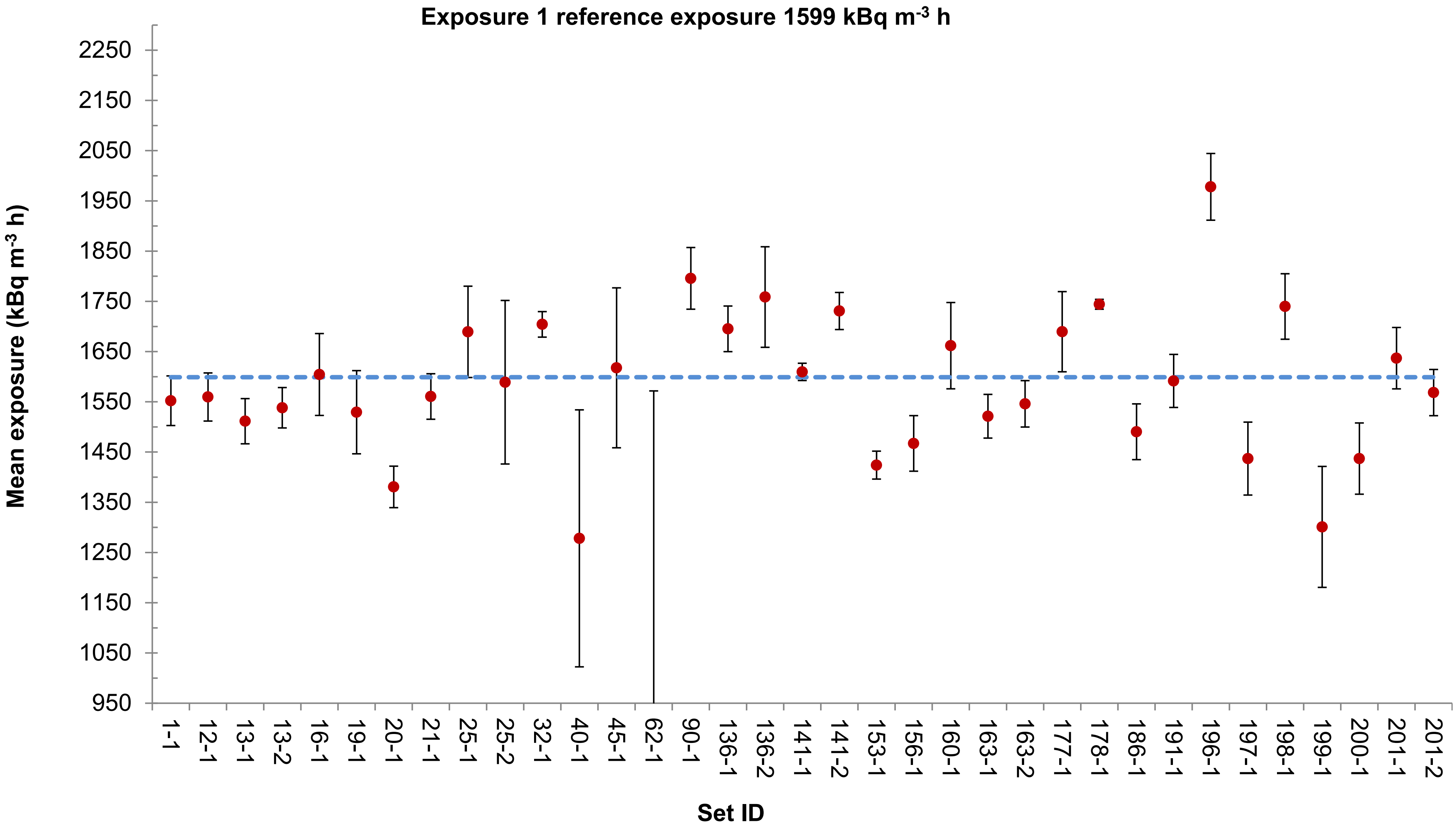


Figure 7. Results as reported by participants for exposure 2 - given in Table 4.2

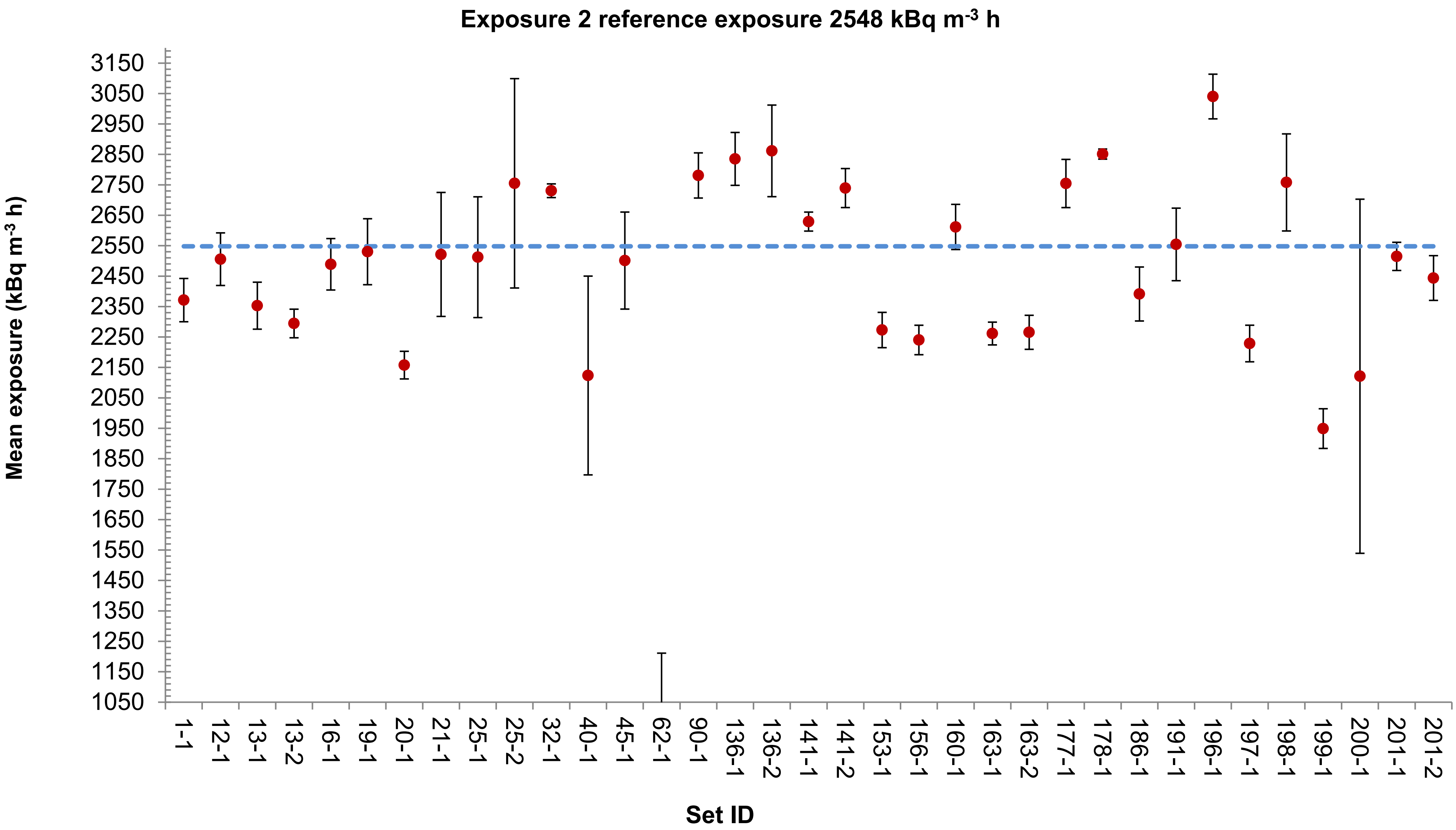


Figure 8. Results as reported by participants for exposure 3 - given in Table 4.3

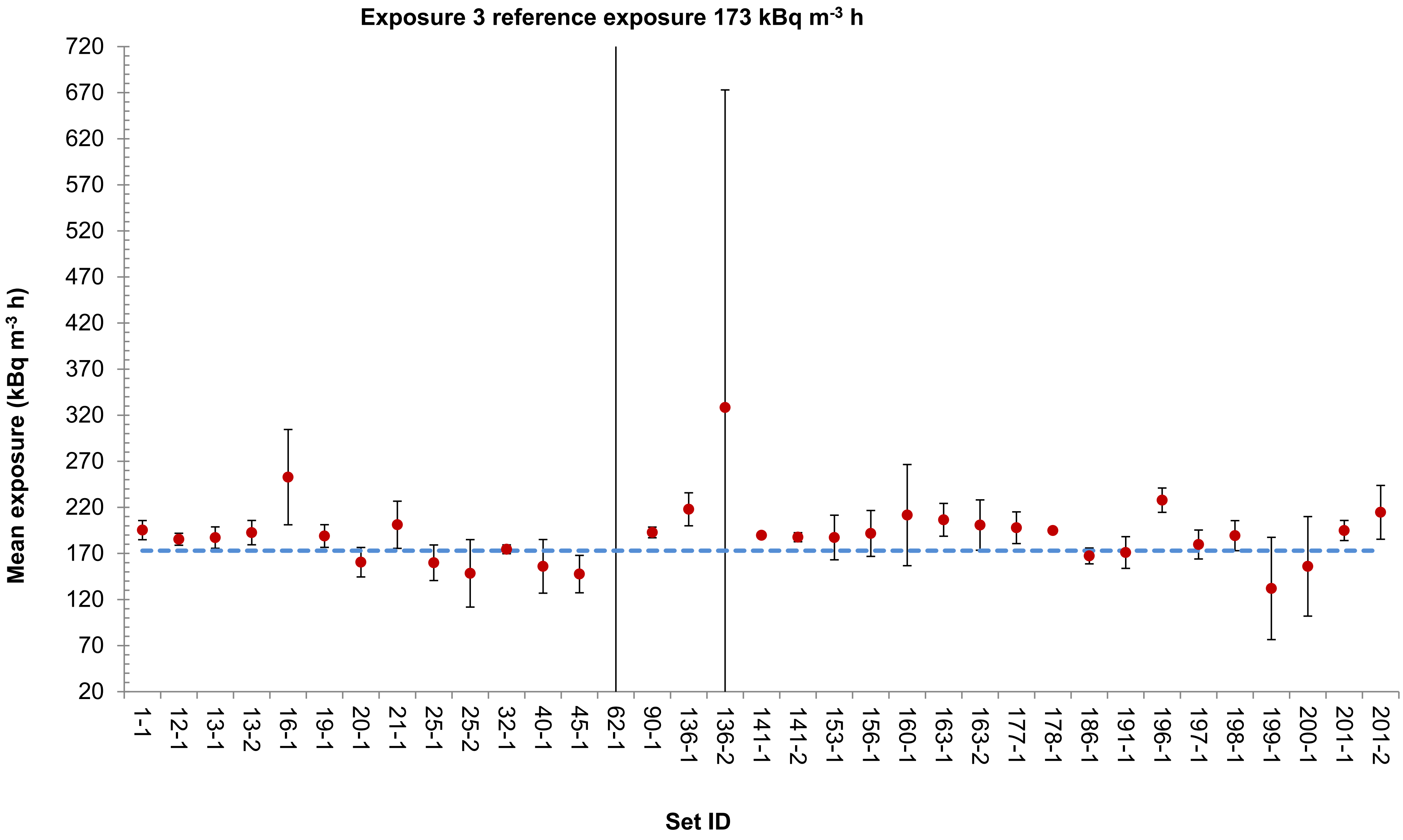


Figure 9. Results as reported by participants for exposure 4 - given in Table 4.4

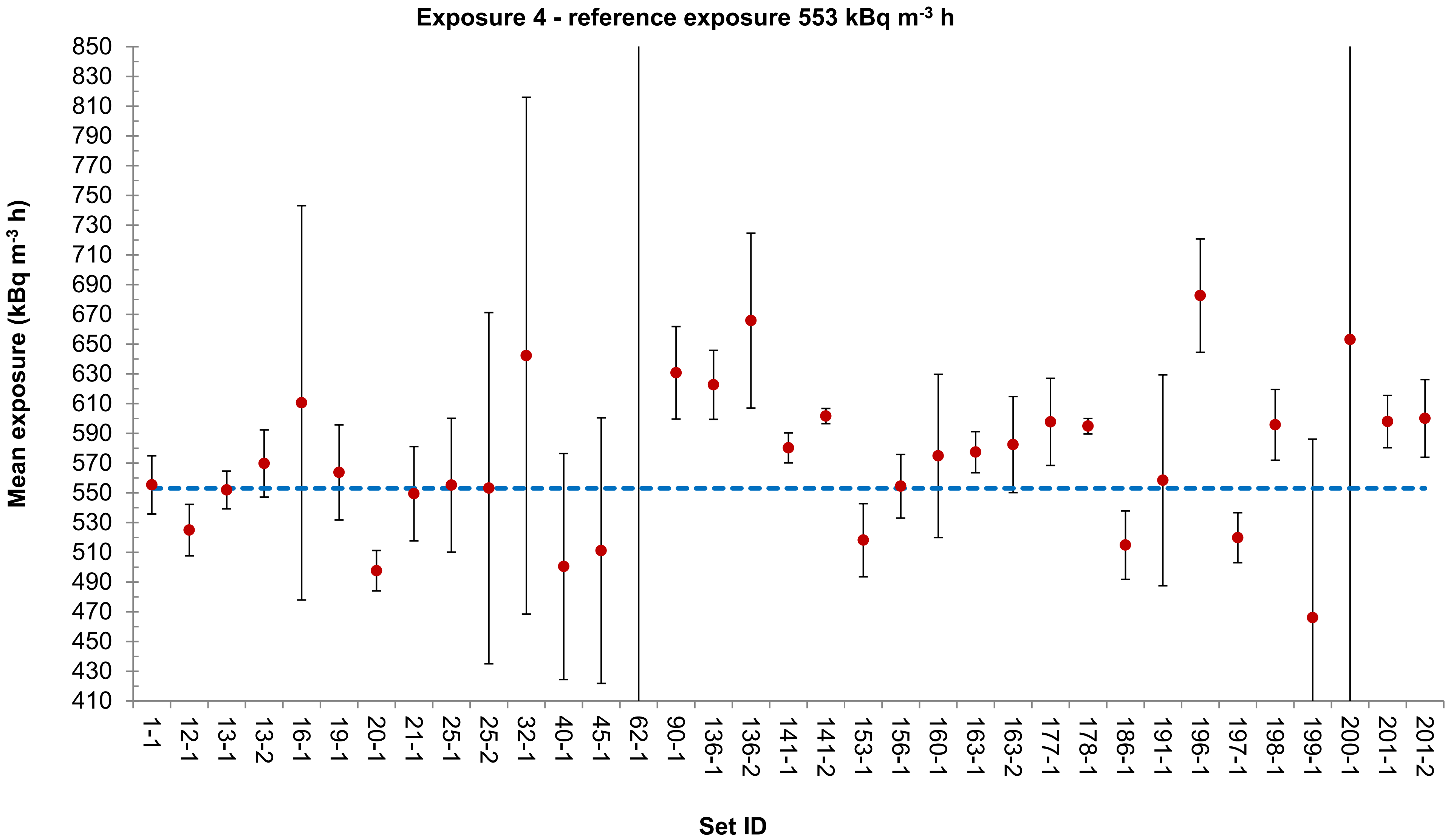


Figure 10. Results as reported by participants for exposure 5 - given in Table 4.5

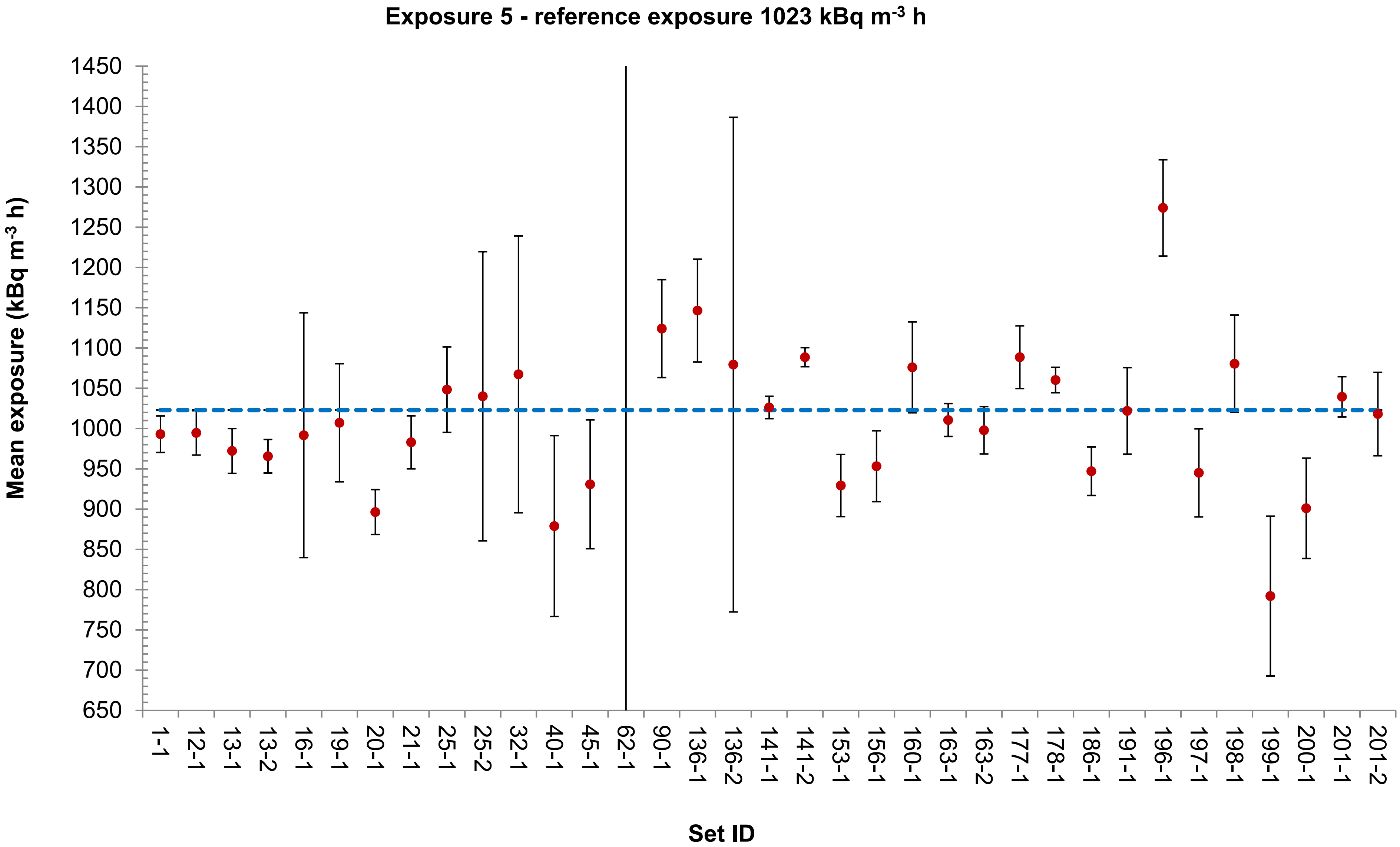


Figure 11. Results as reported by participants for transit exposure - given in Table 4.6

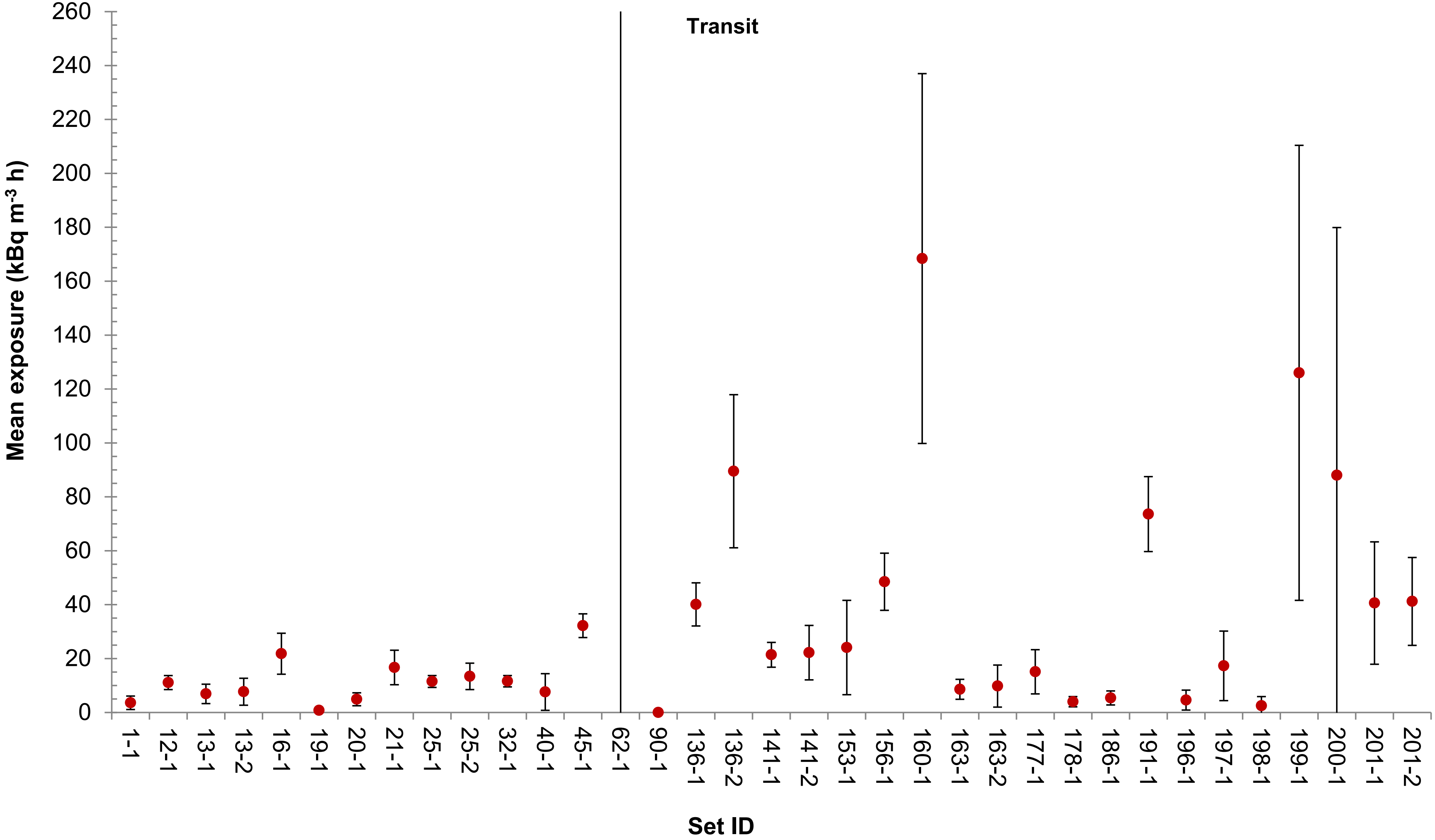


Figure 12. Distribution of mean exposure results for exposure 1 - given in Table 4.1
The vertical dotted line indicates the reference exposure.

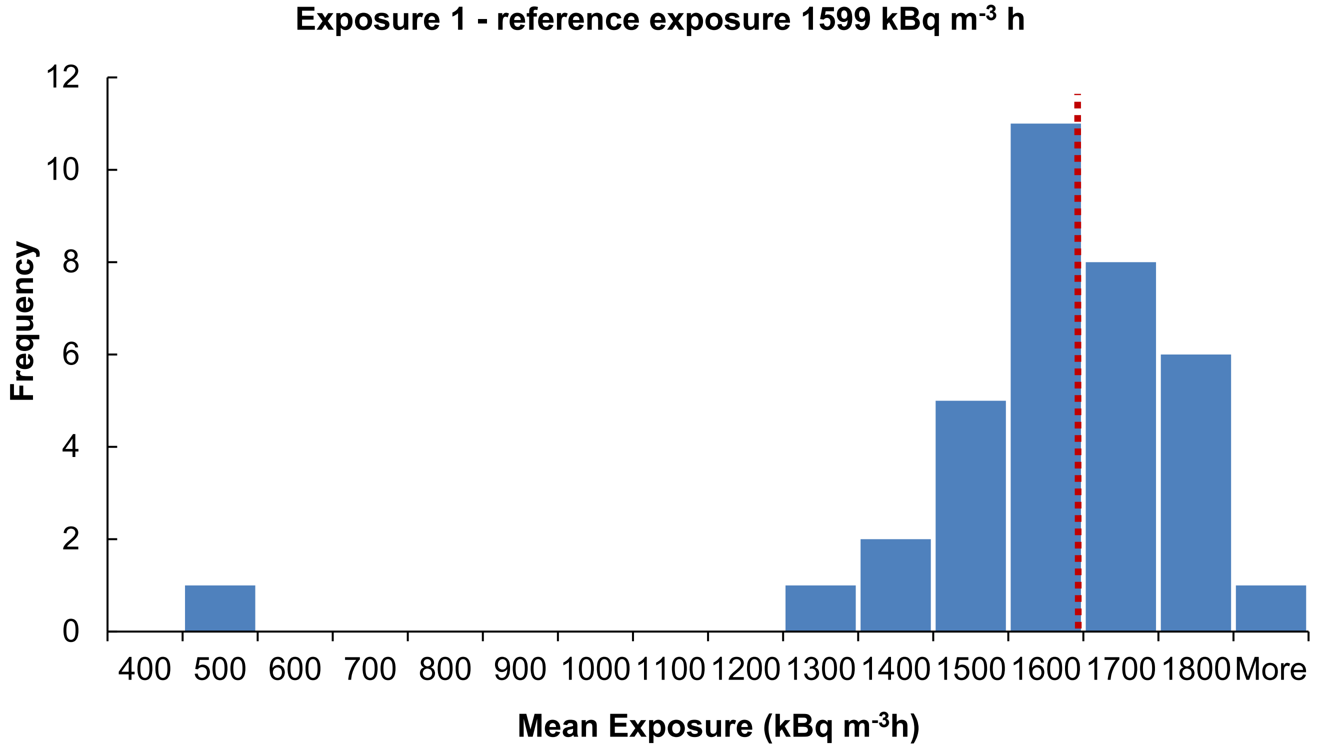


Figure 13. Distribution of mean exposure results for exposure 2 - given in Table 4.2
The vertical dotted line indicates the reference exposure.

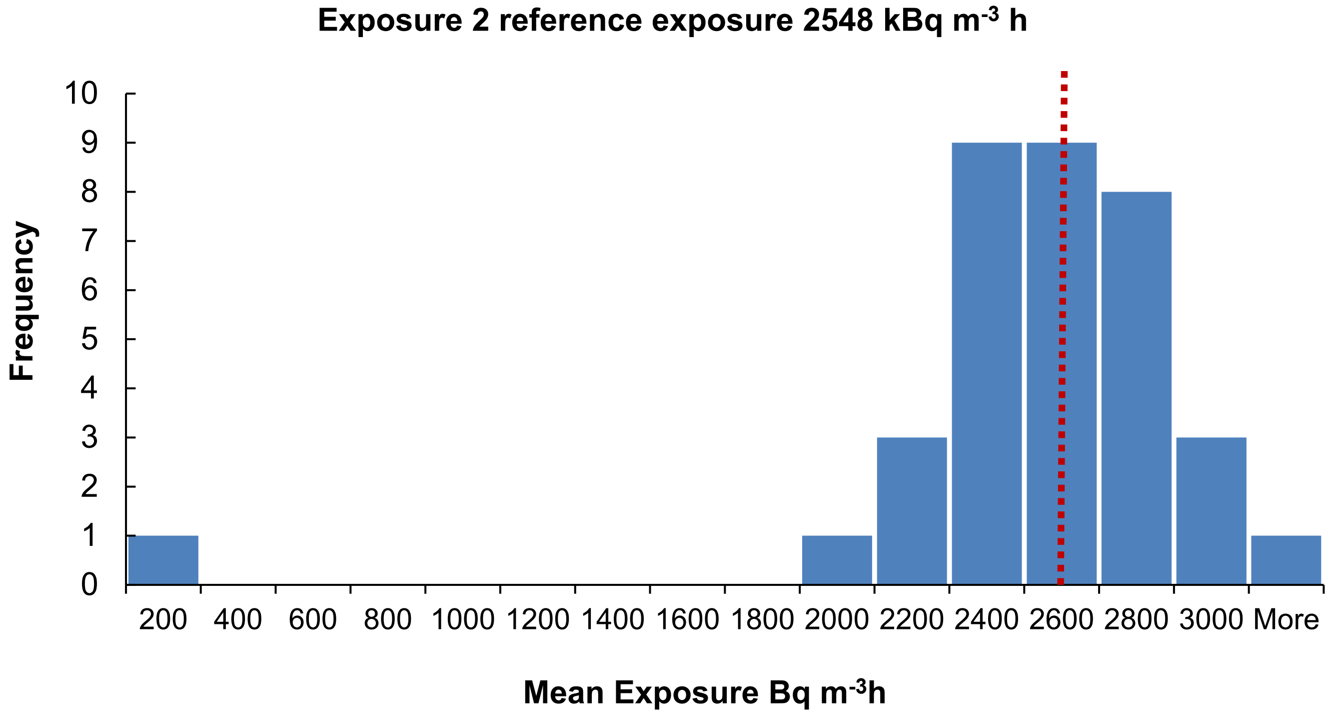


Figure 14. Distribution of mean exposure results for exposure 3 - given in Table 4.3
The vertical dotted line indicates the reference exposure.

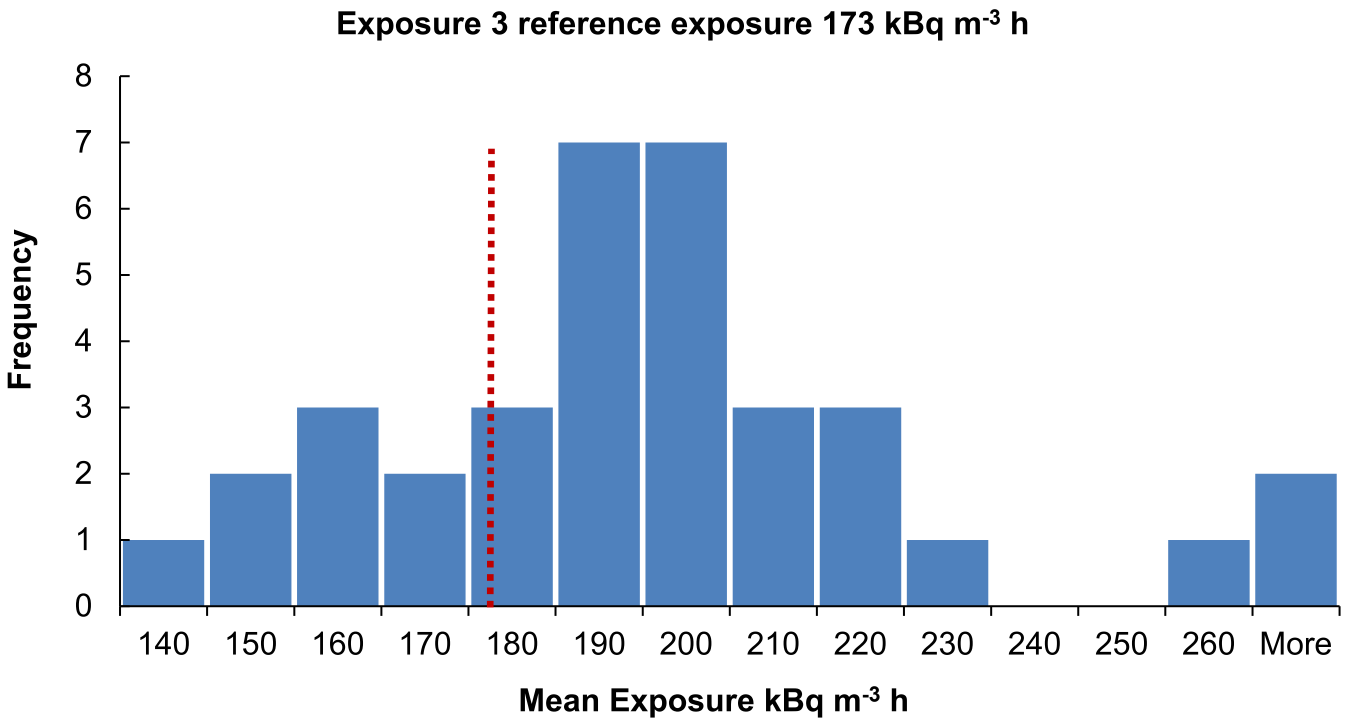


Figure 15. Distribution of mean exposure results for exposure 4 - given in Table 4.4
The vertical dotted line indicates the reference exposure.

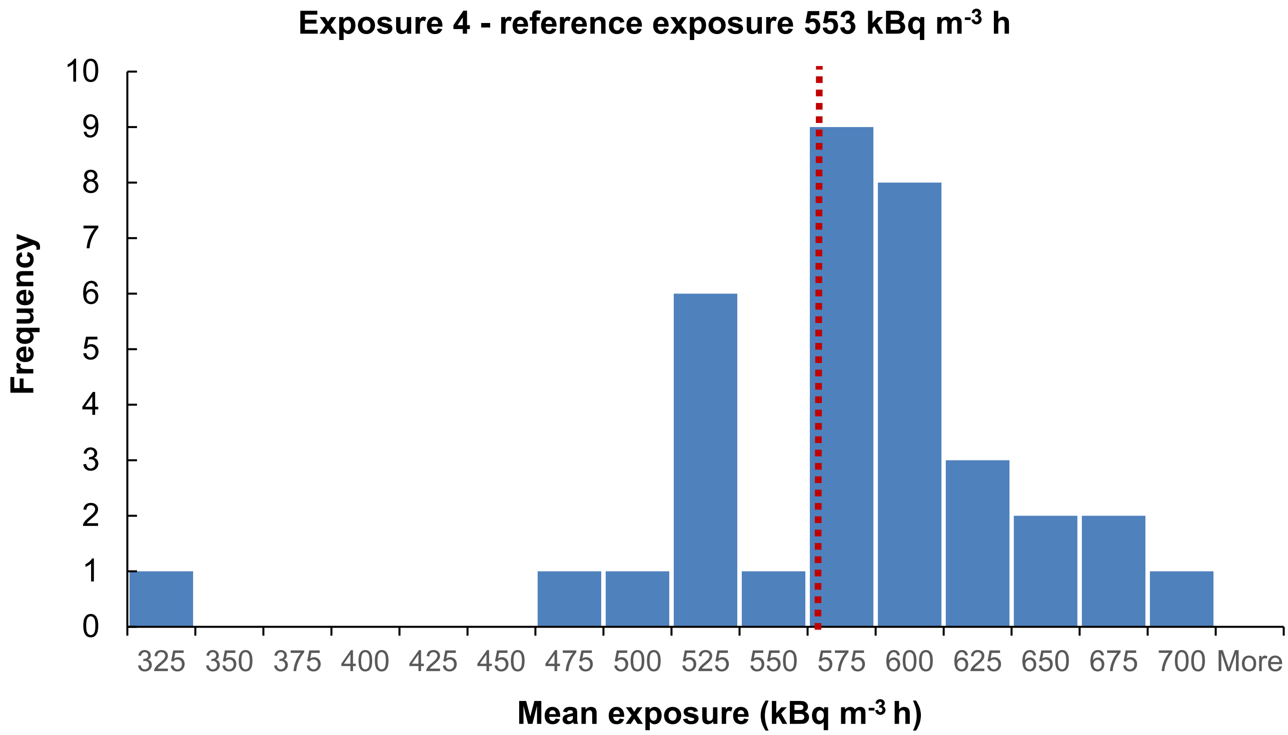


Figure 16. Distribution of mean exposure results for exposure 5 - given in Table 4.5
The vertical dotted line indicates the reference exposure.

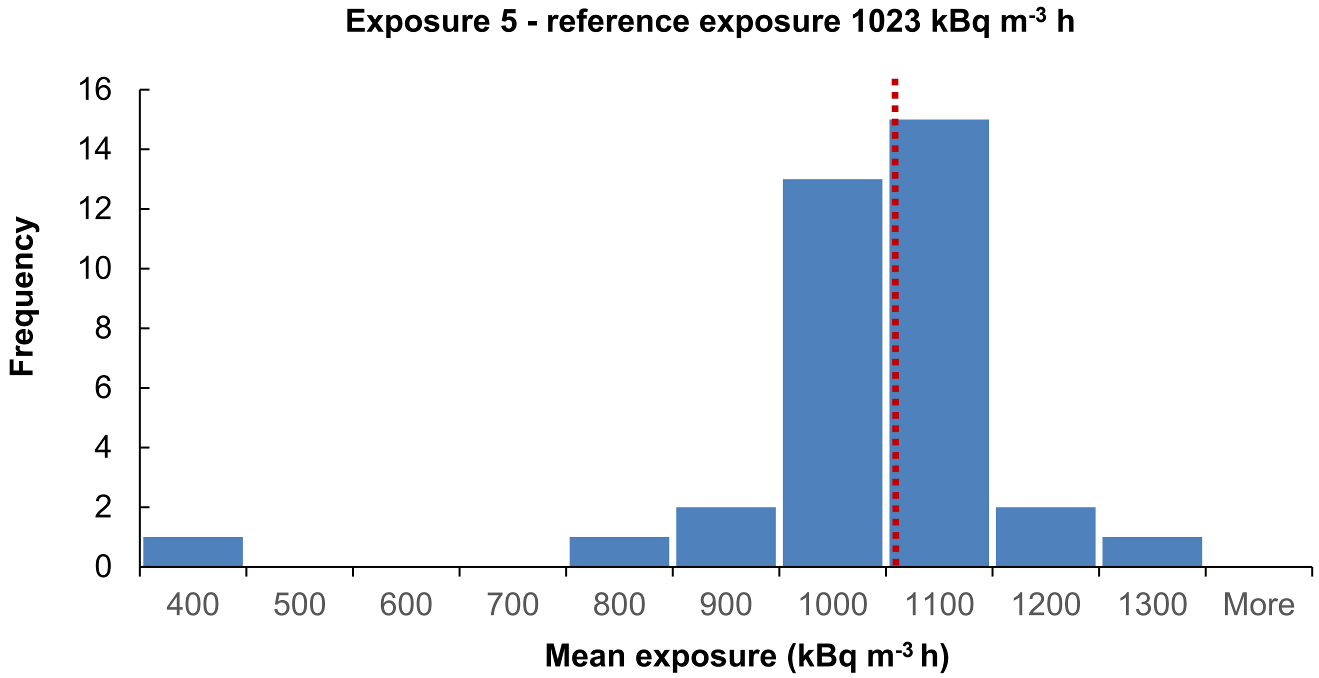


Figure 17. Distribution of mean exposure results for the transit exposure - given in Table 4.6

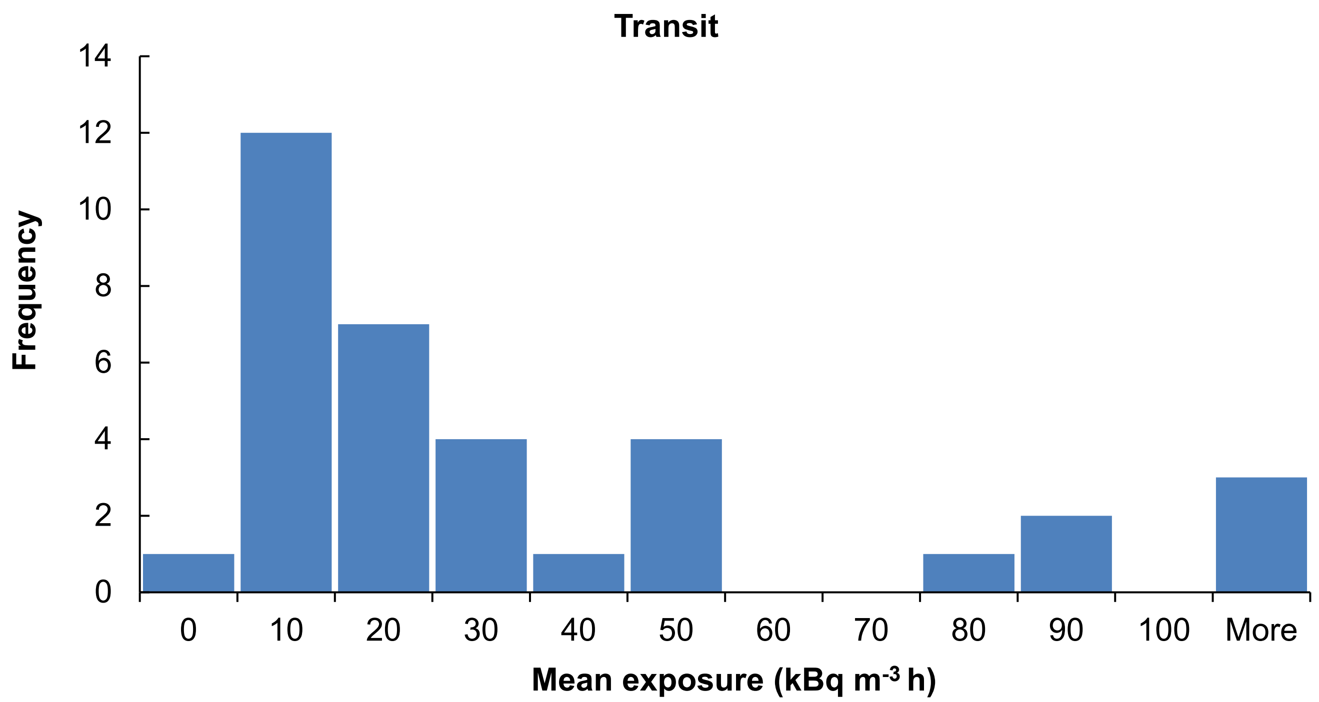
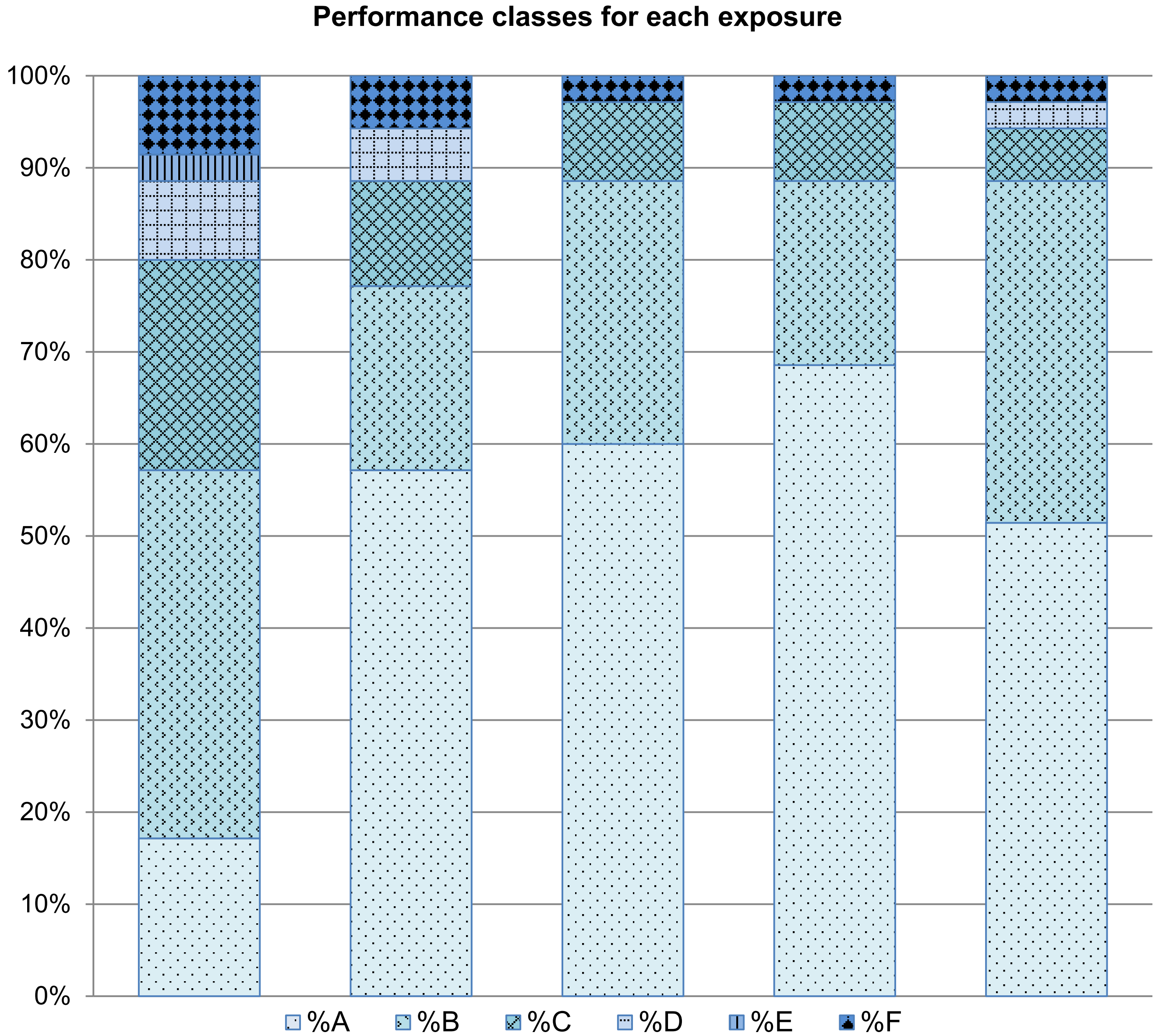


Figure 18. Performance classes for each exposure from A (best) to F (worst)



	Rank EXPOSURE 3 173 kBq m^{-3} h	Rank EXPOSURE 4 553 kBq m^{-3} h	Rank EXPOSURE 5 1023 kBq m^{-3} h	Rank EXPOSURE 1 1599 kBq m^{-3} h	Rank EXPOSURE 2 2548 kBq m^{-3} h
%F	9	6	3	3	3
%E	3	0	0	0	0
%D	9	6	0	0	3
%C	23	11	9	9	6
%B	40	20	29	20	37
%A	17	57	60	69	51

Exposure number (and integrated exposure, kBq m^{-3} h)

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