Radiation Protection Dosimetry (2009), Vol. 136, No. 2, pp. 127–131
Advance Access publication 19 August 2009
doi:10.1093/rpd/ncp154

TECHNICAL NOTE

INDOOR RADON MEASUREMENTS IN AREAS OF NORTHERN GREECE WITH RELATIVELY HIGH INDOOR RADON CONCENTRATIONS

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Received May 3 2009, revised July 14 2009, accepted July 21 2009

Indoor radon concentrations were measured in 77 schools of the prefecture of Xanthi in northern Greece. The arithmetic mean radon concentration is 231 Bq m^{-3} with a range between 45 and 958 Bq m^{-3}. Thirty five schools have mean radon concentration above 200 Bq m^{-3} and nine schools have mean radon concentration above 400 Bq m^{-3}. From continuous radon gas measurements in the school with a relative higher radon concentration (958 Bq m^{-3}) was deduced the 'true' radon concentration, defined as the radon concentration in the school during the hours of the presence of teachers and scholars. The mean 'true' radon concentration for a time period of about 2 weeks was 104 Bq m^{-3}. The mean radon concentration for the same 2 weeks was seven times higher (700 Bq m^{-3}). Greek and International regulations for radon in workplaces refer to only the mean annual radon concentration. It would be preferable for schools to replace the mean annual radon concentration with the 'true' radon concentration.

INTRODUCTION

About half of the effective dose coming from natural sources is estimated to be delivered by inhalation of the short-lived radon decay products. Due to this fact radon is the most 'popular' subject of studies on environmental radioactivity. Large-scale radon surveys have been performed in many countries[(1)]. In Greece, the two relatively larger radon surveys have been carried out by the University of Athens, from 1995 to 1998, using track etch detectors in 1277 dwellings[(2)] and by this team from Nuclear Technology Laboratory, Aristotle University of Thessaloniki from 1999–2006, using passive radon detectors (electrets) in 561 workplaces[(3)].

Greece is divided into 52 administrative regions (prefectures). In the previous work[(3)], 1122 passive radon detectors (electrets) were installed, door to door, in 561 workplaces (mainly schools) of 19 prefectures of Greece (mainland and islands). Among the 19 prefectures, the prefecture of Xanthi had the largest arithmetic mean (AM) radon concentration (229 Bq m^{-3}) and the highest percentage (42 %) of schools with radon concentrations above 200 Bq m^{-3}. Based on these remarks it was decided to perform radon measurements in all schools of the prefecture of Xanthi. In the present work, the results of these measurements are presented and discussed.

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MATERIALS AND METHODS

In the present work 154 passive radon detectors (electrets) were installed, door to door in 77 schools of the prefecture of Xanthi (Figure 1). The prefecture of Xanthi is located in northern Greece and has a population about 100 000. The Xanthi region geotectonically is part of the Rhodope Massif and is characterised by marbles, gneisses and schists.

The detectors were installed in the teachers' or director's office, mainly located in the ground floor. The detectors were installed in 42 schools in December 2007 and in 35 schools in February 2008. All detectors were collected from the 77 schools in October 2008. The schools of Xanthi, as almost all Greek schools are structures of masonry (concrete and brick). Most offices are ventilated only by operable windows (natural ventilation).

In each office two passive detectors (long-term electrets) were installed ~1–1.5 m above the ground. In this way, the risk of an erroneous result, due to a failure of one detector, was reduced. The electret ionisation chamber[(4)] is a small passive integrating device, designed for short- or long-term exposures. The device consists of a 50 mL conducting plastic chamber containing an electret. Radon gas passively diffuses into the chamber through filtered inlets, and the alpha particles emitted by the decay process of radon ionise air molecules. Ions produced inside the chamber volume are collected onto the surface of the electret, causing a reduction of its surface charge. The electret voltage decreases in proportion to the

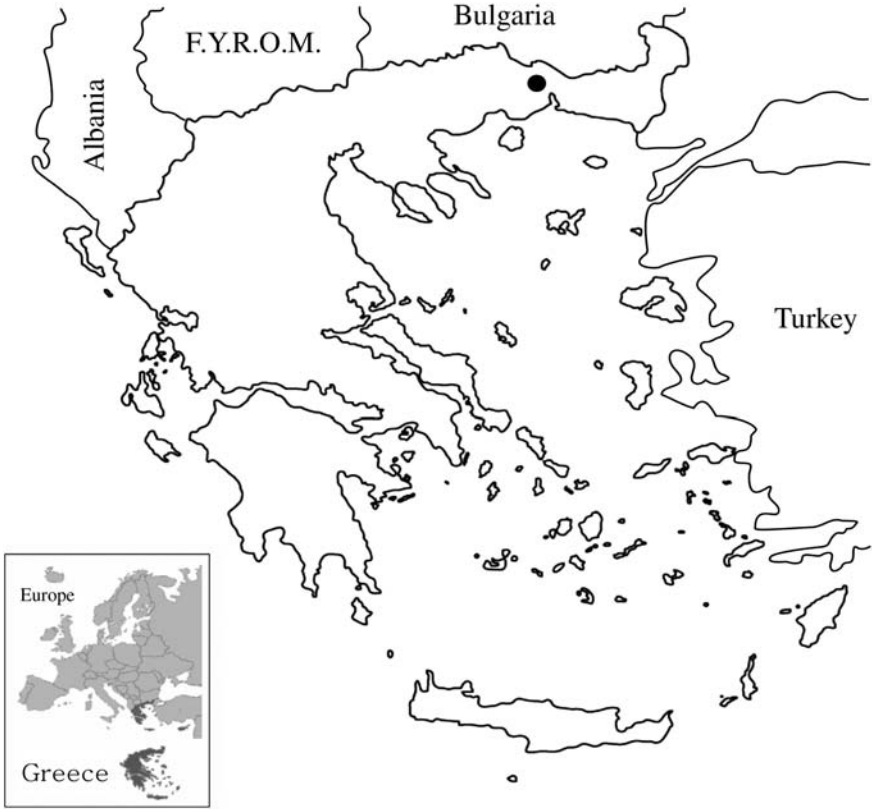

Figure 1. In close circle is shown the location of the prefecture of Xanthi (population ~100 000).

integrated radon concentration. A voltage reader is used to measure the electret surface voltage. Using appropriate calibration factors and exposure time, the mean radon concentration RnC (Bq m^{-3}) can be calculated from equations (1) and (2)

$$\mathrm{RnC} = [(V_\mathrm{I} - V_\mathrm{F})/(\mathrm{CF}\,T) - (G_\mathrm{amma}C_1)]37 \quad (1)$$

$$\mathrm{CF} = C_2 + C_3(V_\mathrm{I} + V_\mathrm{F})/2 \quad (2)$$

V_I and V_F are the initial and final electret voltages, respectively; T is the exposure time in days; G_amma is the gamma background in μR/h; and C_1, C_2 and C_3 are constants that are given by the manufacturer and they depend on the electret (short- or long-term) and on the volume of the conducting plastic chamber. The initial voltage of the long-term electrets here was about 700 V. The manufacturer suggests that the electret voltage must not be <200 V. Therefore the maximum electret decrease is 500 V. In Xanthi G_amma is ~10 μR/h. For about 8 months measurement of the radon concentration with long-term electrets and a 50-mL conducting plastic chamber, the electret decrease of 500 V corresponds (from equations (1) and (2)) to a radon concentration of about 2600 Bq m^{-3} (maximum detection limit). The experimental uncertainty of radon concentration measurements using electret ionisation chambers is <10 %[5]. During the installation of the detectors, indoor gamma exposure rate measurements, with a portable NaI detector, were also performed. The gamma exposure rate measurement is important for the evaluation of the radon concentration measured by the electrets. Radon measurements based on electret detectors are affected by the gamma background radiation, which also contribute to the electret discharge[6]. Therefore, the radon measurement results must be appropriately corrected for gamma background radiation, especially when measuring radon in areas of high gamma background.

RESULTS AND DISCUSSION

The arithmetic mean (AM), the range of the radon gas concentration, as well as the number of schools with radon concentration above 200 and

Table 1. Results of the survey: sample is the number of schools. AM is the arithmetic mean and the error of the AM is the standard deviation. The last two columns refer to the number of workplaces with concentrations above 200 and 400 Bq m^{-3}, respectively.

	Sample	AM (Bq m^{-3})	Range (Bq m^{-3})	>200 Bq m^{-3}	>400 Bq m^{-3}
Present work	77	231 $\pm$ 150	45–958	35 (45 %)	9 (12 %)
Previous work[3]	19	229 $\pm$ 76	110–458	8 (42 %)	1 (5 %)

400 Bq m^{-3}, are presented in Table 1. The values of 200 and 400 Bq m^{-3} are the action levels proposed by the European Commission for new buildings and existing buildings, respectively. In the same table are also presented the results of the previous work[3]. The uncertainty of each measurement is <10 %[5].

An interesting remark is that the AM of radon concentration measured in the present work is almost the same as the one measured previously for a smaller number of schools. In the present work, the high percentage of schools with radon concentration above 200 Bq m^{-3}, found in the previous work[3], is also verified. In addition, in order to check the reliability of the results here, once again the radon concentrations were measured in two schools which had higher values among the 19 schools measured in the previous work[3]. The radon concentrations for both the periods are almost the same (Table 2).

Using the measurements of radon concentration in schools, the percentage of measurements that exceed a specific concentration value C (in Bq m^{-3}) can be determined as a function of the radon concentration (Figure 2). The experimental values in Figure 2 can be very well described by an exponential function with a correlation coefficient almost equal to 1. Under some precautions described later, it can be assumed that the same function is applicable also for the dwellings. This assumption can be used to perform a crude estimation about the expected maximum radon concentration in dwellings in the Xanthi prefecture.

The population of the prefecture of Xanthi is ~100 000. If hypothetically three to four persons live in a dwelling, the number of dwellings <40 000 can be estimated. From Figure 2 is expected that in the case of 40 000 dwellings, theoretically only one dwelling will have radon concentration exceeding 1500 Bq m^{-3}. Of course, this is a rough estimation and must be considered with caution. Moreover, Figure 2 must be read prudently, due to the fact that radon measurements in schools cannot be compared with radon measurements in homes uncritically. Two main differences exist between the measurements in houses and schools.

(1) The variations of the radon concentrations in a building are mainly dependent on the variations of the ventilation conditions and air exchange between rooms. These are caused by meteorological conditions (wind, barometric pressure, temperature) and by human activities, such as opening windows and doors. Human activities are definitively different between schools and homes. Schools in Greece mainly operate from 8 h to 14 or 16 h. The rest of the day they are closed. In addition, with the exception of weekends, there are also long periods in the year when they are closed (Summer holidays, Easter holidays, Christmas Holidays). When schools are closed, an increase of radon concentration is expected due to poor ventilation. In the school with the higher annual radon concentration (958 Bq m^{-3}), radon measurements were performed from 20 January 2009 to 4 February 2009 every 10 min (Figure 3). The values of the AM radon

Table 2. Radon concentration in two schools for two different time periods.

	This work (2007–2008) (Bq m^{-3})	Previous work[3] (2005–2006) (Bq m^{-3})
School A	424 $\pm$ 42	458 $\pm$ 46
School B	387 $\pm$ 39	373 $\pm$ 37

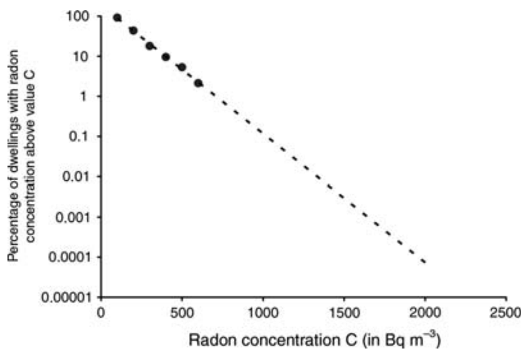

Figure 2. Percentage of dwellings with radon concentration above a certain value C (in Bq m^{-3}). The points are deduced from the experimental measurements in schools and the dashed line is the best exponential function that passes through the experimental values.

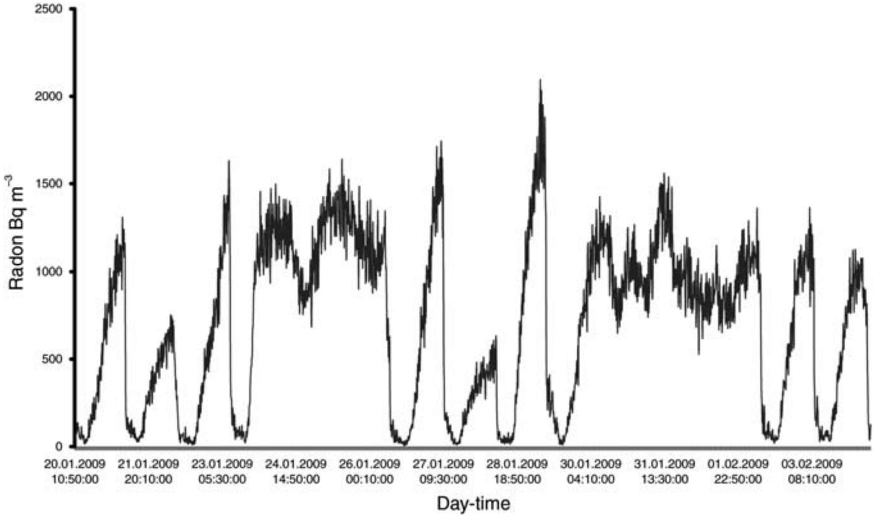

Figure 3. Radon measurements every 10 min in the school with the higher annual radon concentration (958 Bq m^{-3}) from 20 January 2009 to 4 February 2009. The values of the AM radon concentrations when the school was in operation and when it was closed are 104 and 866 Bq m^{-3}, respectively. The mean radon concentration for that period was 700 Bq m^{-3}.

concentrations when the school was in operation (8–16 h) and when it was closed (16–8 h every working day plus Saturdays, Sundays and 30 January all day) are 104 and 866 Bq m^{-3}, respectively. The mean radon concentration for that period was 700 Bq m^{-3}.

(2) Most offices studied in the present work are located in the ground floor. This is not the case for private lodgings where, at least in the big cities, most people stay in multi-storey buildings. It is well known that the radon concentration in the ground floor has the tendency to be higher than in the upper floors.

Due to the above reasons, indoor radon concentrations in schools must be higher than in houses.

According to the Greek Radiation Protection Regulations, the Greek Atomic Energy Commission was informed about the presence of nine schools with mean annual radon concentration above 400 Bq m^{-3}. In January 2009 in collaboration with scientists of the Greek Atomic Energy Commission, 64 short-term passive radon detectors (electrets) were installed in the 9 schools for a period of about 2 months. The detectors were installed in the same places as before (director's or teachers' office) and also in the classrooms. The detectors were collected from the schools in March 2009. The results were analysed and presented in Table 3. Two remarks should be noted:

- In the schools with code numbers 5 and 8 the mean indoor radon concentrations in the teachers' office for the time period January–March 2009 were lower than 400 Bq m^{-3} (265 and 295 Bq m^{-3}, respectively). On the contrary, in the same offices the mean radon concentrations from December 2007 to October 2008 were 536 and 424 Bq m^{-3}, respectively.
- In the school with code number 1 only the teachers' office has relative high radon concentration (751 Bq m^{-3}). In the same office the mean radon concentrations from December 2007 to October 2008 was 958 Bq m^{-3}. All the other rooms (director's office and classrooms) have relatively low radon concentrations.

Table 3. Radon concentrations in different rooms of the nine schools of Xanthi. The measurements were performed with radon passive detectors (short-term electrets) from January to March 2009.

	Teachers' office (Bq m^{-3})	Director's office (Bq m^{-3})	Classrooms (range) (Bq m^{-3})
1	751 ± 75	85 ± 9	133–152
2	486 ± 48		111–317
3	514 ± 51		587–1161
4	754 ± 75	415 ± 41	513–634
5	261 ± 26		164–211
6	438 ± 44		197–273
7	457 ± 46		378–394
8	295 ± 29	250 ± 25	82–294
9	489 ± 49	655 ± 65	223–846

As mentioned previously, in all schools the indoor gamma dose rate was measured with a portable NaI

Table 4. AM and range of indoor gamma dose rates.

	AM (nGy h^{-1})	Range (nGy h^{-1})
This work	101 ± 23	40–180
Previous work[3]	110 ± 26	62–149

detector. The gamma dose rate measurements are within the standard deviations, similar to those previously reported (Table 4).

CONCLUSIONS

The mean arithmetic radon concentration in the 77 schools of Xanthi is 231 Bq m^{-3} with a range between 45 and 958 Bq m^{-3}. Thirty five schools have a mean radon concentration above 200 Bq m^{-3} and nine schools have a mean radon concentration above 400 Bq m^{-3}. The AM of radon concentration measured in the present work is almost the same as the one measured previously on a smaller number (19) of schools. Additionally the present work verified the high percentage of schools with a radon concentration above 200 Bq m^{-3} found in the previous work[3].

In the nine schools, where the value of 400 Bq m^{-3} is exceeded, additional radon measurements were performed not only in the director's and teachers' office but also in the classrooms.

According to the Greek and International regulations for radon concentration in workplaces, only the mean annual radon concentration value is considered. School is a special workplace due to the fact that it remains closed for many hours per day and many days per year (due to holidays) and, consequently, the 'true' radon concentration (the radon concentration during the hours of presence of teachers and scholars) is smaller than the mean annual radon concentration. From continuous measurement of the radon concentration in the school with the relative higher mean annual radon concentration (958 Bq m^{-3}), the mean 'true' radon concentration for a time period of ~2 weeks was 104 Bq m^{-3}. The mean radon concentration for these specific 2 weeks was seven times higher (700 Bq m^{-3}). This particularity of the school as a workplace perhaps should be taken into account in future regulations, and the mean annual radon concentration should be replaced by the mean 'true' radon concentration.

ACNOWLEDGEMENT

The authors would also like to thank Joelle Guilhot (Zoel Gkilo) for participating in the radon measurements.

FUNDING

This work was financially supported by the prefecture of Xanthi.

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