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Results of the 2023 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 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, Chemical 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.

There were no activated charcoal detectors submitted. The sets of 60 etched track or 30 electret detectors were randomised into 6 equal groups at RCE. A total of 5 of these groups were exposed in the RCE radon chamber to radon gas exposures ranging from 160 kBq m^{-3} h to 2,200 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 2023, for which a total of 27 laboratories from 12 countries submitted 31 sets of detectors. One laboratory with two sets of detectors could not be included in the report.

This report therefore covers 26 laboratories and 29 sets of detectors from 12 countries. The 29 sets of detectors comprise 26 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. 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.
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 and Environmental Hazards Directorate (RCE), and has operated annually since 1982. 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 RCE 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 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, 27 laboratories from 12 countries took part in the 2023 UKHSA intercomparison, with sets of 60 etched track detectors or 30 electret detectors. At RCE, each set was randomised into 6 groups of either 10 etched track detectors or 5 electret detectors. A total of 5 of the groups in each set were exposed in the radon chamber, the final group was the transit or control group and this group was not exposed. Some laboratories submitted more than 1 set of detectors, so 31 sets of 5 groups of detectors were exposed in the radon chamber. Following exposure, the detectors were returned to the originating laboratories for processing. One laboratory with two sets of detectors could not be included in the report.

This report therefore covers 26 laboratories and 29 sets of detectors from 12 countries, as shown in Table 2. The 29 sets of detectors were 26 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 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 10 Bq m^{-3} to 34 Bq m^{-3}, with an overall average of 22 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 2% 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 laboratory with two sets of detectors could not be included in the report, so the tables show the results for 26 laboratories and a total of 29 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 83 kBq m^{-3} h (Figure 11). A total of 19 of the reported transit exposures were below 40 kBq m^{-3} h, 10 reported transit exposures between 40 kBq m^{-3} h and 820 kBq m^{-3} h, of which 8 of these were below 122 kBq m^{-3} h. This is a wider range of results than in 2022 (3) where 10 out of a total of 39 reported transit exposures were between 30 kBq m^{-3} h and 270 kBq m^{-3} h, of which 9 were below 130 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 5 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 not as good as 2022.

Approximately 38% of all sets of detectors achieved class A for at least 3 exposures, which is not as good as 2022 (3). For the lowest exposure measurement (156 kBq m^{-3} h), 21% of laboratories achieved class A, a decrease from 2022. For the second lowest exposure (519 kBq m^{-3} h), 38% of laboratories achieved class A, which is worse than in 2022.

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. It could also reflect variable detector material quality from a specific manufacturer.

In order 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, fridge, nitrogen, radon-proof bags in a low radon store, and stored in a unit with filtered pressurised air. The majority of laboratories use a freezer. The maximum storage time before use ranged from a few days to up to 10 years. Of the sets which had a transit exposure less than 50 Bq m^{-3} h, most (18 out of 20) were sent using radon proof bags. Of the 8 sets where the transit exposure equalled or exceeded 50 Bq m^{-3}, 5 of the sets were sent using radon proof bags and the storage (in freezer or low radon room) ranged from 7 days to several years. This indicates that other factors might be affecting the results (including etching methods, ageing of the plastic and staff training) but it should also be noted that the transit doses from and to different laboratories will inevitably be different. The highest transit exposures were due to a record-keeping error for one set and a high result from an unexposed (transit) Electret for another set. The proportion of sets achieving each performance classification (A to F) is given in Figure 18.

Conclusions

In total, 27 laboratories from 12 countries participated in the 2023 UKHSA intercomparison.

One laboratory could not be included in the report, so this report is for 26 laboratories and 29 sets of detectors from 12 countries. The detectors were 26 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. A total of 5 laboratories achieved 5 class A ratings, which is worse than the 2022 intercomparison.

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Tables and figures

Table 2. Participating laboratories

Contact person	Organisation	Country
Nivaldo Carlos da Silva	Brazilian Commission for Nuclear Energy (CNEN)	Brazil
Kremena Georgieva Ivanova	National Center of Radiobiology and Radiation Protection (NCRRP)	Bulgaria
Jussi-Pekka Laine / Tiina Oinas	Radiation and Nuclear Safety Authority (STUK)	Finland
David Doyle	AlphaRadon Ltd.	Ireland
Enrico Chiaberto / Mauro Magnoni / Elena Serena	ARPA Piemonte – Laboratorio Radon	Italy
Massimo Guazzini / Anna Adriani	ARPAT	Italy
Dr. Silvia Penzo	ENEA - Radiation Protection Institute	Italy
Dr. Massimo Moroni	Harmat srls	Italy
Leandro Magro / Anna Maria Sotgiu / Monica Buchetti	ISIN	Italy
Leandro Gemmiti	L.B. Servizi S.r.l.	Italy
Ing. Gianluca Troiano	Niton S.r.l.	Italy
Dr. Mattia Taroni	Protex Italia S.r.l.	Italy
Serena Sanna	U-Series S.r.l.	Italy
Marielle LeComte / Karin Pier	Laboratoire d'Analyses radiologique du Luxembourg	Luxembourg
Trine Kvam Olafsen	DSA Norwegian Radiation and Nuclear Safety Authority	Norway
Mário Reis	IST - LPSR	Portugal
Peter Jovanovič / Matija Škrlep	ZVD d.o.o.	Slovenia
Ismael Fuente / Santiago Celaya	Laboratory of Environmental Radioactivity, University of Cantabria (LaRUC)	Spain
Alberto Otero Pazos	Laboratory of Environmental Radioactivity, University of A Coruña	Spain
Johanna Sjödin	Eurofins Radon Testing Sweden	Sweden
Gilbert Jönssen / Maria Jönssen	Radonanalys GJAB	Sweden
Dr. Tryggve Rönnqvist	Radonova Laboratories AB	Sweden
Denis Henshaw / Peter Fews	TASL / Radosure	United Kingdom
Julie Cowlin	Testair Ltd.	United Kingdom
Kinga Zmijewska	UKHSA Personal Dosimetry Service	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)	166.45	307.05	74.85	125.2	22.12
Radon exposure (kBq m^{-3} h)	1100	2161	519	814	156
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, 1100 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	1225.6	7.2	11.4	0.6	11.4
5-1	1132.5	45.1	3.0	4.0	5.0
12-1	941.8	55.6	-14.4	5.9	15.5
13-1	1108.0	46.9	0.7	4.2	4.3
13-2	1087.8	90.0	-1.1	8.3	8.4
19-1	1057.0	42.0	-3.9	4.0	5.6
20-1	1190.9	30.1	8.3	2.5	8.6
21-1	1202.5	20.3	9.3	1.7	9.5
32-1	1188.2	69.2	8.0	5.8	9.9
40-1	1211.1	271.3	10.1	22.4	24.6
49-1	1251.0	76.3	13.7	6.1	15.0
62-1	1174.1	53.2	6.7	4.5	8.1
141-1	1176.6	13.5	7.0	1.1	7.1
141-2	1215.4	34.8	10.5	2.9	10.9
156-1	1273.5	32.1	15.8	2.5	16.0
160-1	1208.0	49.8	9.8	4.1	10.6
163-1	1058.9	127.6	-3.7	12.1	12.6
163-2	1118.0	46.7	1.6	4.2	4.5
171-1	984.4	93.9	-10.5	9.5	14.2
173-1	1016.8	14.9	-7.6	1.5	7.7
178-1*	185.4	503.7	-83.1	271.7	284.1
181-1**	246.4	45.4	-77.6	18.4	79.8
186-1	1227.9	25.4	11.6	2.1	11.8
195-1	979.1	169.6	-11.0	17.3	20.5
196-1	1192.4	36.5	8.4	3.1	8.9
197-1	1067.3	53.0	-3.0	5.0	5.8
198-1	1128.4	31.6	2.6	2.8	3.8
199-1	1324.7	45.7	20.4	3.4	20.7
207-1	1289.7	68.2	17.2	5.3	18.0

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is excluded from the graph in Figure 6.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is excluded from the graph in Figure 6.

Table 4.2. Analysis of all reported results for etched track and electret detectors: Exposure 2, 2161 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	2438.2	25.9	12.8	1.1	12.9
5-1	2167.4	147.9	0.3	6.8	6.8
12-1	1853.4	108.3	-14.2	5.8	15.4
13-1	2167.4	83.3	0.3	3.8	3.9
13-2	2213.7	91.8	2.4	4.1	4.8
19-1	2162.9	81.4	0.1	3.8	3.8
20-1	2358.5	68.4	9.1	2.9	9.6
21-1	2412.2	76.2	11.6	3.2	12.0
32-1	2402.9	112.8	11.2	4.7	12.1
40-1	2297.9	340.9	6.3	14.8	16.1
49-1	2339.2	86.2	8.2	3.7	9.0
62-1	2392.5	61.0	10.7	2.5	11.0
141-1	2421.0	29.3	12.0	1.2	12.1
141-2	2334.0	57.1	8.0	2.4	8.4
156-1	2426.2	33.2	12.3	1.4	12.3
160-1	2507.2	89.2	16.0	3.6	16.4
163-1	1963.7	633.5	-9.1	32.3	33.5
163-2	2235.8	71.1	3.5	3.2	4.7
171-1	1921.7	131.0	-11.1	6.8	13.0
173-1	2035.6	20.8	-5.8	1.0	5.9
178-1*	1024.0	1176.5	-52.6	114.9	126.4
181-1**	1506.8	98.3	-30.3	6.5	31.0
186-1	2432.2	50.0	12.5	2.1	12.7
195-1	2099.8	257.9	-2.8	12.3	12.6
196-1	2438.4	156.0	12.8	6.4	14.3
197-1	2128.4	59.7	-1.5	2.8	3.2
198-1	2251.2	70.8	4.2	3.1	5.2
199-1	2648.5	114.7	22.6	4.3	23.0
207-1	2493.7	148.9	15.4	6.0	16.5

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is shown as an error bar in the graph in Figure 7.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is excluded from the graph in Figure 7.

Table 4.3. Analysis of all reported results for etched track and electret detectors: Exposure 3, 519 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	584.8	6.7	12.7	1.2	12.7
5-1	479.0	22.1	-7.7	4.6	9.0
12-1	443.9	27.2	-14.5	6.1	15.7
13-1	533.4	20.1	2.8	3.8	4.7
13-2	504.9	27.3	-2.7	5.4	6.1
19-1	511.8	21.0	-1.4	4.1	4.3
20-1	541.7	32.7	4.4	6.0	7.5
21-1	581.5	20.5	12.0	3.5	12.5
32-1	578.8	33.6	11.5	5.8	12.9
40-1	591.6	103.1	14.0	17.4	22.3
49-1	599.9	29.8	15.6	5.0	16.4
62-1	547.5	27.8	5.5	5.1	7.5
141-1	566.7	4.8	9.2	0.9	9.2
141-2	575.0	11.9	10.8	2.1	11.0
156-1	613.1	23.5	18.1	3.8	18.5
160-1	603.4	107.1	16.3	17.7	24.1
163-1	534.5	96.3	3.0	18.0	18.3
163-2	507.4	19.3	-2.2	3.8	4.4
171-1	461.6	52.3	-11.1	11.3	15.8
173-1	472.6	15.4	-8.9	3.3	9.5
178-1*	-38.1	788.7	-107.3	-2070.0	2072.8
181-1**	-128.1	614.5	-124.7	-479.5	495.5
186-1	578.0	10.7	11.4	1.9	11.5
195-1	459.5	93.4	-11.5	20.3	23.3
196-1	586.6	33.2	13.0	5.7	14.2
197-1	507.8	21.5	-2.2	4.2	4.7
198-1	517.6	31.8	-0.3	6.1	6.2
199-1	634.3	39.3	22.2	6.2	23.1
207-1	635.9	30.2	22.5	4.7	23.0

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is shown as an error bar in the graph in Figure 8.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is is shown as an error bar in the graph in Figure 8.

Table 4.4. Analysis of all reported results for etched track and electret detectors: Exposure 4, 814 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	895.1	11.7	10.0	1.3	10.0
5-1	850.5	21.7	4.5	2.6	5.2
12-1	696.8	33.6	-14.4	4.8	15.2
13-1	813.1	30.8	-0.1	3.8	3.8
13-2	796.7	55.9	-2.1	7.0	7.3
19-1	798.3	34.6	-1.9	4.3	4.7
20-1	857.3	54.4	5.3	6.3	8.3
21-1	908.0	33.6	11.5	3.7	12.1
32-1	875.8	47.7	7.6	5.5	9.3
40-1	904.0	211.5	11.1	23.4	25.9
49-1	948.2	33.4	16.5	3.5	16.9
62-1	860.0	43.5	5.6	5.1	7.6
141-1	865.5	10.9	6.3	1.3	6.5
141-2	883.4	22.6	8.5	2.6	8.9
156-1	938.0	33.9	15.2	3.6	15.7
160-1	884.3	137.6	8.6	15.6	17.8
163-1	816.4	176.1	0.3	21.6	21.6
163-2	854.4	20.0	5.0	2.3	5.5
171-1	799.3	87.4	-1.8	10.9	11.1
173-1	737.0	8.1	-9.5	1.1	9.5
178-1*	53.7	439.8	-93.4	819.0	824.3
181-1**	162.0	377.9	-80.1	233.2	246.6
186-1	895.2	19.4	10.0	2.2	10.2
195-1	784.8	99.3	-3.6	12.6	13.1
196-1	856.9	25.1	5.3	2.9	6.0
197-1	786.9	43.0	-3.3	5.5	6.4
198-1	807.9	63.2	-0.7	7.8	7.9
199-1	960.8	42.4	18.0	4.4	18.6
207-1	903.6	232.6	11.0	25.7	28.0

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is excluded from the graph in in Figure 9.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is excluded from the graph in Figure 9.

Table 4.5. Analysis of all reported results for etched track and electret detectors: Exposure 5, 156 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	182.5	6.8	17.0	3.7	17.4
5-1	178.6	16.1	14.5	9.0	17.1
12-1	157.6	16.1	1.0	10.2	10.2
13-1	162.7	11.8	4.3	7.3	8.5
13-2	156.7	9.9	0.4	6.3	6.3
19-1	159.5	14.8	2.2	9.3	9.5
20-1	187.0	10.0	19.9	5.3	20.6
21-1	187.9	22.4	20.4	11.9	23.7
32-1	186.1	21.0	19.3	11.3	22.4
40-1	162.5	37.5	4.2	23.1	23.4
49-1	204.2	23.0	30.9	11.2	32.9
62-1	165.2	12.7	5.9	7.7	9.7
141-1	174.4	2.9	11.8	1.7	11.9
141-2	178.6	6.3	14.5	3.5	14.9
156-1	190.0	19.3	21.8	10.2	24.0
160-1	168.3	16.3	7.9	9.7	12.5
163-1	99.3	16.7	-36.3	16.8	40.0
163-2	159.4	12.3	2.2	7.7	8.0
171-1	150.6	33.4	-3.5	22.2	22.5
173-1	148.9	8.4	-4.6	5.6	7.2
178-1*	16.9	822.2	-89.2	4865.2	4866.0
181-1**	-662.0	158.4	-524.4	-23.9	524.9
186-1	178.2	5.1	14.2	2.9	14.5
195-1	173.2	65.1	11.1	37.6	39.2
196-1	177.8	14.7	14.0	8.3	16.2
197-1	162.1	16.3	3.9	10.1	10.8
198-1	175.7	28.2	12.6	16.0	20.4
199-1	208.0	14.9	33.3	7.2	34.1
207-1	211.4	37.5	35.5	17.7	39.7

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is shown as an error bar in the graph in Figure 10.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is excluded from the graph in Figure 10.

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	3.0	1.9
5-1	22.2	18.7
12-1	16.5	7.1
13-1	5.0	6.0
13-2	4.9	4.0
19-1	14.5	6.4
20-1	12.2	3.6
21-1	36.7	9.9
32-1	16.0	8.7
40-1	8.7	6.1
49-1	52.3	13.3
62-1	11.3	1.9
141-1	43.1	6.0
141-2	11.0	5.5
156-1	39.3	9.8
160-1	121.7	30.2
163-1	58.3	5.1
163-2	7.4	3.7
171-1	41.2	13.0
173-1	38.7	4.2
178-1*	751.1	1066.0
181-1**	819.0	1660.7
186-1	9.0	3.1
195-1	54.5	35.9
196-1	5.2	3.4
197-1	13.9	6.9
198-1	97.6	8.1
199-1	27.3	4.4
207-1	60.4	13.3

Notes:

*Lab 178 - An error was made when sorting the results in ascending numerical order. The result is shown as an error bar in the graph in Figure 11.

**Lab 181 - One of the transit detectors was reported with a high result, so all the grouping results were affected. The result is is shown as an error bar in the graph in Figure 11.

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	1100	1084.9	259.2
2	2161	2209.5	327.8
3	519	503.0	171.2
4	814	799.8	201.6
5	156	138.0	158.0

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

	Exposure 5	Exposure 3	Exposure 4	Exposure 1	Exposure 2	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	156 kBq m^{-3} h	519 kBq m^{-3} h	814 kBq m^{-3} h	1100 kBq m^{-3} h	2161 kBq m^{-3} h					
13-1	A	A	A	A	A	Radtrak2 (closed)		NRPB/SSI	CR-39	RTP Company
13-2	A	A	A	A	A	Radtrak3 (closed)	Yes	Radtrak3	CR-39	Radonova Scientific Ltd
19-1	A	A	A	A	A	Closed	Yes	Radout Mi.am Srl	CR-39	TASL
163-2	A	A	A	A	A	Closed	No	Rad-Elect Inc.	Electret	Rad-Elec Inc.
173-1	A	A	A	A	A	Closed	Yes	TASL	CR-39	TASL
5-1	B	A	A	A	A	Closed	No	TASL	CR-39	TASL
62-1	A	A	A	A	B	alpha track	No	In house (sensitive volume 79 mL)	Makrofol	Covestro
197-1	B	A	A	A	A	Closed	Yes	Radosys	CR-39	Radosys
20-1	C	A	A	A	A	Closed	No	TASL	PADC	TASL
198-1	C	A	A	A	A	Closed	Yes	SSNTD	CR-39	TASL
141-1	B	A	A	A	B	Closed	No	Radosure	TASTRAK	TASL

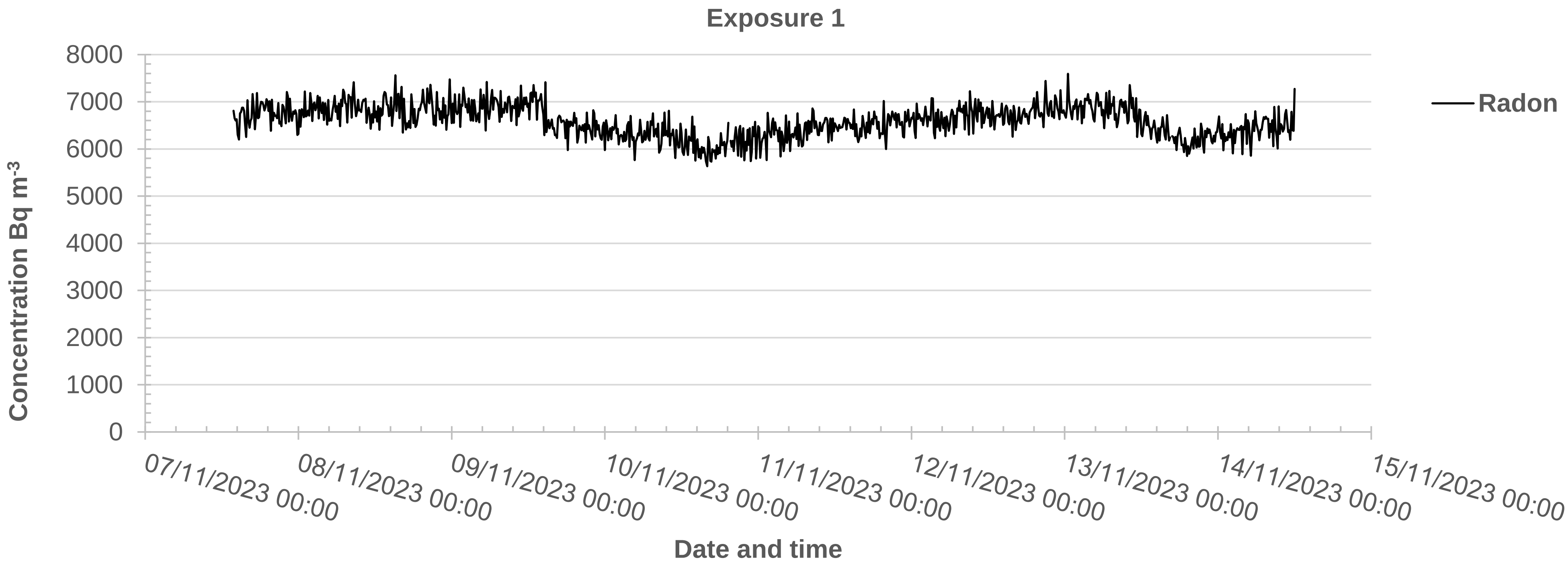
	Exposure 5	Exposure 3	Exposure 4	Exposure 1	Exposure 2	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	156 kBq m^{-3} h	519 kBq m^{-3} h	814 kBq m^{-3} h	1100 kBq m^{-3} h	2161 kBq m^{-3} h					
141-2	B	B	A	B	A	Closed	Yes	E-Perm	Electret	E-Perm
196-1	B	B	A	A	B	Closed	Yes	Radout (Mi.am Italy)	CR-39	Radonova Scientific Ltd
32-1	C	B	A	A	B	Closed	Yes	NRPB/SSI	CR39 /PADC	TASL
21-1	C	B	B	A	B	Closed	No	ENEA	CR-39	TASL
49-1	D	B	B	B	A	Closed	No	Radosys	CR-39	Radosys
1-1 [a]	B	B	B	B	B	Closed	No	NRPB	CR-39	Mi-Net
12-1	B	B	B	B	B	Closed	No	Own	CR-39	Own
186-1	B	B	B	B	B	Closed		TASL	TASTRAK PADC	TASL
156-1	C	B	B	B	B	Closed	No		CR-39	Radosys Ltd Hungary
160-1 [b]	B	C	B	B	B	Closed	No	TASL	CR-39	TASL
171-1 [c]	C	B	B	B	B	Closed	Yes	Own	LR115	Dosirad
207-1	D	C	C	B	B	Closed	No		PADC	Radosys

	Exposure 5	Exposure 3	Exposure 4	Exposure 1	Exposure 2	Detector type	Filter	Holder	Detector material	Detector material supplier
Set ID	156 kBq m^{-3} h	519 kBq m^{-3} h	814 kBq m^{-3} h	1100 kBq m^{-3} h	2161 kBq m^{-3} h					
195-1	D	C	B	C	B	Closed	No	RADOUT - Mi.am. Srl	CR-39	Mi.am Srl
163-1 [d]	E	B	C	B	D	SSNTD	No		CR-39	TASL
40-1 [a]	C	C	C	C	B	Closed	No	NRPB - yellow	PADC	Mi-Net
199-1	D	C	B	C	C	Closed	No	Mi.am S.r.l.	PADC	GM-Scientific
181-1 [e]	F	F	F	F	D	Electret (LLT)	Yes		Teflon	
178-1 [f]	F	F	F	F	F	Closed	No	TASL	CR-39	TASL

NOTES:

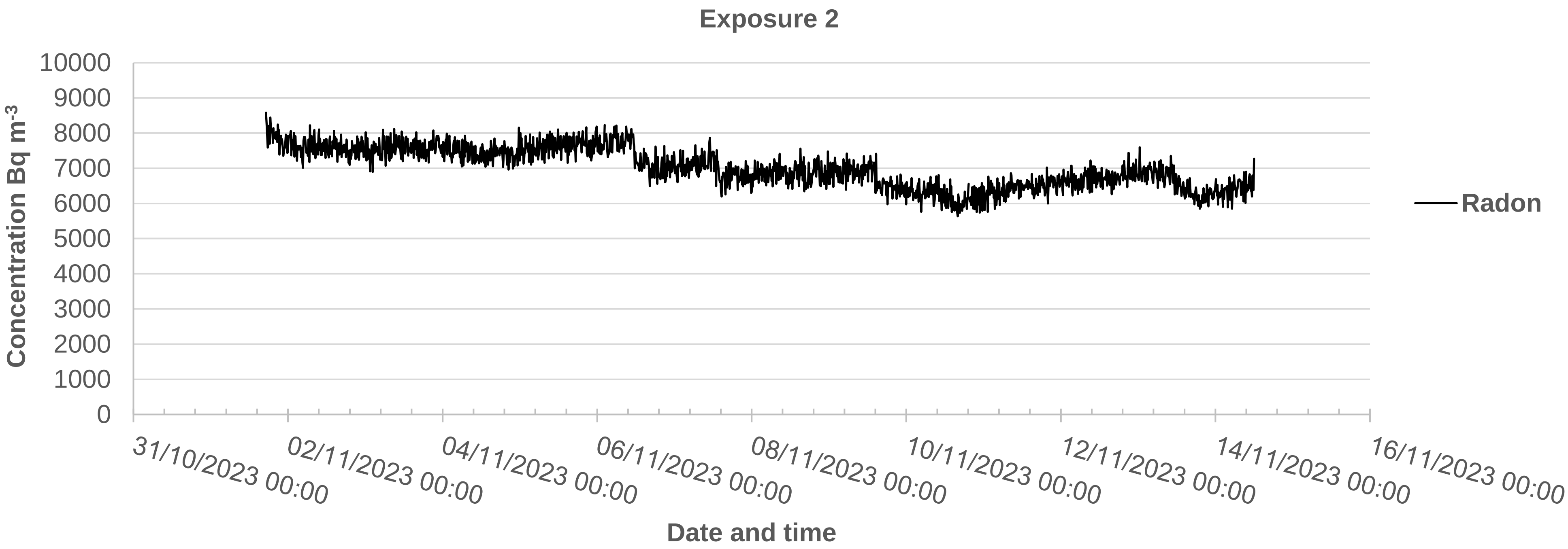
a. Detector material supplier Mi-Net is Mi-Net Technology Ltd (Instrument Plastics)
b. 160-1 - The results for detectors 45 and 54 may have been transposed. Without this error, the ranking would have been: BBBBB
c. 171-1 - The results for detectors 29 and 41 have been transposed. Without this error, the ranking would have been: CBABB
d. 163-1 - Detector 11 incorrectly reported as 224 Bq m^{-3} h but was actually 2244 Bq m^{-3} h, the ranking would have been: EBCBA
e. 181-1 - Detector 21 was in the transit group (no exposure) but had a high radon result. Client suspected package may have been x-rayed inhomogeneously during transport. Without this issue, the ranking would have been FFEBA
f. 178-1 - Error when sorting detector results into ascending detector number order. Detector 28 was recorded as number 282, so sorting was out of sequence; results were submitted against the wrong detector number. The ranking would have been CABCC

Figure 1. Radon concentrations for exposure 1



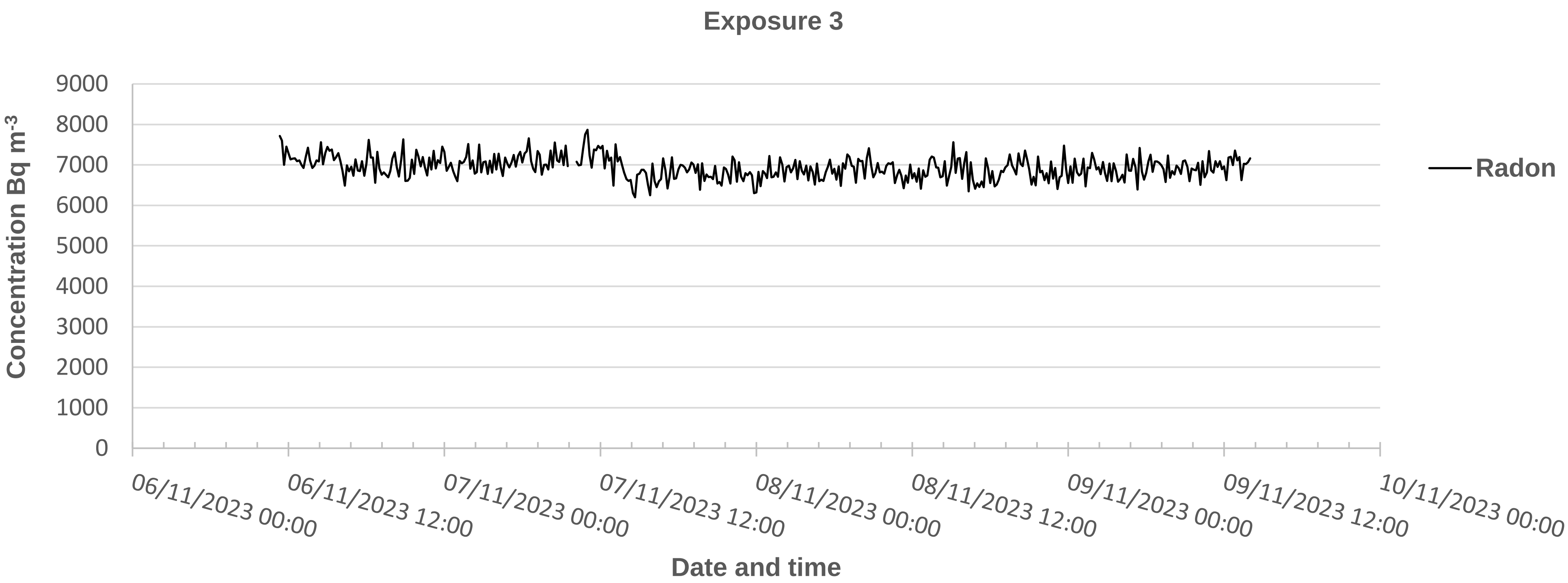
The above figure shows the fluctuation of radon concentration during exposure 1, which covers the period 7 November 2023 to 14 November 2023. The radon concentration hovered between 5,600 Bq m^{-3} and 7,600 Bq m^{-3}, initially starting high then dropping slightly, rising again later, then dropping again and finally starting to rise.

Figure 2. Radon concentration for exposure 2



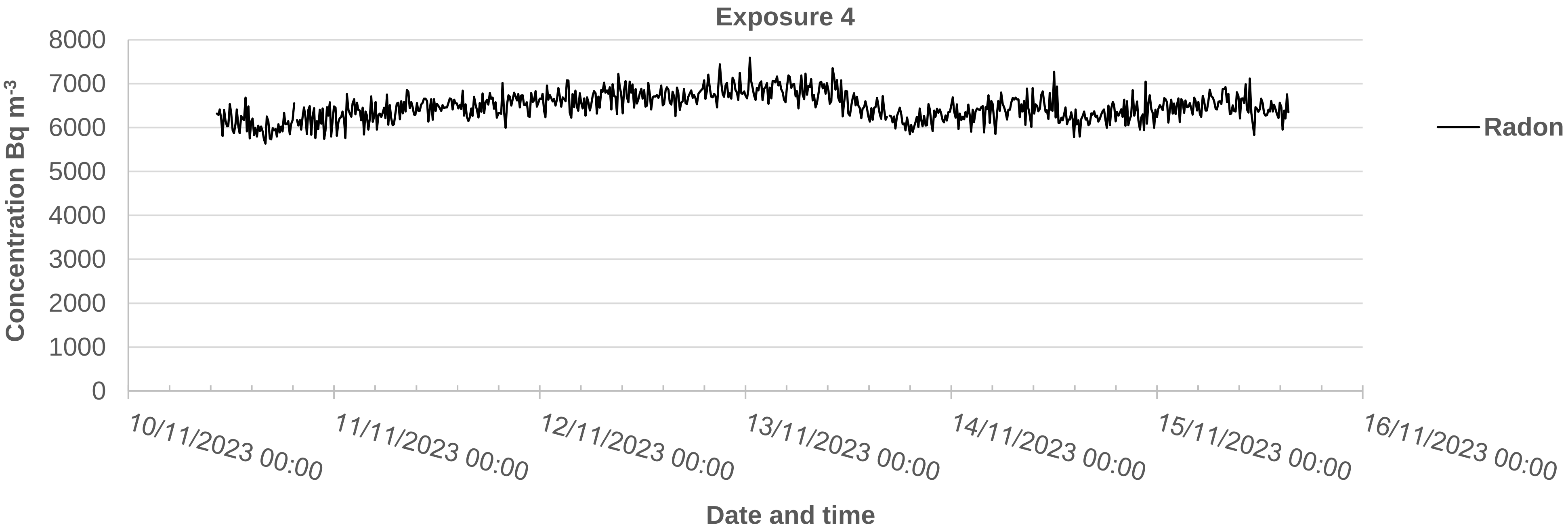
The above figure shows the fluctuation of radon concentration during exposure 2, which covers the period 1 November 2023 to 14 November 2023. The radon concentration began at over 8,000 Bq m^{-3} and then reduced in stages, eventually fluctuating between 7000 Bq m^{-3} and 6000 Bq m^{-3}.

Figure 3. Radon concentration for exposure 3



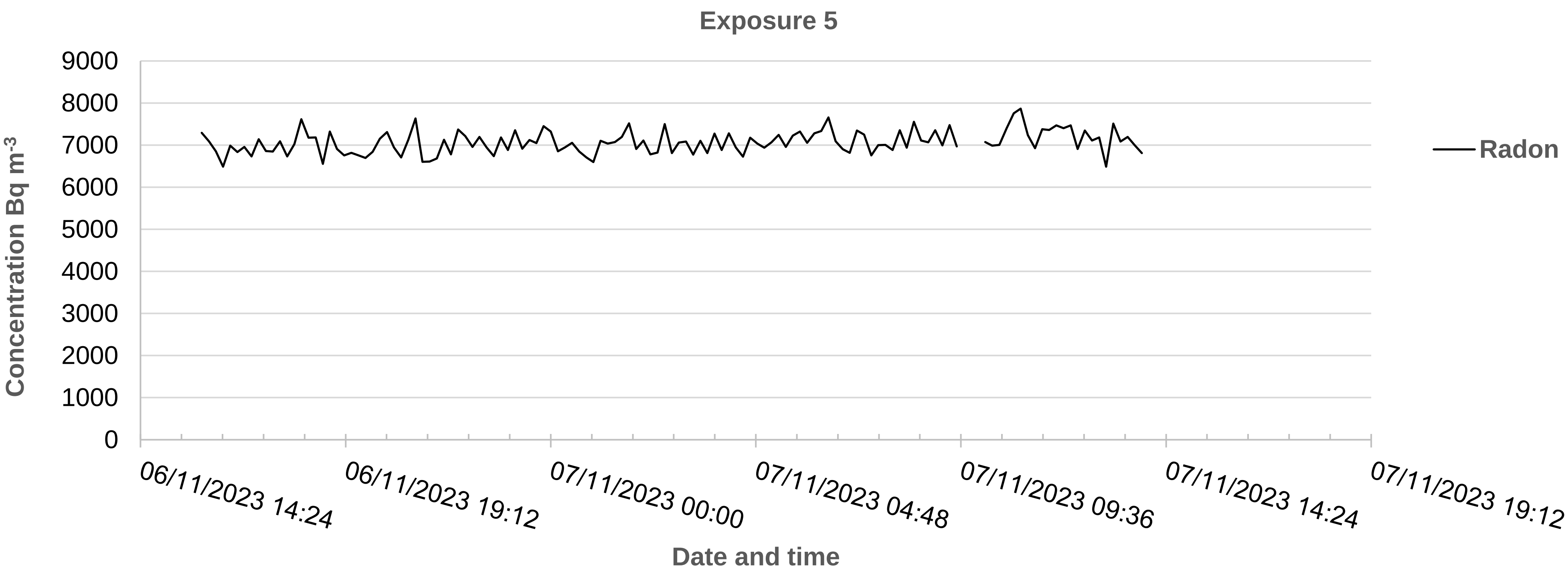
The above figure shows the fluctuation of radon concentration during exposure 3 which covers the period 6 November 2023 to 9 November 2023. The radon concentration hovered around 7000 Bq m^{-3}. The gap in the trace line was caused by a communication error between the ATMOS instrument and the data logging system.

Figure 4. Radon concentration for exposure 4



The above figure shows the fluctuation of radon concentration during exposure 4, which covers the period 10 November 2023 to 15 November 2023. The radon concentration began at over 6000 Bq m^{-3} , slowly rising to a peak of over 7000 Bq m^{-3} and then dropped to around 6,000 Bq $m^{-3,}$ with further fluctuations between 7,000 Bq m^{-3} (highest) and 6,000 Bq m^{-3} (lowest).

Figure 5. Radon concentration for exposure 5



The above figure shows the fluctuation of radon concentration during exposure 5, which covers the period 6 November 2023 to 7 November 2023. The radon concentration fluctuated around 7000 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 6. Results as reported by participants for exposure 1 - given in Table 4.1

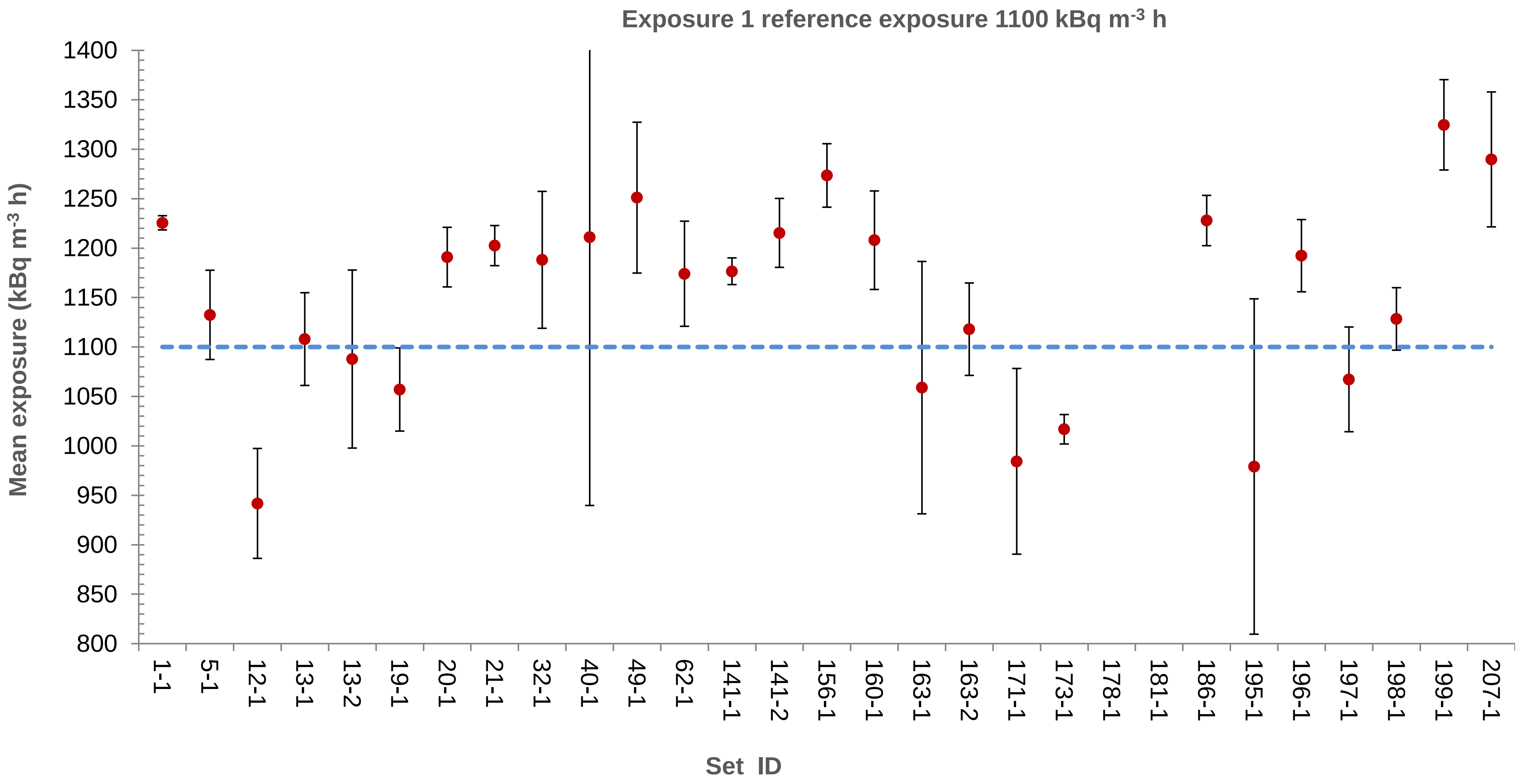


Figure 7. Results as reported by participants for exposure 2 - given in Table 4.2

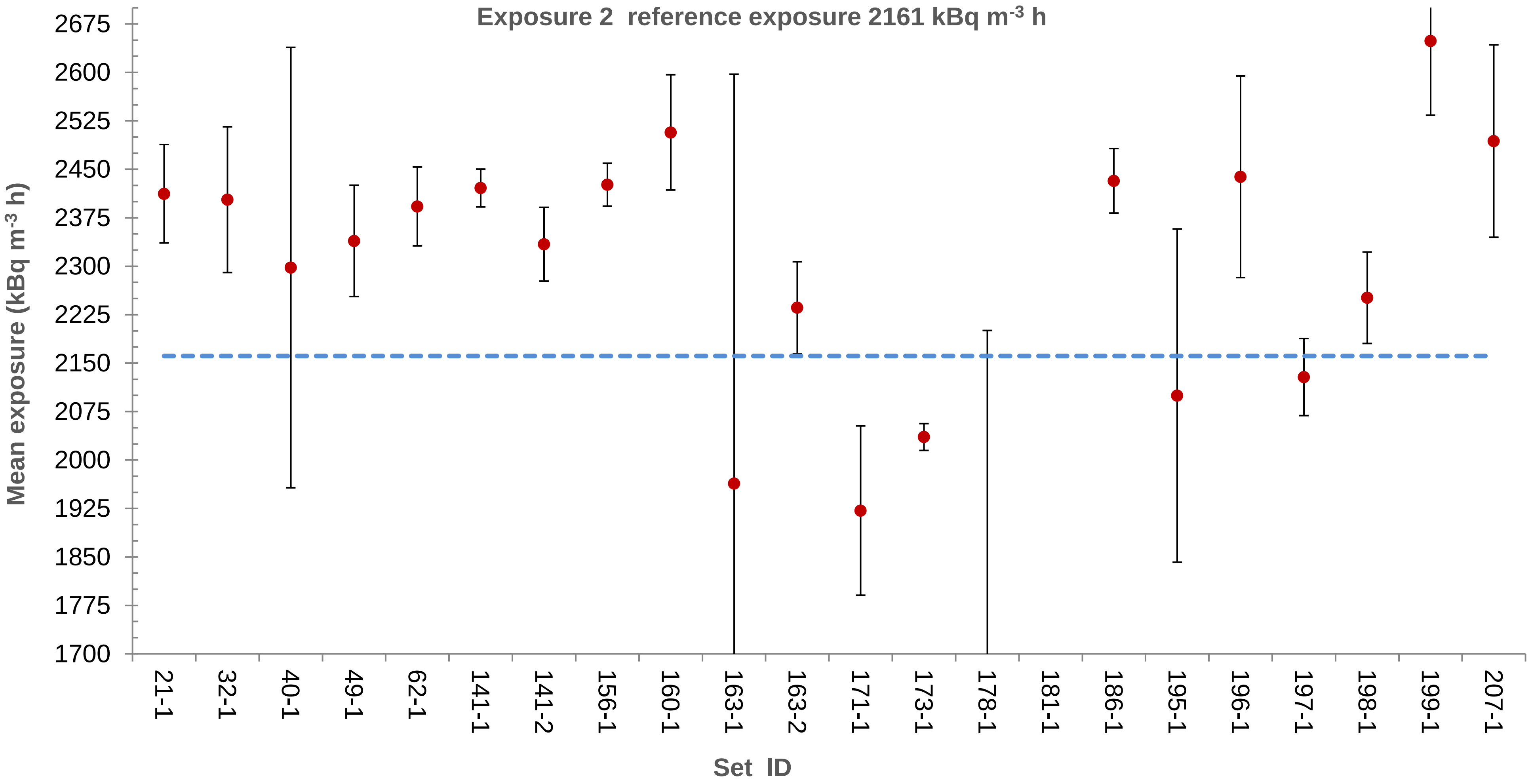


Figure 8. Results as reported by participants for exposure 3 - given in Table 4.3

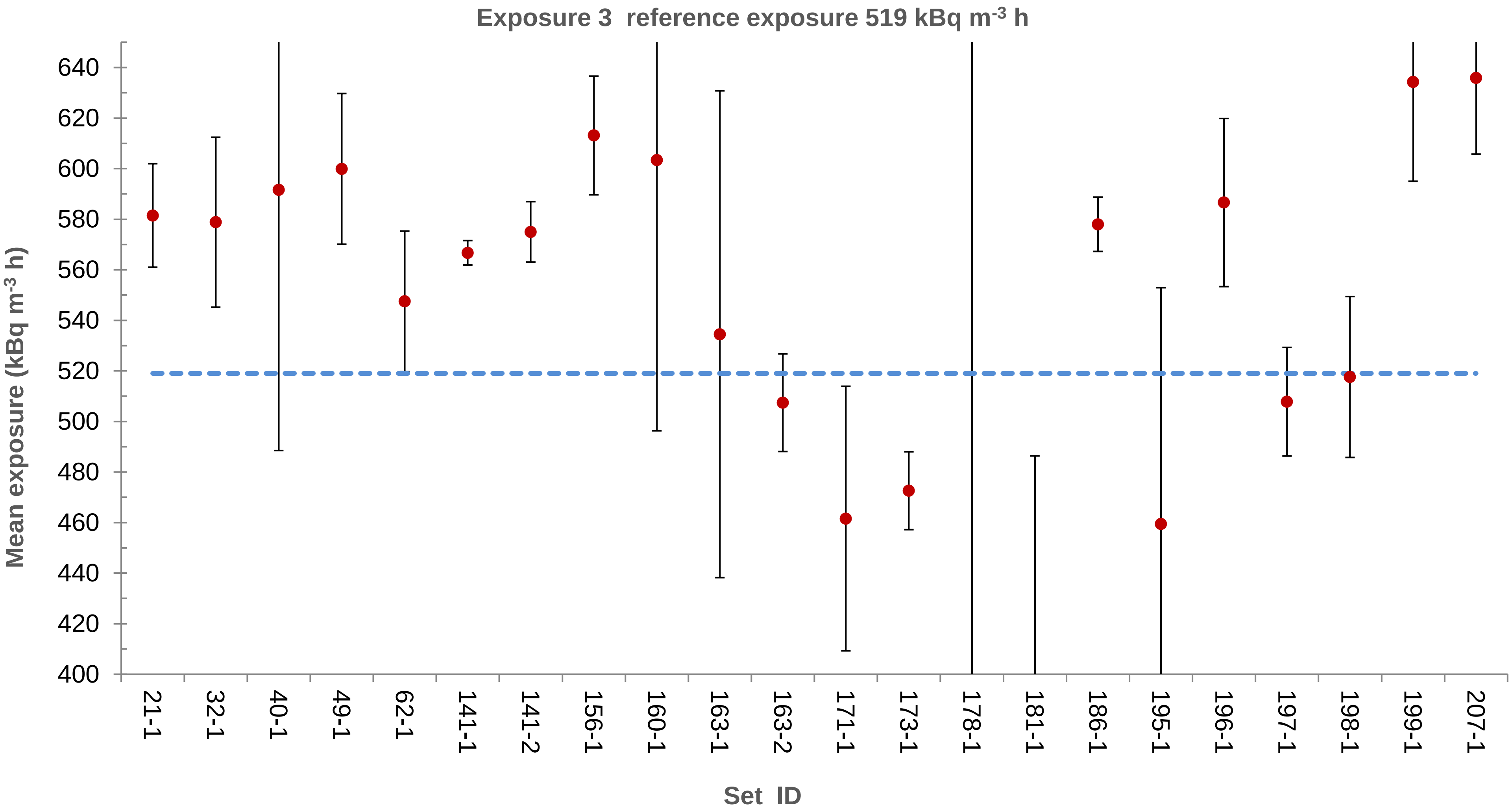


Figure 9. Results as reported by participants for exposure 4 - given in Table 4.4

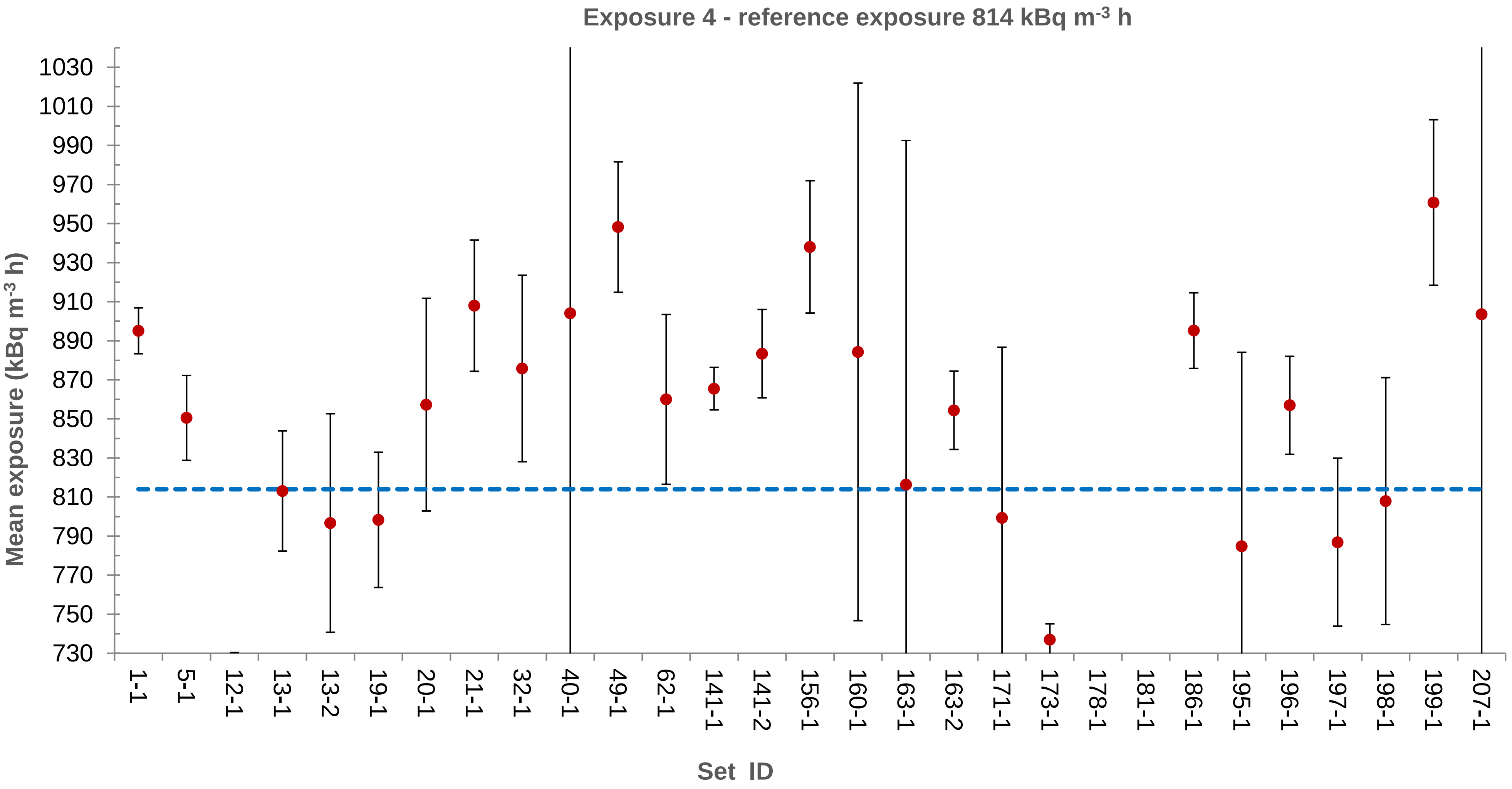


Figure 10. Results as reported by participants for exposure 5 - given in Table 4.5

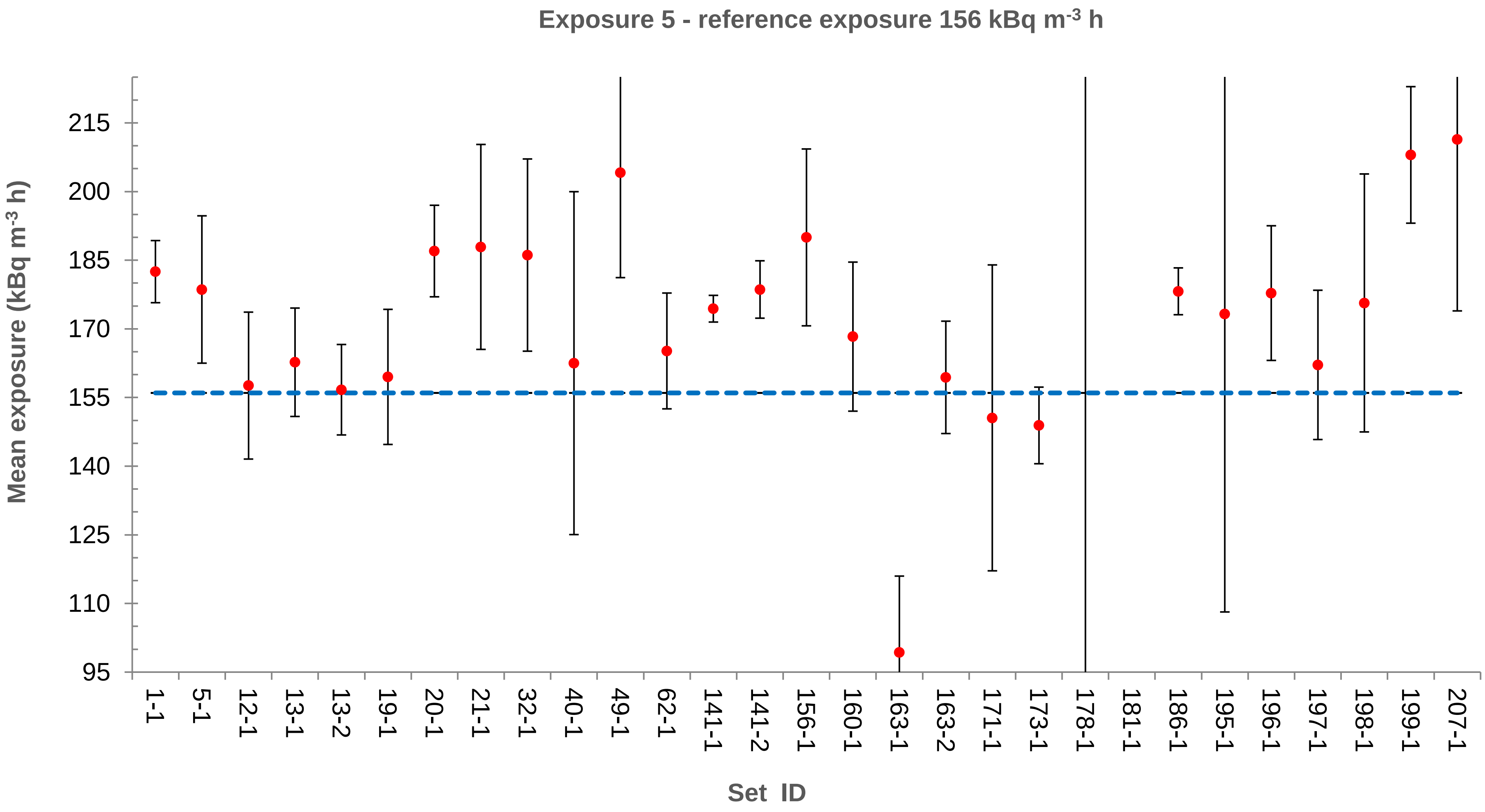


Figure 11. Results as reported by participants for transit exposure - given in Table 4.6

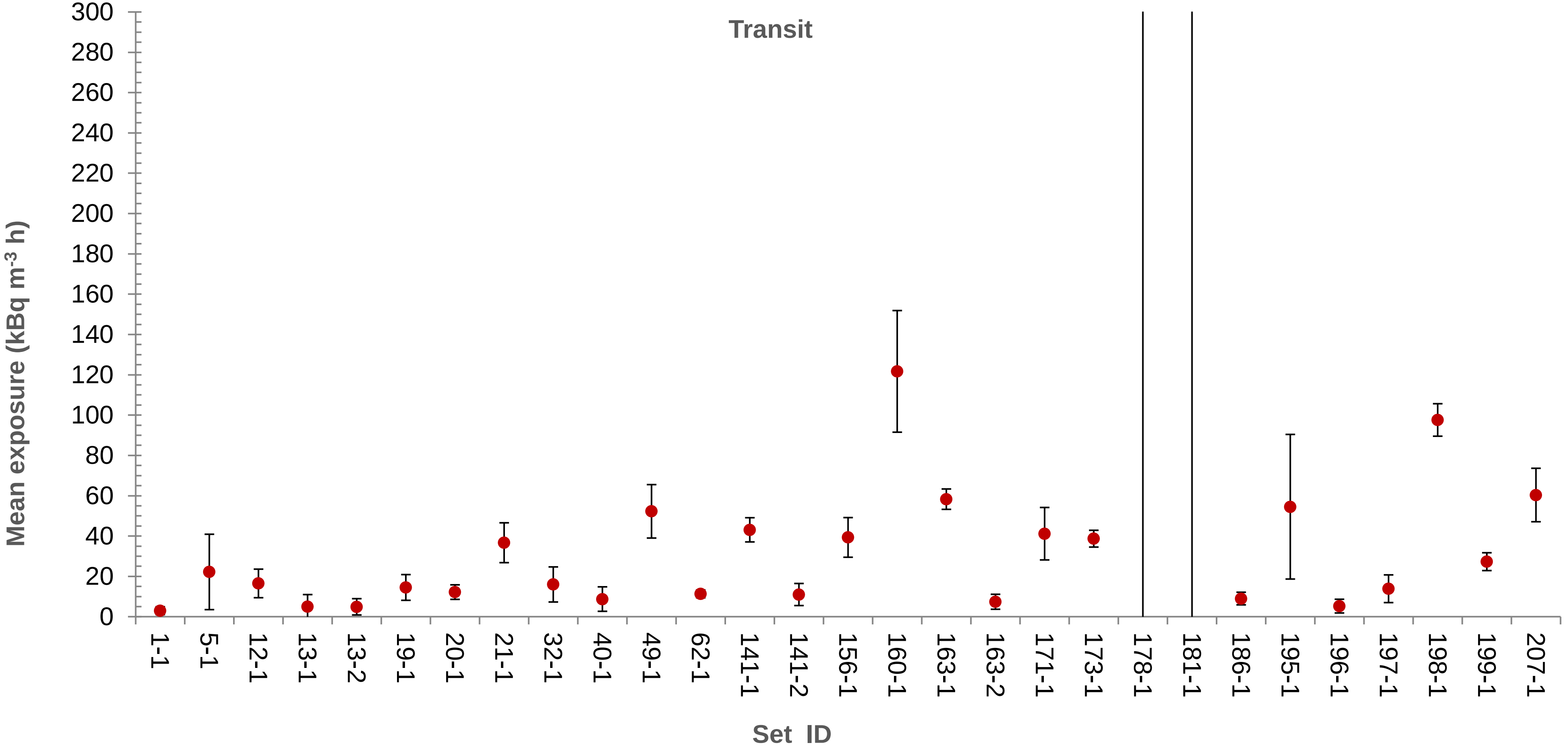


Figure 12. Distribution of mean exposure results for exposure 1 - given in Table 4.1. The vertical dotted line indicates the reference exposure.

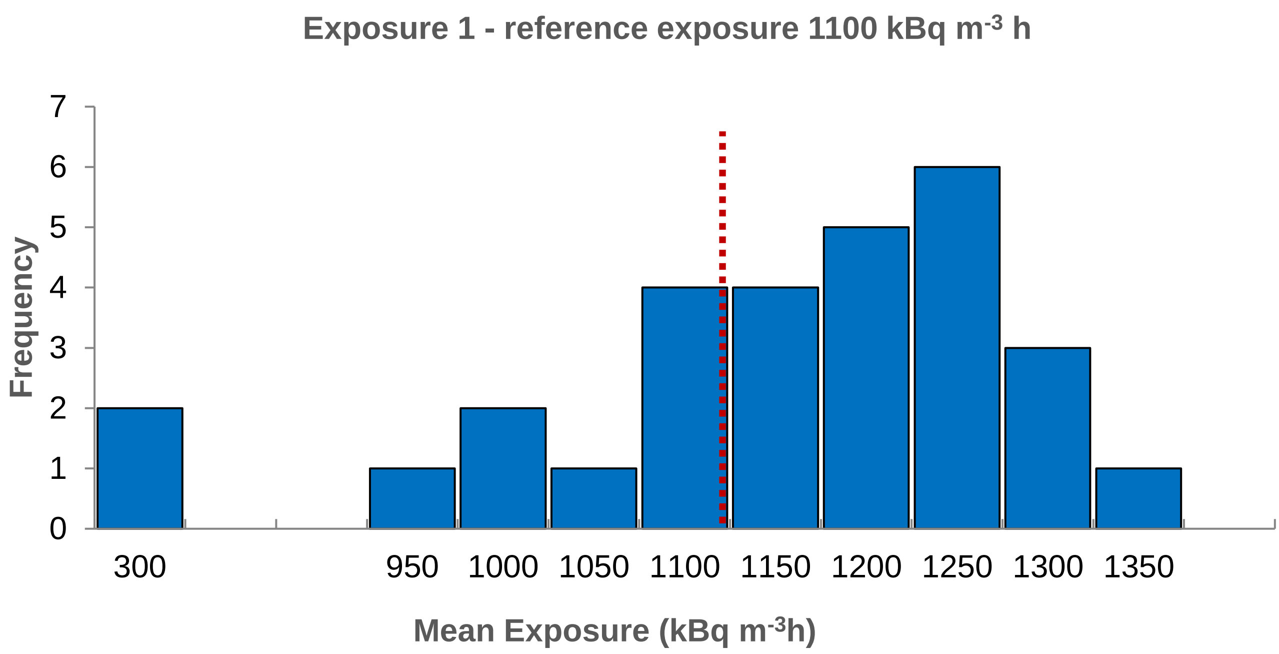


Figure 13. Distribution of mean exposure results for exposure 2 - given in Table 4.2.

The vertical dotted line indicates the reference exposure.

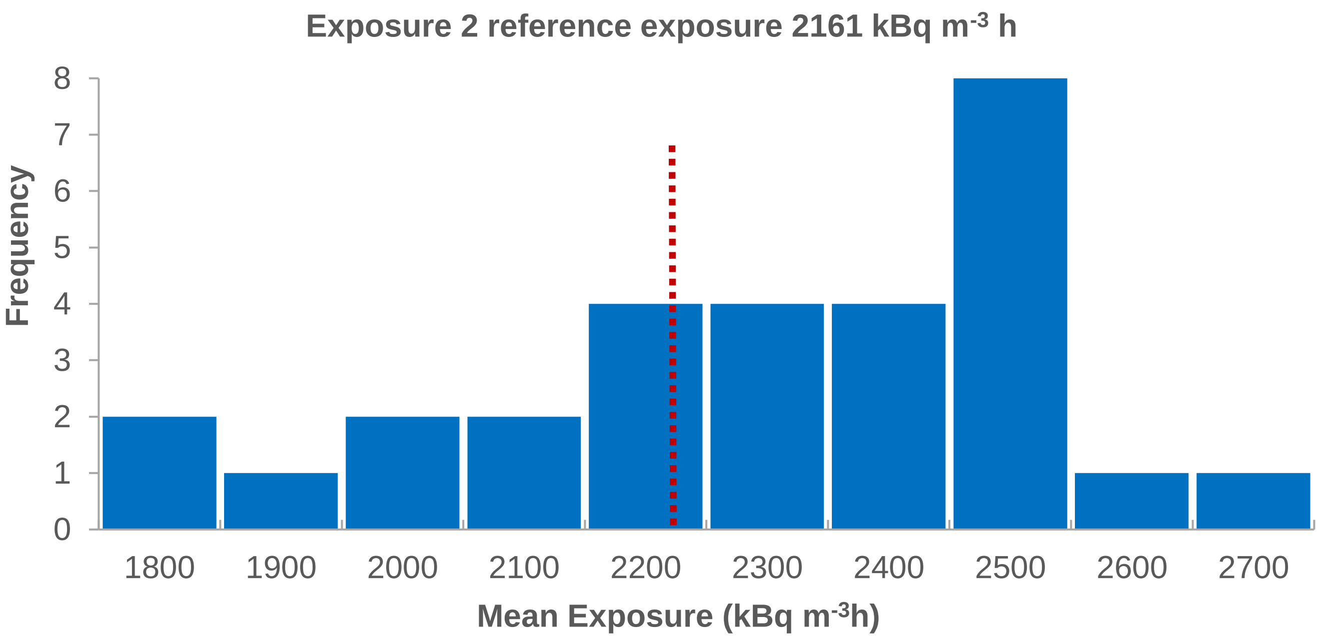


Figure 14. Distribution of mean exposure results for exposure 3 - given in Table 4.3. The vertical dotted line indicates the reference exposure.

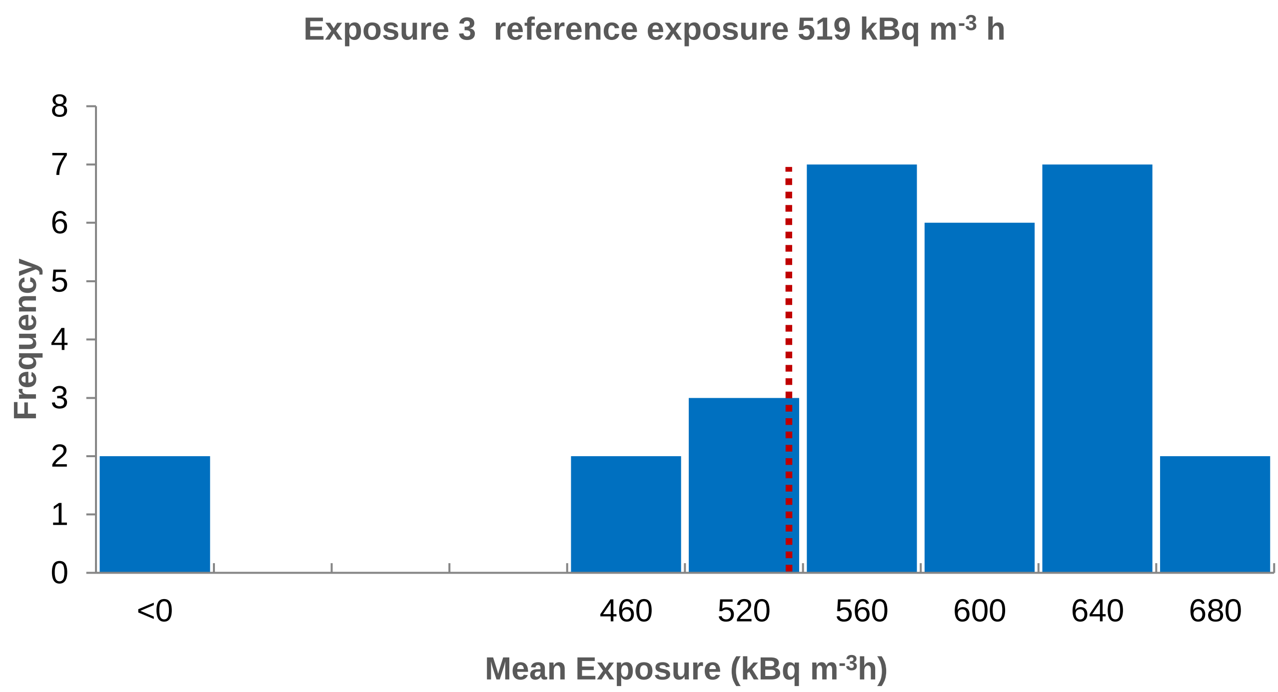


Figure 15. Distribution of mean exposure results for exposure 4 - given in Table 4.4. The vertical dotted line indicates the reference exposure.

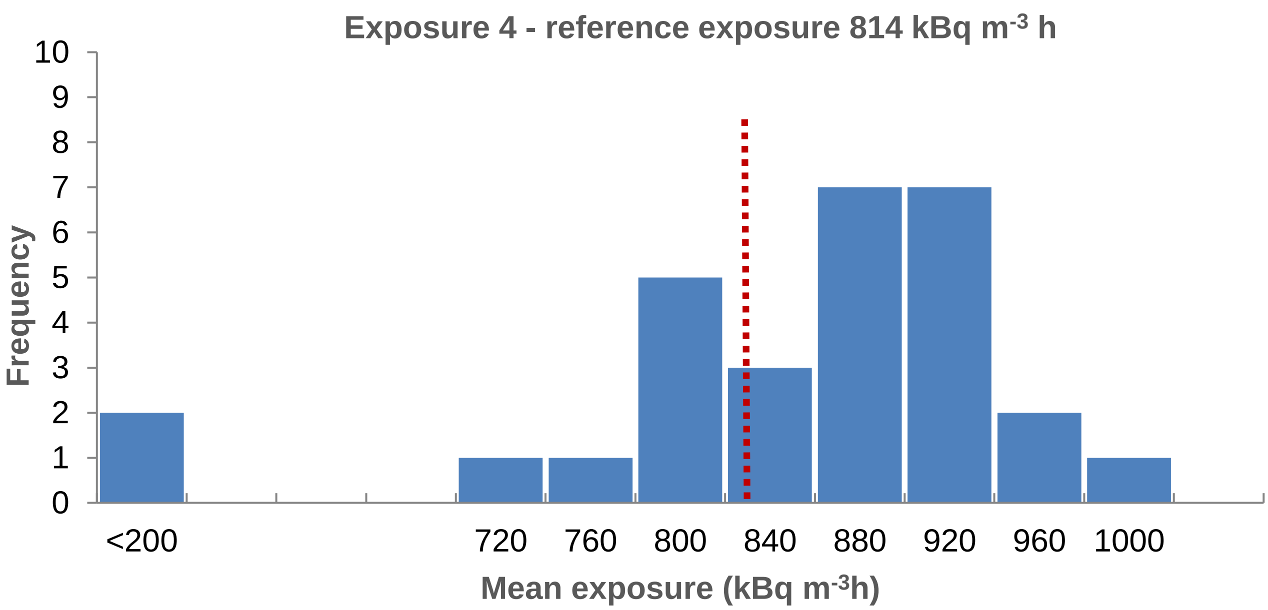


Figure 16. Distribution of mean exposure results for exposure 5 - given in Table 4.5. The vertical dotted line indicates the reference exposure.

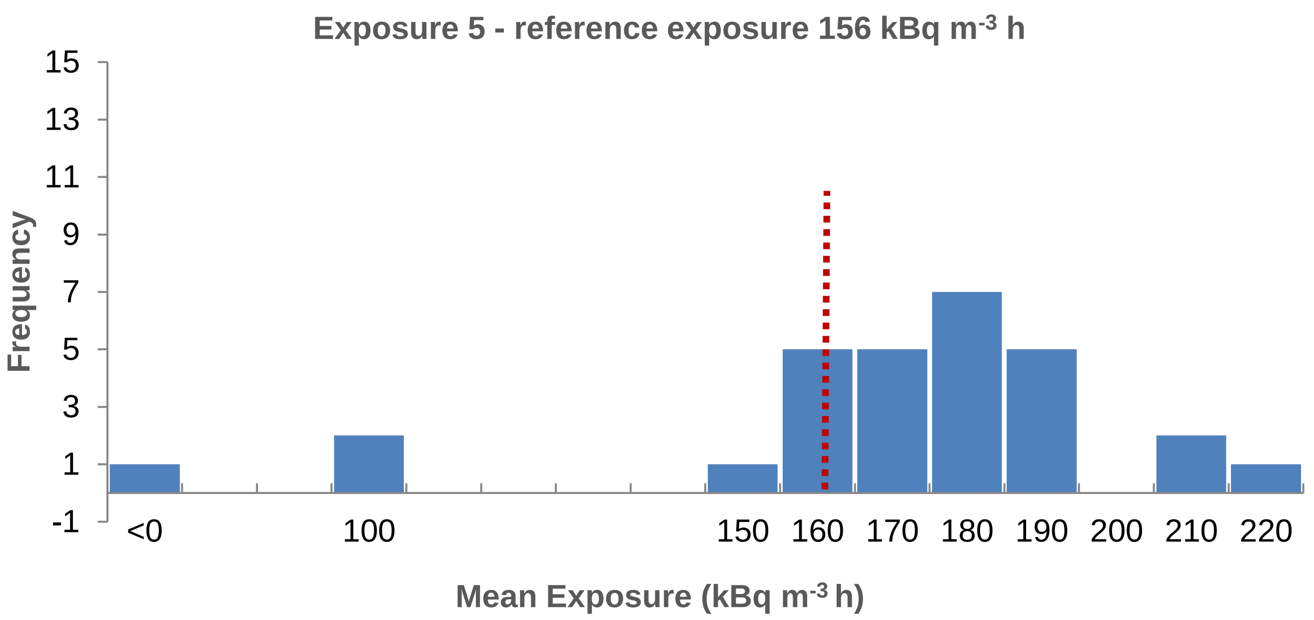


Figure 17. Distribution of mean exposure results for the transit exposure - given in Table 4.6.

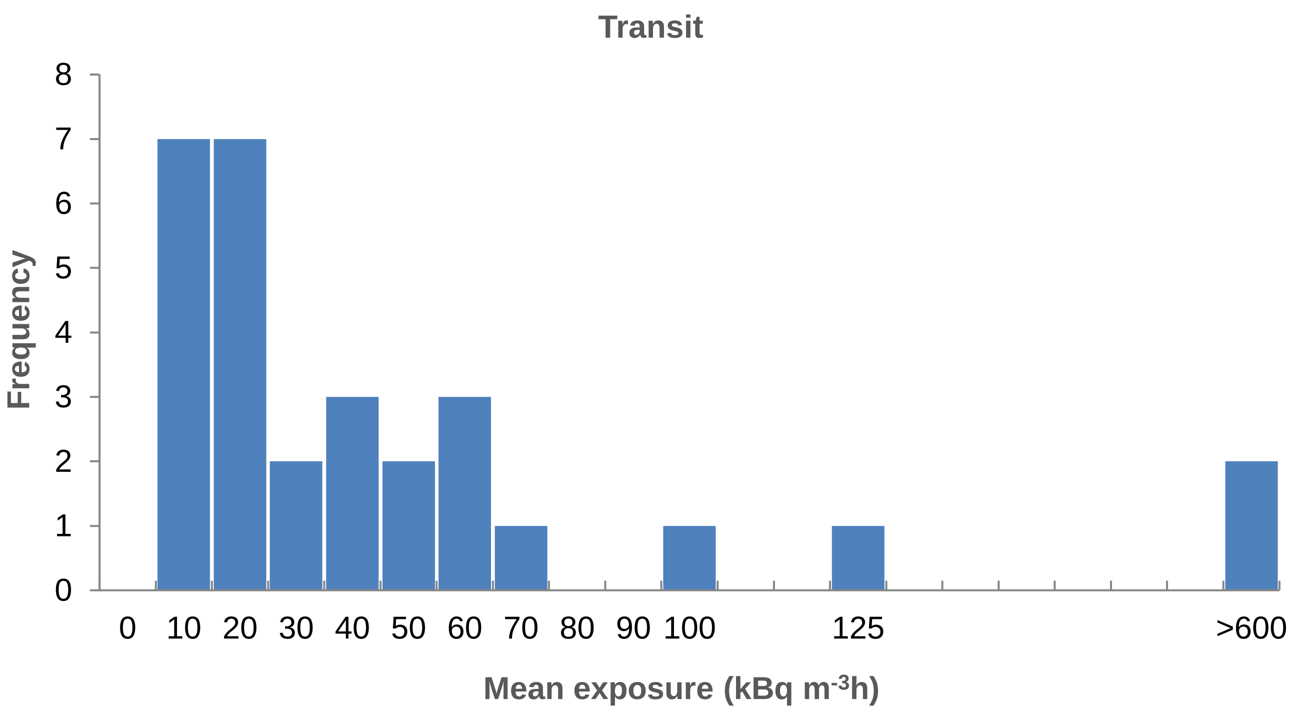


Figure 18. Performance classes for each exposure from A (best) to F (worst) summarised in Table 7 below

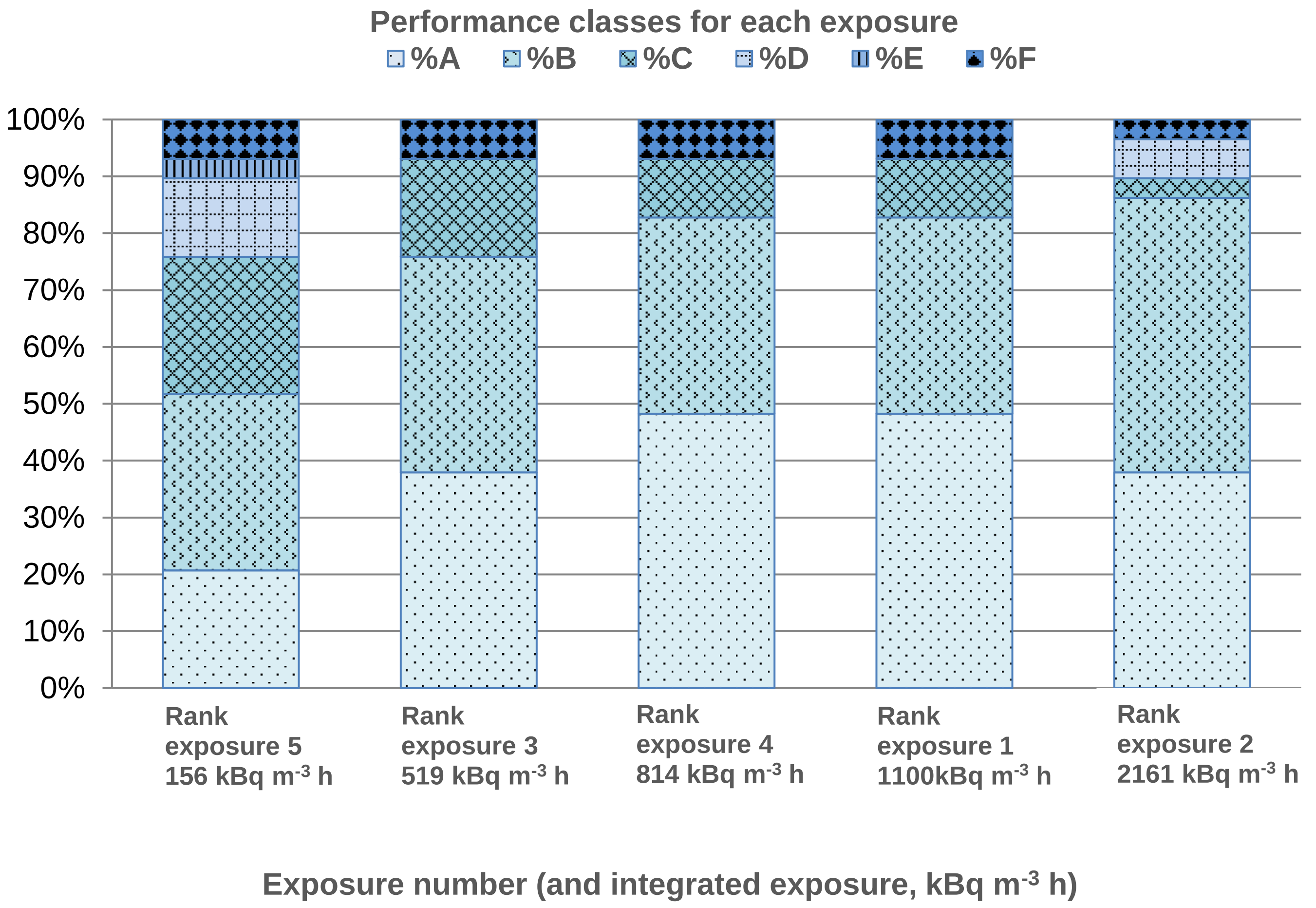


Table 7. Exposure number (and integrated exposure, kBq m^{-3} h)

	Rank exposure 5 156 kBq m^{-3} h	Rank exposure 3 519 kBq m^{-3} h	Rank exposure 4 814 kBq m^{-3} h	Rank exposure 1 1100 kBq m^{-3} h	Rank exposure 2 2161 kBq m^{-3} h
%F	7	7	7	7	3
%E	3	0	0	0	0
%D	14	0	0	0	7
%C	24	17	10	10	3
%B	31	38	35	35	48
%A	21	38	48	48	38

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