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Results of the 2024 intercomparison of passive radon detectors

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Executive summary

Radon is the largest and most variable contributor of ionising radiation dose to the general population. For more than 40 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 completed 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 "interlaboratory comparisons" to achieve accreditation under ISO/IEC 17025:2017 'General requirements for the competence of testing and calibration laboratories'.

The Radiation, Chemical, Climate and Environmental Hazards Directorate (RCCE) 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). RCCE carries out international intercomparisons of passive radon detectors each year. For this latest intercomparison, laboratories were invited to submit sets of 60 etched track detectors, 30 electret detectors and/or 15 activated charcoal detectors.

There were no activated charcoal detectors submitted. At RCCE, each set of detectors was randomised into 6 groups – for etched track detectors this was 6 groups of 10 detectors, for electret detectors this was 6 groups of 5 detectors. Five of these groups were exposed in the RCCE radon chamber to radon gas exposures ranging from 200 kBq m^{-3} h to 2,300 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 after the deadline for submission of results for the report.

This report considers the results for the intercomparison carried out in 2024, for which a total of 24 laboratories from 10 countries submitted 29 sets of detectors. Two laboratories were unable to provide results as they had problems with the etching of their etched track detectors: consequently they are excluded from the report.

This report therefore covers 22 laboratories and 27 sets of detectors from 9 countries. The 27 sets of detectors comprise 25 sets of etched track detectors and 2 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. Although 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 *F*.
2. Activated charcoal detectors work by retaining adsorbed radon in a charcoal volume. The radon is subsequently measured in the originating laboratory. This measurement must be completed within 3 days of exposure, so only UK laboratories can take part in the intercomparison with these detectors.
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.

This intercomparison programme was established by the National Radiological Protection Board (NRPB), now the UKHSA Radiation, Chemical, Climate and Environmental Hazards Directorate

(RCCE), in 1982 and has operated annually since 1997. It 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. Operational procedures and equipment have been described previously (1).

Laboratory exposure and measurement facilities

The exposures in this intercomparison were carried out in the UKHSA radon chamber. This 43 m^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 standard source, most recently supplied by Laboratoire National Henri Becquerel, France.

There were no open detectors submitted, therefore the radon decay products were not sampled and measured. All chamber-monitored data were automatically transferred to a database. Radon exposures were calculated subsequently.

Logistical arrangements

In total, 24 laboratories from 10 countries took part in the 2024 UKHSA intercomparison. Some laboratories submitted more than 1 set of detectors, so 29 sets of detectors were exposed in the radon chamber. Following exposure, the detectors were returned to the originating laboratories for processing. Two laboratories (each with 1 set of detectors) did not provide results and so could not be included in the report.

This report therefore covers 22 laboratories and 27 sets of detectors from 9 countries, as shown in Table 2. The 27 sets of detectors were 25 sets of etched track detectors and 2 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 the laboratories included in this report.

Radon exposures

Appropriate conditions for typical domestic radon exposure were established in the chamber before introducing the etched track and electret detectors.

The chamber exposures were calculated after the deadline for return of results by participants and are shown with exposure durations in Table 3. 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 15 Bq m^{-3} to 51 Bq m^{-3}, with an overall average for the exposure period of 30 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 between 0.1% and 2% of the exposure in the chamber. 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 in Table 1:

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. Two laboratories were unable to provide results therefore they are excluded from the report. The tables show the results for 22 laboratories and a total of 27 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 23 kBq m^{-3} h (Figure 11). A total of 22 reported transit exposures were below 40 kBq m^{-3} h, 5 reported transit exposures between 40 kBq m^{-3} h and 95 kBq m^{-3} h, of which 3 of these were below 60 kBq m^{-3} h. This is a much narrower range of results than in 2023 (3) where 10 out of a total of 29 reported transit exposures were between 40 kBq m^{-3} h and 820 kBq m^{-3} h, of which 8 were below 122 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.

A total of 12 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 significantly better than in 2023.

Approximately 67% of all sets of detectors achieved class A for at least 3 exposures, which is improved compared to 2023 (3). For the lowest exposure measurement (208 kBq m^{-3} h), 52% of laboratories achieved class A, an increase from 2023. For the second lowest exposure (379 kBq m^{-3} h), 67% of laboratories achieved class A, which is significantly better than in 2023.

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.

To identify sources of errors, the laboratories should take into account changes in various parameters such as: calibration factor, sensitivity and background (4). Reviews of sources of errors for etched track detectors are given in references (5), (6) and (7). 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, freezer in radon proof bags; radon-proof bags; in a low radon storage room; and stored in a unit with carbon-filtered pressurised air. Most laboratories use a freezer. The maximum storage time before use ranged from 14 days to up to 10 years. Of the sets that had a transit exposure less than 50 Bq m^{-3} h, most (19 out of 21) were sent using radon proof bags. Of the 4 sets where the transit exposure was at or above 50 Bq m^{-3} but below 100 Bq m^{-3}, all the sets were sent using 'radon proof' bags and the storage (in a freezer or radon proof bags) ranged from 6 months to 10 years. This indicates that other factors apply – this may include the radon resistance of some 'radon-proof' bags, the etching methods used, ageing of the plastic and staff training. The proportion of sets achieving each performance classification (A to F) is given in Figure 18.

Conclusions

In total, 24 laboratories from 10 countries participated in the 2024 UKHSA intercomparison.

Two laboratories could not be included in the report, so this report is for 22 laboratories and 27 sets of detectors from 9 countries. The detectors were 25 sets of etched track detectors and 2 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. A total of 12 laboratories achieved 5 class A ratings, which is a significant improvement on the 2023 intercomparison.

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Tables and figures

Table 2. Participating laboratories

Contact person	Organisation	Country
Nivaldo Carlos da Silva / Ricardo Bastos Smith	Brazilian Commission for Nuclear Energy (CNEN)	Brazil
Jussi-Pekka Laine / Tiina Oinas	Radiation and Nuclear Safety Authority (STUK)	Finland
David Doyle	Alpharadon Ltd.	Ireland
Mauro Magnoni / Enrico Chiaberto / Elena Serena	ARPA Piemonte - Laboratorio Radon	Italy
Gabriele Pratesi / Massimo Guazzini	ARPAT - Agenzia regionale per la protezione ambientale della Toscana	Italy
Silvia Penzo / Fabio Alessio Vittoria	ENEA	Italy
Dr. Massimo Moroni	Harmat srls Radon Lab	Italy
Dr Giacomo Zambelli	Lavoro e Ambiente s.r.l. - Protex Italia s.r.l. (Gruppo Laboratori Protex)	Italy
Leandro Gemmiti	L.B. Servizi per le Aziende s.r.l.	Italy
Sotgiu AM, Hazn Hassan Awad N, Magro L	National Inspectorate for nuclear safety and radiation protection (ISIN)	Italy
Gianluca Troiano	Niton srl	Italy
Dr. Claudio Cazzato	Radongas srl	Italy
Daniele Bonamini /Stefano Pasquato	Tecnorad s.r.l.	Italy
Domiziana Fazio / Simone Stefanini / Marta Rossetti / Massimo Esposito	U-Series - WhiteLab Srl.	Italy
Jostein Hoftuft	Norwegian Radiation & Nuclear Safety Authority (DSA)	Norway
Matija Škrlep	ZVD d.o.o.	Slovenia
Ismael Fuente/ Santiago Celaya	Laboratory of Environmental Radioactivity, University of Cantabria (LaRUC)	Spain
Gilbert Jönsson / Maria Jönsson	Radonanalys GJAB	Sweden
Vanda Jakabová / Tryggve Rönnqvist	Radonova Laboratories AB	Sweden
Denis Henshaw/ Peter Fews	Radosure	United Kingdom
Julie Cowlin	Testair Ltd.	United Kingdom
Dr. Jaroslaw Wasikiewicz	UKHSA Radon Dosimetry	United Kingdom

Table 3. Exposure parameters – etched track and electret detectors

Exposure	**1**	**2**	**3**	**4**	**5**
Duration (h)	24.13	117.25	329.35	50.25	189.75
Radon exposure (kBq m^{-3} h)	208	804	2294	379	1317
Uncertainty (%) at 68% Confidence Level	3.0	3.0	3.0	3.0	3.0

Table 4.1. Analysis of all reported results for etched track and electret detectors: Exposure 1, 208 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	237.3	32.5	14.1	13.7	19.6
1-2	217.7	3.2	4.7	1.5	4.9
5-1	198.2	17.1	-4.7	8.6	9.8
13-1	239.8	12.5	15.3	5.2	16.1
13-2	231.1	15.8	11.1	6.9	13.1
19-1	217.1	17.5	4.4	8.1	9.2
20-1	222.8	10.0	7.1	4.5	8.4
21-1	212.7	13.4	2.3	6.3	6.7
32-1	214.0	18.7	2.9	8.8	9.2
49-1	255.2	22.0	22.7	8.6	24.3
62-1	208.7	17.4	0.3	8.3	8.3
136-1	174.6	2.2	-16.1	1.2	16.1
136-2	142.4	57.3	-31.5	40.2	51.1
141-1	223.2	3.4	7.3	1.5	7.5
141-2	233.8	6.6	12.4	2.8	12.7
144-1	191.7	31.6	-7.8	16.5	18.2
160-1	145.3	6.7	-30.1	4.6	30.5
163-1	189.6	12.5	-8.8	6.6	11.0
163-2	208.8	18.3	0.4	8.7	8.8
171-1	298.6	67.2	43.6	22.5	49.0
173-1	198.9	5.6	-4.4	2.8	5.2
186-1	230.7	7.6	10.9	3.3	11.4
196-1	210.6	9.8	1.2	4.7	4.8
197-1	194.7	10.6	-6.4	5.4	8.4
198-1	207.5	19.9	-0.2	9.6	9.6
200-1	183.3	27.3	-11.9	14.9	19.1
209-1	214.4	2.8	3.1	1.3	3.3

Table 4.2. Analysis of all reported results for etched track and electret detectors: Exposure 2, 804 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	834.9	19.9	3.8	2.4	4.5
1-2	795.0	20.3	-1.1	2.5	2.8
5-1	753.9	34.6	-6.2	4.6	7.7
13-1	872.2	22.7	8.5	2.6	8.9
13-2	897.3	32.4	11.6	3.6	12.2
19-1	802.6	46.4	-0.2	5.8	5.8
20-1	842.0	23.4	4.7	2.8	5.5
21-1	796.7	26.7	-0.9	3.4	3.5
32-1	842.5	37.5	4.8	4.5	6.5
49-1	923.4	22.1	14.9	2.4	15.0
62-1	836.5	23.1	4.0	2.8	4.9
136-1	815.6	19.7	1.4	2.4	2.8
136-2	796.0	13.5	-1.0	1.7	2.0
141-1	822.3	13.1	2.3	1.6	2.8
141-2	895.4	10.8	11.4	1.2	11.4
144-1	800.9	50.6	-0.4	6.3	6.3
160-1	576.7	13.1	-28.3	2.3	28.4
163-1	779.3	21.8	-3.1	2.8	4.2
163-2	793.0	53.7	-1.4	6.8	6.9
171-1	914.9	141.3	13.8	15.4	20.7
173-1	722.7	16.6	-10.1	2.3	10.4
186-1	882.2	19.1	9.7	2.2	10.0
196-1	780.5	24.8	-2.9	3.2	4.3
197-1	733.5	18.7	-8.8	2.5	9.1
198-1	785.1	39.2	-2.4	5.0	5.5
200-1	725.2	95.6	-9.8	13.2	16.4
209-1	823.9	6.7	2.5	0.8	2.6

Table 4.3. Analysis of all reported results for etched track and electret detectors: Exposure 3, 2294 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	2319.3	41.2	1.1	1.8	2.1
1-2	2269.4	32.7	-1.1	1.4	1.8
5-1	2126.8	41.3	-7.3	1.9	7.5
13-1	2663.5	48.7	16.1	1.8	16.2
13-2	2596.4	108.7	13.2	4.2	13.8
19-1	2257.2	72.5	-1.6	3.2	3.6
20-1	2457.4	43.4	7.1	1.8	7.3
21-1	2175.8	104.8	-5.2	4.8	7.1
32-1	2385.3	80.4	4.0	3.4	5.2
49-1	2450.0	77.7	6.8	3.2	7.5
62-1	2361.9	70.7	3.0	3.0	4.2
136-1	2375.6	58.4	3.6	2.5	4.3
136-2	2419.2	81.5	5.5	3.4	6.4
141-1	2405.4	18.2	4.9	0.8	4.9
141-2	2557.6	46.4	11.5	1.8	11.6
144-1	2270.8	35.0	-1.0	1.5	1.8
160-1	1650.1	47.6	-28.1	2.9	28.2
163-1	2084.3	55.6	-9.1	2.7	9.5
163-2	2257.2	58.7	-1.6	2.6	3.1
171-1	2695.9	226.5	17.5	8.4	19.4
173-1	2041.7	47.8	-11.0	2.3	11.2
186-1	2530.6	56.6	10.3	2.2	10.6
196-1	2243.5	75.8	-2.2	3.4	4.0
197-1	2124.2	38.8	-7.4	1.8	7.6
198-1	2260.6	44.8	-1.5	2.0	2.5
200-1	2070.5	149.3	-9.7	7.2	12.1
209-1	2405.5	6.4	4.9	0.3	4.9

Table 4.4. Analysis of all reported results for etched track and electret detectors: Exposure 4, 379 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	404.9	17.3	6.8	4.3	8.1
1-2	368.3	9.5	-2.8	2.6	3.8
5-1	361.7	16.8	-4.6	4.7	6.5
13-1	438.2	15.2	15.6	3.5	16.0
13-2	418.0	16.4	10.3	3.9	11.0
19-1	385.4	17.9	1.7	4.6	4.9
20-1	401.1	16.5	5.8	4.1	7.1
21-1	384.9	16.0	1.5	4.2	4.4
32-1	412.1	20.8	8.7	5.1	10.1
49-1	449.7	25.6	18.7	5.7	19.5
62-1	390.3	15.3	3.0	3.9	4.9
136-1	388.5	10.6	2.5	2.7	3.7
136-2	360.6	8.3	-4.9	2.3	5.4
141-1	408.7	14.6	7.8	3.6	8.6
141-2	429.0	9.6	13.2	2.2	13.4
144-1	381.8	35.2	0.7	9.2	9.2
160-1	278.6	10.2	-26.5	3.7	26.7
163-1	377.8	18.4	-0.3	4.9	4.9
163-2	392.3	27.3	3.5	7.0	7.8
171-1	509.4	95.0	34.4	18.7	39.1
173-1	345.7	6.4	-8.8	1.8	9.0
186-1	426.8	14.2	12.6	3.3	13.0
196-1	366.1	16.8	-3.4	4.6	5.7
197-1	356.5	11.9	-5.9	3.3	6.8
198-1	391.9	27.8	3.4	7.1	7.9
200-1	357.2	39.4	-5.8	11.0	12.4
209-1	392.2	6.0	3.5	1.5	3.8

Table 4.5. Analysis of all reported results for etched track and electret detectors: Exposure 5, 1317 kBq m^{-3} h, etched track and electret detectors. See Figure 10.

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)	% biased error	% precision error	% measurement error
1-1	1358.9	20.1	3.2	1.5	3.5
1-2	1244.4	38.0	-5.5	3.1	6.3
5-1	1221.0	23.7	-7.3	1.9	7.5
13-1	1456.7	39.6	10.6	2.7	10.9
13-2	1490.0	31.2	13.1	2.1	13.3
19-1	1263.2	59.5	-4.1	4.7	6.2
20-1	1370.2	35.3	4.0	2.6	4.8
21-1	1285.0	89.2	-2.4	6.9	7.4
32-1	1374.7	67.7	4.4	4.9	6.6
49-1	1504.5	39.1	14.2	2.6	14.5
62-1	1340.6	64.6	1.8	4.8	5.1
136-1	1337.4	45.6	1.5	3.4	3.7
136-2	1325.0	19.7	0.6	1.5	1.6
141-1	1320.3	19.8	0.3	1.5	1.5
141-2	1483.4	25.5	12.6	1.7	12.8
144-1	1322.0	31.6	0.4	2.4	2.4
160-1	920.0	43.7	-30.1	4.7	30.5
163-1	1227.1	40.4	-6.8	3.3	7.6
163-2	1247.5	47.1	-5.3	3.8	6.5
171-1	1609.9	156.8	22.2	9.7	24.3
173-1	1162.4	34.6	-11.7	3.0	12.1
186-1	1444.6	32.2	9.7	2.2	9.9
196-1	1287.2	35.3	-2.3	2.7	3.6
197-1	1281.6	37.3	-2.7	2.9	4.0
198-1	1311.6	42.9	-0.4	3.3	3.3
200-1	1146.1	77.5	-13.0	6.8	14.6
209-1	1404.8	4.4	6.7	0.3	6.7

Table 4.6. Analysis of all reported results for etched track and electret detectors: Transit exposure, etched track and electret detectors, see Figure 11.

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
1-1	10.0	19.9
1-2	0.4	0.7
5-1	4.6	6.3
13-1	7.0	5.2
13-2	5.5	2.6
19-1	24.8	8.7
20-1	11.3	2.1
21-1	21.5	5.7
32-1	28.3	9.4
49-1	26.4	17.1
62-1	12.0	2.8
136-1	48.4	1.9
136-2	95.1	57.5
141-1	6.6	3.5
141-2	13.6	7.4
144-1	10.6	8.9
160-1	22.2	5.0
163-1	49.5	4.3
163-2	10.0	3.5
171-1	56.3	16.6
173-1	3.0	1.8
186-1	15.0	3.8
196-1	1.7	1.7
197-1	8.1	5.9
198-1	73.8	10.1
200-1	32.3	15.5
209-1	9.0	1.4

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	208	211.2	31.3
2	804	809.0	71.6
3	2294	2313.2	220.8
4	379	391.8	41.4
5	1317	1323.7	135.0

Table 6. Performance classification scheme for all five exposures based on measurement error

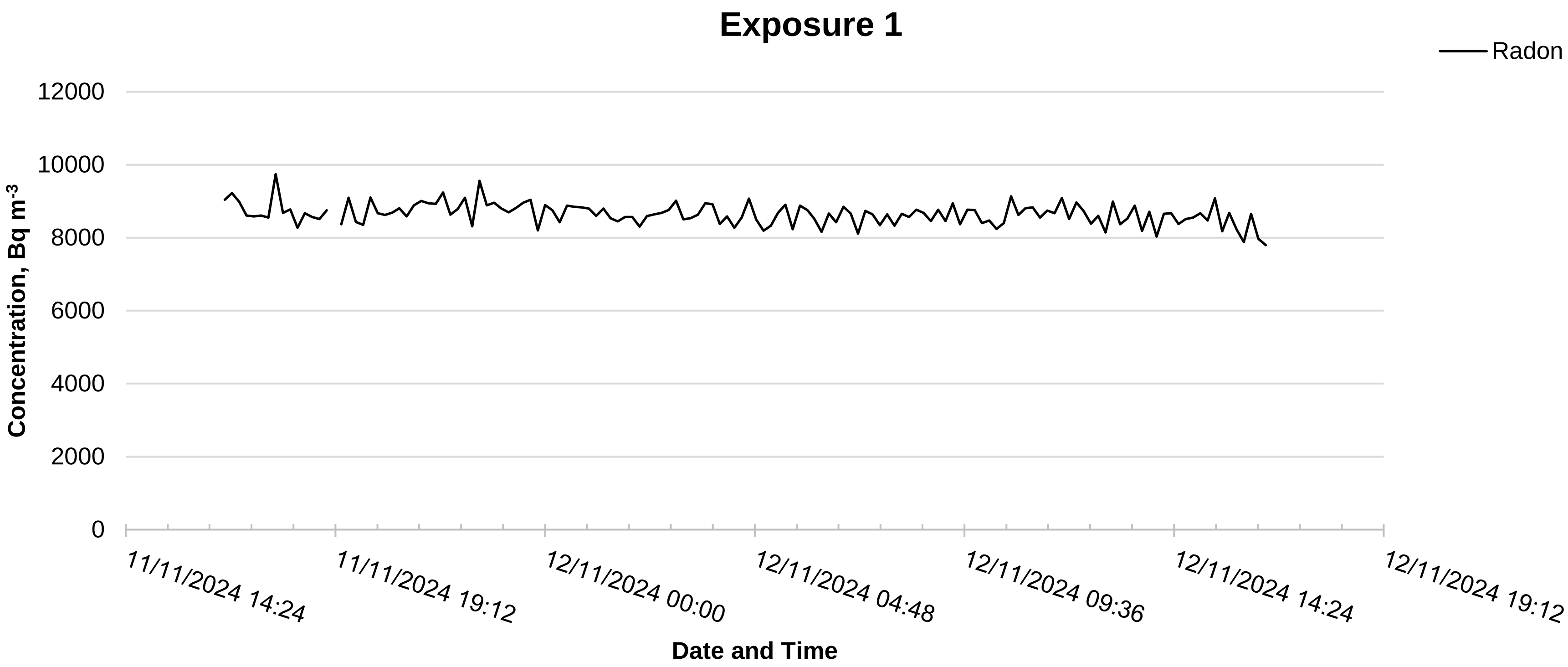
	Exposure 1	Exposure 4	Exposure 2	Exposure 5	Exposure 3	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	208 kBq m^{-3} h	379 kBq m^{-3} h	804 kBq m^{-3} h	1317 kBq m^{-3} h	2294 kBq m^{-3} h					
1-2	A	A	A	A	A	Closed	No	NRPB/SSI	CR-39	Mi-Net
5-1	A	A	A	A	A	Closed	No	TASL	CR39	TASL
19-1	A	A	A	A	A	Closed	Yes	Radout - Mi.am Srl	CR-39	TASL
20-1	A	A	A	A	A	Closed	No	TASL	PADC	TASL
21-1	A	A	A	A	A	Closed	No	Own design	CR39	TASL
62-1	A	A	A	A	A	Closed	No	In-house (sensitive volume 79 mL)	Makrofol	Covestro
141-1	A	A	A	A	A	Closed	No	Radosure	TASTRAK	TASL
163-2	A	A	A	A	A	Closed	No		Electret	Rad-Elec Inc.
196-1	A	A	A	A	A	Closed	No	Radout (Mi.am)	PADC	Radonova Scientific Ltd.
197-1	A	A	A	A	A	Closed	Yes	Radosys	CR-39	Radosys

	Exposure 1	Exposure 4	Exposure 2	Exposure 5	Exposure 3	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	208 kBq m^{-3} h	379 kBq m^{-3} h	804 kBq m^{-3} h	1317 kBq m^{-3} h	2294 kBq m^{-3} h					
198-1	A	A	A	A	A	Closed	No	Radosure TASL	TASTRAK PADC	TASL
209-1	A	A	A	A	A	Closed	No	TASL	CR-39	TASL
1-1	B	A	A	A	A	Closed	No	NRPB/SSI	CR-39	Mi-Net
32-1	A	B	A	A	A	Closed	Yes	NRPB/SSI	CR39/ PADC	TASL
136-1	B	A	A	A	A	Closed	No	NRPB/SSI, Frohe AB - Sweden	PADC	TASL
144-1	B	A	A	A	A	Closed	Yes	RSKS - Radosys	CR-39	Radosys
163-1	B	A	A	A	A	Closed	No	SSNTD	PADC (CR39)	
136-2	F	A	A	A	A	Closed	Yes	Own design (Badge)	PADC	TASL
173-1	A	A	B	B	B	Closed	Yes	TASL	CR39	TASL
186-1	B	B	A	A	B	Closed	No	TASL	TASTRAK PADC	TASL
13-1	B	B	A	B	B	Closed	Yes	Radtrak 2	PADC / CR-39	Radonova Scientific Ltd.

	Exposure 1	Exposure 4	Exposure 2	Exposure 5	Exposure 3	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	208 kBq m^{-3} h	379 kBq m^{-3} h	804 kBq m^{-3} h	1317 kBq m^{-3} h	2294 kBq m^{-3} h					
49-1	C	B	B	B	A	Closed	No	Radosys	CR-39	Radosys
13-2	B	B	B	B	B	Closed	Yes	Radtrak3	PADC / CR-39	Radonova Scientific Ltd.
141-2	B	B	B	B	B	Closed	Yes	E-Perm	Electret	E-Perm
200-1	B	B	B	B	B	Closed	No	Mi.am S.r.l.	PADC	TASL
171-1	E	D	C	C	B	Closed	Yes	Own design	LR115	Algade
160-1	D	C	C	D	C	Closed	No	TASL		TASL

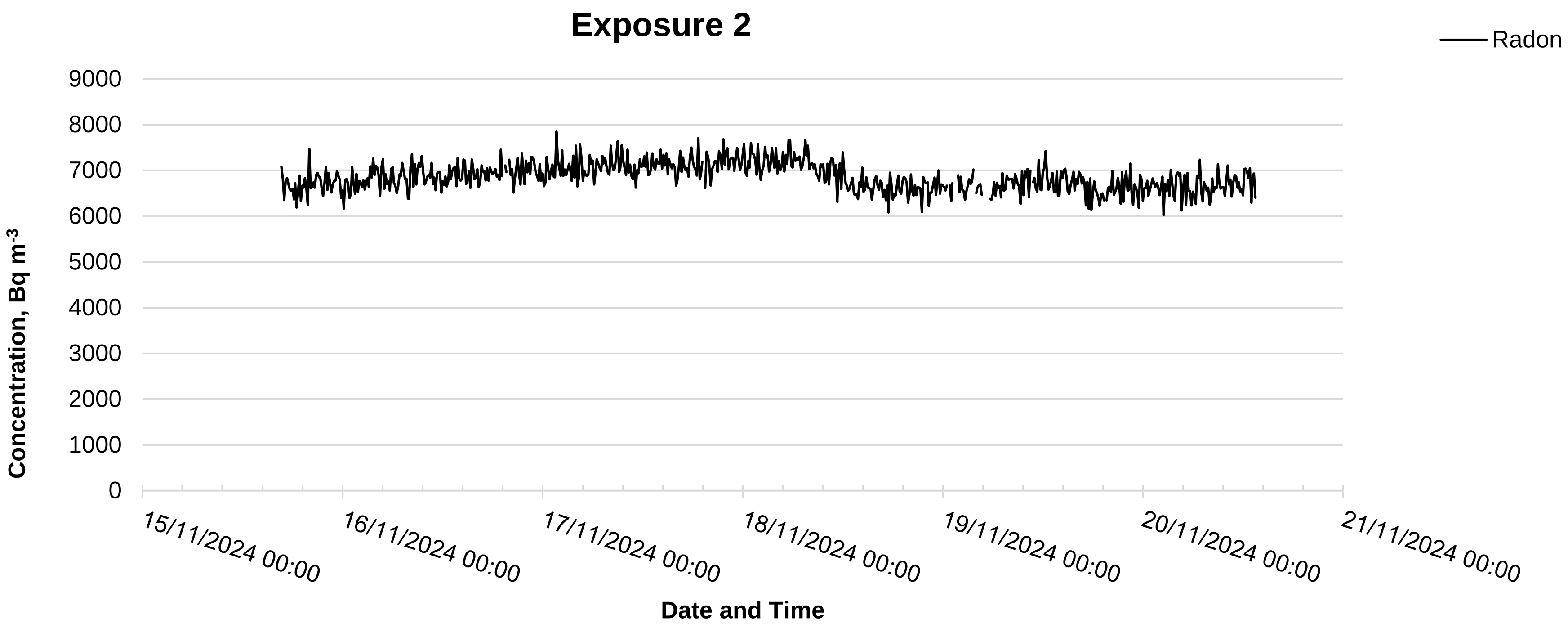
Note: Set 136-2 – one of the exposure 1 detector results and one of the transit detector results appear to have been transposed. Without this, the result would have been B A A A A.

Figure 1. Radon concentrations for exposure 1



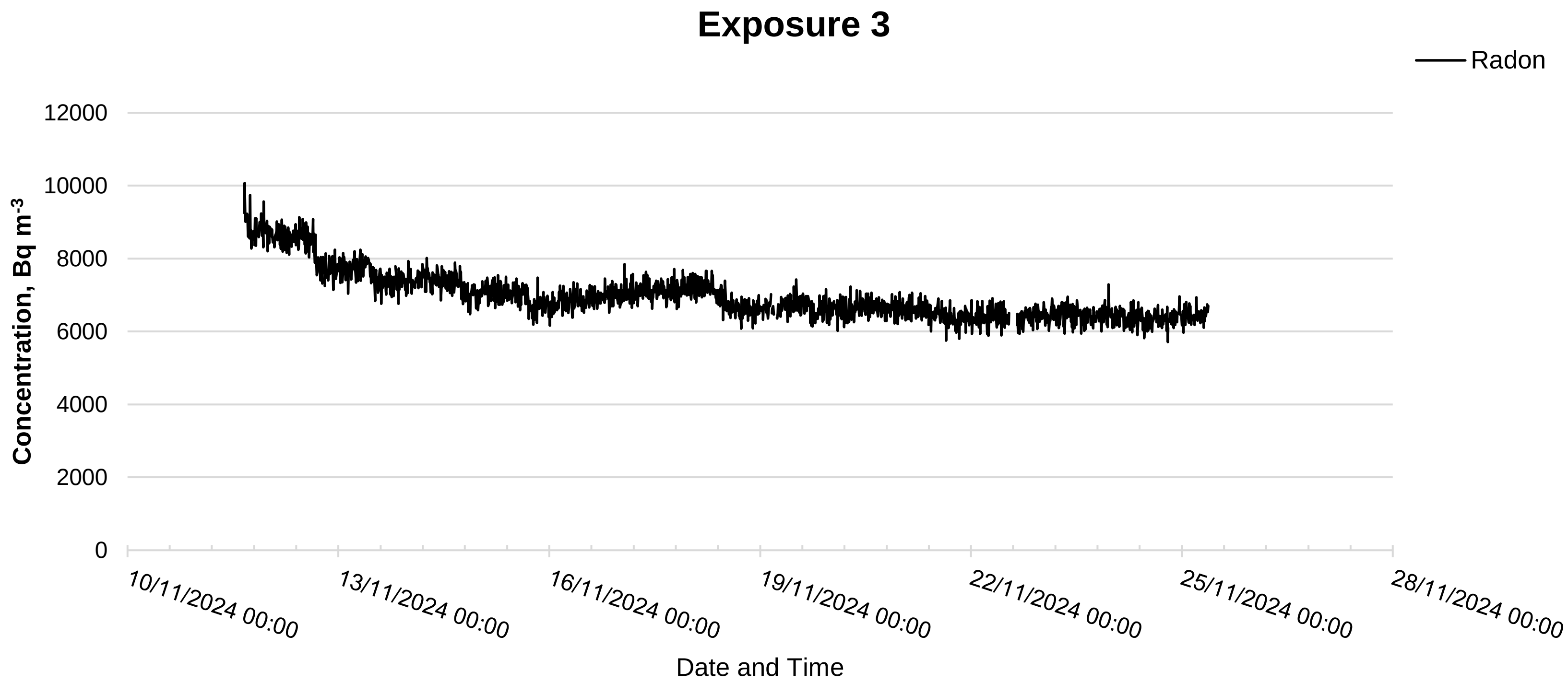
The above figure shows the fluctuation of radon concentration during exposure 1, which covers the period 11 November 2024 to 12 November 2024. The radon concentration fluctuated around 8,600 Bq m^{-3}, slowly reducing to end at around 8000 Bq m^{-3}. The gap in the trace line was caused by a communication error between the ATMOS instrument and the data logging system.

Figure 2. Radon concentration for exposure 2



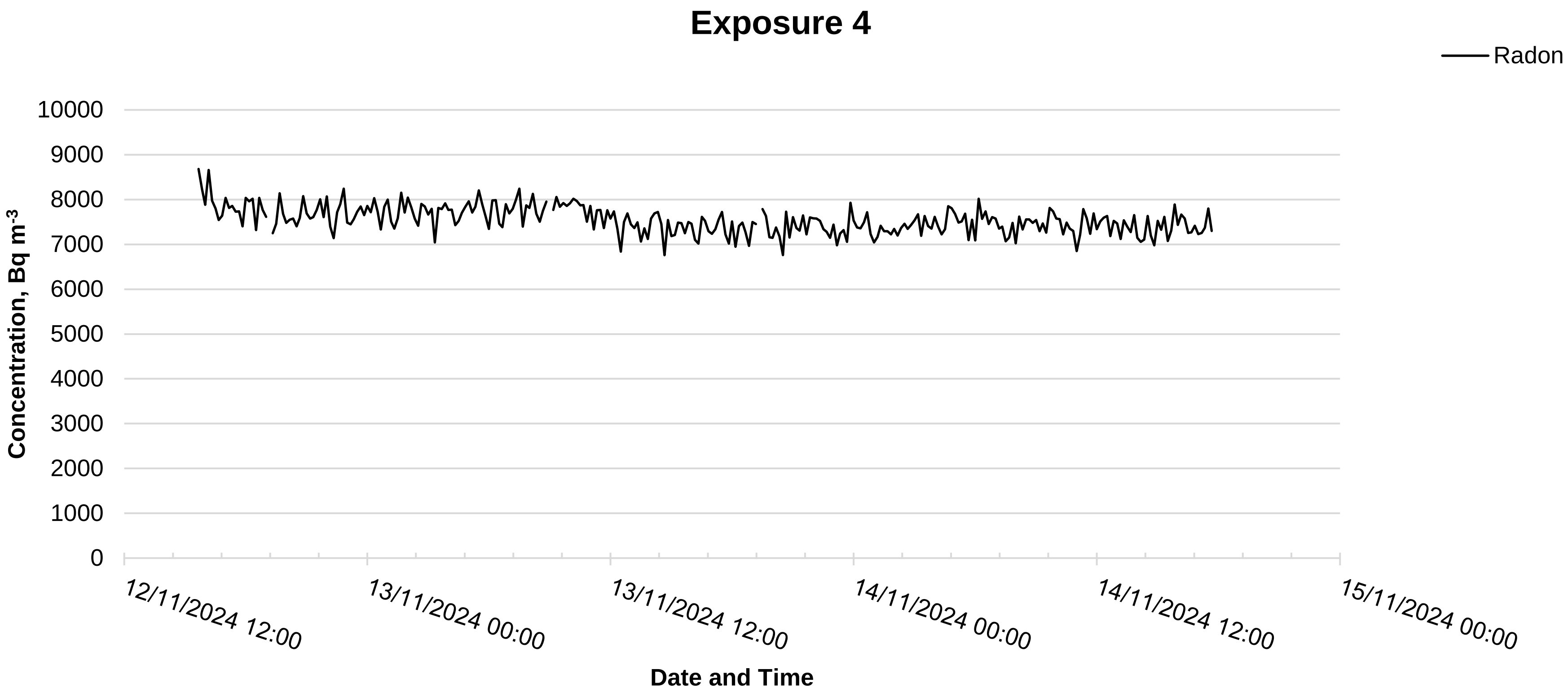
The above figure shows the fluctuation of radon concentration during exposure 2, which covers the period 15 November 2024 to 20 November 2024. The radon concentration began at over 6,500 Bq m^{-3}, slowly climbed to a peak of just over 7,100 Bq m^{-3} and then reduced to around 6,800 Bq m^{-3} with some minor fluctuations. The gaps in the trace line were caused by communication errors between the ATMOS instrument and the data logging system.

Figure 3. Radon concentration for exposure 3



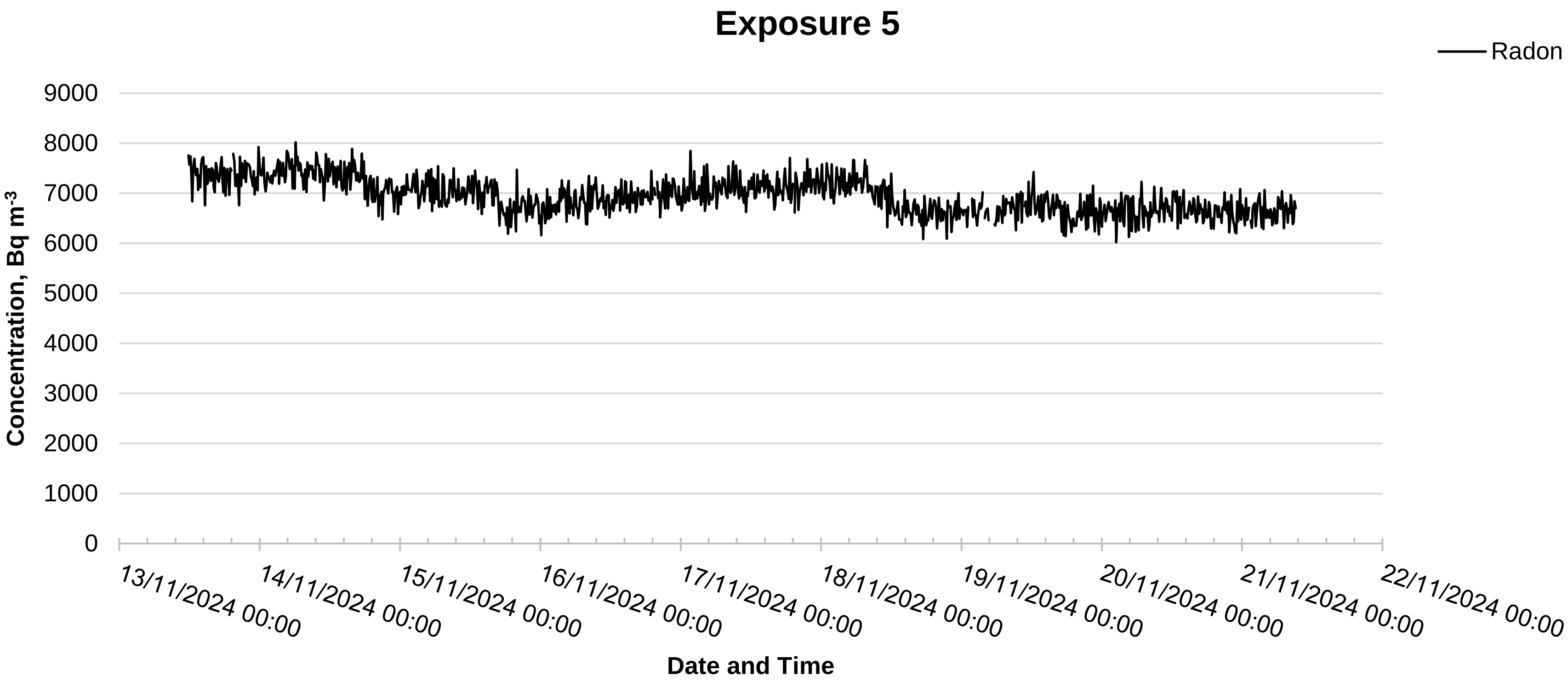
The above figure shows the fluctuation of radon concentration during exposure 3 which covers the period 11 November 2024 to 25 November 2024. The radon concentration began at over 9,000 Bq m^{-3}, with a gradual decline to around 6,200 Bq m^{-3}. The gap in the trace line was caused by a communication error between the ATMOS instrument and the data logging system.

Figure 4. Radon concentration for exposure 4



The above figure shows the fluctuation of radon concentration during exposure 4, which covers the period 12 November 2024 to 14 November 2024. The radon concentration began at over 8,000 Bq m^{-3}, reduced, then fluctuated between 8,000 Bq m^{-3} (highest) and 7,000 Bq m^{-3} (lowest). The gaps in the trace line were caused by communication errors between the ATMOS instrument and the data logging system.

Figure 5. Radon concentration for exposure 5



The above figure shows the fluctuation of radon concentration during exposure 5, which covers the period 13 November 2024 to 21 November 2024. The radon concentration initially fluctuated around 7,500 Bq m^{-3}, dropped to around 7,000 Bq m^{-3} then dropped further, ending at around 6,800 Bq m^{-3}. The gaps in the trace line were caused by communication errors between the ATMOS instrument and the data logging system.

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

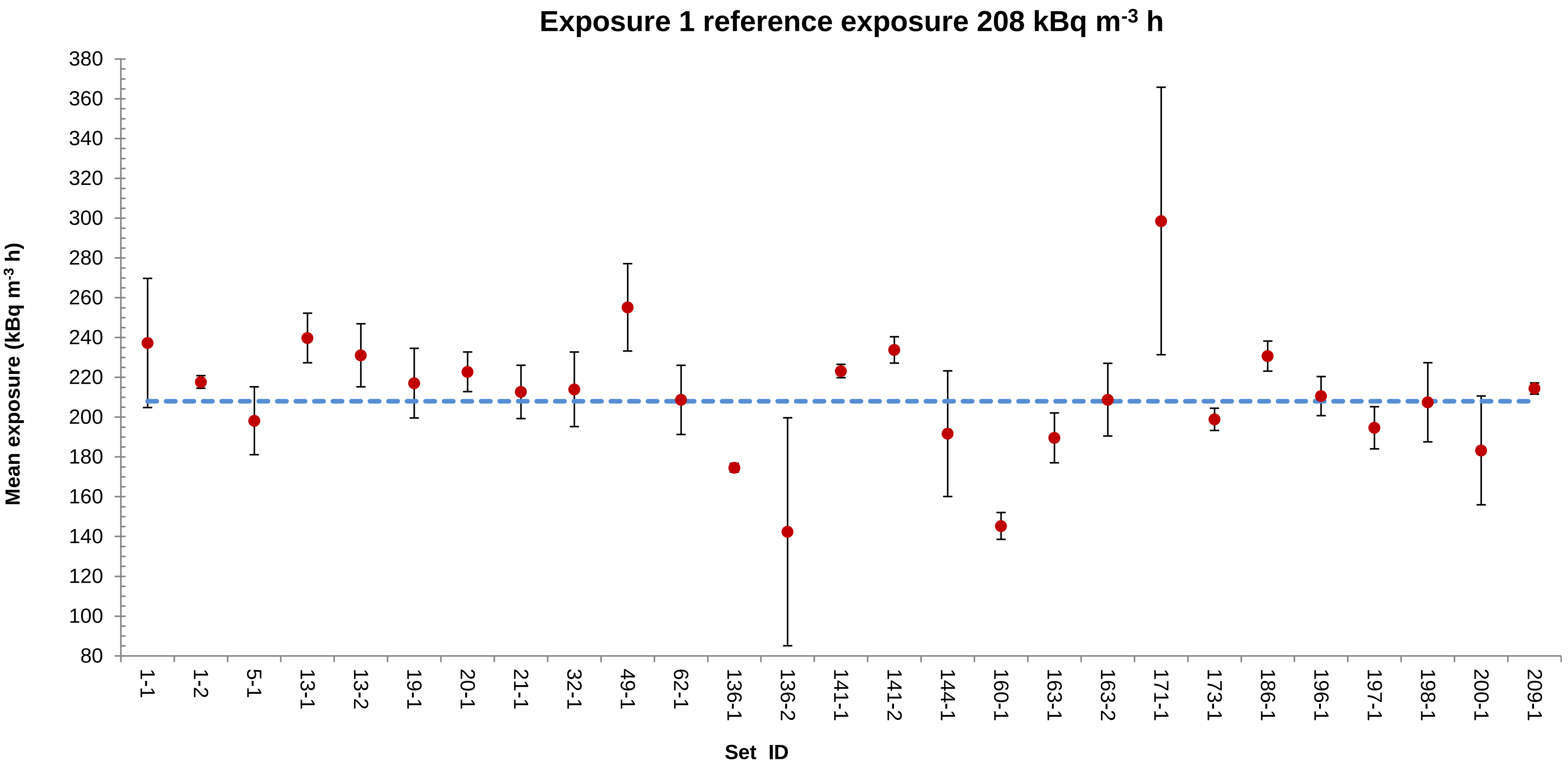


Figure 7. Results as reported by participants for exposure 2 - given in Table 4.2

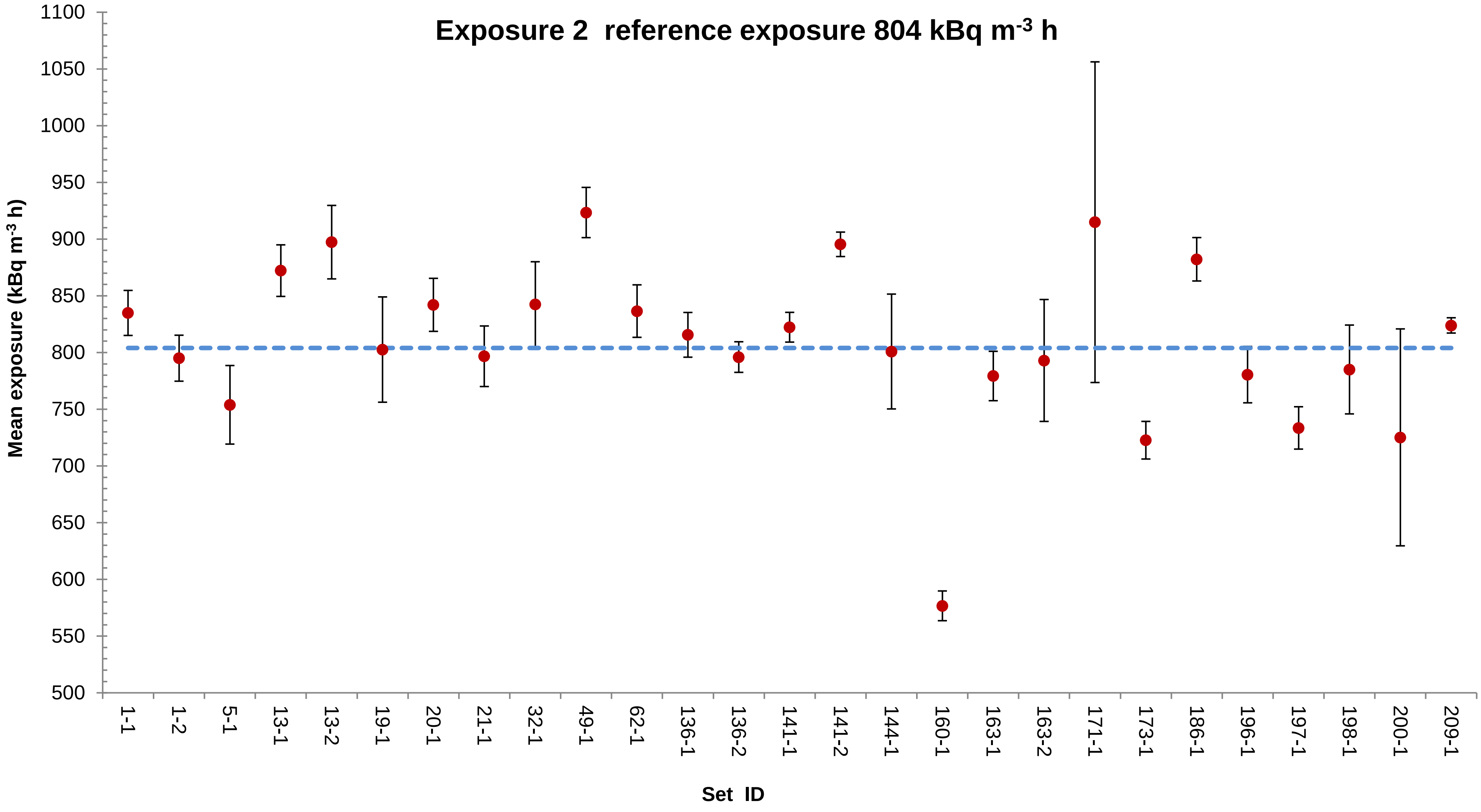


Figure 8. Results as reported by participants for exposure 3 - given in Table 4.3

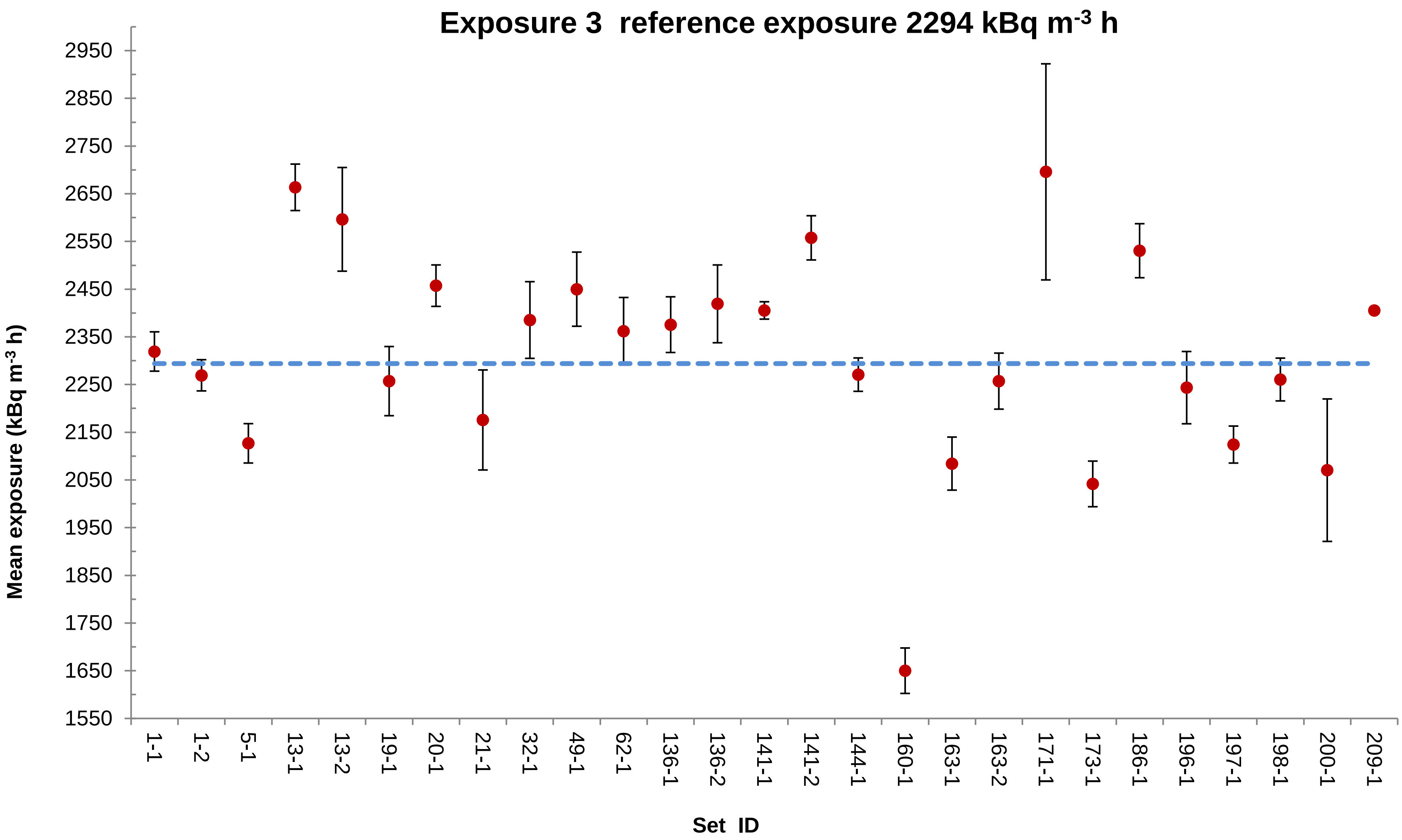


Figure 9. Results as reported by participants for exposure 4 - given in Table 4.4

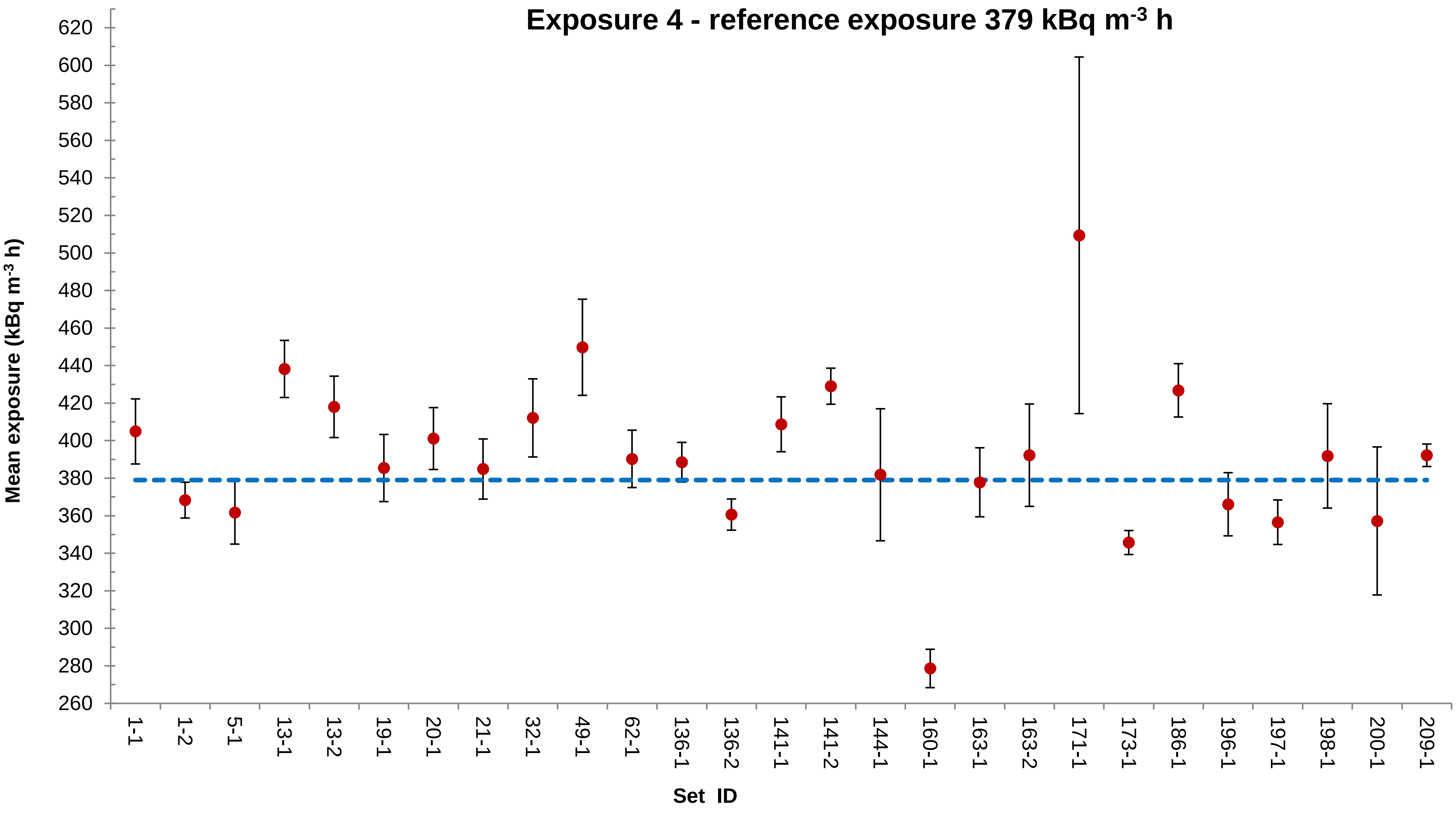


Figure 10. Results as reported by participants for exposure 5 - given in Table 4.5

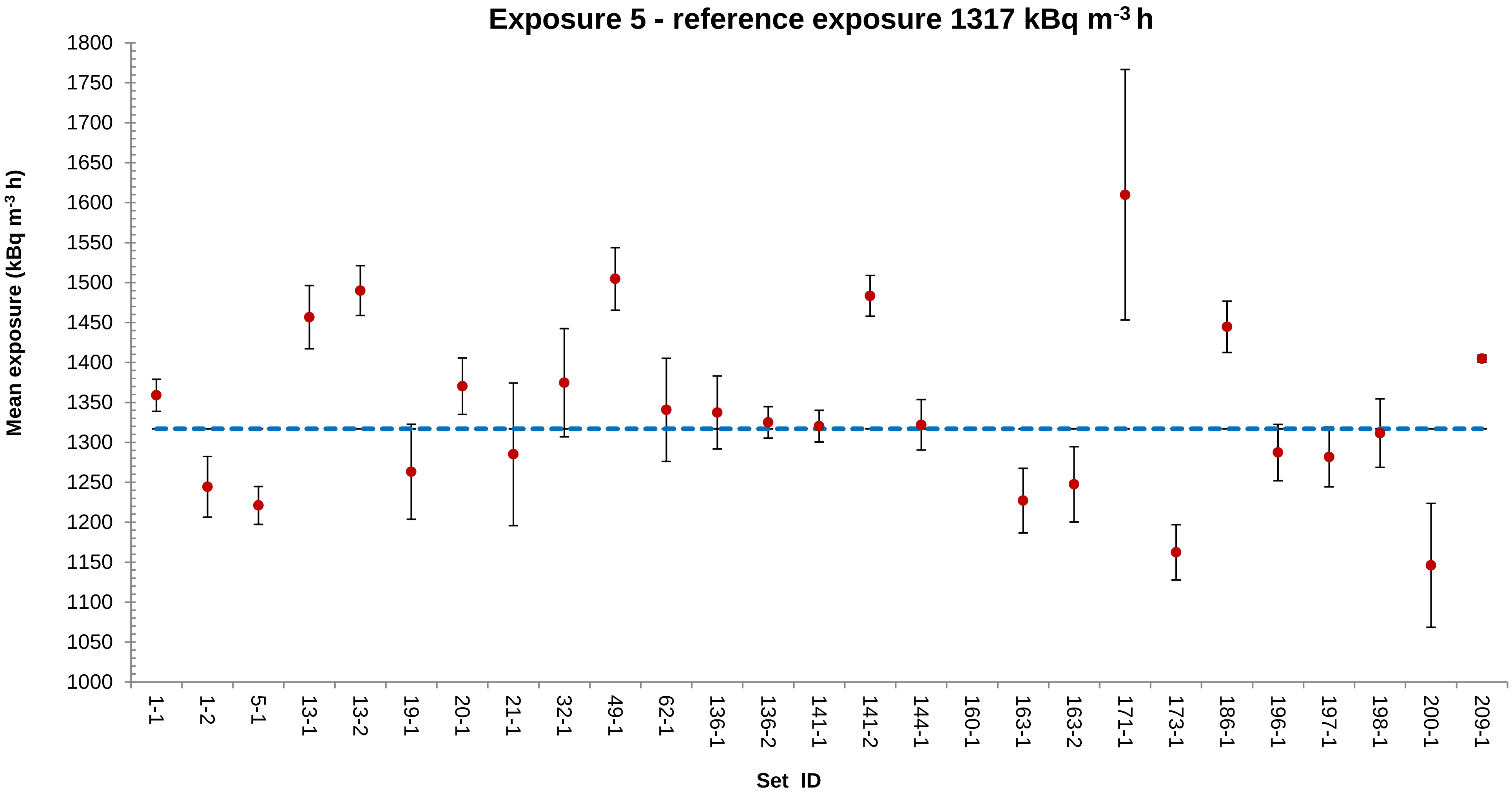


Figure 11. Results as reported by participants for transit exposure - given in Table 4.6

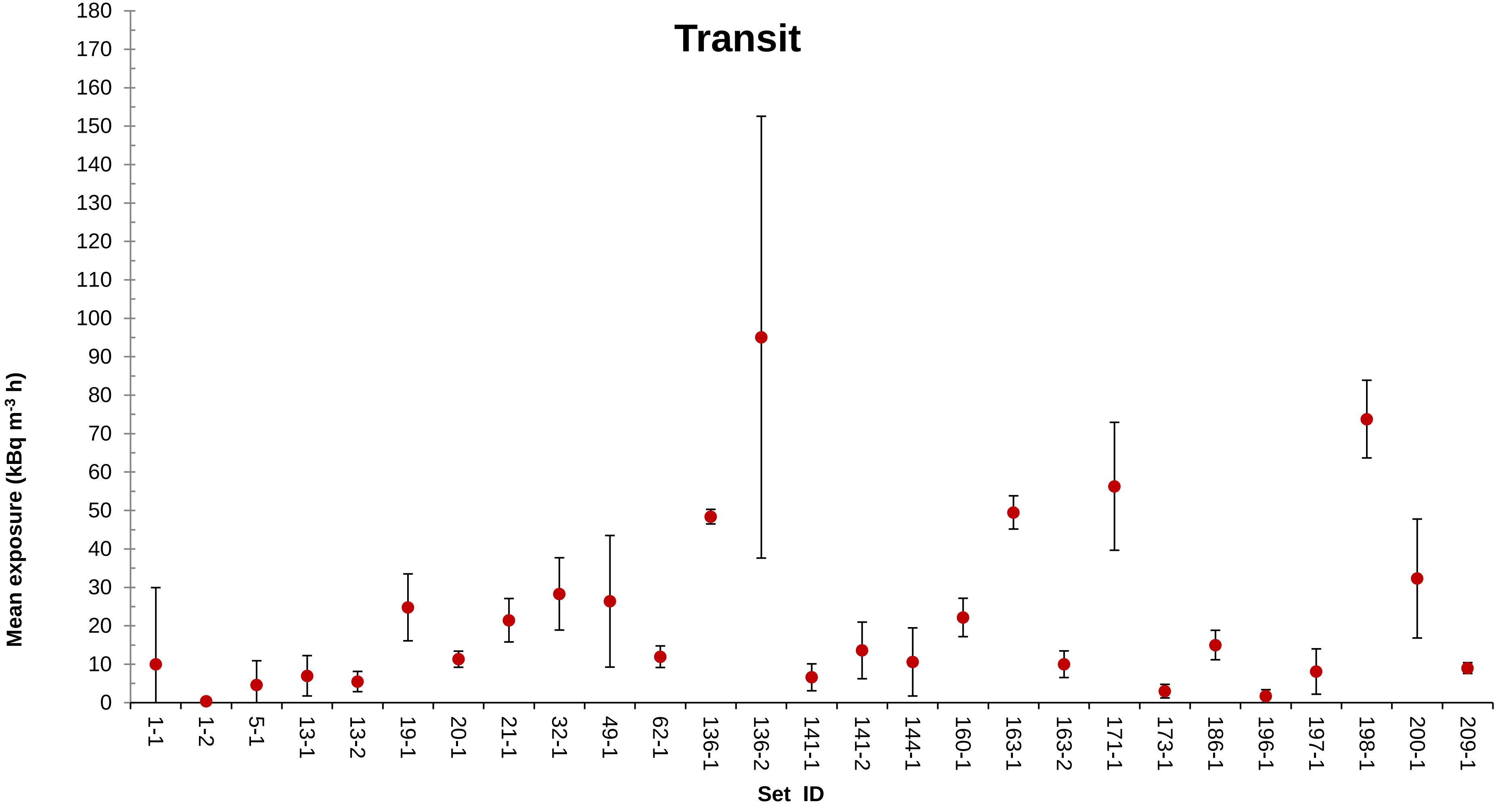


Figure 12. Distribution of mean exposure results for exposure 1 - given in Table 4.1. The vertical dotted line indicates the reference exposure.

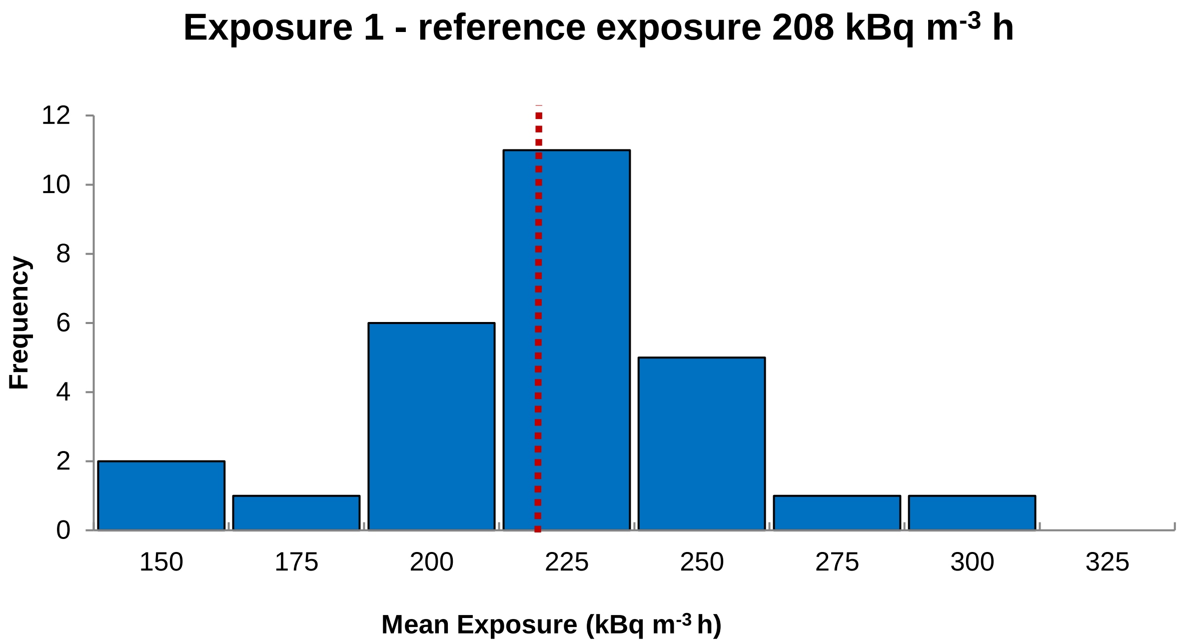


Figure 13. Distribution of mean exposure results for exposure 2 - given in Table 4.2. The vertical dotted line indicates the reference exposure.

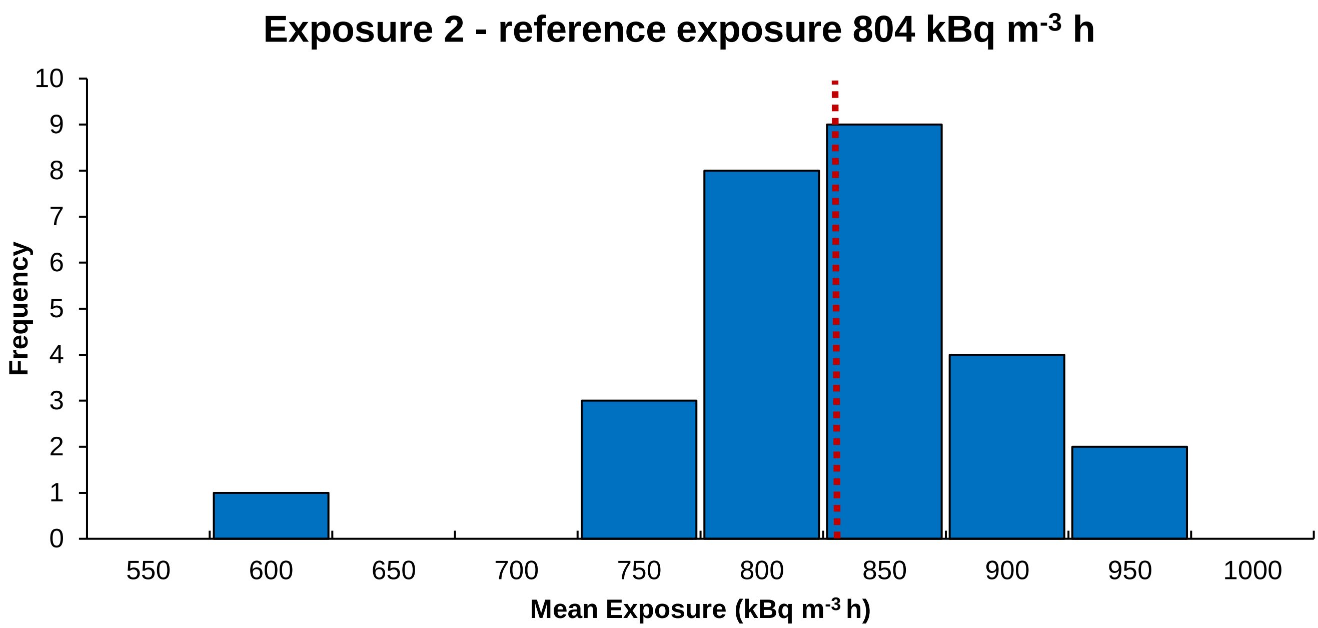


Figure 14. Distribution of mean exposure results for exposure 3 - given in Table 4.3. The vertical dotted line indicates the reference exposure.

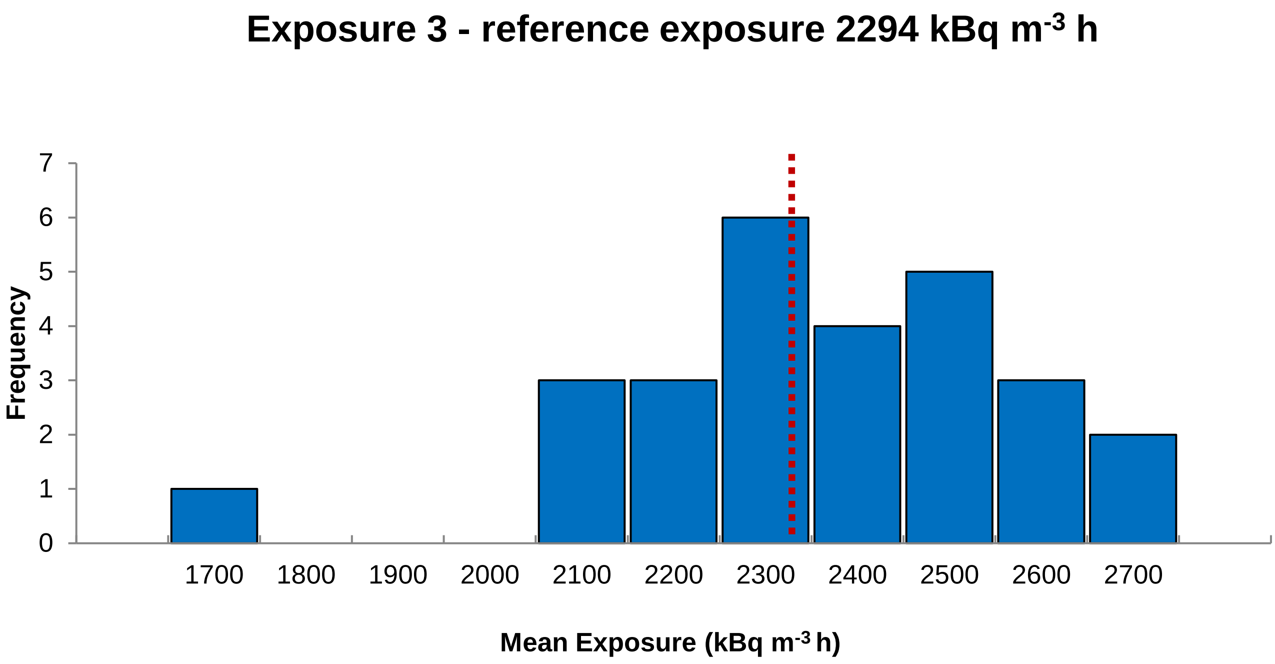


Figure 15. Distribution of mean exposure results for exposure 4 - given in Table 4.4. The vertical dotted line indicates the reference exposure.

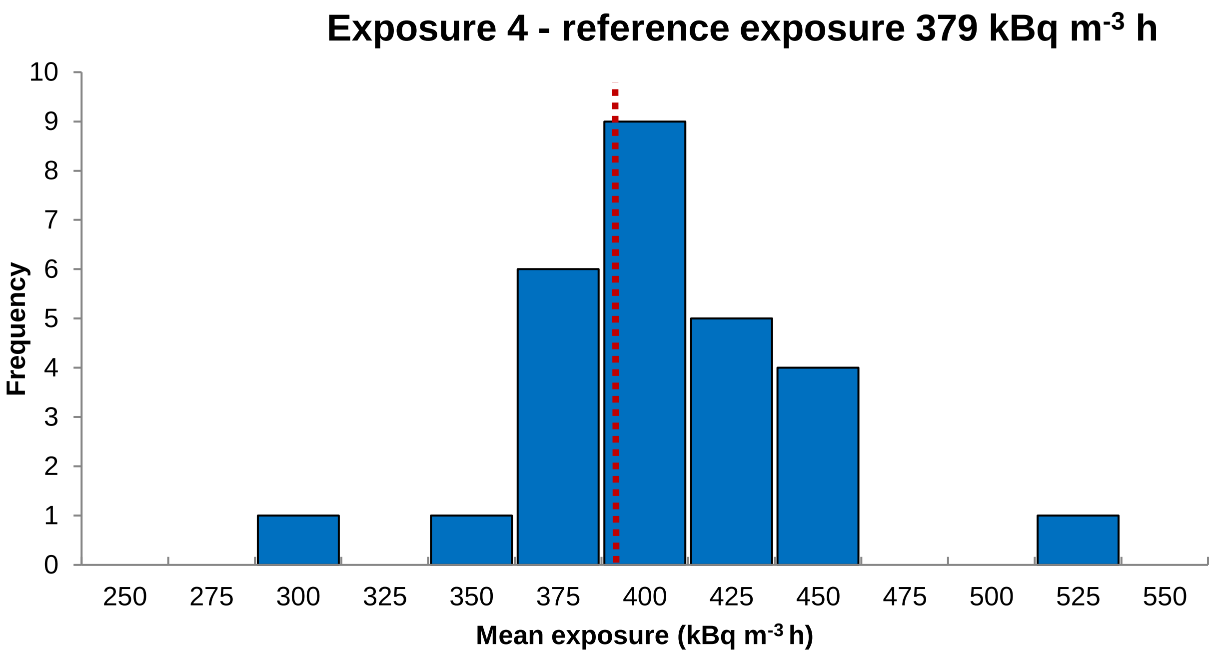


Figure 16. Distribution of mean exposure results for exposure 5 - given in Table 4.5. The vertical dotted line indicates the reference exposure.

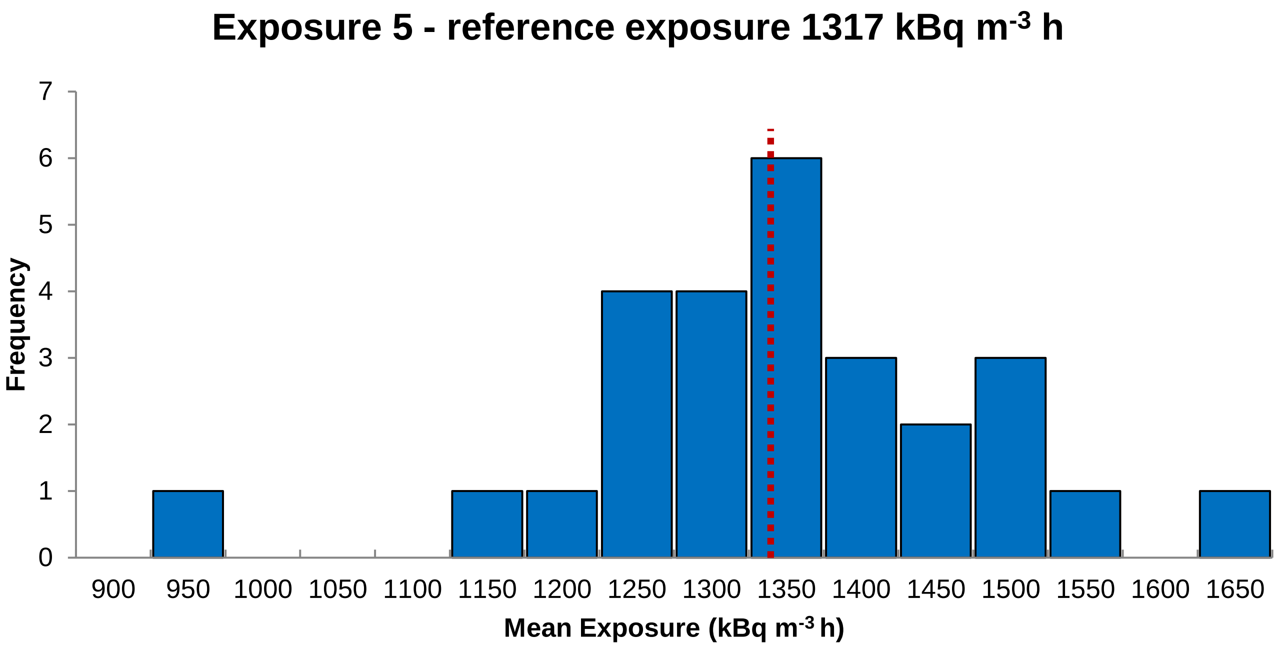


Figure 17. Distribution of mean exposure results for the transit exposure - given in Table 4.6.

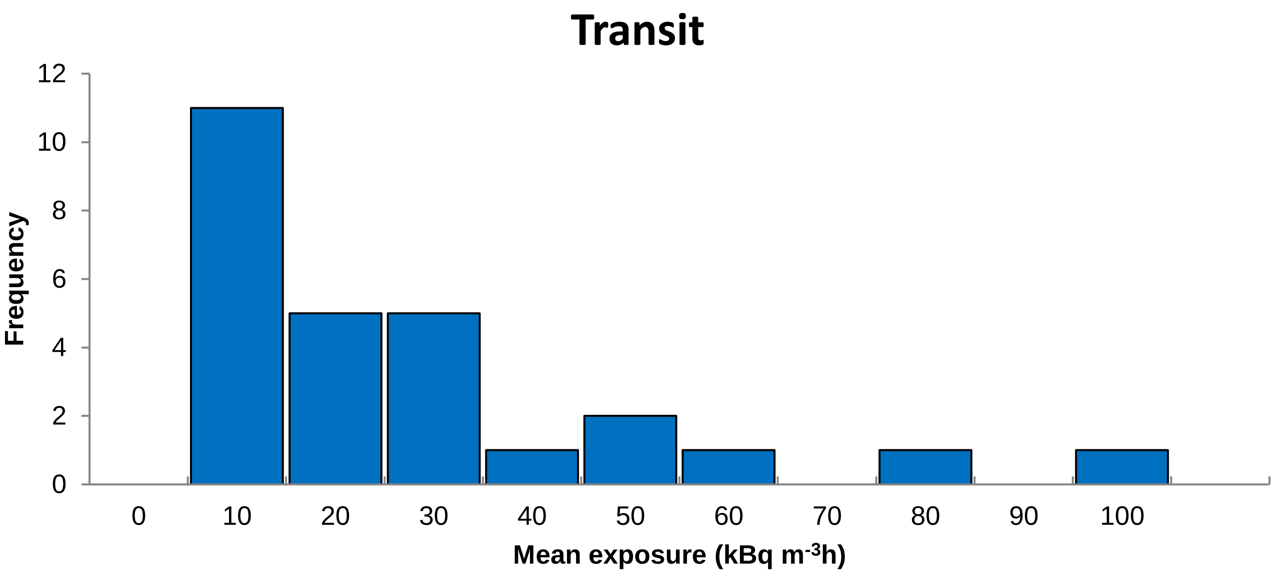


Figure 18. Performance classes for each exposure from A (best) to F (worst) summarised in Table 7 below

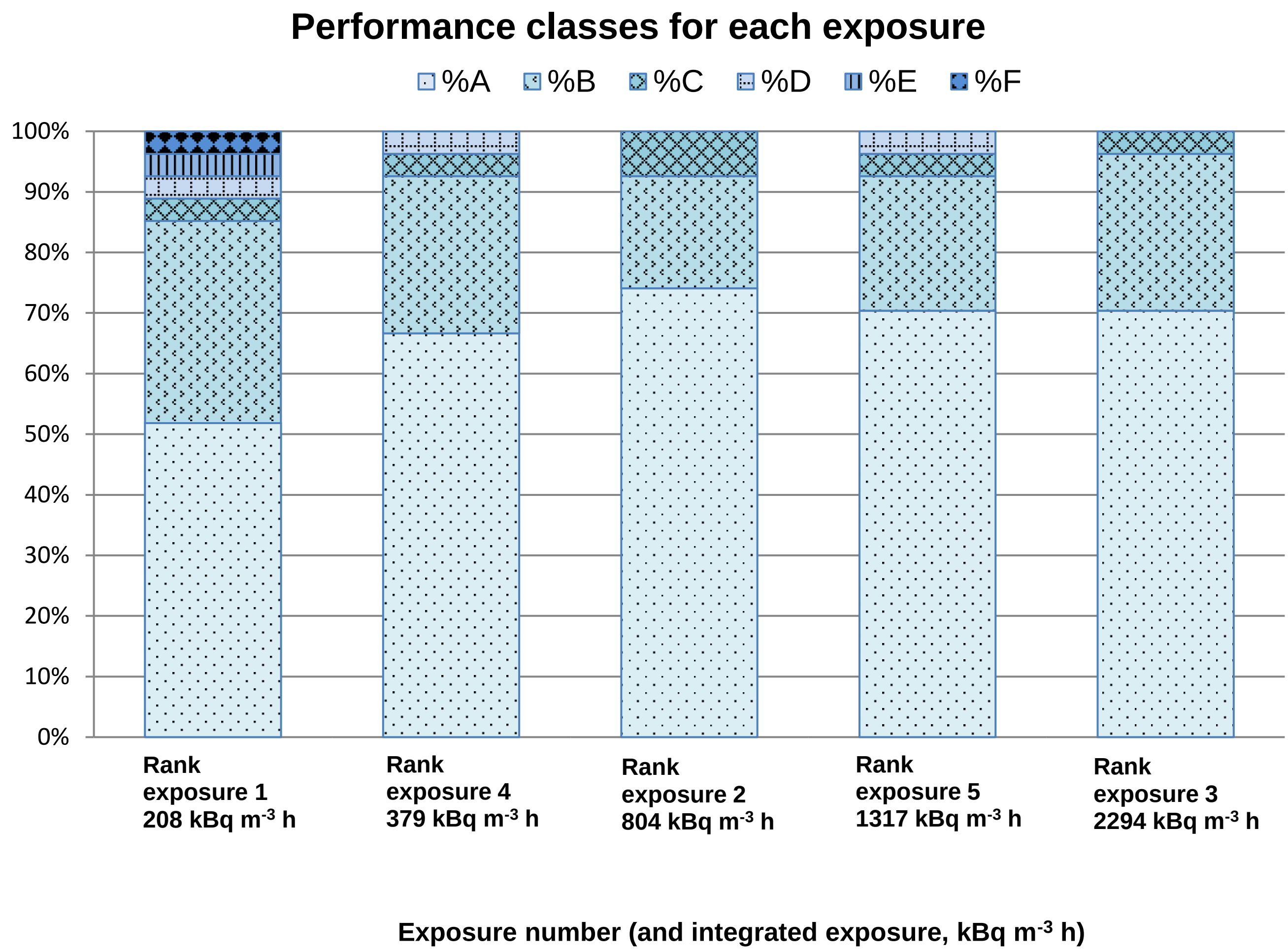


Table 7. Exposure number (and integrated exposure, kBq m^{-3} h)

	Rank exposure 1 208 kBq m^{-3} h	Rank exposure 4 379 kBq m^{-3} h	Rank exposure 2 804 kBq m^{-3} h	Rank exposure 5 1317 kBq m^{-3} h	Rank exposure 3 2294 kBq m^{-3} h
%F	4	0	0	0	0
%E	4	0	0	0	0
%D	4	4	0	4	0
%C	4	4	7	4	4
%B	33	26	19	22	26
%A	52	67	74	70	70

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