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Assessment of Airborne Radon Daughter Concentrations in Dwellings in Great Britain

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ABSTRACT. Calculations of the activity concentration of RaA (^{218}Po) in the air within living rooms and in the outside air were made at 87 dwellings in England and Scotland. From these measurements together with a determination of the ventilation rate existing in the room at the time of the measurements, the rate at which ^{222}Rn is emanating from room surfaces into room air in pCi l^{-1} h^{-1} can be calculated. For the dwellings studied the mean emanation rate is 0·54 pCi l^{-1} h^{-1} and on the basis of a mean ventilation rate of one room change per hour throughout the year and assuming an occupancy factor of 0·8 the population exposure rate for the population of Great Britain to the short-lived daughters of ^{222}Rn is estimated to be 0·15 Working Level Months per year.

1. Introduction

Within five years of Becquerel's discovery of radioactivity Elster and Geitel (1901) demonstrated that radioactive nuclides are present in the atmosphere. Investigations of this finding revealed that the nuclides present were radon (^{222}Rn) and thoron (^{220}Rn) and their respective daughter products. Interest in atmospheric radioactivity has continued from these pioneer studies to the present day.

Underground miners in certain areas of the world (where the uranium content of the subsoil is high) have been recorded as suffering from an excess of respiratory disease since the sixteenth century (Agricola 1556). Towards the end of the last century a large proportion of respiratory disease in miners was diagnosed as lung cancer and in some mining communities the prevalence of this disease may be regarded as reaching epidemic proportions. In Schneeberg, Germany, between 1877 and 1879 75% of the deaths among working miners were due to lung cancer (Harting and Hesse 1879 quoted in Lorenz 1944). Similar mortality was occurring in miners in Joachimstal, Czechoslovakia, although the cause was not recognised until 1926. Autopsy studies between 1929 and 1938 revealed that 50% of deaths among miners at Joachimstal were due to lung cancer (Peller 1939). From 1924 suggestions were made that the causative agent leading to the excess of respiratory disease in uranium miners might be radon-222 in the mine air (Ludewig and Lorenser 1924, Sikl 1930, Saupe 1933). Bale (1951, quoted in Stewart and Simpson 1963) calculated that the major proportion, greater than 99%, of the dose delivered to lung was due to the short-lived daughters of radon-222 and not the radon itself. These short-lived daughters of ^{222}Rn are ^{218}Po (half-life 3·05 min), ^{214}Pb (half-life

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26·8 min), ^{214}Bi (half-life 19·7 min) and ^{214}Po (half-life $1{\cdot}6 \times 10^{-4}$ s). These nuclides have traditionally been given the names RaA, RaB, RaC and RaC^1 respectively. RaA and RaC^1 are emitters of alpha particles but due to the short half-life of RaC^1 this nuclide is, for all practical purposes, always in equilibrium with RaC and the alpha particle emitted by RaC^1 may be regarded as a prompt alpha particle from RaC. Following the indictment of the short-lived daughters of radon and in view of the difficulty in measuring the individual daughter activity concentrations under working conditions in a mine, a special unit was adopted for measuring the potential hazard. This unit, the Working Level (WL), is defined as any combination of the short-lived decay products of radon-222; RaA, RaB, RaC and RaC^1 in one litre of air which will result in the ultimate release of $1{\cdot}3 \times 10^5$ MeV of alpha energy in decaying to ^{210}Pb (RaD). Although this definition is satisfied by an activity concentration of 100 pCi l^{-1} each of RaA, RaB, RaC and RaC^1 the definition is independent of any particular state of daughter equilibrium (Evans 1969; this reference is an excellent introductory text to the properties of radon daughters). The cumulative exposure to the short-lived daughters of radon-222 is measured in Working Level Months (WLM), one WLM being an exposure at one Working Level for one working month (taken as 170 hours), or 0·5 WL for two working months and so on. Following an intensive study of the mortality of uranium miners in the United States (Lundin, Wagoner and Archer 1971) the correlation between the cumulative exposure to the short-lived daughters of radon and the excess incidence of lung cancer was demonstrated beyond reasonable doubt.

Exposure to the short-lived daughters of radon is not confined to underground miners. Uranium is widely distributed in the earth's crust, typically in concentrations of 2–4 parts per million (Evans 1969) and in consequence is found in most materials commonly used by the building industry. Radium being a decay product of uranium is also found in building materials and acts as the source of radon. Clay bricks contain typically 1·4 parts per million of radium whereas granite bricks have an elevated concentration of 2·4 parts per million (Hamilton 1971). Radon, being a noble gas, diffuses from the room surface materials and from the subsoil below the building into room air, where it and its daughters are available for inhalation by the room occupants.

Over the last 25 years various authors have expressed concern at the actual or proposed use of building materials with radium concentrations substantially in excess of those in traditional materials (e.g. Hultqvist 1956, Pensko 1975). An assessment of the radiological implications of using by-product gypsum from the phosphate fertiliser industry, which has a higher radium concentration than the natural product, was undertaken by O'Riordan, Duggan, Rose and Bradford (1972) and they considered the effect of the resultant additional exposure to radon and its daughters. For future exercises of this kind it would be helpful to have a knowledge of the current exposure of the general population to these nuclides. Such knowledge may also be useful in assessing the significance of some of the radioactive nuclides present in the atmosphere as a result of mankind's various activities. Caruthers and Waltner (1975) and Parthasarathy (1976) called upon the United States National Council on

Radiation Protection to set maximum permissible concentrations of ^{222}Rn in buildings in the light of the activity concentrations that had been measured in public and private buildings. The setting of such a limit can be made meaningfully only if the range of concentrations existing in traditionally constructed buildings and in particular in dwellings is known.

Extensive surveys of the activity concentrations of radon and its daughters have been reported in Sweden (Hultqvist 1956), Hungary (Toth 1972), Poland (Pensko 1972) and Austria (Steinhausler 1975). Toth and Pensko give results only for poorly ventilated rooms. Steinhausler assumes equilibrium between radon-222 and its short-lived daughters in poorly ventilated rooms but gives no information as to the actual ventilation conditions of the room existing at the time of the measurements. Haque, Collinson and Blyth-Brooke (1965) measured radon activity concentrations in several rooms in London but merely categorised the rooms as adequately or inadequately ventilated. Davies and Forward (1970) reported levels of radon-222 indoors and out-of-doors at a location in Surrey but did not measure the equilibrium conditions existing at the time of their measurements. Hultqvist (1956) discussed the effect of ventilation but again gave results in terms of ventilated and unventilated rooms. Duggan and Bradford (1974) reported the results of a preliminary survey of radon and its short-lived daughter activity concentrations in domestic dwellings. These authors took account of the ventilation rate existing at the time of the measurements in the rooms under investigation. The work reported in this paper is an extension of the survey initiated by Duggan and Bradford and relies heavily on the foundations laid by those authors.

2. Method of measurement

2.1. *Outline of the method*

In both outside air and the air within buildings the activity concentrations of radon and its daughters exhibit large temporal fluctuations. Steinhausler (1975) measured activity concentrations of radon-222 in rooms of buildings which were stated to be unventilated and attempted to correlate the wide fluctuations observed with a number of meteorological variables. However, no measurements of actual ventilation rate were made and in a closed room ventilation by infiltration through brick work and cracks surrounding doors and windows is far from constant (see section 3 below). Such changes in ventilation rate will alter the concentration of radon and its daughters existing within the room.

The approach adopted by Duggan and Bradford (1974) and continued by this author is to assume that the most important factors which determine the radon and daughter concentrations within a room are:

(i) the rate of exhalation of radon into the room, and
(ii) the ventilation rate existing in the room.

The first factor may be regarded as essentially constant as it is mainly dependent upon the radium content of the material used in the construction of the building and of the ground beneath it; relative humidity, atmospheric pressure and temperature being secondary influences. The effects of ventilation will be considered later.

Following the approach adopted by Hultqvist (1956), consider a room with a constant ventilation rate of j room changes per hour. Let

- Q be the number of atoms of the nuclide of interest per litre of room air,
- Q^1 be the number of atoms of the nuclide of interest per litre of outdoor air,
- C be the activity concentration of the nuclide of interest, in pCi l^{-1}, in the room air,
- C^1 be the activity concentration of the nuclide of interest in pCi l^{-1}, in the outdoor air,
- λ be the decay constant of the nuclide of interest expressed in h^{-1}. The values for ^{222}Rn; RaA, RaB and RaC being taken as $0{\cdot}00755\ h^{-1}$, $13{\cdot}63\ h^{-1}$, $1{\cdot}552\ h^{-1}$ and $2{\cdot}111\ h^{-1}$ respectively,
- k be the number of radon atoms emanating from the room surfaces per litre of room air per hour,
- K be the number of picocuries of radon emanating from the room surfaces per litre of room air per hour (pCi l^{-1}, h^{-1}). K will be called the radon output of the room.

The subscripts R and A refer to radon and RaA respectively.

Assuming that air enters the room from outside at a constant rate, mixes uniformly with the room air and that this mixed air leaves the room at the same constant rate then

$$\frac{dQ_R}{dt} = k - \lambda_R Q_R - jQ_R + jQ^1_R \tag{1}$$

and in the steady state

$$k = \lambda_R Q_R + jQ_R - jQ^1_R. \tag{2}$$

Using this relationship k may be found from the measurement of j, Q_R and Q^1_R. However, it was found more convenient to calculate the RaA concentration than the radon concentration. For RaA the corresponding equation to eqn (2) is

$$\lambda_R Q_R = \lambda_A Q_A + jQ_A - jQ^1_A. \tag{3}$$

Assuming that $j \gg \lambda_R$ (valid for all practical ventilation rates) and that $\lambda_R Q^1_R = \lambda_A Q^1_A$ (i.e. in outdoor air RaA is in equilibrium with radon) then eqns (2) and (3) may be combined to yield

$$\lambda_R K = \frac{j(\lambda_A + j)}{\lambda_A} (\lambda_A Q_A - \lambda_A Q^1_A) \tag{4}$$

or

$$K = j\left(1 + \frac{j}{\lambda_A}\right) (C_A - C^1_A). \tag{5}$$

But $\lambda_A = 13{\cdot}63\ h^{-1}$ so

$$K = j(1 + 0{\cdot}0734j)(C_A - C^1_A). \tag{6}$$

It follows from eqn (6) that K can be determined from the measurement of C_A, C^1_A and j. However, eqn (6) is true only in the steady state, i.e. when

dQ_R/dt is zero. The question therefore arises as to how long one must wait after a change in ventilation rate before conditions again approach a steady state. From eqn (2) and remembering that for all practical circumstances $j \gg \lambda_R$ we have

$$K = j_1 C_{R1} - j_1 C^1_R \tag{7}$$

where C_{R1} is the radon activity concentration in the steady-state condition with a ventilation rate j_1. If the ventilation rate is suddenly changed from j_1 to j_2 then the radon activity concentration C_{Rt} at any subsequent time t is given by

$$\frac{dC_{Rt}}{dt} = K + j_2 C^1_R - j_2 C_{Rt} \tag{8}$$

and integration gives

$$\ln\left|\frac{(j_1 - j_2)(C_{R1} - C^1_R)}{j_1 C_{R1} - j_2 C_{Rt} - (j_1 - j_2) C^1_R}\right| = j_2 t \tag{9}$$

or

$$C_{Rt} = \frac{j_1 C_{R1} - (j_1 - j_2) C^1_R}{j_2} - \frac{(j_1 - j_2)(C_{R1} - C^1_R)\exp(-j_2 t)}{j_2}. \tag{10}$$

The first term in eqn (10) represents the steady-state value of the radon activity concentration, $C_{R\infty}$, at the new ventilation rate j_2 and this value is approached asymptotically. Calculations were carried out for a number of values of j_1, j_2, K and C^1_R in order to obtain a general idea of the time, T, which should elapse after a change in ventilation rate before carrying out measurements of C_A for the determination of K. The steady state was taken to be sensibly reached when C_{Rt} reached $0{\cdot}8C_{R\infty}$ (for $j_1 > j_2$) or C_{Rt} reached $1{\cdot}2C_{R\infty}$ (for $j_1 < j_2$). As would be expected, T is generally much shorter in the situation where $j_1 < j_2$. T is longest when j falls from a high to a low value. This was usually the case during measurements: in order to reduce counting uncertainties to a minimum C_A was usually increased by closing windows and doors before carrying out measurements.

From eqn (10)

$$\frac{C_{Rt}}{C_{R\infty}} = 1 - \frac{(j_1 - j_2)(C_{R1} - C^1_R)}{j_1 C_{R1} - (j_1 - j_2) C^1_R}\exp(-j_2 t). \tag{11}$$

If $T_{0{\cdot}8}$ is the value of t for which $C_{Rt} = 0{\cdot}8C_{R\infty}$ then

$$T_{0{\cdot}8} = \frac{1}{j_2}\ln\frac{5(j_1 - j_2)(C_{R1} - C^1_R)}{j_1 C_{R1} - (j_1 - j_2) C^1_R}. \tag{12}$$

If $j_1 = 3\ \text{h}^{-1}$, $j_2 = 0{\cdot}5\ \text{h}^{-1}$, $K = 0{\cdot}5$ pCi l^{-1} and $C^1_R = 0{\cdot}07$ pCi l^{-1} then $C_{R1} = 0{\cdot}24$ pCi l^{-1} and $T_{0{\cdot}8} = 2{\cdot}7$ h. In any practical situation $T_{0{\cdot}8}$ is unlikely to be larger than this.

2.2. *Calculation of the RaA activity concentration*

The activity concentrations, C_A and C^1_A, of RaA were calculated using a Radon Daughter Monitor designed by James and Strong (1973) and using the method of measurement described by Cliff (1978). In this instrument air is drawn through a filter paper (Whatman GFA) which is positioned in front of a silicon surface barrier detector. The associated detector circuit has a discriminator level set to exclude the counting of β-particles. The arrangement allows a gross alpha count from decaying nuclides deposited on the filter paper to be recorded while sampling is in progress as well as after the end of sampling. The regime most commonly adopted for calculating the activity concentration of RaA was to sample the air for a period of 15 min and record the gross alpha count obtained during this period. The sample ceased at 15 min and two further gross alpha counts were recorded from 16 to 36 and 37 to 57 min from the start of the sampling period. From the three counts recorded, A_1, A_2 and A_3, the activity concentration, C_A of RaA is found (in pCi l^{-1}) from

$$C_A = (1/VE)(0{\cdot}01305A_1 - 0{\cdot}01152A_2 + 0{\cdot}008043A_3) \qquad (13)$$

where V is the volume flow rate (l min^{-1}) and E is the counter efficiency (cpm/dpm). With a counter efficiency of 0·2 and a flow rate of 50 l min^{-1} the sensitivity of this method is such that for an RaA activity concentration of 0·07 pCi l^{-1} the relative standard deviation due to counting statistics is 0·5. From the three counts obtained the Working Level can be calculated as

$$\text{WL} = \frac{10^{-3}}{VE}(0{\cdot}00453A_1 - 0{\cdot}00135A_2 + 0{\cdot}01937A_3). \qquad (14)$$

The sensitivity of the measurement of RaA activity concentration was always adequate for measurements of C_A within the room and in the majority of cases adequate in the outside air for measuring $C^1{}_A$. If $C^1{}_A$ was very low the uncertainty in the measurement of $C^1{}_A$ was unacceptable. In these cases the Working Level was evaluated and $C^1{}_A$ calculated from this on the assumption that equilibrium existed, i.e. $C^1{}_A = C^1{}_B = C^1{}_C$. Under equilibrium conditions with a flow rate of 50 l min^{-1} and detection efficiency 0·2 the coefficient of variation at 10^{-4} WL is 14%; 10^{-4} WL corresponds to 0·01 pCi l^{-1} each of RaA, RaB and RaC. In those cases where this last method was adopted it is unlikely that the uncertainty in $C^1{}_A$ determination exceeds 50% (one standard deviation).

2.3. *Measurement of ventilation rate*

The measurement of ventilation rate, j, was carried out by the usual method of releasing and rapidly mixing a tracer gas into the room air (Dick 1950). If the ventilation rate is constant then the concentration of tracer gas will decrease exponentially with time. A plot of the logarithm of concentration against time will yield a straight line the slope of which is the ventilation rate. Krypton-85 was used as the tracer gas and its concentration measured by scaling the counts from a B12H Geiger–Müller tube. The release of 0·1 mCi of ^{85}Kr into a room produced a concentration whose decrease could be followed for a period dependent upon the volume of the room and the ventilation rate; for a normal size living room and a ventilation rate of one room change per hour this period was about one hour.

2.4. *Other measurements*

Changes in atmospheric pressure, temperature and relative humidity probably influence the emanation rate of radon-222, but of these factors only a pressure change is likely to produce a prompt change in emanation rate (Jonassen and McLaughlin 1977). Atmospheric pressure was continuously recorded on a microbarograph during each measurement exercise. Temperature was recorded on a thermograph.

The determination of the radon output of a room by the method described depends inherently on the assumption that the air exchange is solely between that in the room and that outside the dwelling. This will not usually be the case when a wind is blowing and the room being studied is on the leeward side of the house. The wind direction at each site was noted and, where practical, the room chosen for study was situated on the windward side of the house.

One factor in the translation of exposure to radon daughters into dose to bronchial epithelium which is considered important by many authors is the fraction of daughters (in particular RaA) unattached to condensation nuclei. A rough value of this fraction can be determined from a knowledge of the concentration of condensation nuclei in the air (Duggan and Howell 1969). Measurements of condensation nuclei were carried out using a portable condensation nuclei counter (Portable semi-automatic monitor, Environment One Corporation).

3. Organisation of the measurements

The usefulness of this survey depends on the assumption that the radon output of the room as determined by this measurement procedure is reasonably constant with time. As shown in section 2.1 any change in the ventilation rate requires some two and a half hours before conditions may be taken to have returned to the steady state. The ventilation rate may alter due to changing meteorological conditions as well as by deliberate action such as closing windows. In a similar fashion it can be demonstrated that a change in the radon concentration in the outside air will not be immediately reflected in the concentration of radon found in the room air. On this basis a single measurement of each of the parameters, C_A, $C^1{}_A$ and j might not result in a representative value for the radon output, K, of the room.

To investigate the constancy of K for a given room, one room was studied day and night for a period of four days. Measurements of C_A, $C^1{}_A$ and j were made at approximately five-hourly intervals during this four-day period. The room was closed throughout this period and ventilation was solely that due to natural leakage around doors and windows and the up-draught in the chimney flue behind a gas fire which was not operated during the measurement period. Fig. 1 shows the results of these measurements together with calculated values of radon output K. The uncertainties shown are one standard deviation due to counting statistics only. Fig. 1 demonstrates that all the parameters exhibit large temporal variations. In particular, the changes in ventilation rate demonstrate that caution is called for in classifying rooms loosely as poorly or

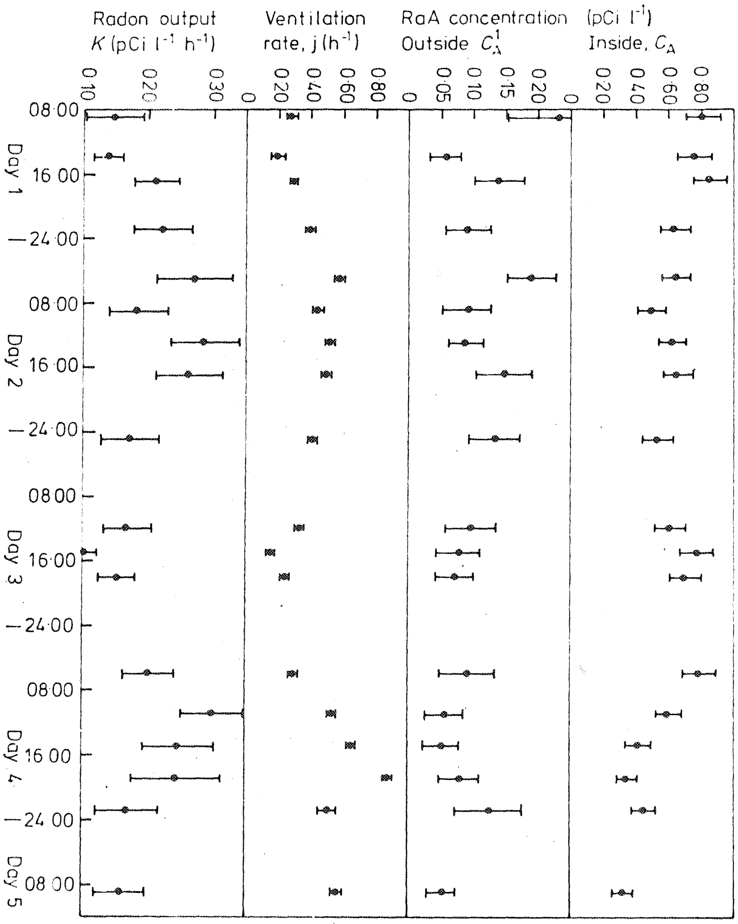

Fig. 1. Temporal variation in room air RaA concentration C_A, outside air RaA concentration C^1_A, ventilation rate j and radon output K for one room over a four-day period.

well ventilated. The temporal variations in each of the parameters are reflected in the variability of the individual determinations of radon output. However, if the radon output for the room is calculated using the mean values of C_A, C^1_A and j for the entire four-day period the value is 0·222 pCi l^{-1} h^{-1} and this may be taken as a better approximation to the true radon output than any individual calculation of K based on single determinations of C_A, C^1_A and j. Table 1 shows the values of radon output calculated from the mean parameter values over each day, together with the deviation ΔK per cent from the four-day mean given above. It is concluded from these results that whereas the measurement of radon output based on measurements in a given room over a period of one day may not be a reliable estimation of the true mean radon output of that room, the uncertainty in such a determination is unlikely to exceed 50%. In a survey of a large number of dwellings such uncertainties should be equally

Table 1. Deviation of the radon output calculated using the mean parameter values over a one-day period from the radon output calculated from the means of four days' values (0·222 pCi l^{-1} h^{-1})

	Mean				
Day	C_A (pCi l^{-1})	C^1_A (pCi l^{-1})	j (h^{-1})	K (pCi l^{-1} h^{-1})	ΔK (%)
1	0·763	0·141	0·286	0·182	−18
2	0·600	0·128	0·508	0·249	+12
3	0·646	0·093	0·280	0·158	−29
4	0·514	0·074	0·572	0·262	+18

distributed about the mean and the overall mean radon output calculated from the survey results will not be far removed from the true mean. On the basis of these considerations and to limit the time and staff requirements for the survey, as well as the inconvenience incurred by members of the public agreeing to participate in the project, measurements were confined to a one-day period. The equipment was usually installed at about 08.30 hours in the room to be studied and the doors and windows closed. Measurements of C_A, C^1_A and j were taken periodically throughout the day starting at 11.00 hours and finishing around 18.30 hours.

Dwellings studied were located in the counties of Berkshire, Cornwall, Dorset, Essex, Hampshire, Hertfordshire, Merseyside, Oxfordshire, Suffolk and Wiltshire and in the towns or conurbations of Aberdeen, Birmingham, Edinburgh, Glasgow, Leeds, London and Manchester. In all 87 dwellings were surveyed. Fig. 2 illustrates the distribution of dwellings by age, style and main structural material of both the main frame of the dwelling and the inner walls of the room studied.

4. Results of the measurements

In fig. 3 are displayed the radon outputs for the dwellings investigated categorised as in fig. 2. In terms of the small numbers in each category and the similarity in the range of radon output within each group it is not considered that there is a strong dependence of radon output on the age of the dwelling. For the range of dates built, from 1900 to 1915, the mean appears to be significantly higher than for the other age ranges but this is due to the highest radon output measured of 5·5 pCi l^{-1} h^{-1} lying in this range. If this high value is removed the mean for this range is reduced to 0·66 pCi l^{-1} h^{-1} which is similar to that for other age ranges. Similar arguments apply to the distribution of outputs regarding the style; the removal of the high of 5·5 pCi l^{-1} h^{-1} from the semidetached house group reduces the mean for this group to 0·451 pCi l^{-1} h^{-1}. In the case of the ground floor and first floor flats it is normally expected that the radon concentration falls as one progresses to higher floors (Toth 1972). This appears to be reversed in this investigation but as the numbers in these categories are small (five ground floor flats and four

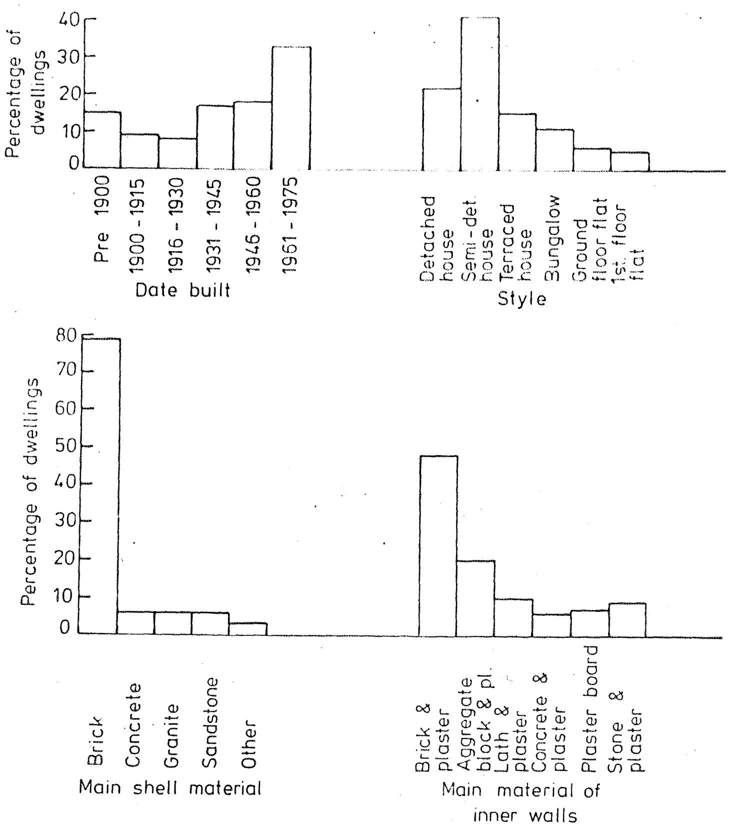

Fig. 2. Distribution of dwellings surveyed by date of construction, style of property, main material of the shell of the building and the main material of the inner walls of the room studied.

first floor flats) the difference in the means is not significant. The distribution of radon outputs according to material used for the main shell demonstrates that the only group exhibiting a significantly higher mean radon output is that of buildings constructed from granite and this group contains the highest value measured. The distribution of radon outputs appears, as might be expected, to be largely dependent upon the materials used for the inner walls, the highest radon outputs being found in those properties having inner walls of stone and plaster. In particular all rooms with exposed stone, which is often used for ornamental purposes, showed a high radon output regardless of the group in which they occurred. For the dwellings with some exposed stone within the room measured the mean radon output was 2·5 pCi l^{-1} h^{-1} with a range from 0·80 to 5·5 pCi l^{-1} h^{-1}. Fig. 4(*a*) shows the distribution of radon outputs according to a broad geological classification of the subsoil at the location of the dwelling. In view of the similarity in the range of results in each group the influences of subsoil on emanation rate is not pronounced. It must be borne in mind that in both sandstone and granite areas the dwellings were often

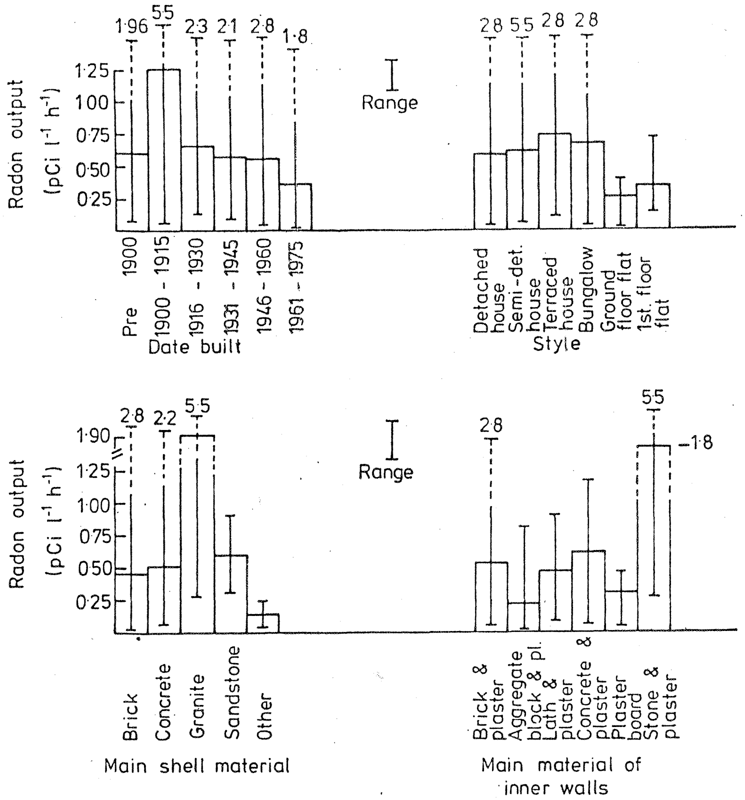

Fig. 3. Distribution of radon outputs of rooms studied according to the age of the dwelling, the style of the dwelling, the main shell material and the main materials used for the inner walls of the room.

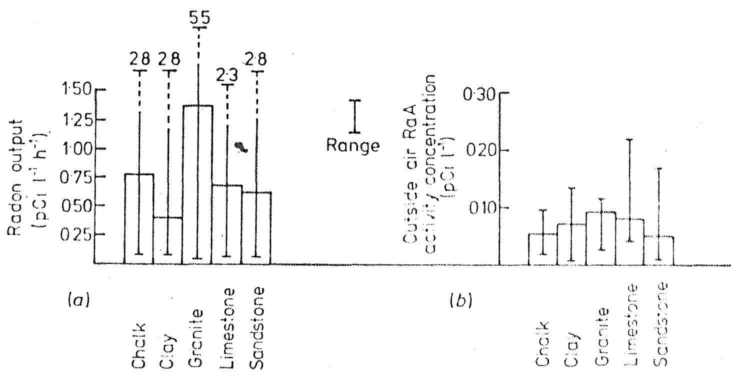

Fig. 4. (*a*) Distribution of radon outputs of rooms studied; and (*b*) distribution of outside air RaA concentration according to a broad geological classification of the subsoil at the site of the dwelling.

constructed from locally obtained materials and these materials influence the radon output more than the subsoil. However, for a room with a given radon output and ventilation rate the actual activity concentrations of radon and its daughters existing in the room are influenced by the concentrations in the outside air and this is dependent upon the subsoil among other factors. Fig. 4(*b*) shows the distribution of mean outside air RaA activity concentrations as measured during this survey with subsoil type.

Fig. 5 shows the distribution of radon outputs for all dwellings surveyed. As the distribution is very unsymmetrical when plotted linearly it is plotted to a logarithmic scale. The median value obtained is 0·32 pCi l^{-1} h^{-1} with a geometric standard deviation of 3·1. The arithmetic mean for all the dwellings surveyed is 0·60 pCi l^{-1} h^{-1}.

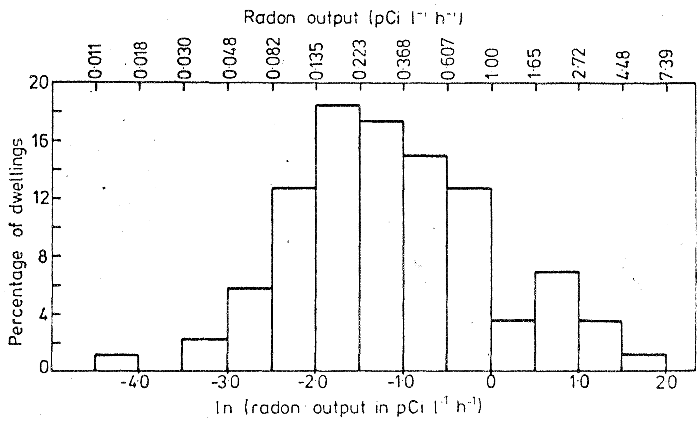

Fig. 5. Radon-222 output of living rooms in dwellings in Great Britain.

5. Estimation of population exposure

The highest value for radon output recorded was 5·5 pCi l^{-1} h^{-1} and is almost twice that of the next highest value found (2·8 pCi l^{-1} h^{-1}). This high value occurred in a dwelling in Cornwall constructed from local granite known to contain a relatively high radium activity concentration (> 2·5 pCi g^{-1}). As such dwellings are uncommon and the population density of Cornwall is low it is reasonable to exclude this value when attempting to estimate population exposure to the short-lived daughters of radon-222. With this highest value of radon output removed the arithmetic mean radon output is reduced to 0·54 pCi l^{-1} h^{-1}. For a room with a given radon output the actual activity concentrations of each daughter product in the room air are strongly dependent upon the ventilation rate. Table 2 shows the activity concentrations of the short-lived daughters in a room emanating 0·54 pCi l^{-1} h^{-1} radon-222 for various ventilation conditions (in room changes per hour). In compiling this table it is assumed that the activity concentration of radon in the outside air is 0·07 pCi l^{-1} and that the activity ratios Rn : RaA : RaB : RaC are

Table 2. Radon daughter activity concentrations in a room emanating 0·54 pCi l^{-1} h^{-1} for various ventilation rates (room changes per hour)

Ventilation rate (h^{-1})	Concentration (pCi l^{-1})			Working level (WL)
	RaA	RaB	RaC, RaC¹	
0·1	5·07	4·76	4·55	0·0471
0·2	2·64	2·35	2·15	0·0230
0·5	1·10	0·85	0·69	0·0081
1·0	0·57	0·37	0·26	0·0035
1·5	0·39	0·23	0·15	0·0022
2·0	0.31	0·17	0·11	0·0016

1 : 1 : 0·8 : 0·6. This figure for mean radon activity concentration is in agreement with measurements made during this survey and with figures quoted in the literature (e.g. Davies and Forward 1970, Harley 1973). Thus before an assessment can be made of mean population exposure, a mean ventilation rate over a year must be assumed. Surveys of ventilation rates in dwellings in Great Britain are virtually non-existent. Dick and Thomas (1951) measured heat loss in two occupied dwellings and inferred from these results that the ventilation rate was between two and three air changes per hour. However, at the time of this research open solid fuel fires, with their attendant up-draughts, were more common than at the present time. During the survey of radon daughter concentrations in dwellings it was common to find ventilation rates in the region of 0·7 h^{-1} with doors and windows closed. In a number of cases the ventilation rate was as low as 0·2 h^{-1}. With the increasing costs of domestic heating fuels and the consequential increase in the use of double glazing and draft-excluding materials around doors it can be reasoned that ventilation rates are generally below one room change per hour for seven months of the year. Even in the warmer seasons windows are often shut at night. Thus a typical mean ventilation rate over the year of one room change per hour has been assumed.

On the basis of a mean ventilation rate of one room change per hour and assuming people spend 80% of their time within buildings (occupancy factor 0·8, UNSCEAR 1977) then the mean population cumulative exposure rate is 0·144 WLM y^{-1} from exposure within buildings. To this must be added the 0·005 WLM y^{-1} received while in the open air. Thus the overall mean exposure rate to the short-lived daughters of radon is calculated to be 0·15 WLM y^{-1}. Over a 70-year life span the total cumulative exposure of 10·5 WLM corresponds to 8·8% of the cumulative exposure which in uranium miners produces a statistically significant increase in lung cancer (Lundin *et al.* 1971).

Many workers have attempted to relate exposure in WLM to dose in rads to bronchial epithelium with conversion factors ranging from 0·2 rad WLM^{-1} (Harley and Pasternak 1972) to 12 rad WLM^{-1} (Haque and Collinson 1967). Toth (1972) adopted a figure of 0·66 rad WLM^{-1} when estimating the bronchial epithelium dose rate for the population of Hungary. Using the same conversion factor, the Great Britain mean population dose rate to bronchial epithelium is

99 mrad y^{-1} which becomes 2·0 rem y^{-1} when the quality factor of 20 for alpha particles is applied (ICRP 1977).

This figure of 2·0 rem y^{-1} mean population bronchial epithelium dose equivalent rate may be disputed because of the uncertainties in the conversion factors used in its derivation. This author is of the opinion that exposure to the short-lived daughters of radon-222 is best expressed as WLM although caution must be exercised in interpreting the consequences of a cumulative exposure expressed in WLM. Jacobi (1976) has reviewed the data for the increased incidence of lung cancer in uranium and other miners and has derived a risk factor for this group of 200 excess lung cancers per 10^6 persons per WLM. It must be stressed that this risk estimate applies only to the group studied and cannot be applied to the population at large. One of the main factors influencing the bronchial epithelium dose resulting from an exposure in WLM is breathing rate. It is unlikely that many members of the population working within buildings, and in particular in dwellings, have a respiratory rate as high as that of underground miners. For part of the time over which the exposure in dwellings occurs the person is relaxing and for perhaps seven hours he is asleep when his breathing rate is much reduced. To illustrate the absurdity of applying the risk estimate derived from miners' exposure to the population exposure Reissland (1977) has applied the miners' risk estimate to the population exposure derived from this work and predicted the incidence of lung cancer in women in Great Britain on this basis. Women were chosen since they generally smoke less than men. His table 3 compares the predicted incidence of lung cancer with that actually observed and for women below 40 years of age there are more lung cancers predicted than the total number observed due to all causes of cancer of the bronchus and lung. This emphasises that the risk estimate for miners' exposure cannot be used for population exposure due to building materials.

The above calculation of radon daughter concentration inside the room assumes that the equilibrium conditions in the incoming air are the same as in the outside air. However, in a closed room the ingress of outside air will be through small cracks around windows and outside doors. Within these cracks there is a high probability of deposition of some of the daughter activity from the outside air thus changing the equilibrium conditions in the incoming air. However, for the mean ventilation rate of one room change per hour even if the extreme (and very unlikely) case is taken of all the daughters in the incoming air being deposited within the cracks this will reduce the Working Levels in the room by only 7%. It should be noted that changes in the equilibrium conditions in the incoming air do not affect the validity of eqn (4).

6. Conclusion

On the basis of this survey the mean exposure to the short-lived daughters of radon-222 for the population of Great Britain is 0·15 Working Level Months per year giving a dose equivalent rate to bronchial epithelium of 2·0 rem y^{-1}. Regardless of the uncertainties in the estimation of dose equivalent it can unquestionably be concluded that of all body cells those receiving the highest dose equivalent from any source of natural radioactivity are those of the bronchial epithelium and this is largely due to exposure within buildings. With continuing efforts at energy conservation resulting in generally lower ventilation rates in the colder months, and with the probable increase in the use of by-product materials with slightly enhanced radium concentration as building materials, this dose equivalent rate will increase.

The method described in this paper has not been tested independently by the direct measurement of radon gas concentrations in the air within a room and in the outside air. It is planned to carry out such measurements in the near future at the same time as measurements are repeated using the method reported here. The room used for this study will be that used to investigate the temporal variations in radon output assessment as described in section 3. These results will be published at a later date together with a summary of the actual values of Working Levels found in dwellings during the survey.

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Résumé

Evaluation des concentrations filles aériennes de radon dans les résidences en Grande-Bretagne

Des calculs de la concentration d'activité du RaA (^{218}Po) dans l'air ambiant des salles de séjour et dans l'air extérieur ont été faits sur 87 residences en Angleterre et en Escosse. A partir de ces mesures, ainsi qu'à l'aide d'une détermination du rythme de ventilation dans les pièces au moment de la prise des mesures, le taux de ^{222}Rn émanant des surfaces de la pièce dans l'air en pCi l^{-1} h^{-1} peut être calculé. Pour les études des résidences, le taux moyen d'émanation est de 0,54 pCi l^{-1} h^{-1} et, sur la base d'un taux de ventilation moyen d'un renouvellement d'air par heure et par pièce sur l'ensemble de l'année, de même qu'en supposant un coefficient d'occupation de 0,1 l'on a estimé que le taux d'exposition de la population en Grande-Bretagne aux substances filles de ^{222}Rn à vie courte était de 0,15 moins à niveau de travail par an.

Zusammenfassung

Bewertung von Konzentrationsanhäufungen von Tochterelementen des Radons, die von der Luft getragen werden, in Häusern in Grossbritannien

Berechnungen der Aktivitätskonzentration von RaA (^{218}Po) in den Luftvolumina von Wohnräumen und in der Aussenluft wurden für 87 Häuser in England und Schottland durchgeführt. Diese Messungen erlauben es, die Austritts[illegible]windigkeit von ^{222}Rn aus den Wandflächen des Raumes in die Raumluft in pCi $l^{-1}h^{-1}$ [illegible] indem man zusätzlich noch die Ventilationsgeschwindigkeit im Raum zur Zeit der Durchführung der Messungen misst und bei den Rech[illegible]nungen zugrundelegt. Bei den untersuchten Gebäuden lag die mittlere Austrittsgeschw[illegible] bei 0,54 pCi $l^{-1}h^{-1}$. Unter Zugrundelegung einer durchschnittlichen Ventilationsrate, [illegible] dase Luftvolumen eines Raumes ständlich erneuert wird—und dies trifft für das [illegible] sowie unter der Voraussetzung eines Bewohnungs- bzw. Nutzfaktors von 0,8 erg[illegible] britische Bevölkerung ein Einwirkungsniveau der kurzlebigen Tochterelemente [illegible] Schätzungswiese 0,15 Monate pro Jahr, umgerechnet auf Arbeitsverhältnisse.

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