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Indoor Air 1993, 3: 361–368
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Indoor Air
ISSN 0905-6947

Challenges in Comparing Radon Data Sets from the Same Swedish Houses: 1955-1990

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Abstract

We compare data sets from two different Swedish studies which included measurements of the indoor radon concentration both in 1955 and in 1990 in 178 of the same houses. The purpose is to learn more about how the indoor radon concentration changes over a time scale of years in the same houses. Many sources of both systematic and random errors exist when comparing these types of data sets. Specific types of errors are due to uncertainties in the calibration of the epuipment, the influence of the weather, the time lengths of sampling, airing of some of the dwellings, and changes in ventilation rates. The data indicate a general increase of the radon concentration in the dwellings between 1955 and 1990, with a 1990/1955 ratio of the averages of 1.3. The average radon concentration in all alum shale houses, (where the building material is a source of radon) in 1990 versus 1955 is 204 ± 22 and 163 ± 23 Bq/m³ and in non-alum shale houses is 62 ± 8 and 42 ± 7 Bq/m³, respectively.

KEY WORDS:
Radon surveys, Swedish dwellings, Comparison of radon data sets, Radon time variation

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Introduction

Knowledge on the changes over time in indoor radon concentrations in the same dwellings is essential in the estimation of the exposure history in radon epidemiologic studies. There are indications of a general increase of the indoor radon concentration in Swedish dwellings since the beginning of the century (Swedjemark et al., 1987). One possible reason for this trend is that decreasing the ventilation rate in a dwelling (to conserve heat) will, with the same radon source strength, increase the indoor radon concentration (e.g., Stranden, 1979, and Swedjemark, 1985). This can happen in the housing stocks of both Sweden and of other countries. The study discussed here is designed to check this trend, and is carried out to be one part of the estimation of errors in the Swedish nationwide radon epidemiologic study (Pershagen et al., 1993). Other Swedish studies with the same purpose, but different designs, have been carried out (Swedjemark, 1993; Burén-Haglund, 1990; Bäverstam and Swedjemark, 1991) In the few epidemiologic studies that have been reported which included house measurements of the radon concentration, no change in the radon concentration over the lifetime of the house was assumed (Pershagen, 1993).

This study makes use of a unique data set consisting of radon concentrations measured in Swedish dwellings in 1954-55 (Hultqvist, 1956). Some of the dwellings have been revisited and remeasured in 1990. There is a variety of errors associated with both studies and with their comparison. The errors come from (I) comparing grab samples with three month averaged samples, (II) inconsistencies in filling in the questionnaire, and differences in (III) the habits of the 1990 inhabitants compared with those in 1955, (IV) how the air was sampled, (V) the calibrations of the instruments, (VI) the errors of each measurement technique, and (VII) the environmental parameters during the measurement period. The information reported here is a portion of a more detailed report (Hubbard and Swedjemark, 1993b). To our knowlegde no other comparison of radon data taken at two different times, separated by years, from the same houses have been made, either in Sweden or in other countries.

Material and Methods

As part of a study in 1954-55 of the gamma radiation in the 1945 Swedish housing stock, the radon equivalent content (defined below) was measured in a subset of 287 homes in four towns in central Sweden by Hultqvist (Hultqvist, 1956). In 1990 the radon gas concentration has been measured in 178 of these homes, 136 dwellings in multi-family buildings and 42 detached (single-family) houses. The ventilation systems were originally of natural draught type in all houses. Natural draught ventilation in Swedish houses consists of a system of outlet ducts from wet rooms such as kitchens and bathrooms. The ducts are connected to one or more ventilation chimneys and the system works due to thermal forces. Most of the multi-family houses were built with two or three floors above a basement. Almost all of the detached houses had basements.

In 1955 the radon samples were all taken before noon, usually in the living room. The houses were divided into two groups; one termed 'aired', where the dwellings had been aired one or two hours before the measurements, typically for a time less than an hour. The dwellings in the group 'non-aired' had not been aired since the day prior to the measurements. Most of the samples were taken between March and June 1955.

The 1990 measurements were three-month integrated samples collected during the heating season between 15 December and 15 May. The inhabitants were asked to ventilate their homes throughout the measurement period as they normally would. The building was inspected at the same time that the detectors were placed in the dwellings. The final data set contains the radon concentration, type of building material, the airing conditions from the 1955 data set, and a variety of digitized information from the 1990 sampling. This information contains both bedroom and living room radon concentrations each averaged over three months, level of house where these rooms are located, whether it is a single- or multi-family building, whether the ventilation is still natural draught or has been changed, and whether or not 11 different types of physical changes have been made to the building since 195 In the following discussion and figures, the 19 living room radon concentrations are compared the 1955 values. A comparison between 1990 bed room and living room values can be found in Hub bard (1993b).

Ion chambers were used for the instantaneou sampling in 1955. The air samples were pumpe directly into the chambers without filters. Whe radioactive equilibrium was reached, a voltage wa applied between the outer wall and the central elec trode. The charge due to ionization was collecte on the central electrode and measured. This charg was directly proportional to the radon equivalen content when the exposure time was known. Th air sampled in the ion chambers contained both radon-222 and radon-220 (thoron) together with thei progeny, but the short-lived radon progeny and th thoron gas which was initially present in th sampled air had decayed at the time the charge was measured. The results, therefore, depend on the actual combination of the concentrations of radon and thoron, the thoron progeny, and, with lesser significance, the long-lived radon progeny, and was called the radon equivalent content (Hultqvist, 1956). The standard deviation due to counting statistics was estimated to be about 3%.

The decay products from thoron present a bigger problem than those from radon when comparing radon gas concentrations from 1990 with the radon equivalent content from 1955. Disintegration of the thoron progeny decreased it to one third by the time of the measurement of the charge, and therefore the thoron, if present, will add to the signal measured in 1955. Thus, the radon equivalent content will overestimate the radon-222 concentration if thoron was present in significant quantities. Hultqvist found the contribution from thoron and decay products low in the studied houses. The average Th of the 61 houses measured was found to be a factor of 18 less than the average Rn. Other studies suggest that the concentrations of thoron and decay products could have contributed to the radon equivalent content in 1955, although these other studies included only a small part of the Swedish housing stock (Mjönes et al., 1993; Falk 1992), and none of the houses from the present study.

The 1990 integrated measurements of the radon gas were performed using a CR-39 alpha track detector material, chemical etch, and automatic readout by an image analysis system (Mellander and Enflo, 1993). For a measurement time of 90 days the total measurement uncertainty at the 65% confidence level is 10% at 60 Bq/m^3 (becqurel per cubic meter), 7% at 115 Bq/m^3, and 5% at 370 Bq/m^3 (Mellander and Enflo, 1993).

The calibration of the 1955 ion chamber was carried out using the same principles as today. The difference is that now the known amount of radon is taken from the Standard Reference Material of the National Institute of Standards and Technology (Falk et al., 1982, 1990). The 1955 known amount was determined by counting each alpha particle disintegration in a volume containing the same amount of radon as that of the instrument calibrated. As a summary, the total estimated uncertainties within a 65% confidence interval due to the detector systems were about 13% for the 1955 measurements and 5-10% for the 1990 measurement. Of these errors 12% (Hultqvist, 1956) and 2% (Mellander and Enflo, 1993), respectively, depend on the calibration. If these errors are treated independently, they add to give 14%, and this is one possible source of a systematic error. Other errors in the comparison are discussed in the results section.

Although the 1955 radon concentrations were collected using grab samples, the sampling was performed by Hultqvist in a carefully executed study at Sweden's Radiation Protection Institute as part of his doctorate research, under the direction of Professor Rolf Sievert. Among other things, Hultqvist pioneered a measurement of the diurnal variation of indoor radon (Hultqvist, 1956). He, thus, chose to perform all of his measurement close to the same time of day, between 8 and 12 noon. Although his measurements were performed using grab samples, with all their inherent uncertainties due to the time variations of radon, they were performed in a carefully planned study.

Results

Figure 1 shows the frequency distribution of all data with the radon concentration less than 510 Bq/m^3 (176 cases). There are two more cases, not plotted for graphical purposes, both with concentrations less than 1200 Bq/m^3. Their 1990/1955 values are 726/1169 and 833/252, and both are alum shale houses. These points are included in all the reported results and discussion below. The distributions show that the 1990 data are more heavily weighted towards higher radon concentrations. The 1990 data resemble a log-normal distribution, but the 1955 data do not.

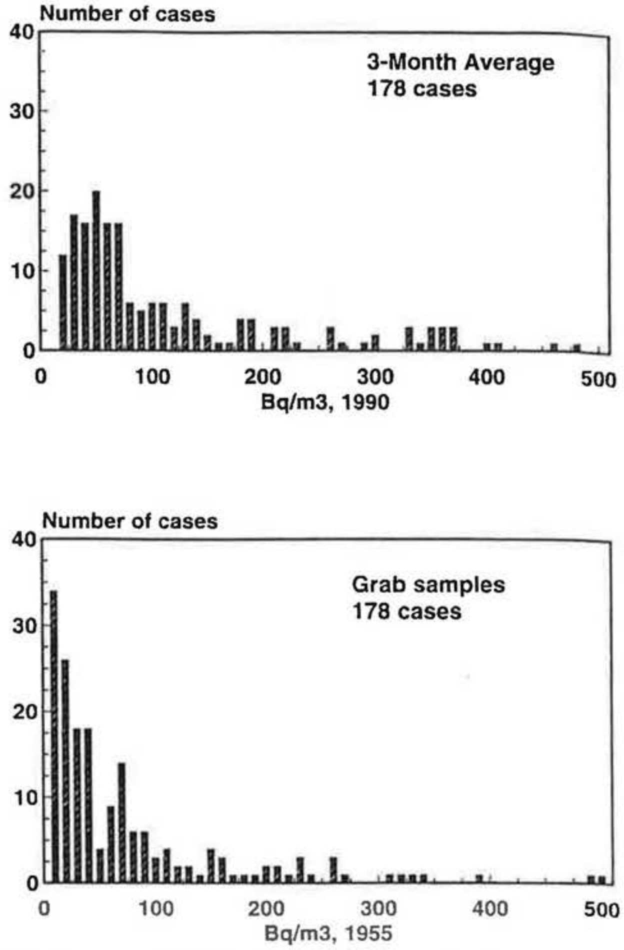

Fig. 1 Frequency distribution of all 176 cases less than 510 Bq/m^3 for both 1955 and 1990.

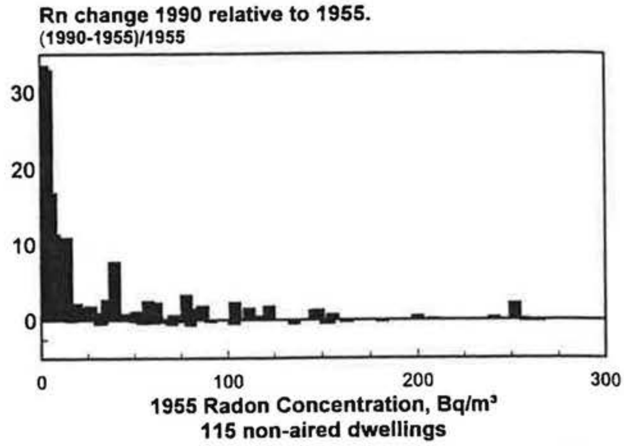

Fig. 2 All 115 non-aired cases. (Rn(1990) − Rn(1955))/Rn(1955) as a function of Rn(1955) in Bq/m^3, plotted as a bar-chart.

Sixty-three of the homes had been aired before the grab samples were taken in 1955. It is obvious to expect that the data from the aired houses in 1955 will underestimate the average radon concentration.

Figure 2 displays the data without the 63 aired cases, plotted as the difference between the radon concentration in 1990 and 1955, relative to the 1955 measurement result. A positive value means the radon concentration was greater in 1990 than in 1955. It is obvious that after removal of the data from the aired houses, the 1990 values are still in general greater than the 1955 values. Using the Kolmogorov-Smirnov statistics to test whether the two distributions are different, both the original sets of 1990/1955 distributions with 178 cases and the reduced, non-aired distributions with 115 cases are found to be different with a $P \le 0.01$.

Of the 115 cases remaining after the aired 1955 data were removed, 63% (or 72 cases) show an increase in 1990 over 1955. If we remove all cases less than 20 Bq/m^3, where any absolute error in the measurement gives a large relative error, as can be seen in Figure 2, there is still 63% (or 58 cases of 92) which show an increase in radon in 1990 over 1955. Removal of all cases less than 20 Bq/m^3 also does not change the shape of the 1955 distribution shown in Fig. 1.

The best comparison between 1955 grab sampling and 1990 3-month average sampling should be for the class of houses which have a source of radon from the building material and not from the ground, since the radon source strength in soil gas entry varies with the weather and soil conditions. The radon source strength from the building material is relatively constant with time, and the indoor radon concentration varies with the ventilation rate. If we choose the data with the conditions of alum-shale concrete, apartments with no ground contact in multi-family buildings, natural draught ventilation, and no reported changes made to the house since 1955, there remains 16 out of the original 178 cases, plotted in Figure 3. These are too few points to perform any meaningful statistics. However, we find it quite remarkable that of the 16 cases, 13 pairs of the data are in close agreement to each other, with a linear fit r^2 of 0.96. Three more points are all about triple the 1955 value in 1990. This gives credibility to the comparison of the two data sets.

Comparing Three-month Measurements with Instantaneous Ones

Three-month integrated and instantaneous measurements of radon concentrations were compared in a study conducted in 1990 in Gävle in Central Sweden (Swedjemark and Hubbard, 1993), in a different set of houses than in this study. The data are displayed in Figure 4. These data are the best one could hope for in comparing averaged with instantaneous measurements, since they were taken in the same houses by the same people, and using equivalent calibration techniques. The instantaneous samples were collected using the radon gas detector RM3, and a 30-minute sampling time taken on the first day of the integrated sampling time. The grab samples were taken between 8:00 and 17:00 in the Gävle study compared to always between 8:00 and 12:00 in the 1955 study. (There are three groups of dwellings marked in Figure 4. Those marked by boxes in the figure are single-family dwellings with natural draught ventilation. The circles mark multi-

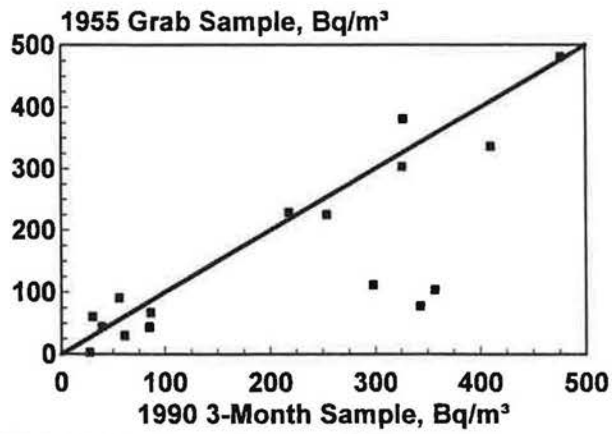

Fig. 3 Radon concentrations in Bq/m^3. The 16 benchmark cases which should have the best agreement between 1990 and 1955. These cases are multi-family dwellings with alum-shale building material, no ground contact, natural draught ventilation, and no changes made to the dwelling since 1955.

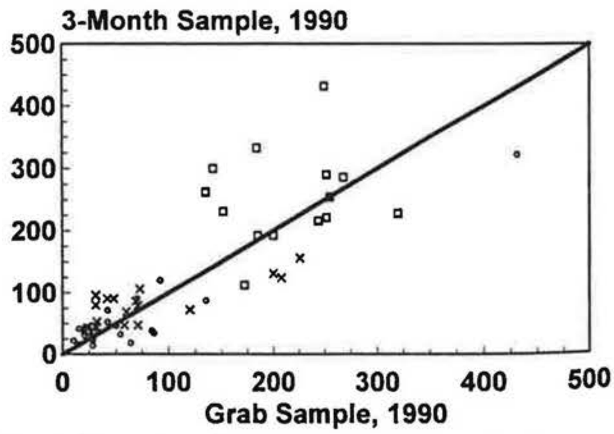

Fig. 4 Comparison of instantaneous and integrated radon concentrations (in Bq/m^3) measured in the same 58 dwellings in 1990. These dwellings were not part of the Hultqvist study discussed herein. ○ = multi-family dwellings with mechanical exhaust ventilation. × = single-family dwellings with mechanical exhaust ventilation. □ = single-family dwellings with natural draught ventilation.

family and the x's mark single-family dwellings, both groups with mechanical exhaust ventilation.)

There are too few points to obtain a statistically meaningful distribution. However, it is interesting to note that the best agreement between a grab and integrated sample (i.e., to the y = x line displayed in the figure) is for the multi-family homes with mechanical exhaust ventilation, (with linear fit coefficients of a = 11, b = 0.7, and $r^2 = 0.88$). Of the three types of dwellings, this group should have radon levels which vary the least, (and therefore give the best agreement between grab and integrated measurements), since multi-family dwellings have less influence from soil radon than single-family dwellings, and mechanical exhaust ventilation keeps the ventilation rate more constant than natural draught ventilation.

The distribution with the most spread (and least agreement between grab and integrated samples), is for the single-family dwellings with natural draught ventilation, (with linear fit $r^2 = 0.40$). Again, this is what one would expect since these dwellings have the widest time variations in radon source strengths and ventilation rates, and thus indoor radon concentration. Finally, of the data displayed in Figure 4, 70% of the points deviate from the y = x line by less than 25% of the measured integrated radon level.

Influence of Environmental Parameters

Changes in indoor and outdoor temperatures and in the wind speed change the amount of air flowing across the building shell. The radon exhalation from the ground also changes with environmental parameters. This means that the radon levels vary on short as well as long time scales. The variations are not very high for dwellings in multi-family buildings without direct contact with the ground, when the major radon source is the building materials. However, large short-term variations are common in detached houses with natural draught ventilation systems (Swedjemark, 1985: Hubbard, 1993a).

The temperatures for 1989/90 were all significantly higher than in 1955. Table 1 shows the averaged monthly temperatures for some towns in central Sweden where the homes in this study are located. Data presented and discussed in ref. (Hubbard et al., 1993a) show that higher outdoor temperatures can lead to higher indoor radon values in natural draught ventilated dwellings because of decreased ventilation. This is especially true if the temperature is not so high as to cause occupants to open windows. Since all the homes in this study originally had natural draught ventilation and most still do, the temperature effect can be part of the explanation for generally higher radon values in 1990. It is not at all clear, however, without house specific data on the radon dependence on temperature, how a temperature correction could be applied to the data without introducing one more source of error. We have thus not attempted to apply any temperature correction.

Perhaps more important, however, is the fact that the 1955 samples were always taken between 8:00 and 12:00 noon. In the presence of only temperature dependent pressure differences across a building shell, daily radon profiles are similar (or opposite) to daily temperature profiles, and often sinusoidal in nature. Figure 4 of reference (Hubbard et al., 1993a), shows the averaged diurnal profile of the outdoor temperature and indoor radon in two different houses with natural draught ventilation, during a period when there was no wind or other forces causing pressure differences. The daily variation of the indoor radon in one house, as an average of several days, follows the daily temperature profile while in another house it is exacly the opposite. But in both houses the time between 8:00 and 12:00 falls in a portion of the radon profile which is close to the daily average radon concentration, and thus a good time to grab a radon sample. This is not necessarily true during windy days. It has been shown that the time for grab sampling is of less importance for houses where the dominant radon source is the building materials (Swedjemark, 1985). The errors which can be attributed to the weather can be summarized as follows. The overall higher temperatures in 1990 compared to 1955 could have given higher averaged indoor radon concentrations in 1990. There is not enough data from this or other studies to know how much this could have influenced the concentrations, either on the

Table 1 Average monthly temperatures (Celsius) for some towns in central Sweden. (Swedish Meteorological and Hydrological Institute).

	Stockholm		Örebro		Linköping	
	1955	1989/90	1955	1989/90	1955	1989/90
Jan	−2.7	+1.3	−4.1	+1.6	−2.3	+2.3
Feb	−4.5	+4.3	−6.2	+4.3	−5.0	+4.8
March	−2.7	+4.8	−2-9	+5.1	−2.1	+5.3
April	+1.7	+7.4	+2.4	+6.9	+3.3	+7.2

average or in individual houses. The period of the day between 8:00 and 12:00 noon is a representative time of the daily averaged concentration and a good time to grab a radon sample in a house with natural draught ventilation on non-windy days.

Changes Made on the Homes

The questionnaire which was completed by the house occupants in 1990 contained a question on whether or not 10 different types of changes which could influence the radon concentration had been performed on the house (Hubbard and Swedjemark, 1993b). Some of the changes could increase the radon concentration, such as various types of tightenings to save energy. Other of the changes could decrease the radon concentration, such as installations which increased the ventilation rates. Some homes had made no changes, some had made more than one type of change which could both increase or decrease the radon, and some had made a change or changes which should act in one direction or the other.

Considering the 115 non-aired cases, 37% (or 42 cases) of the dwellings had made a change between 1955 and 1990 which could have increased the radon levels. Of the 42 cases, 74% showed an increase in the measured radon levels in 1990 over 1955. In the subset of homes reporting no changes, (48% or 55 cases of the 115 total), 69% showed an increase in the radon level in 1990. If the increase is real in all or even a subset of these homes, and not due to the errors inherent in the comparison of the two data sets, then the radon levels may have increased due to natural changes from aging of the houses. Examples of the effects of aging are cracks in the building shell, in the ventilation tubes, and increasing levels of dirt in the ventilation tubes.

In addition to the errors discussed above, there are inherent inconsistencies in how the questionnaires were filled out in the 1990 study, so there will be errors in dividing the data into subsets af data. We assume that this source of error will give random and unbiased deviations.

Discussion

Figures 5 and 6 show the subsets of the data for alum-shale and non-alum-shale building materials for the non-aired 1955 data (55 and 60 cases, respectively). A small subset of these buildings may have also had a radon source from the soil. Both distributions had higher radon concentrations in 1990 than in 1955. The alum-shale dwellings had higher radon concentrations than the non-alum-shale dwellings with arithmetic averages and standard errors of 204 ± 22 Bq/m^3 and 163 ± 24 Bq/m^3, respectively for 1990 and 1955. The non-alum-shale dwellings had average values of 62 ± 8 Bq/m^3 in 1990 and 42 ± 7 Bq/m^3 in 1955. The difference between the alum-shale 1990 and 1955 averages is 41 ± 32 Bq/m^3, and for the non-alum-shale buildings it is 20 ± 11 Bq/m^3, both statistically significant ignoring systematic errors.

This brings us to the question as to whether the general tendency for the 1990 radon concentrations to be higher is a real signal or due to a systematic error. From the data discussed above, the systematic error due to calibrations sums to 14%. The systematic error due to different sampling lengths has been estimated at not higher than 20% (Swedjemark, 1985), By adding the variances, possible because the

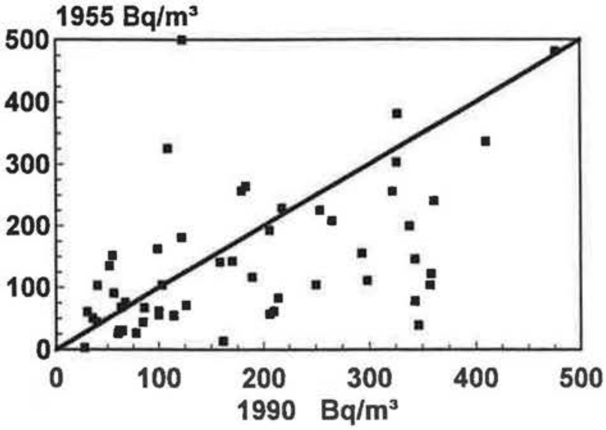

Fig. 5 Dwellings made of alum-shale concrete, 55 cases. Non-aired 1955 data. y = x line displayed.

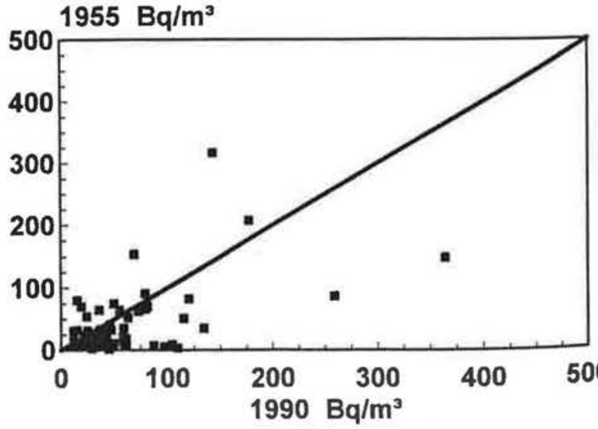

Fig. 6 Dwellings not made of alum-shale concrete, 60 cases. Non-aired 1955 data. y = x line displayed.

uncertainties are independent, the systematic error sums to 24%. In the extreme case, this error acts entirely in the direction of increasing the 1990 values, and we can ask whether the 1990 values are in general higher than the 1955 values only because of these systematic errors. A test of the significance of this tendency has been performed by decreasing the 1990 values by 24% and performing a Kolmogorov-Smirnov statistics on the two distributions, which shows that they still differ but with less confidence than before; P lies between 0.1 and 0.15. The distribution with the 1990 values reduced by 24% still has 54% of the cases with the 1990 radon concentration greater than 1955.

This result suggests that the difference between the climate conditions during the 1990 and 1955 measurements can be part of the explanation of the higher radon concentrations in the 1990 data, as discussed above. However, it could also indicate that aging of the buildings, e.g., cracks in the foundation, is an influence causing higher radon concentrations in the 1990 data. This should have a greater importance for non-alum-shale dwellings with ground contact where the soil is the major radon source. For the alum-shale dwellings without ground contact, detoriorated ventilation systems could be an important cause for increased radon concentrations.

Conclusions

A majority of the radon concentrations were lower than 200 Bq/m^3 in both the 1955 and the 1990 data set (89% and 81% respectively) which is not far from the corresponding percentage for the whole of Sweden (90%) measured in 1980-82. All levels were lower than 500 Bq/m^3 with the exception of two alum-shale dwellings which had levels lower than 1200 Bq/m^3.

The major systematic errors in the two data sets are the following:

- The estimated systematic error due to calibration is 14%.
- It is not probable that the average systematic error due to different sampling time lengths is higher than 20%. Big differences due to this parameter can occur for individual data, but the sign of the differences can be opposite.
- The contribution of thoron will overestimate the 1955 data.
- If the two first systematic errors are independent, then the systematic error is approximately 24%.

Decreasing the 1990 data by 24% and testing the distributions to see if they differ shows that they do, using Kolmogorov-Smirnov statistics, with P between 0.1 and 0.15. The unchanged, original distributions differed with $P <= 0.01$. Although some of this tendency may still depend on some of the errors described, it is also possible that this tendency is a real change due to aging or a change carried out on the house.

A final and important conclusion from this study is that it is extemely difficult to compare different data sets for radon concentrations, even those taken from the same homes and by the same institute. Different years and weather, sampling and calibration techniques, and individual and therefore inconsistent answers to questionnaires are all complicating factors. Because of this, it is clear that one must be extremely cautious in performing comparisons of any kind. This caution should especially be remembered in any future studies comparing data from different countries.

Acknowledgements

We thank Agneta Burén-Haglund, Lars Mjönes, and Gabor Szendrö for work during the initial measuring phase, together with Hillevi Giertz and Istvan Horvath, who also produced and evaluated the alpha track films. We are grateful to the local health inspectors for the inspection of the dwellings and to the inhabitants for their cooperation. We thank Ulf Bäverstam for valuable discussions and Hans Möre for his critical reading of the section on calibrations.

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