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Results of the 2022 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.

The sets of etched track and 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 130 kBq m^{-3} h to 2,600 kBq m^{-3} h; the 6th group was used to determine transit exposures. The activated charcoal detectors were randomised into 3 equal groups at RCE and all 3 groups were exposed in the RCE radon chamber to radon gas exposures ranging from 130 kBq m^{-3} h to 2,600 kBq m^{-3} h.

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 2022, for which a total of 35 laboratories from 14 countries submitted 42 sets of detectors. One laboratory was unable to process their exposed detectors due to equipment failure and another laboratory did not receive their time-sensitive charcoal detectors quickly enough, due to uncontrollable courier /customs delays. One laboratory submitted 2 sets of detectors, but withdrew 1 set of their results.

This report therefore covers 33 laboratories and 39 sets of detectors from 14 countries. The 39 sets of detectors comprise 35 sets of etched track detectors and 4 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, 35 laboratories from 14 countries took part in the 2022 UKHSA intercomparison. Some laboratories submitted more than 1 set of detectors, so 42 sets of detectors were exposed in the radon chamber. Following exposure, the detectors were returned to the originating laboratories for processing.

Two laboratories were unable to process their exposed detectors, due to (a) etched track reading equipment failure and (b) courier / customs delays to the return of time-sensitive activated charcoal detectors. One laboratory withdrew their electret results. This report covers 33 laboratories and 39 sets of detectors from 14 countries, as shown in Table 2. The 39 sets of detectors were 35 sets of etched track detectors and 4 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 13 Bq m^{-3} to 35 Bq m^{-3}, with an overall average of 21 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 1% of the exposure in the chamber for the lowest exposure, and between 1% and 2% 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. Two of the participating laboratories were unable to analyse their exposed detectors and 1 laboratory withdrew 1 set of their results, so the tables show the results for 33 laboratories and a total of 39 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 35 kBq m^{-3} h (Figure 11). Most of the reported transit exposures were below 30 kBq m^{-3} h, 10 reported transit exposures between 30 kBq m^{-3} h and 270 kBq m^{-3} h, and 9 of these were below 130 kBq m^{-3} h. This is a smaller range of results than in 2021 (3) where 11 out of a total of 35 reported transit exposures were between 30 kBq m^{-3} h and 780 kBq m^{-3} h, of which 10 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.

A total of 7 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 better than in 2021.

Approximately 67% of all sets of detectors achieved class A for at least 3 exposures, which is worse than in 2021 (3). For the lowest exposure measurement (138 kBq m^{-3} h), 26% of laboratories achieved class A, an increase from 2021. For the second lowest exposure (383 kBq m^{-3} h), 62% of laboratories achieved class A, an improvement from 2021.

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 (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 hours to 4 years or more. Most (34 out of 39) sets were sent using radon proof bags and had a transit exposure less than 50 Bq m^{-3}. Of the 8 sets where the transit exposure equalled or exceeded 50 Bq m^{-3}, 6 of the sets were sent using radon proof bags and the storage (in freezer or nitrogen) ranged from 7 days to years. This indicates that other factors apply – including etching methods, ageing of the plastic and staff training. The highest transit exposure was due to a record-keeping error. The proportion of sets achieving each performance classification (A to F) is given in Figure 18.

Conclusions

In total, 35 laboratories from 14 countries participated in the 2022 UKHSA intercomparison.

Two laboratories were unable to process their exposed detectors and one laboratory withdrew a set of their results, so this report is for 33 laboratories and 39 sets of detectors from 14 countries. The detectors were 35 sets of etched track detectors and 4 sets of electret detectors.

As a result of courier / customs problems which prevented the charcoal detectors from being analysed within 3 days, future intercomparisons will only include charcoal detectors from UK laboratories.

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 7 laboratories achieved 5 class A ratings, an improvement on the 2021 intercomparison.

References

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Tables and figures

Table 2. Participating laboratories

Contact person	Organisation	Country
Nivaldo Carlos da Silva / Danila Carrijo S. Dias	Brazilian Commission for Nuclear Energy (CNEN)	Brazil
Kremena Ivanova / Desislava Dzhunakova	National Center of Radiobiology and Radiation Protection (NCRRP)	Bulgaria
Jussi-Pekka Laine	Radiation and Nuclear Safety Authority (STUK)	Finland
Roselyne Ameon	ALGADE - Laboratorie Environnement et Dosimétrie	France
Erdanay Kurt	Pôle d'Expertise et d'Analyse Radioactivité Limousin (PearL-SAS)	France
Erik Hülber / Tímea Hülber	Radosys, Ltd.	Hungary
David Doyle	AlphaRadon Teo	Ireland
Claudia Marchesoni	Agenzia per l'Ambiente e la tutela del clima	Italy
Enrico Chiaberto / Mauro Magnoni / Elena Serena	Agenzia Regionale per la Protezione Ambientale Piemonte (ARPA Piemonte)	Italy
Dr. Silvia Penzo / Dr. Fabio Alessio Vittoria	ENEA Radiation Protection Institute	Italy
Dr. Simona Rullo	Gaia Consulting & Technologies srl	Italy
Dr. Massimo Moroni	Harmat srls	Italy
Dr. Giacomo Zambelli	Lavoro e Ambiente S.r.l.	Italy
Marcello Tognacci / Lorenzo Godenzini	L.A.V. S.r.l.	Italy
Leonardo Baldassarre / Oliviero Tito Sandri	L.B. Servizi per le Aziende S.r.l.	Italy
Dr. Antonio Parravicini	Mi.am srl	Italy
Ing. Gianluca Troiano	Niton srl	Italy
Dr. Mattia Taroni	Protex Italia srl	Italy
Dr. Claudio Cazzato	Radongas srl	Italy
Serena Sanna	U-Series S.r.l.	Italy
Marielle LeComte / Karin Pier	Direction de la Santé	Luxembourg
Jostein Hoftuft	DSA Norwegian Radiation and Nuclear Safety Authority	Norway
Alcides Pereira	Laboratório de Radioatividade Natural da Universidade de Coimbra	Portugal
Ismael Fuente / Santiago Celaya / LaRUC	Laboratory of Environmental Radioactivity, University of Cantabria (LaRUC)	Spain
Josefina Ortiz / Belén Juste	Laboritorio Radiactividad Ambiental, Universitat Politècnica de València	Spain
Johanna Sjödin	Eurofins Radon Testing Sweden	Sweden
Gilbert Jönssen / Maria Jönssen	Radonanalys GJAB	Sweden
Dr. Tryggve Rönnqvist	Radonova Laboratories AB	Sweden

Işık Demiröz / Sema Şen / Mehmet Abdurrahman Korkmaz	Turkish Energy, Nuclear and Mineral Research Agency	Türkiye
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)	95.2	19.6	314.9	185.8	50.6
Radon exposure (kBq m^{-3} h)	732	138	2501	1387	383
Uncertainty (%) at 68% CL*	3.0	3.0	3.0	3.0	3.0
* Confidence level					

Table 4.1. Analysis of all reported results for etched track and electret detectors: Exposure 1, 732 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	753.9	13.3	3.0	1.8	3.5
1-2	667.8	12.4	-8.8	1.9	9.0
12-1	667.8	31.6	-8.8	4.7	10.0
13-1	813.3	31.5	11.1	3.9	11.8
13-2	794.4	27.6	8.5	3.5	9.2
15-1	697.6	32.0	-4.7	4.6	6.6
16-1	709.8	97.5	-3.0	13.7	14.1
19-1	721.5	64.3	-1.4	8.9	9.0
20-1	713.1	20.7	-2.6	2.9	3.9
21-1	752.0	37.6	2.7	5.0	5.7
28-1	732.4	38.9	0.1	5.3	5.3
32-1	764.6	43.5	4.5	5.7	7.2
40-1	785.3	62.3	7.3	7.9	10.8
45-1	729.7	98.9	-0.3	13.6	13.6
62-1	782.8	27.9	6.9	3.6	7.8
134-1	685.4	28.8	-6.4	4.2	7.6
136-1	746.7	20.6	2.0	2.8	3.4
136-2	720.0	16.7	-1.6	2.3	2.8
141-1	743.8	9.8	1.6	1.3	2.1
141-2	751.4	25.0	2.7	3.3	4.3
156-1	712.6	31.8	-2.7	4.5	5.2
159-1	688.2	30.9	-6.0	4.5	7.5
160-1	626.5	21.5	-14.4	3.4	14.8
163-1	642.0	13.2	-12.3	2.1	12.5
171-1	765.1	52.9	4.5	6.9	8.3
173-1	771.8	14.4	5.4	1.9	5.7
177-1	778.2	17.4	6.3	2.2	6.7
178-1	725.8	7.5	-0.8	1.0	1.3
181-1*	34.2	1.9	-95.3	5.5	95.5
186-1	662.4	16.2	-9.5	2.4	9.8
196-1	622.7	39.9	-14.9	6.4	16.2
196-2	658.5	35.3	-10.0	5.4	11.4
197-1	721.2	34.2	-1.5	4.7	5.0
199-1	726.5	30.6	-0.8	4.2	4.3
200-1	806.3	32.1	10.2	4.0	10.9
204-1	604.7	23.7	-17.4	3.9	17.8
205-1	654.9	34.6	-10.5	5.3	11.8
206-1	701.0	36.5	-4.2	5.2	6.7
206-2	628.7	132.2	-14.1	21.0	25.3

* Laboratory 181 used days instead of hours in their electret result calculations. Their results are excluded from the graph in Figure 6.

Table 4.2. Analysis of all reported results for etched track and electret detectors: Exposure 2, 138 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	146.0	6.1	5.8	4.2	7.1
1-2	168.3	5.9	21.9	3.5	22.2
12-1	136.8	26.0	-0.9	19.0	19.0
13-1	150.0	12.3	8.7	8.2	11.9
13-2	156.8	10.8	13.6	6.9	15.3
15-1	141.2	12.3	2.3	8.7	9.0
16-1	143.0	13.9	3.6	9.7	10.4
19-1	139.6	19.3	1.2	13.8	13.9
20-1	143.2	14.1	3.8	9.9	10.6
21-1	160.4	15.6	16.2	9.7	18.9
28-1	151.8	27.7	10.0	18.3	20.8
32-1	160.1	14.9	16.0	9.3	18.5
40-1	149.3	9.2	8.2	6.2	10.2
45-1	158.2	18.5	14.6	11.7	18.7
62-1	145.4	8.6	5.3	5.9	8.0
134-1	163.2	61.3	18.2	37.6	41.8
136-1	147.9	2.5	7.2	1.7	7.4
136-2	142.0	3.7	2.9	2.6	3.9
141-1	145.6	4.6	5.5	3.2	6.4
141-2	147.6	2.9	7.0	2.0	7.2
156-1	143.4	15.4	3.9	10.7	11.4
159-1	262.7	384.4	90.4	146.3	172.0
160-1	123.9	17.3	-10.2	14.0	17.3
163-1	225.0	327.4	63.0	145.5	158.6
171-1	137.7	20.0	-0.3	14.5	14.5
173-1	152.3	9.4	10.4	6.2	12.1
177-1	155.9	13.1	13.0	8.4	15.4
178-1	132.4	3.5	-4.1	2.6	4.8
181-1*	7.2	0.4	-94.8	5.9	95.0
186-1	139.8	5.4	1.3	3.8	4.0
196-1	119.1	8.7	-13.7	7.3	15.5
196-2	120.1	8.9	-13.0	7.4	14.9
197-1	136.4	14.9	-1.2	10.9	11.0
199-1	139.9	15.4	1.4	11.0	11.1
200-1	167.4	9.2	21.3	5.5	22.0
204-1	109.3	3.0	-20.8	2.8	21.0
205-1	146.3	19.1	6.0	13.1	14.4
206-1	140.3	13.5	1.7	9.6	9.8
206-2	317.7	542.2	130.2	170.7	214.7

* Laboratory 181 used days instead of hours in their electret result calculations. Their results are excluded from the graph in Figure 7

Table 4.3. Analysis of all reported results for etched track and electret detectors: Exposure 3, 2501 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	2566.0	21.6	2.6	0.8	2.7
1-2	2464.9	61.3	-1.4	2.5	2.9
12-1	2305.7	55.8	-7.8	2.4	8.2
13-1	2682.3	86.4	7.2	3.2	7.9
13-2	2684.5	47.4	7.3	1.8	7.5
15-1	2257.5	53.1	-9.7	2.4	10.0
16-1	2531.6	64.7	1.2	2.6	2.8
19-1	2498.7	50.3	-0.1	2.0	2.0
20-1	2386.2	115.3	-4.6	4.8	6.7
21-1	2584.3	85.5	3.3	3.3	4.7
28-1	2402.2	28.8	-3.9	1.2	4.1
32-1	2647.0	78.1	5.8	3.0	6.5
40-1	2576.7	264.5	3.0	10.3	10.7
45-1	2175.9	204.4	-13.0	9.4	16.0
62-1	2638.3	93.9	5.5	3.6	6.5
134-1	2462.3	125.7	-1.5	5.1	5.3
136-1	2478.5	61.0	-0.9	2.5	2.6
136-2	2499.7	82.5	-0.1	3.3	3.3
141-1	2649.4	34.5	5.9	1.3	6.1
141-2	2633.6	99.0	5.3	3.8	6.5
156-1	2320.6	52.5	-7.2	2.3	7.6
159-1	2306.4	53.9	-7.8	2.3	8.1
160-1	2112.1	50.7	-15.5	2.4	15.7
163-1	1974.2	81.0	-21.1	4.1	21.5
171-1	2463.8	245.0	-1.5	9.9	10.1
173-1	2747.8	65.8	9.9	2.4	10.2
177-1	2644.9	32.0	5.8	1.2	5.9
178-1	2492.0	39.5	-0.4	1.6	1.6
181-1*	110.3	4.1	-95.6	3.7	95.7
186-1	2258.6	64.0	-9.7	2.8	10.1
196-1	2136.7	103.2	-14.6	4.8	15.3
196-2	2362.3	77.4	-5.5	3.3	6.4
197-1	2485.6	64.6	-0.6	2.6	2.7
199-1	2449.9	65.6	-2.0	2.7	3.4
200-1	2750.3	90.7	10.0	3.3	10.5
204-1	2001.9	57.8	-20.0	2.9	20.2
205-1	2250.3	84.5	-10.0	3.8	10.7
206-1	2335.4	66.0	-6.6	2.8	7.2
206-2	2650.0	150.4	6.0	5.7	8.2

* Laboratory 181 used day instead of hour in their electret result calculations. Their results are excluded from the graph in Figure 8.

Table 4.4. Analysis of all reported results for etched track and electret detectors: Exposure 4, 1387 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	1438.1	19.2	3.7	1.3	3.9
1-2	1397.9	33.9	0.8	2.4	2.5
12-1	1297.0	49.9	-6.5	3.8	7.5
13-1	1540.1	45.0	11.0	2.9	11.4
13-2	1506.6	67.6	8.6	4.5	9.7
15-1	1269.1	42.9	-8.5	3.4	9.1
16-1	1393.3	63.6	0.5	4.6	4.6
19-1	1369.6	48.7	-1.3	3.6	3.8
20-1	1371.9	43.0	-1.1	3.1	3.3
21-1	1455.2	75.9	4.9	5.2	7.2
28-1	1418.7	40.5	2.3	2.9	3.7
32-1	1427.1	71.8	2.9	5.0	5.8
40-1	1376.1	156.7	-0.8	11.4	11.4
45-1	1385.0	143.2	-0.1	10.3	10.3
62-1	1513.3	76.8	9.1	5.1	10.4
134-1	1378.2	82.5	-0.6	6.0	6.0
136-1	1382.4	41.6	-0.3	3.0	3.0
136-2	1395.7	21.7	0.6	1.6	1.7
141-1	1400.9	16.5	1.0	1.2	1.5
141-2	1475.2	20.5	6.4	1.4	6.5
156-1	1305.6	46.7	-5.9	3.6	6.9
159-1	1219.5	382.4	-12.1	31.4	33.6
160-1	1201.8	43.9	-13.4	3.7	13.8
163-1	1064.0	337.4	-23.3	31.7	39.3
171-1	1488.6	104.7	7.3	7.0	10.2
173-1	1501.1	33.0	8.2	2.2	8.5
177-1	1470.7	27.9	6.0	1.9	6.3
178-1	1346.0	21.8	-3.0	1.6	3.4
181-1*	62.3	1.8	-95.5	2.8	95.5
186-1	1285.8	31.1	-7.3	2.4	7.7
196-1	1163.0	46.5	-16.2	4.0	16.6
196-2	1305.3	58.9	-5.9	4.5	7.4
197-1	1456.3	67.3	5.0	4.6	6.8
199-1	1364.4	30.0	-1.6	2.2	2.7
200-1	1506.7	52.1	8.6	3.5	9.3
204-1	1135.0	36.7	-18.2	3.2	18.5
205-1	1249.1	45.0	-9.9	3.6	10.6
206-1	1316.6	60.4	-5.1	4.6	6.8
206-2	1426.4	256.8	2.8	18.0	18.2

* Laboratory 181 used day instead of hour in their electret result calculations. Their results are excluded from the graph in Figure 9.

Table 4.5. Analysis of all reported results for etched track and electret detectors: Exposure 5, 383 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	390.7	6.6	2.0	1.7	2.6
1-2	392.7	20.1	2.5	5.1	5.7
12-1	336.5	30.2	-12.1	9.0	15.1
13-1	420.7	21.9	9.8	5.2	11.1
13-2	410.2	21.3	7.1	5.2	8.8
15-1	369.0	12.5	-3.7	3.4	5.0
16-1	433.1	54.6	13.1	12.6	18.2
19-1	383.4	18.8	0.1	4.9	4.9
20-1	390.4	28.8	1.9	7.4	7.6
21-1	410.6	33.5	7.2	8.2	10.9
28-1	398.3	20.0	4.0	5.0	6.4
32-1	414.5	21.6	8.2	5.2	9.7
40-1	407.4	22.4	6.4	5.5	8.4
45-1	364.2	36.9	-4.9	10.1	11.2
62-1	391.9	16.4	2.3	4.2	4.8
134-1	409.7	93.1	7.0	22.7	23.8
136-1	387.3	10.4	1.1	2.7	2.9
136-2	383.9	8.3	0.2	2.2	2.2
141-1	394.6	8.2	3.0	2.1	3.7
141-2	379.8	10.1	-0.8	2.7	2.8
156-1	369.5	18.8	-3.5	5.1	6.2
159-1	390.5	21.4	2.0	5.5	5.8
160-1	339.8	17.3	-11.3	5.1	12.4
163-1	331.7	20.4	-13.4	6.2	14.7
171-1	396.3	68.4	3.5	17.3	17.6
173-1	403.2	15.4	5.3	3.8	6.5
177-1	401.5	15.4	4.8	3.8	6.2
178-1	386.4	6.0	0.9	1.5	1.8
181-1*	17.6	0.5	-95.4	2.6	95.4
186-1	352.4	10.3	-8.0	2.9	8.5
196-1	330.6	28.0	-13.7	8.5	16.1
196-2	350.5	12.3	-8.5	3.5	9.2
197-1	387.7	21.2	1.2	5.5	5.6
199-1	378.9	24.4	-1.1	6.4	6.5
200-1	427.5	38.6	11.6	9.0	14.7
204-1	309.1	8.5	-19.3	2.7	19.5
205-1	349.5	25.5	-8.7	7.3	11.4
206-1	377.5	18.6	-1.4	4.9	5.1
206-2	777.4	1025.5	103.0	131.9	167.3

* Laboratory 181 used day instead of hour in their electret result calculations. Their results are 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

Set ID	Mean (kBq m^{-3} h)	1 SD (kBq m^{-3} h)
1-1	3.0	2.8
1-2	2.0	2.6
12-1	19.0	10.6
13-1	6.7	9.2
13-2	5.7	3.8
15-1	6.0	3.5
16-1	18.1	5.7
19-1	31.5	19.3
20-1	16.0	4.3
21-1	17.2	3.8
28-1	46.4	16.6
32-1	25.7	13.7
40-1	6.3	1.7
45-1	18.5	3.6
62-1	14.1	2.7
134-1	128.4	71.0
136-1	52.4	3.0
136-2	88.0	5.0
141-1	53.5	3.6
141-2	26.0	4.2
156-1	74.8	9.8
159-1	5.1	6.1
160-1	120.6	11.2
163-1	23.5	15.6
171-1	22.1	6.1
173-1	4.0	2.9
177-1	33.9	5.8
178-1	19.2	2.5
181-1	0.3	0.1
186-1	9.8	6.4
196-1	9.0	4.3
196-2	7.9	4.7
197-1	9.2	5.9
199-1	19.5	7.3
200-1	24.5	6.5
204-1	27.5	9.7
205-1	56.9	38.4
206-1	29.6	8.8
206-2	270.4	215.5

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	732	699.1	121.8
2	138	150.6	44.1
3	2501	2384.1	422.9
4	1387	1334.9	236.4
5	383	383.2	91.7

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

	Exposure 2	Exposure 5	Exposure 1	Exposure 4	Exposure 3					
Set ID	138 kBq m^{-3} h	383 kBq m^{-3} h	732 kBq m^{-3} h	1387 kBq m^{-3} h	2501 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
1-1	A	A	A	A	A	Closed		NRPB	CR-39	Mi-Net
136-1	A	A	A	A	A	Closed	No	NRPB/SSI	PADC	TASL
136-2	A	A	A	A	A	Badge		Radongas srl copyright	PADC	TASL
141-1	A	A	A	A	A	Closed	No	Radosure	TASTRAK	TASL
141-2	A	A	A	A	A	Closed	Yes	E-Perm	Electret	E-Perm
178-1	A	A	A	A	A	TASL		TASL	CR-39	TASL
206-1	A	A	A	A	A	Closed - RSKS	No		CR-39	Radosys
13-2	B	A	A	A	A	Radtrak 3	Yes	Radtrak 3	CR-39	Radonova Scientific Ltd.
15-1	A	A	A	A	B	SSNTD	No	RadOutTM	PADC CR-39	TASL
19-1	B	A	A	A	A	SSNDT	Yes	RadOutTM	CR-39	TASL
20-1	B	A	A	A	A	Etched track diffusion	No	TASL	PADC	TASL
32-1	B	A	A	A	A	SSNTD		NRPB/SSI	CR-39/ PADC	TASL

	Exposure 2	Exposure 5	Exposure 1	Exposure 4	Exposure 3					
Set ID	138 kBq m^{-3} h	383 kBq m^{-3} h	732 kBq m^{-3} h	1387 kBq m^{-3} h	2501 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
62-1	A	A	A	B	A	Closed	Yes (Mylar)	In-house (sensitive volume 79 ml)	Makrofol	Covestro
156-1	B	A	A	A	A	SSNTD	No	Radosys Ltd., Hungary	CR-39	Radosys Ltd., Hungary
177-1	B	A	A	A	A	Closed	No	TASL	CR-39	TASL
186-1	A	A	A	A	B	CR-39	No	TASL	TASTRAK PADC	TASL
197-1	B	A	A	A	A	SSNTD	yes		CR-39	Radosys
199-1	B	A	A	A	A	RadoutTM	no	Mi.Am	PADC	TASL
1-2	C	A	A	A	A	Closed		NRPB	CR-39	Mi-Net
28-1	C	A	A	A	A	Radosys - RSKS	No	-	CR-39	Radosys
12-1	B	B	A	A	A	Closed	Yes	Eurofins	CR-39	
21-1	B	B	A	A	A	Closed, air gap	No	ENEA	CR-39	TASL
173-1	B	A	A	A	B	Radonalpha-C	yes	TASL	CR-39	TASL
196-2	B	A	B	A	A	Closed	No	RadOut^{TM}	CR-39	Radonova Scientific Ltd.
134-1	E	C	A	A	A	Electret LT	Yes	N/A	N/A	Rad Elec

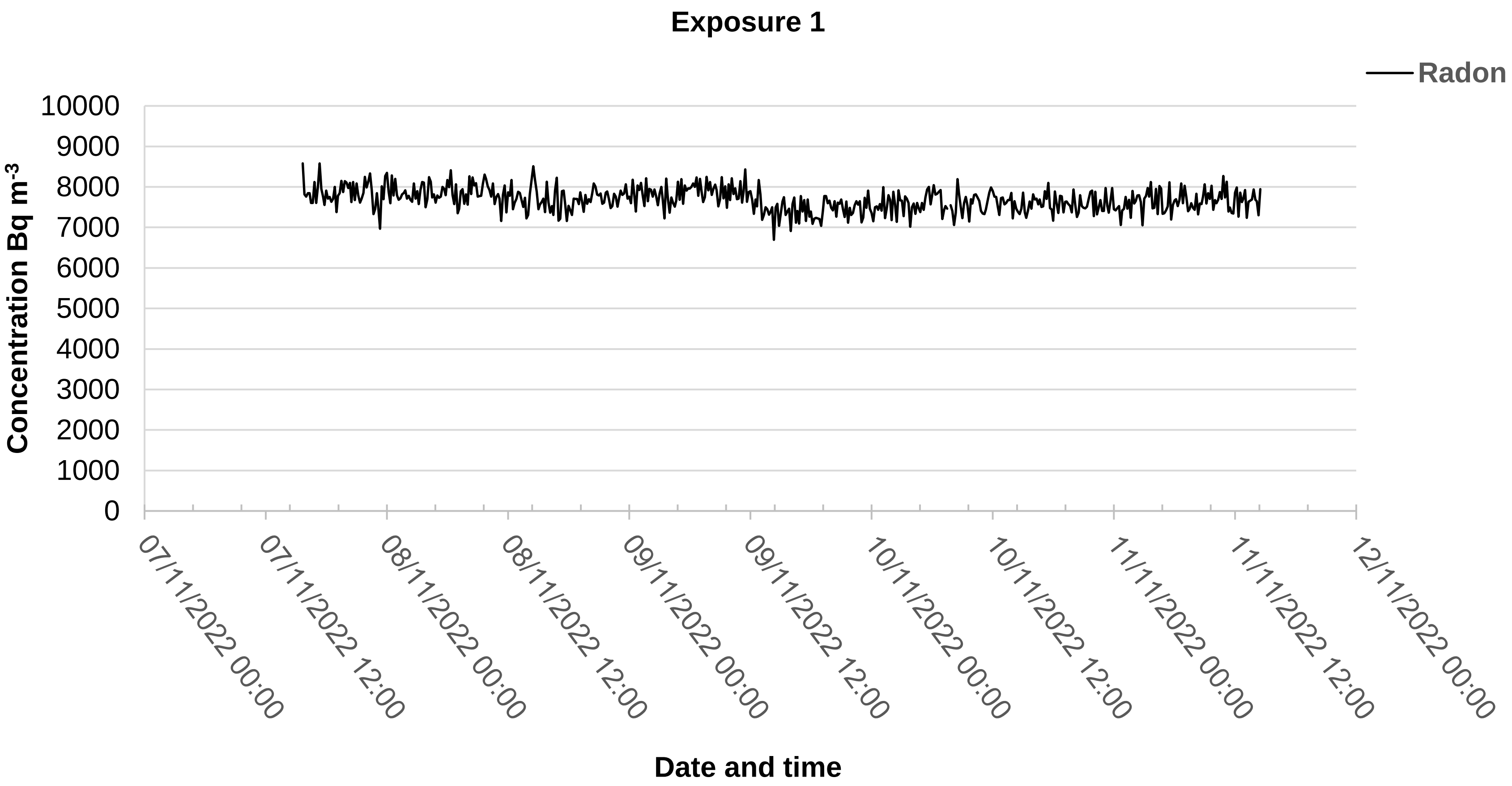
	Exposure 2	Exposure 5	Exposure 1	Exposure 4	Exposure 3					
Set ID	138 kBq m^{-3} h	383 kBq m^{-3} h	732 kBq m^{-3} h	1387 kBq m^{-3} h	2501 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
159-1a	F	A	A	D	A	Closed - SSNTD	Yes		CR-39	Radosys
16-1	B	B	B	A	A	RSK	No	Cylindrical	PADC	Radosys
13-1	B	B	B	B	A	Radtrak 2		NRPB/SSI	CR-39	RTP Company
40-1	B	A	B	B	B	SSNTD	no	NRPB - yellow	PADC	Mi-Net Technology Ltd (Instrument Plastics)
171-1	B	B	A	B	B	SSNTD	yes	own	LR115	Dosirad
200-1	C	B	B	A	B	RadOutTM	No	Mi.am	PADC	GM Scientific
45-1	B	B	B	B	B	Closed	Yes	DPR3	LR115	Algade
160-1	B	B	B	B	B	Closed	No	TASL	CR-39	TASL
196-1	B	B	B	B	B	Closed	No	RadOutTM	CR-39 (RNT)	Radonova Scientific Ltd.
205-1b	B	B	B	B	B	SSNTD	No	Miam - RadOut	PADC CR-39	TASL
204-1	C	B	B	B	C	RSFS	No		PADC / CR-39	Radosys

	Exposure 2	Exposure 5	Exposure 1	Exposure 4	Exposure 3					
Set ID	138 kBq m^{-3} h	383 kBq m^{-3} h	732 kBq m^{-3} h	1387 kBq m^{-3} h	2501 kBq m^{-3} h	Detector type	Filter	Holder	Detector material	Detector material supplier
163-1[c]	F	B	B	D	C	SSNTD	No		CR-39	TASL
206-2d	F	F	C	B	A	Electret	No		L-00 chamber +LT electret	Rad Elec
181-1e	F	F	F	F	F	Electret (SLT)	No	Electet	Teflon	

Notes to Table 6

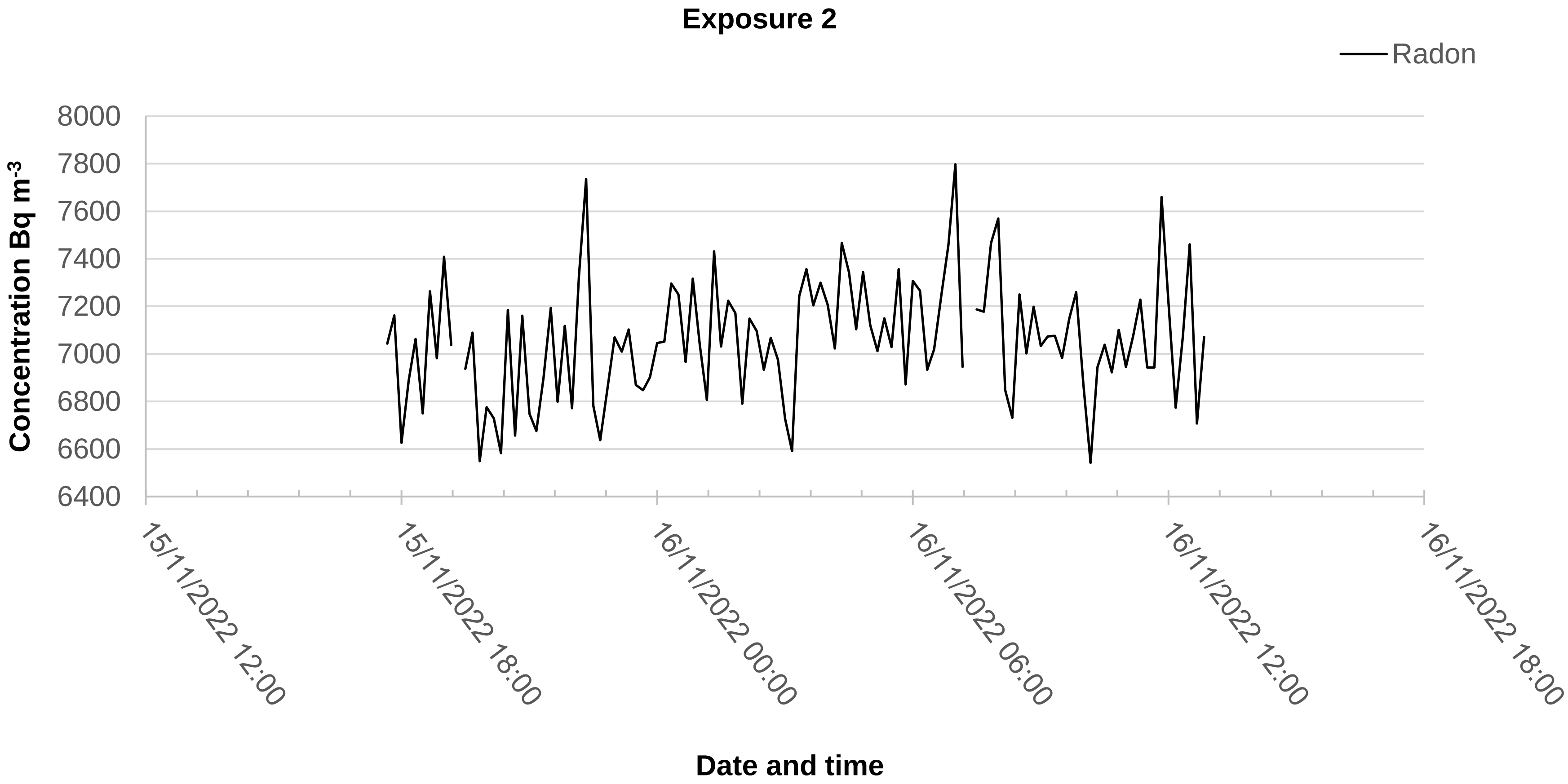
a. Set 159-1, 2 of the detector results were not recorded correctly against their laboratory detector numbers. Without this error, the classification would have been B A A A A.
b. Set 205-1, 1 transit detector result was not recorded correctly against their laboratory detector number. Without this error, the classification would have been B A B A B.
c. Set 163-1, 2 of the detector results were not recorded correctly against their laboratory detector numbers. Without this error, the classification would have been A B A B C.
d. Set 206-2, 4 of the detector results were not recorded due to problems with the electrets. Without these issues, the classification would have been D D B B B.
e. Set 181-1, Day rate used for electret result calculations instead of hourly rate. With the correct values, the classification would have been C B B A A.

Figure 1. Radon concentrations for exposure 1



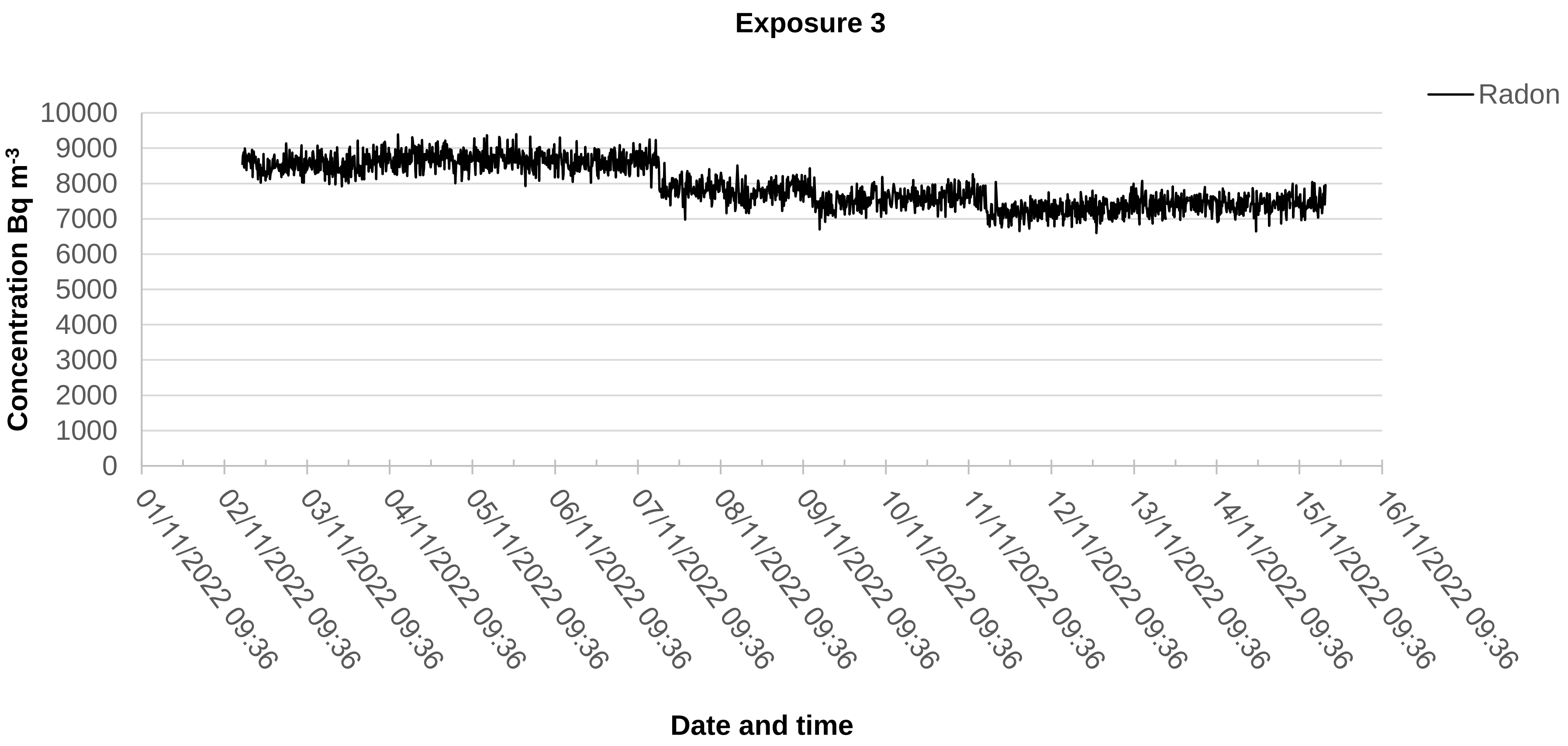
The above figure shows the fluctuation of radon concentration during exposure 1, which covers the period 7 November 2022 to 11 November 2022. The radon concentration hovered between 6,800 Bq m^{-3} and 8,500 Bq m^{-3}, initially starting high then dropping slightly.

Figure 2. Radon concentration for exposure 2



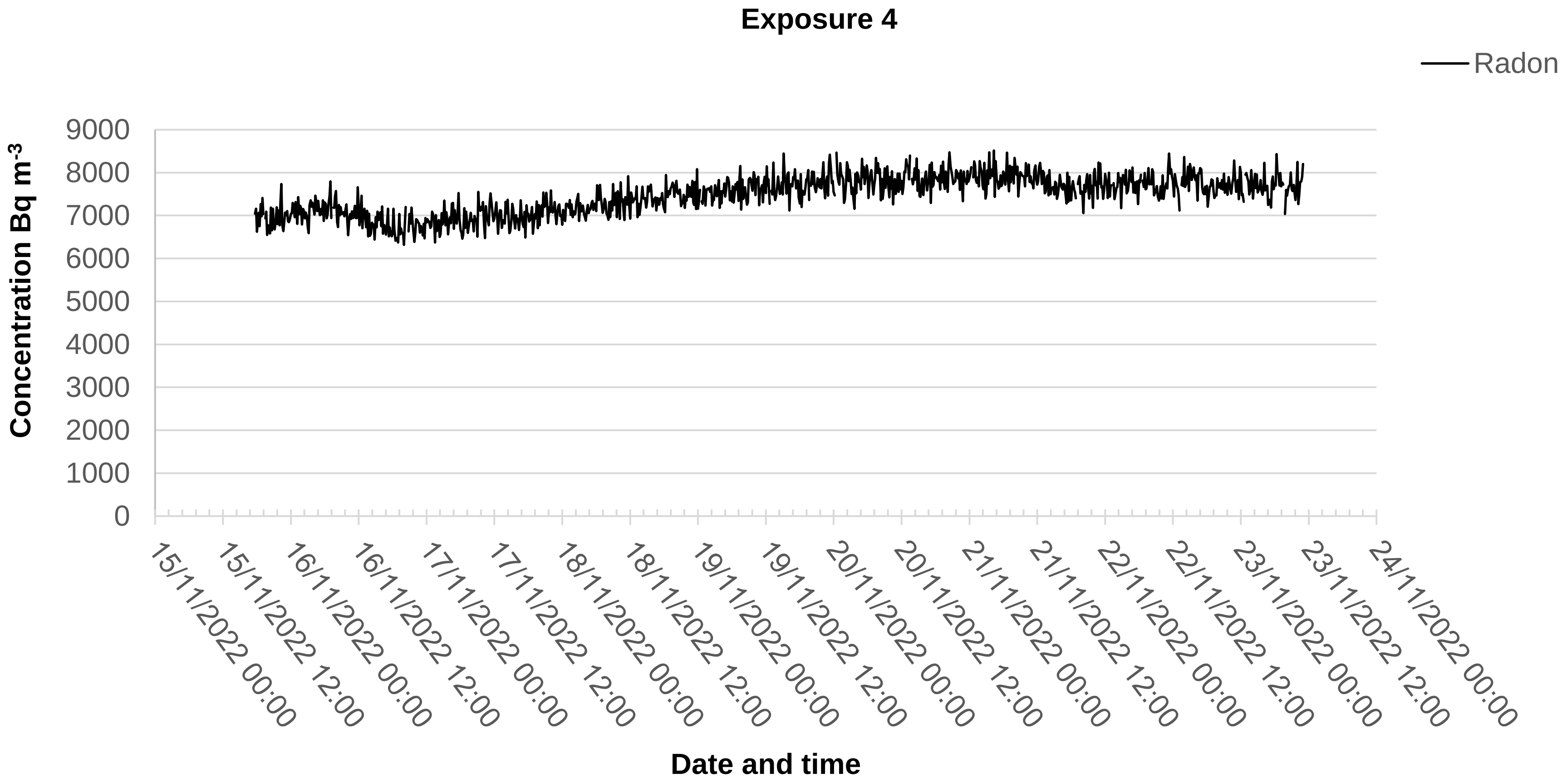
The above figure shows the fluctuation of radon concentration during exposure 2, which covers the period 15 November 2022 to 16 November 2022. The radon concentration began at over 7000 Bq m^{-3} and then dropped to around 6,600 Bq m$^{-3,}$ regularly climbing and falling with spikes and troughs between 7,800 Bq m^{-3} (highest) and 6,600 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 3. Radon concentration for exposure 3



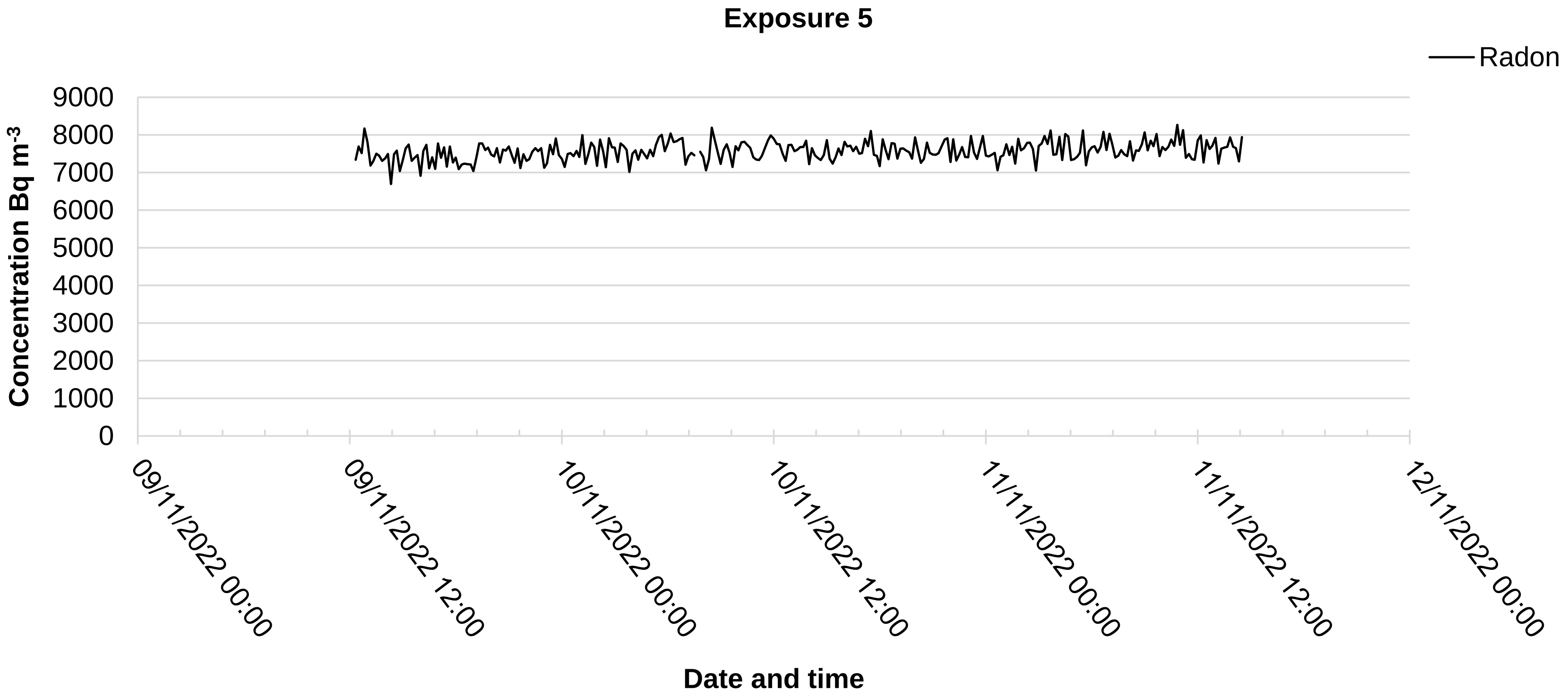
The above figure shows the fluctuation of radon concentration during exposure 3, which covers the period 2 November 2022 to 15 November 2022. The radon concentration began at over 8,500 Bq m^{-3} and then reduced in stages, eventually fluctuating between 8000 Bq m^{-3} and 7000 Bq m^{-3}.

Figure 4. Radon concentration for exposure 4



The above figure shows the fluctuation of radon concentration during exposure 4, which covers the period 15 November 2022 to 23 November 2022. The radon concentration varied between 6,000 Bq m^{-3} and 8000 Bq m^{-3} initially falling then rising gradually then falling again slightly, but ending higher than at the start.

Figure 5. Radon concentration for exposure 5



The above figure shows the fluctuation of radon concentration during exposure 5 which covers the period 9 November 2022 to 11 November 2022. The radon concentration hovered around 7500 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

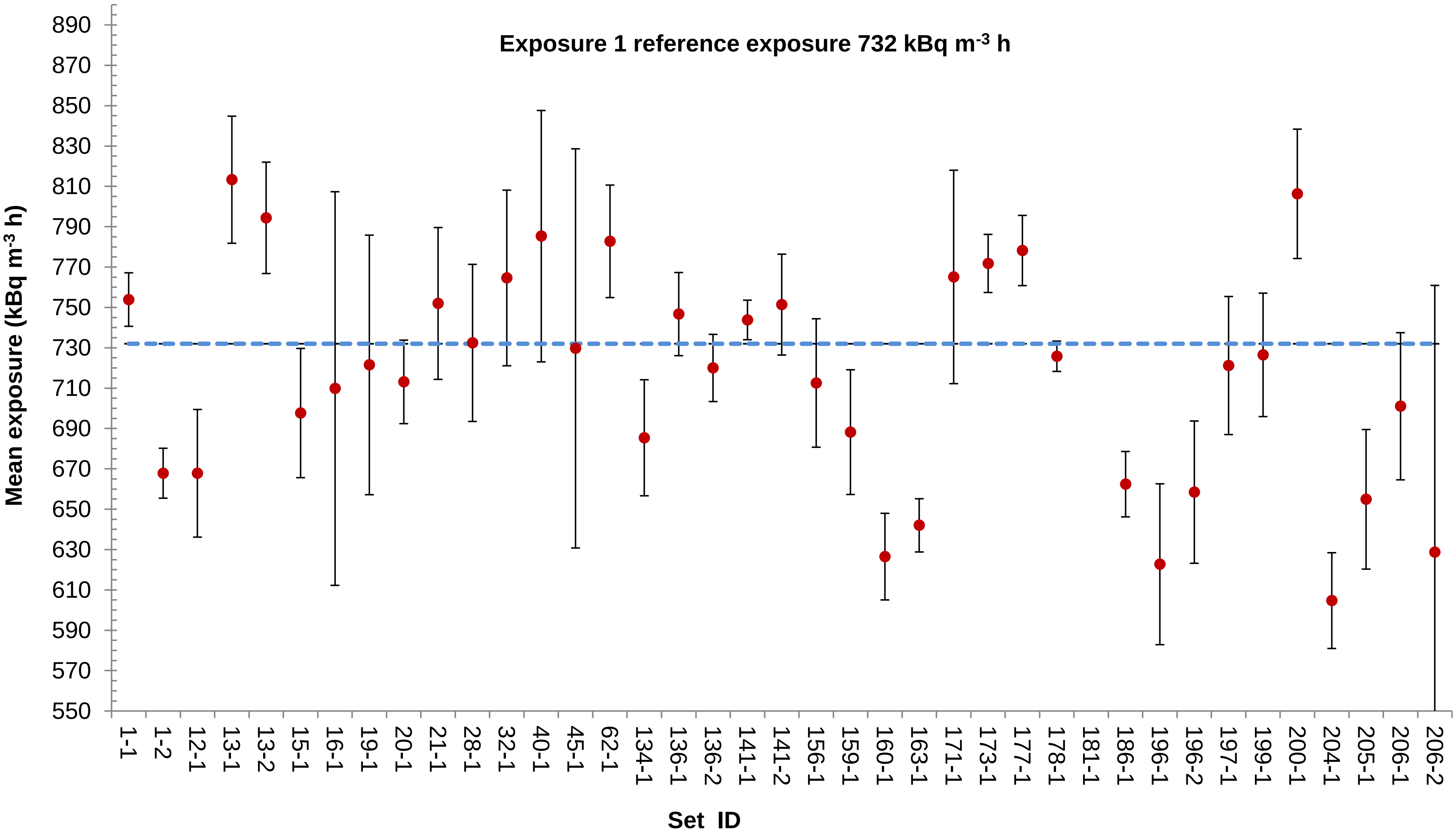


Figure 7. Results as reported by participants for exposure 2 - given in Table 4.2

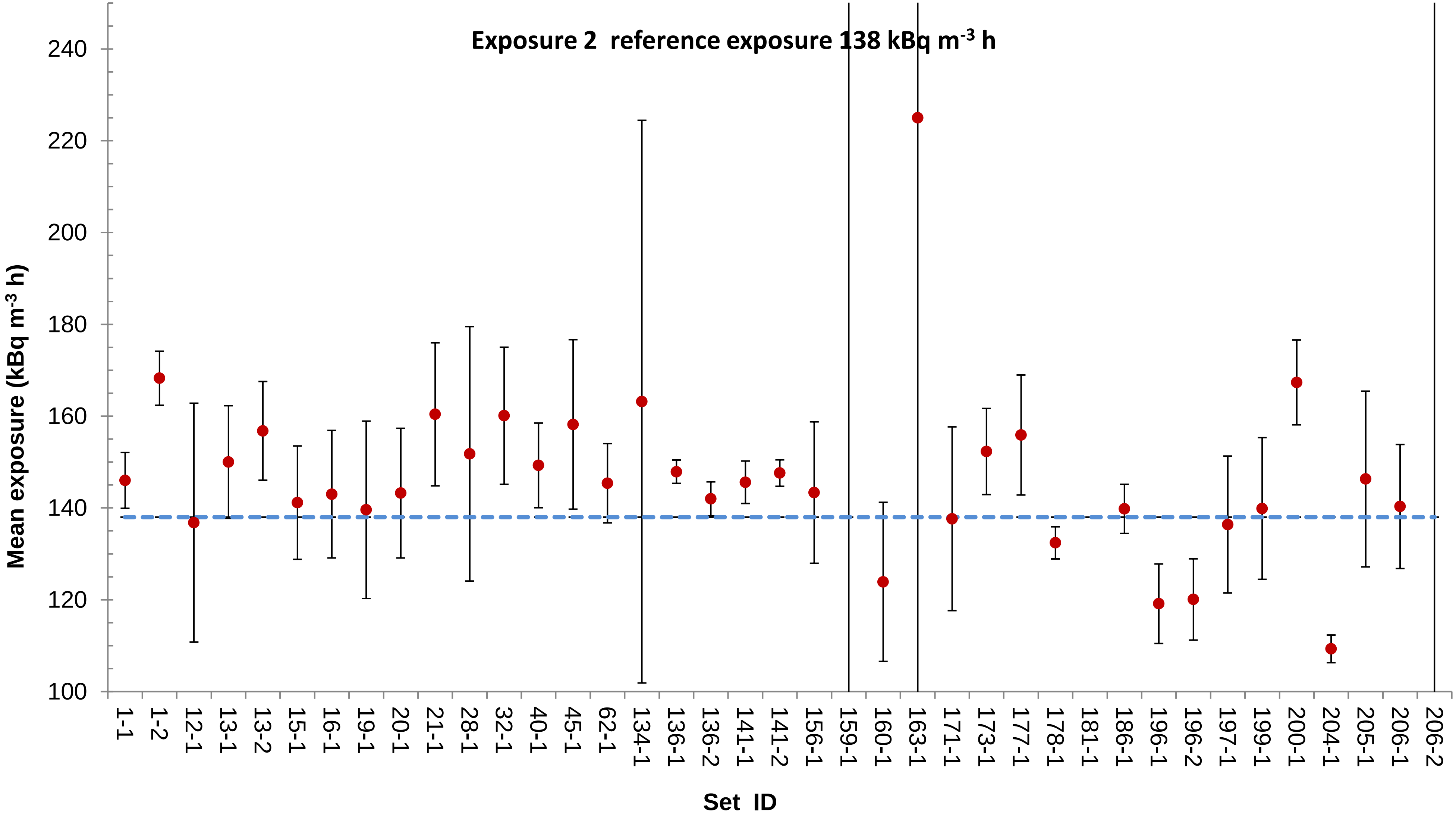


Figure 8. Results as reported by participants for exposure 3 - given in Table 4.3

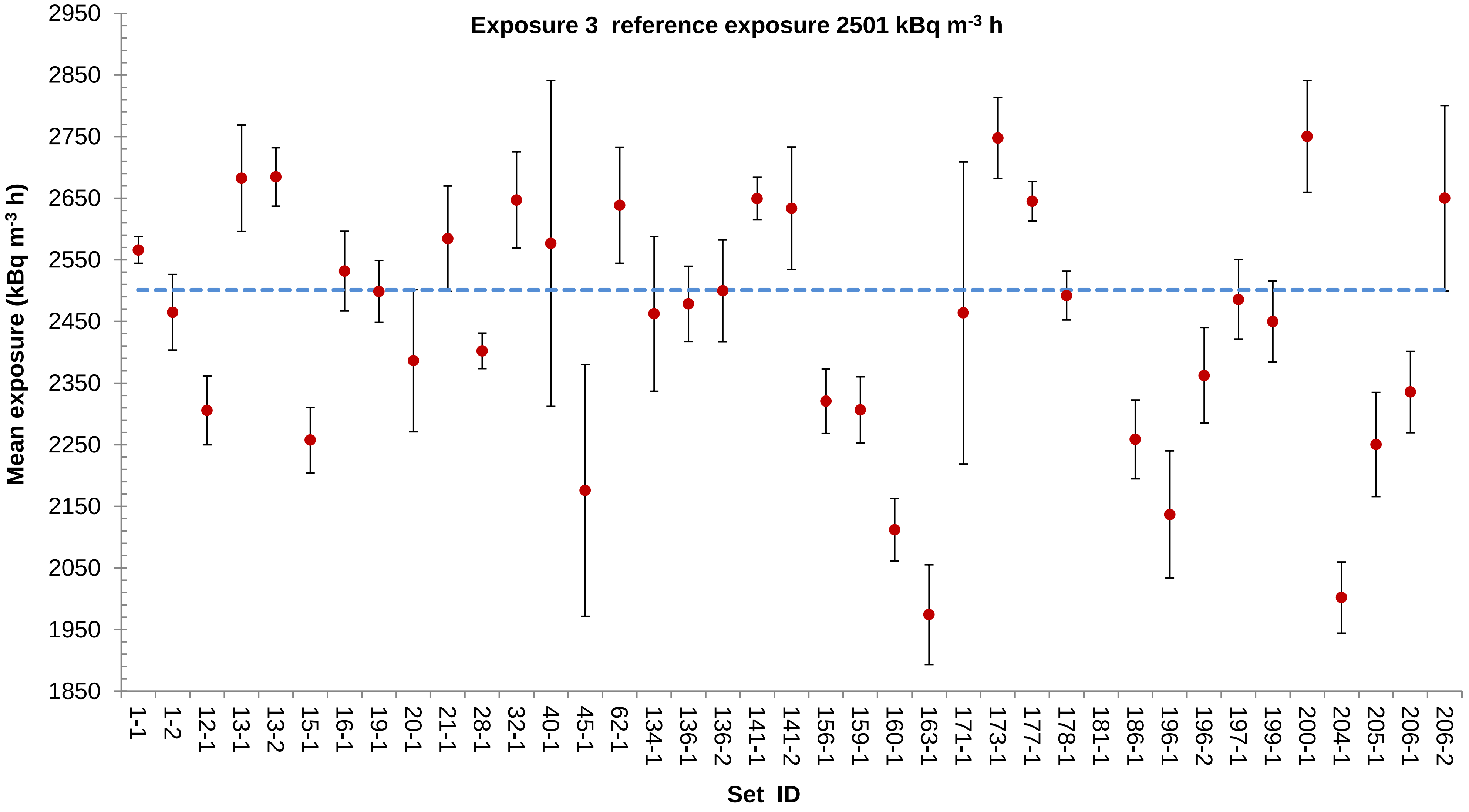


Figure 9. Results as reported by participants for exposure 4 - given in Table 4.4

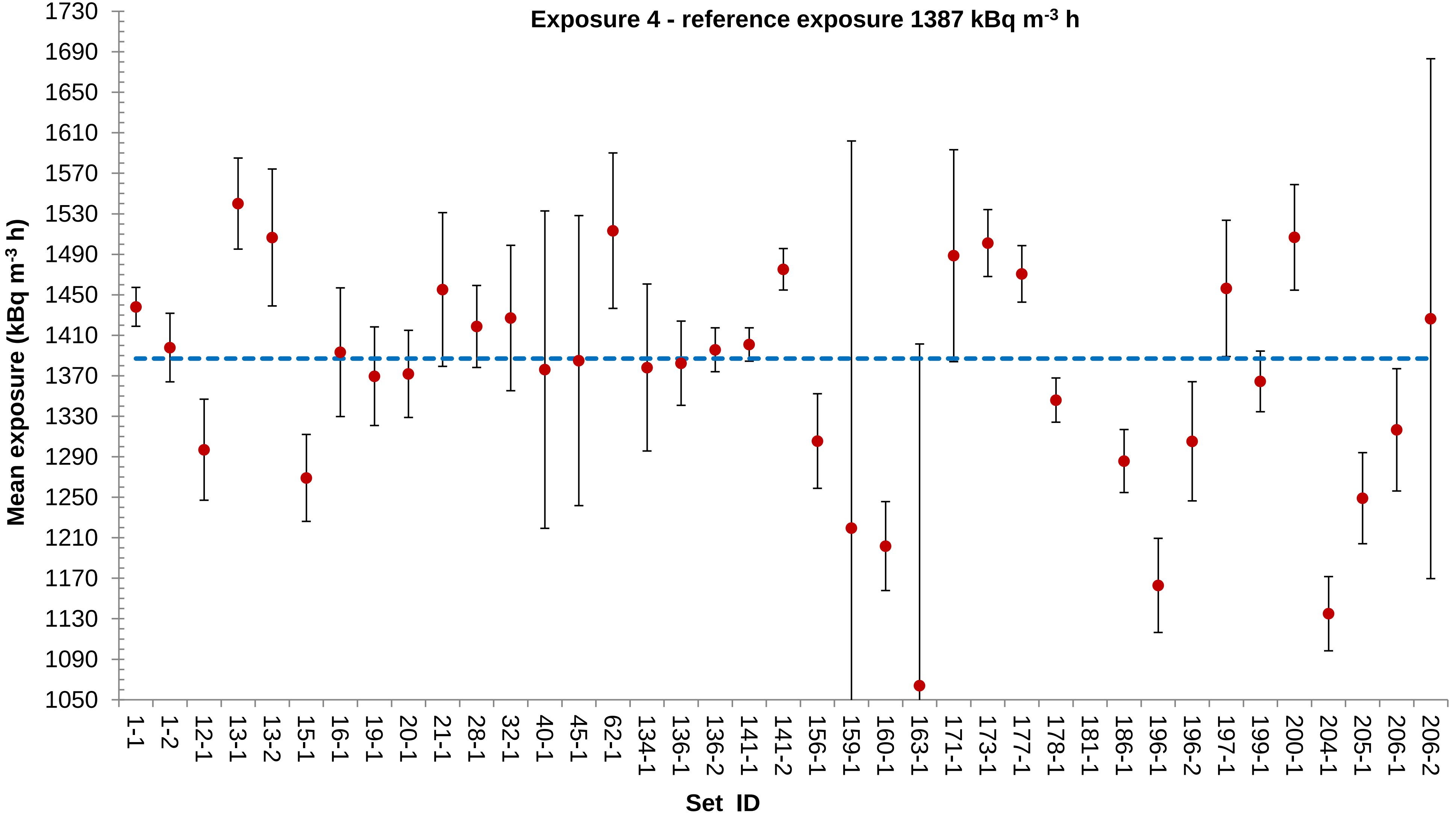


Figure 10. Results as reported by participants for exposure 5 - given in Table 4.5

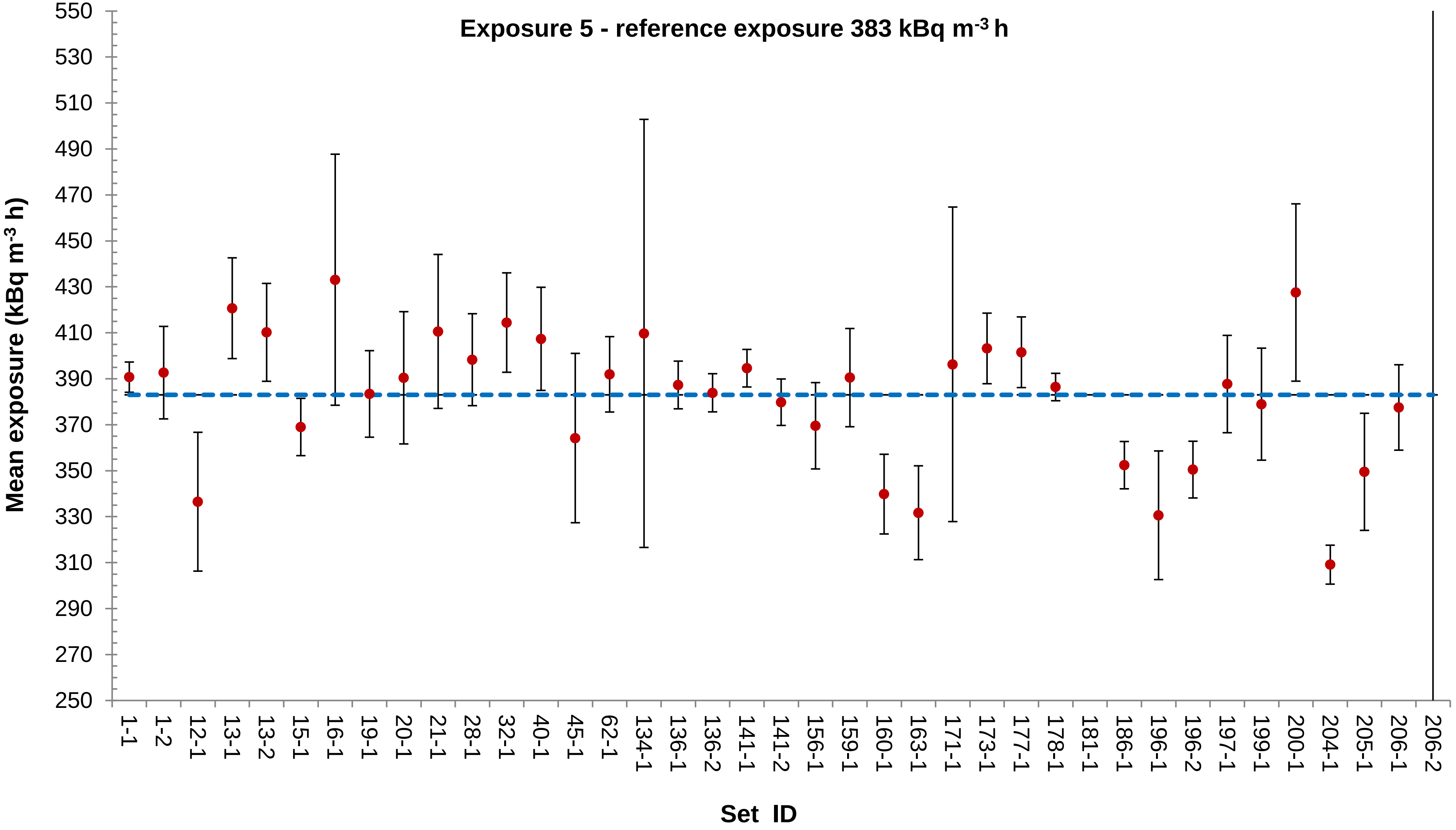


Figure 11. Results as reported by participants for transit exposure - given in Table 4.6

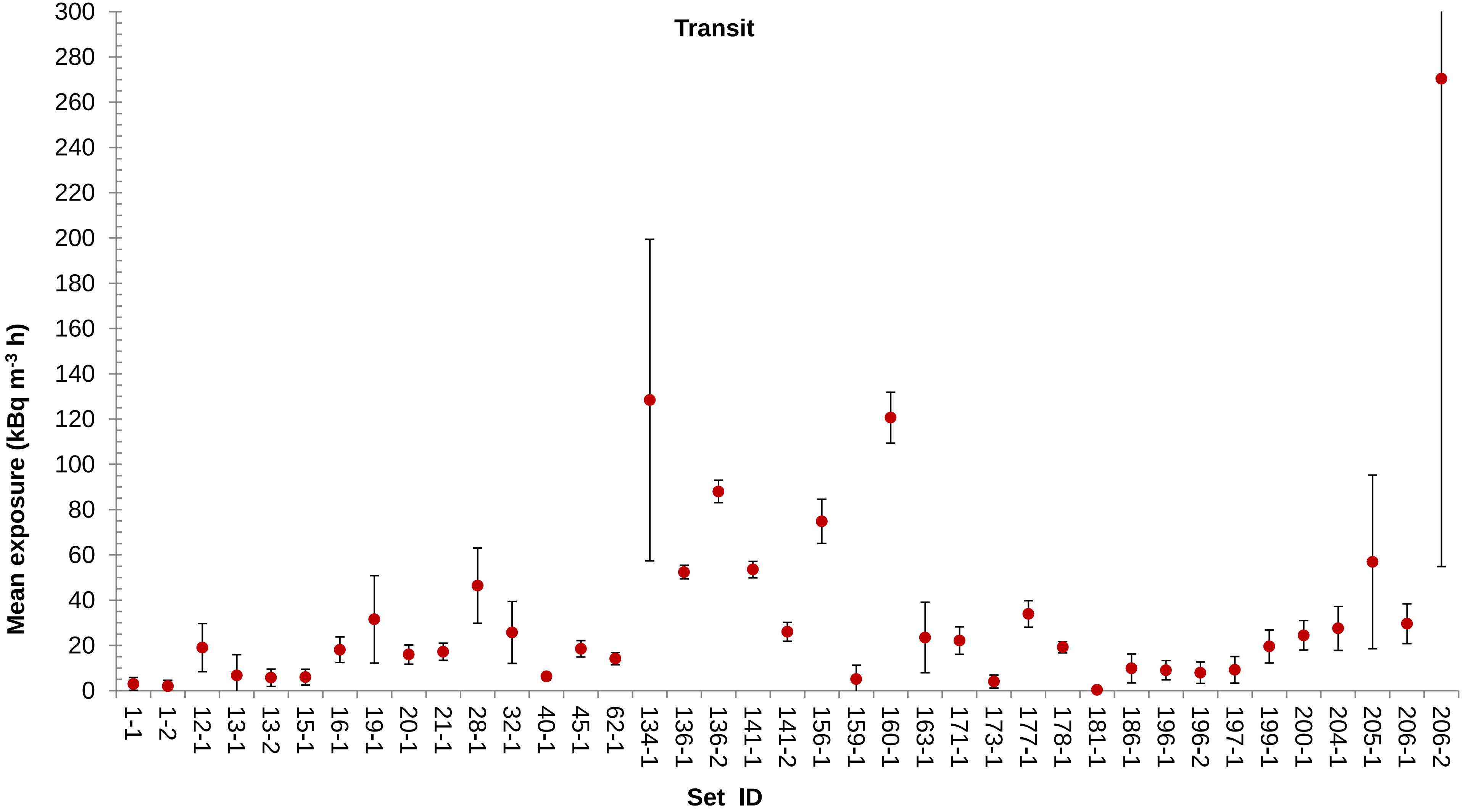


Figure 12. Distribution of mean exposure results for exposure 1 - given in Table 4.1. The vertical dotted line indicates the reference exposure.

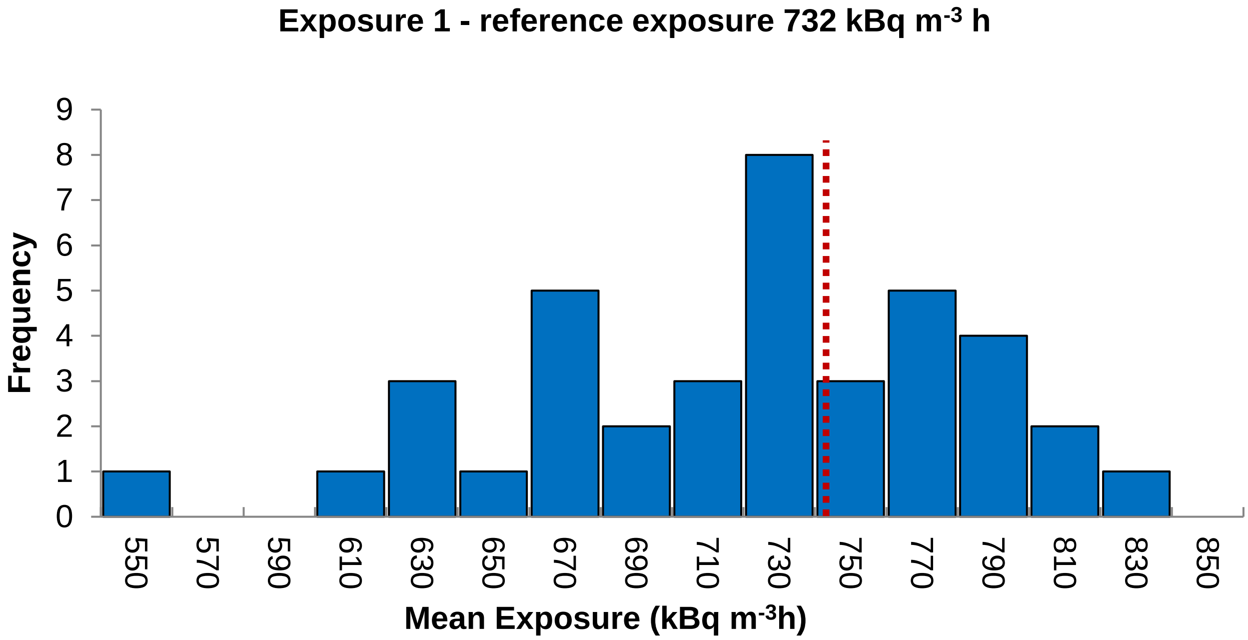


Figure 13. Distribution of mean exposure results for exposure 2 - given in Table 4.2. The vertical dotted line indicates the reference exposure.

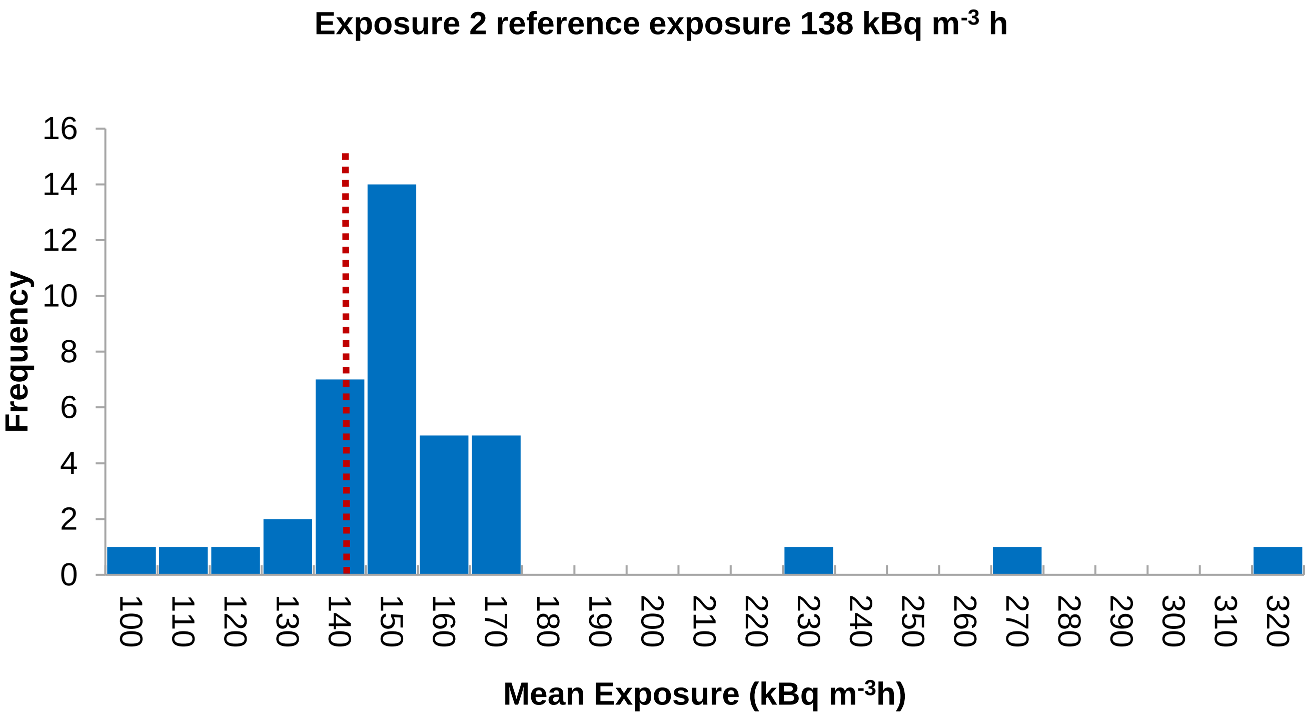


Figure 14. Distribution of mean exposure results for exposure 3 - given in Table 4.3. The vertical dotted line indicates the reference exposure.

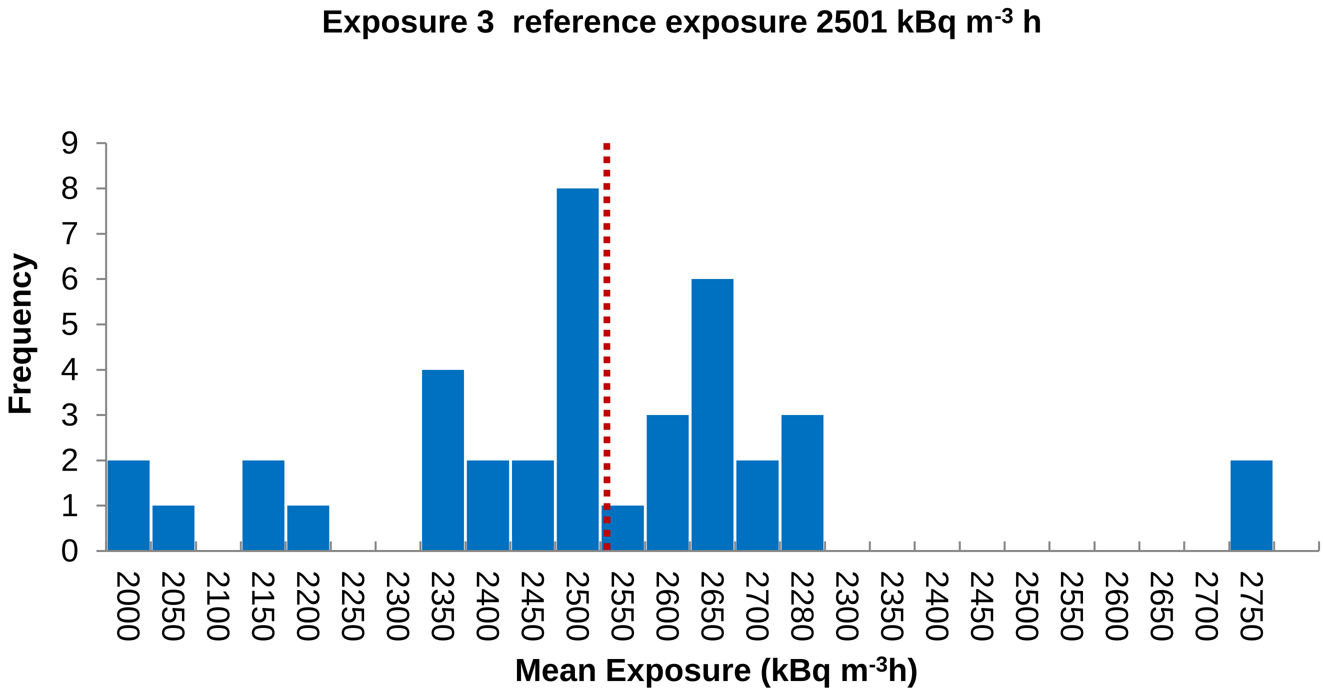


Figure 15. Distribution of mean exposure results for exposure 4 - given in Table 4.4. The vertical dotted line indicates the reference exposure.

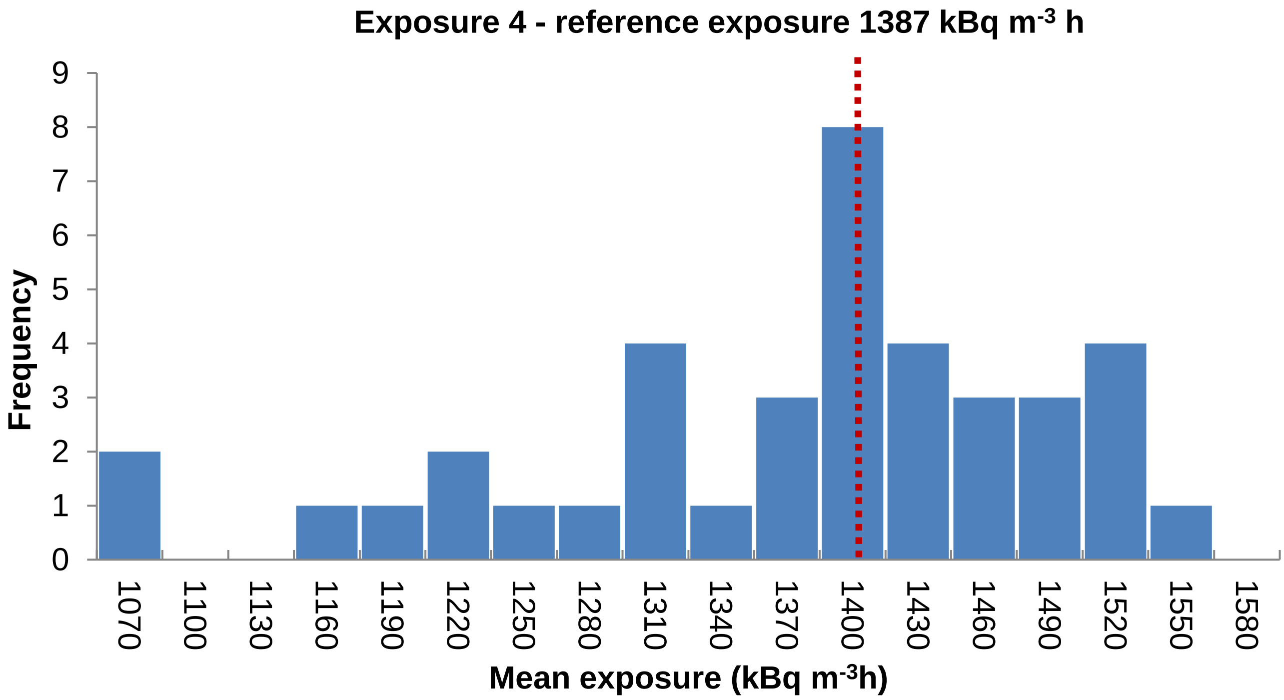


Figure 16. Distribution of mean exposure results for exposure 5 - given in Table 4.5. The vertical dotted line indicates the reference exposure.

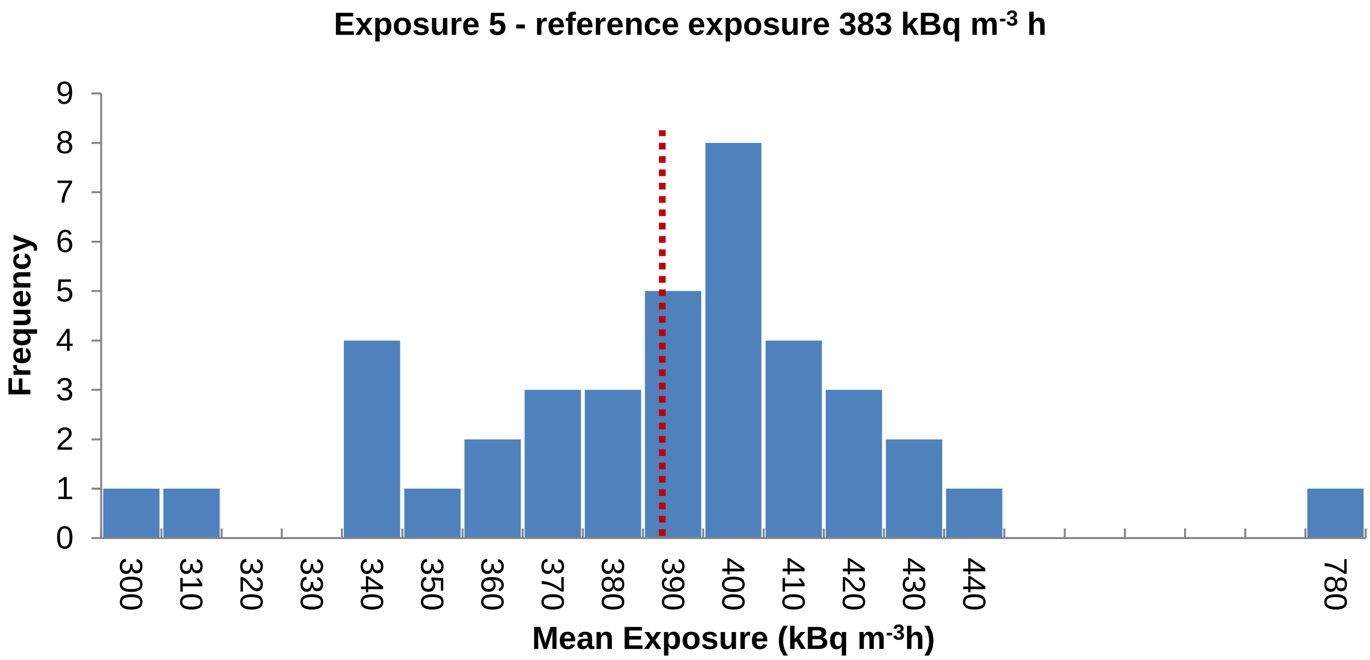


Figure 17. Distribution of mean exposure results for the transit exposure - given in Table 4.6.

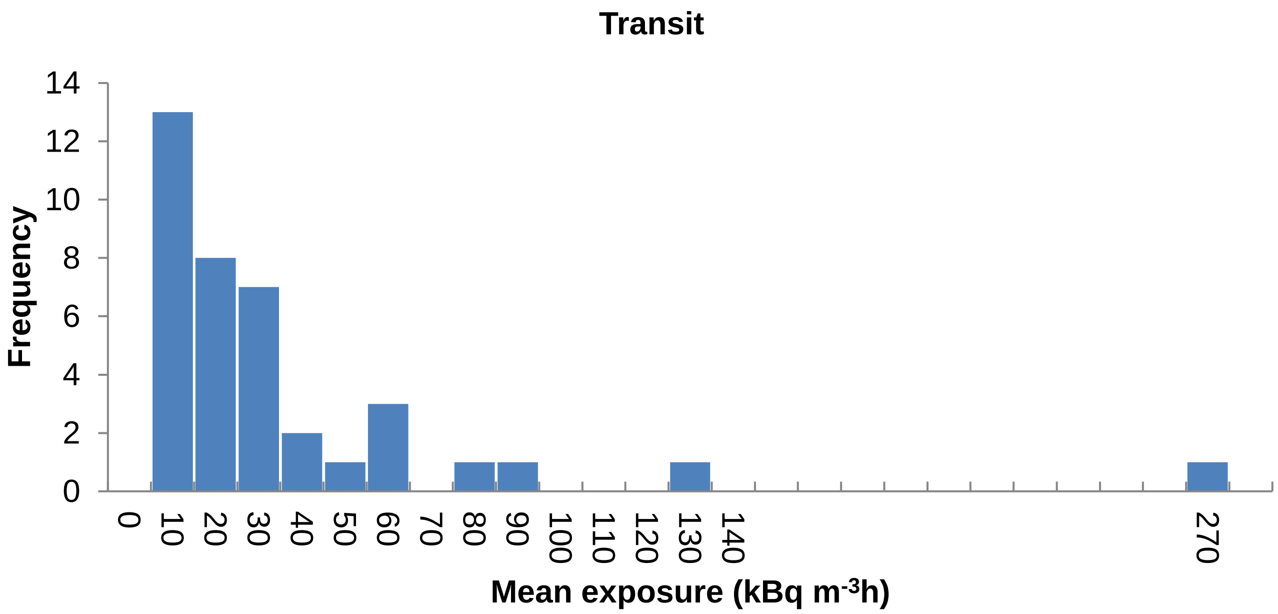


Figure 18. Performance classes for each exposure from A (best) to F (worst) summarised in Table 7 below

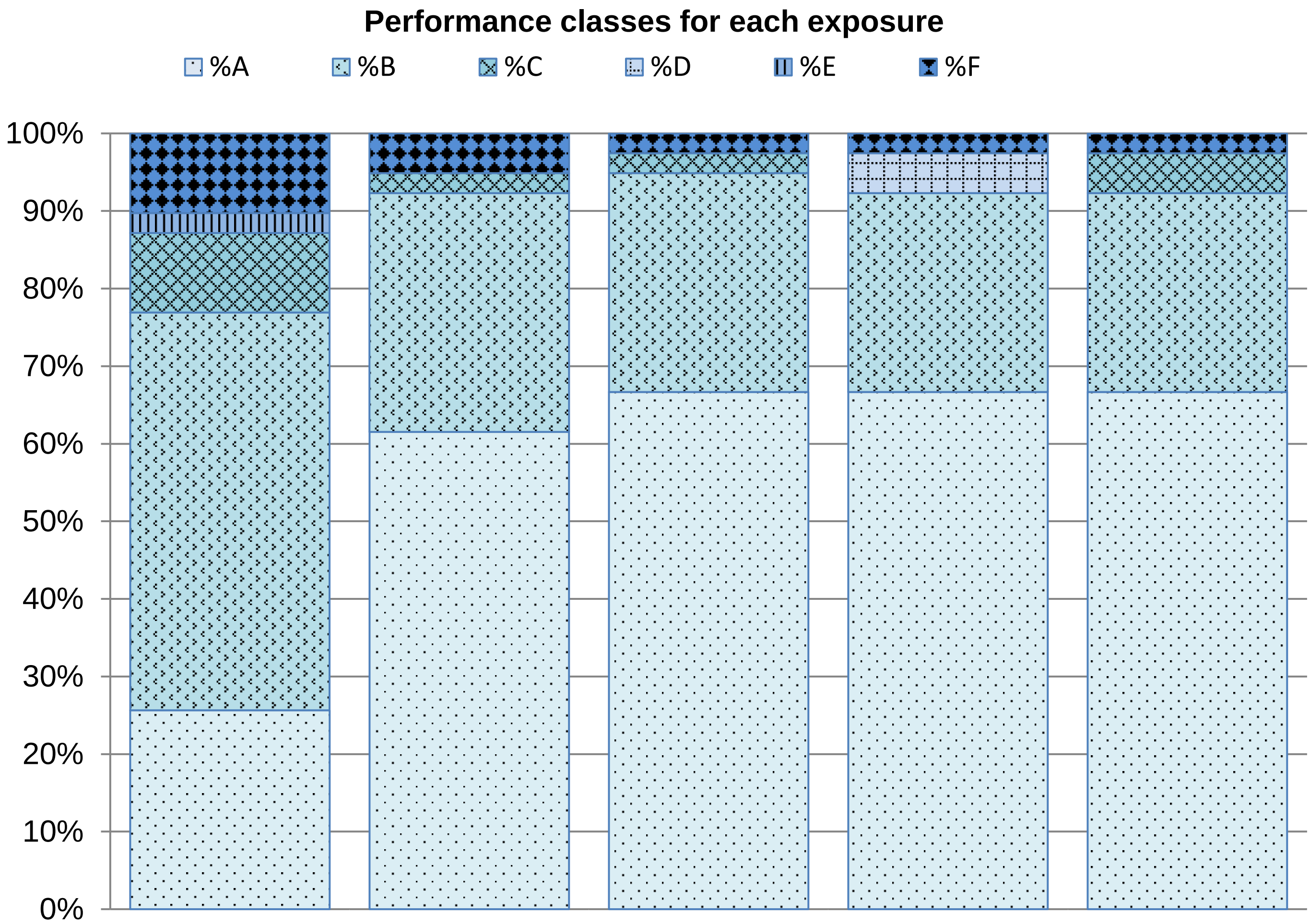


Table 7. Exposure number (and integrated exposure, kBq m-3 h)

	Rank EXPOSURE 2 138 kBq m^{-3} h	Rank EXPOSURE 5 383 kBq m^{-3} h	Rank EXPOSURE 1 732 kBq m^{-3} h	Rank EXPOSURE 4 1387 kBq m^{-3} h	Rank EXPOSURE 3 2501 kBq m^{-3} h
%F	10	5	3	3	3
%E	3	0	0	0	0
%D	0	0	0	5	0
%C	10	3	3	0	5
%B	51	31	28	26	26
%A	26	62	67	67	67

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