Ventilation requirements in relation to the emanation of radon from building materials

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Since radioactive nuclides exist in the ground they are also present in all mineral based building materials. One of the commonest groups of radionuclides is the uranium-radium chain, one link of which is the decay of radium-226 to the noble gas radon-222. Since the half-life of radon is 3.8 days, some of the gas diffuses out of the ground and the building materials into the surrounding air. Radon-222 decays to radon daughters, consisting of radioactive metal ions, which to a great extent become attached to dust particles. When air is inhaled some of the radon daughters remain in the bronchial regions of the lung and will cause a risk of lung cancer.

Another naturally occurring radionuclide chain is that which starts with thorium-232. One of the daughters is radon-220 (thoron) with a half-life of 54 seconds. Because of its short half-life the gas emanates from the material to a less degree than is the case for radon-222. However, thoron might cause a problem when the content of thorium-232 is high.

The levels of radon and radon daughters indoors depend on

- o The contents of radium-226 or radon-222 in the materials from which the radon emanates. This material might be the ground, the building materials or tap water.
- o The emanation rate from the sources. This varies with the nature and the surface treatment of the material. It also varies with parameters such as the atmospheric pressure (1), the humidity, the temperature etc.
- o The ventilation rates and the treatment of the air.

Of these three parameters, the ventilation rate is of particular importance for the indoor levels of radon and radon daughters.

Ventilation systems and radon concentration

For the air exchange rates which exist in most homes, the concentration of radon is approximately inversely proportional to the air exchange rate. This approximation is not valid for very low air exchange rates, below about 0.3 h^{-1}, nor for very high rates. When the air exchange rates are very high, several air exchanges per hour, the radon concentration outdoors has an essential influence on the indoor levels.

If the radon concentration indoors is decreased to the same level as outdoors, e.g. after thoroughly airing the dwelling, it takes some time for the radon concentration to approach again an equilibrium with the air exchange rate. Fig 1 shows the growth in the radon concentration with time, after airing until the concentration was neglible, for three different air exchange rates (1, 0.5 and 0.08 changes per hour).

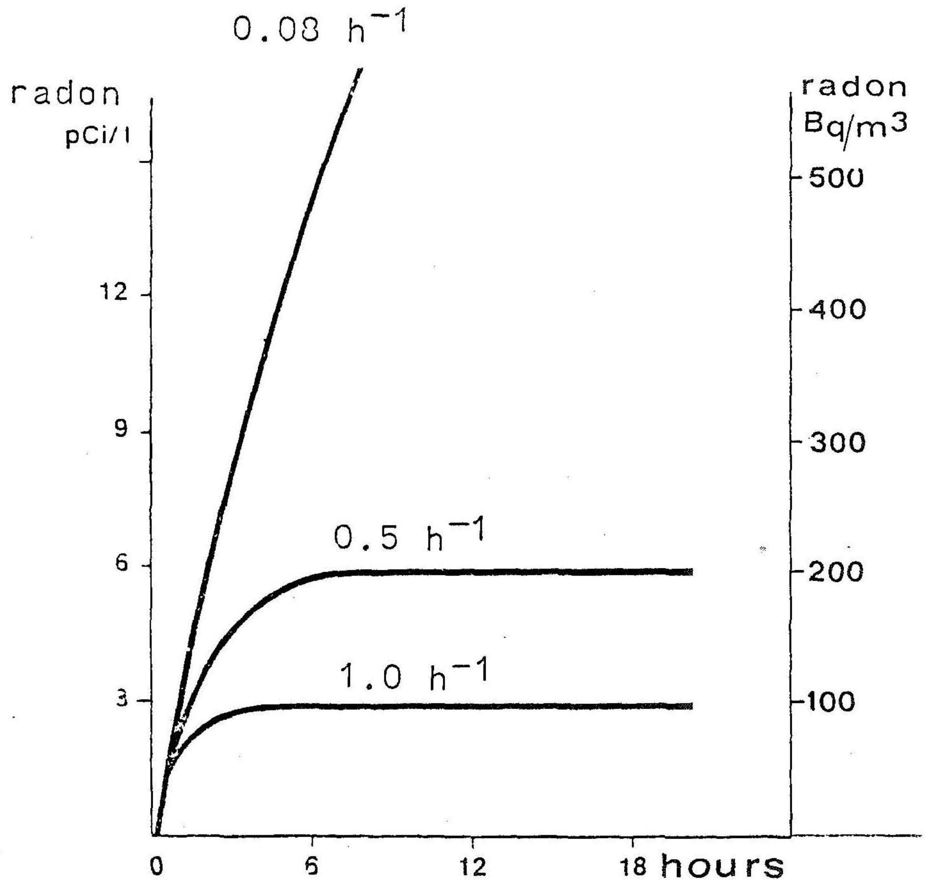

Figure 1. The growth in the radon concentration with time after airing until neglible concentration for three different air exchange rates. The example shows a radon concentration which may be expected in a dwelling with elements of both ordinary concrete and aerated concrete based on alum shale.

The ventilation rate varies with several parameters such as the weather conditions and the behaviour of the occupants. This causes problems when determining the average levels of radon and radon daughters. Fig 2 shows an example of how the radon concentration varies in a typical bedroom in a detached house with a natural draught ventilation system. As is commonly found in Swedish homes, the bedroom had no direct ventilation ducts.

The door to the room was closed at the beginning of the measurement and the radon concentration then increased. From the beginning of the measurement, the wind direction was towards the opposite side of the house. After some hours the wind direction changed towards the side of the house where the measured room had its window. This caused a decrease in the radon level to one third of the previous value.

Bedrooms without direct ducts for exhaust air present special problems. When the doors and windows to a bedroom are closed, the concentration of radon and radon daughters may increase as in Fig 3, which shows a long term registration in a house with a mechanical exhaust air ventilation system. When the door to the bedroom was closed the radon level increased by a factor of five.

The ventilation rates in houses with forced ventilation systems for both the supply and exhaust air are less dependant on the weather provided that the houses are sufficiently air-tight.

The filters usually used in ventilation systems reduce the concentrations of radon daughters, but not of radon since it is a noble gas. It is therefore not sufficient to recirculate the air through such filters in order to decrease the content of the very short-lived radon daughters in the recirculated air.

Intensive efforts to develop new technical solutions for heating and ventilation systems of dwellings are in progress. Some will cause a better hygienic environment from the radiation protection point of view, for example the use of recuperative heat exchangers for the exhaust air. Others could give rise to substantially increased radon concentrations, e.g. when thermal energy is stored in gravel, bricks or other mineral materials or when the supply air is drawn through long

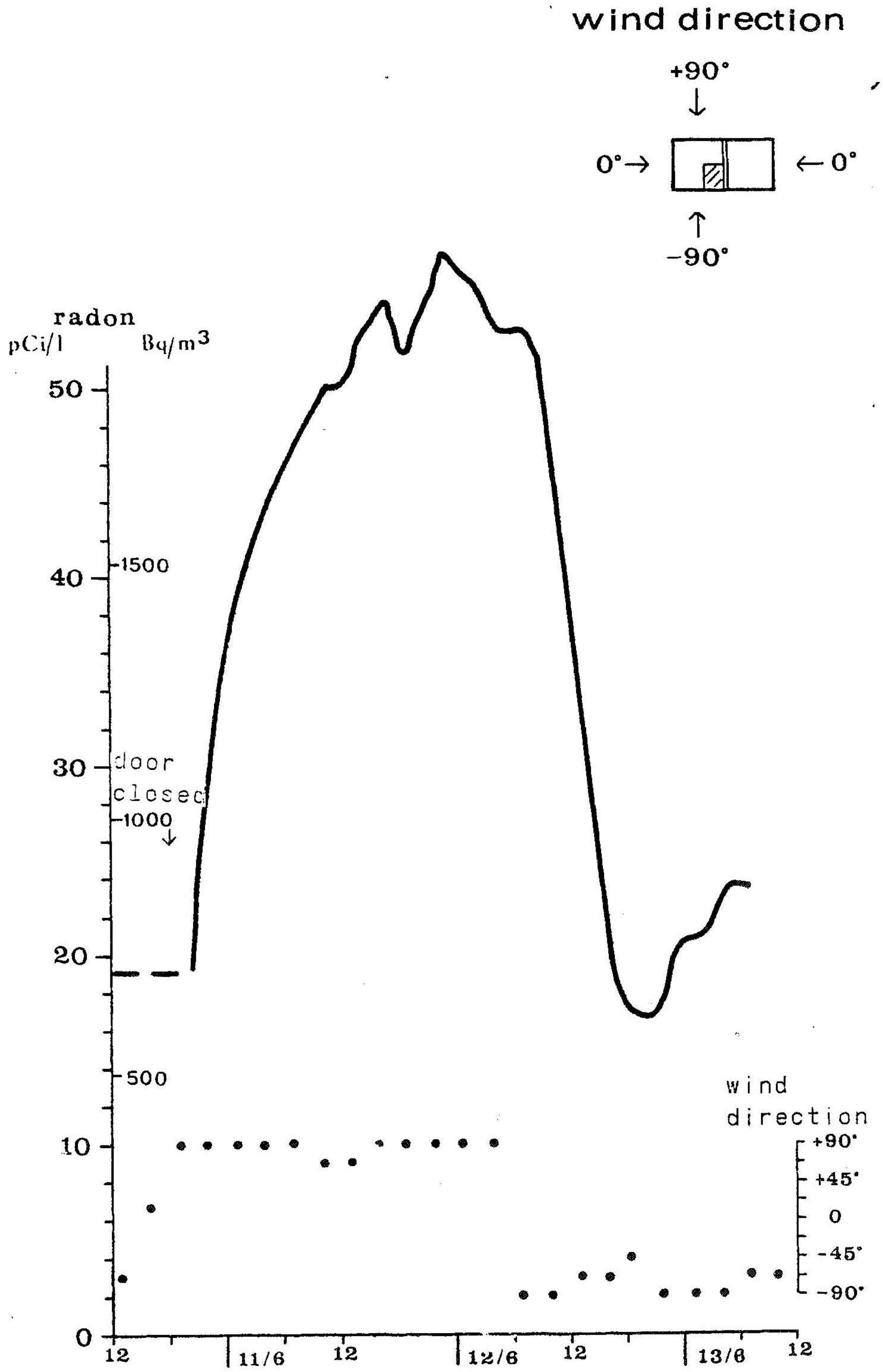

Fig 2. The dependence on the wind direction of the radon concentration in a detached house with a natural draught ventilation system. The door to the room was closed at the beginning of the measurement.

concrete ducts to pre-heat it.

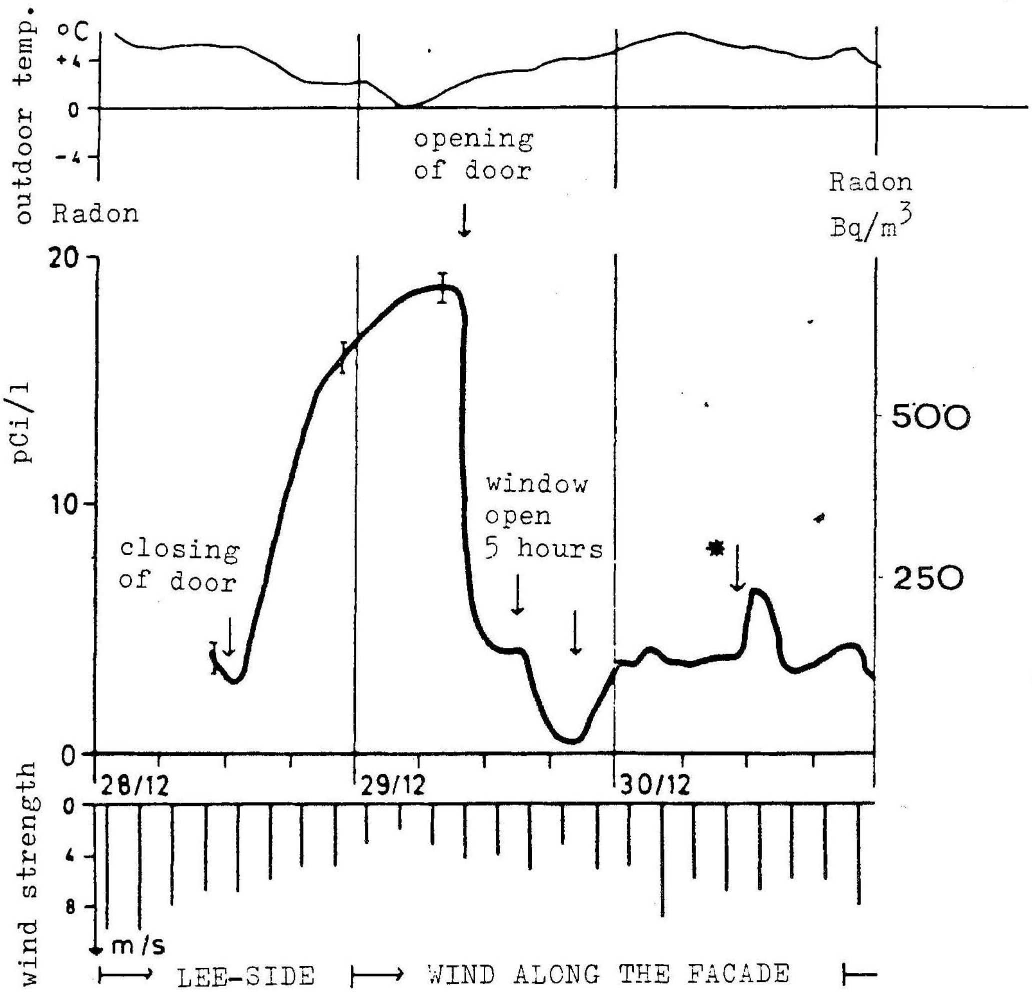

Figure 3. The variation of the radon concentration in a dwelling in an apartment house built of elements of both ordinary concrete and aerated concrete based on alum shale and with forced ventilation system for the exhaust air. The arrow shows when a secondary door from an adjacent room was opened after having been closed during 9 hours.

Average levels of radon and radon daughters

For the health hazards it is the average radon daughter levels which are of interest, not occasional peaks in the concentrations.

Different structural materials may result in different average concentrations of radon and radon daughters. This is illustrated in Table 1, which shows the average levels of radon in Swedish houses for various building materials and building periods calculated from measurements made in the beginning of the 1950s (2) and in the 1970s (3). For other countries other

Apartment houses

Building period	Wood Bq/m3	Clay-brick, concrete Bq/m3	Aerated concrete based on alum shale Bq/m3
Prior 1951	15	40	116
1951 - 60	-	83	148
1961 - 70	-	95	180
1971 - 75	-	138	277

Detached houses

Building period	Wood Bq/m3	Wood with the basement aerated concrete based on alum shale Bq/m3	Clay-brick, concrete Bq/m3	Sandbased aerated concrete Bq/m3	Aerated concrete based on alum shale Bq/m3
Prior 1951	15	-	40	(15)	116
1951 - 60	48	110	94	37	91
1961 - 70	59	148	118	46	123
1971 - 75	74	195	149	57	158

1 Bq is one disintegration per second.
The old unit was the curie. 1 pCi/1 = 37 Bq/m^3

Table 1. Average concentration of radon in Swedish homes classified by main building materials and building periods (5).

Country	Absorbed dose mGy/y
Hungary	7.0
Poland	0.5
Sweden	3.2
United Kingdom	0.4
United States	1.3

Table 2. Estimated annual absorbed dose indoors in the segmental bronchial epitelium of the respiratory system due to radon daughters. From the 1977 UNSCEAR report (5).

levels are found as illustrated in Table 2. Particularly the aerated concrete based on alum shale is a problem in Sweden, but most countries seem to have some similar problem from other kinds of sources. The values in Table 1 illustrate the variations both between various building materials and between new and old houses. The differences between the building periods depend both on the various building techniques used and on the increased ability to build houses more air-tight than before. Recently the ambition to conserve energy by further reducing the air exchange rates has added to the change in radon concentrations.

It is not only the radium content in the material, which determines the radon level at a given ventilation rate. The emanation rate is different for different materials and is also influenced by the coating of the material. It is difficult, however, to reduce the radon emanation by coatings so this is only possible to a limited degree.

Risks

Epidemiological studies on miners have shown an increased frequency of lung cancer in proportion to the radon daughter levels in the mines. The risk factors are found to be between 200 and 450 per working level month (WLM)[a] and million persons, according to the 1977 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (5). In 1978 both higher and lower risk factors for miners have been given. The risk factor for lung cancer given by ICRP (6) is lower than that given above.

There might be a synergistic effect between cigarette smoking and radon. However, it has not been possible

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[a] 1 WL is defined as any combination of short-lived radon daughters per litre of air that will result in the emission of 1.3 10^5 MeV of alpha energy. 1 WL corresponds to an activity concentration of 100 pCi/litre of radon-222 in equilibrium with its daughters. 1 WLM corresponds to an exposure during 170 working hours in a radon concentration of 1 WL.

to give evidence of this because of the small fraction of non smokers among the miners.

If the risk factors given by UNSCEAR and by ICRP are applied to the Swedish population assuming an occupancy time of 80 per cent in a home and taking into account the lower breathing rates while at a home in comparison with those during hard work in a mine, the average radon levels from Table 1 would give a lung cancer incidence of 80 to 400 per year in Sweden with a population of 8 millions, from houses existing in 1950 (Table 3). From houses existing in 1975 the lung cancer incidence might be doubled, but these cases would be seen at first around year 2000 because of the long latency time. An estimate of lung cancer incidences has also been made for the period 1976 - 1985 for various alternatives.

Houses existing in		Apartment houses	Detached houses	Total
1950		56 - 310	26 - 150	82 - 460
1975		145 - 800	56 - 310	200 - 1100
1985	A	140 - 780	64 - 360	205 - 1140
	C	175 - 970	76 - 430	250 - 1400
	D	160 - 910	74 - 410	235 - 1300

The following three alternative assumptions for the 1985 buildings have been used:

A The ventilation rates are unchanged and equal to that in the houses existing in 1975.

C The air exchange rates are reduced from the values in the houses existing in 1975 to the lowest value, 0.5 h^{-1}, as specified in the 1975 Swedish Building Code.

D The same assumption as in C, but the air exchange rates are not reduced in houses built of aerated concrete based on alum shale.

Table 3. The expected number of lung cancer caused by radon and radon daughter products in Swedish dwellings existing in 1950, 1975 and 1985. Two sources have been used for the risk factor; ICRP (6) and the risk factors extrapolated from miners given in the 1977 UNSCEAR report (5).

The daughter products are very seldom in equilibrium with the radon. For the calculations in Table 1 the equilibrium factor has been taken as constant and equal to 0.5. In reality, however, the equilibrium factor varies with the ventilation rate. At very low exchange rates, it may be as high as 0.7 - 0.8, but it decreases as the rate increases. At very high exchange rates it is the conditions outdoors which dominate the concentrations of radon and radon daughters and in this case too the equilibrium factor may be high.

The risk can therefore only approximately be assumed to be proportional to the radon concentration. However, Fig 4 give some idea of the relation between the risk and the air exchange rate. The concentration of radon has been indicated as a function of the air exchange rates for a dwelling built of materials with unusually high radium contents, about 2000 Bq/kg (55 pCi/g) and for a house built of ordinary concrete. The risk factor for lung cancer calculated from the values given by ICRP (6) would be $0.4 \cdot 10^{-6}$ per year for an average radon concentration of 1 Bq/m^3.

Norms

No norms have yet been worked out for radioactivity concentration in building materials in general. However, in some countries norms have been specified for particular situations. For example, in the USA, norms have been issued for the gamma radiation level and the radon daughter concentration in homes built in the beginning of the 1950s when uranium mill tailings were used as filling materials below and round houses in Grand Junction (7). Another example derives from Canada where homes were built on piles of wastes from radium mines (8). Still another example is plaster board of gypsum made of waste from the phosphate industry for which Great Britain have given norms for the content of radium-226 (9).

Since 1974, international work has been going on within OECD/NEA regarding the problems of radioactivity in dwellings. Initially most attention was paid to the health hazard represented by the gamma radiation since

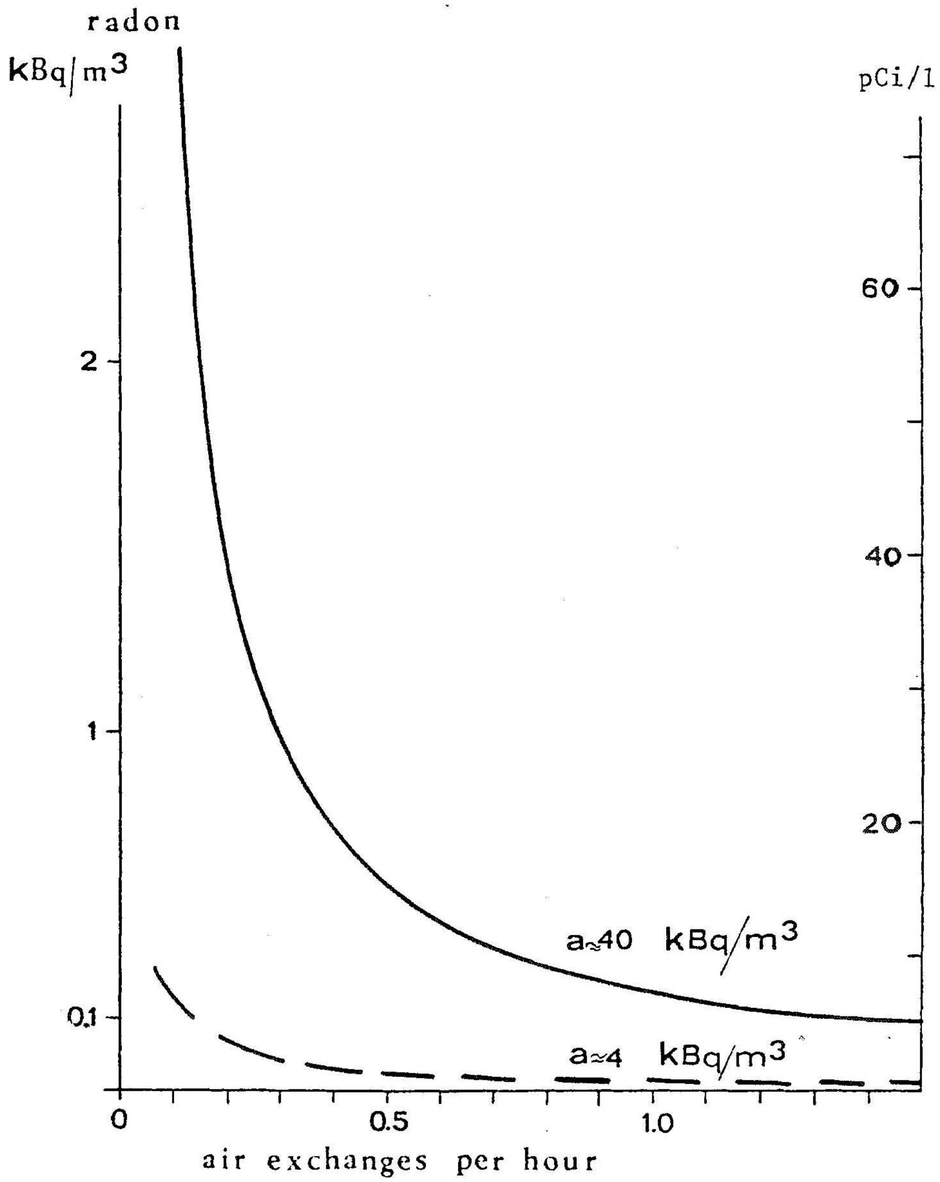

Fig 4. The relation between radon concentration and air exchange rate. No account has been taken of the outdoor concentration of radon. a = the radon concentration in a room with an air exchange rate equal to 0.

it was argued that radon could always be eliminated by "good" ventilation. However, during the last few years many countries have become aware of the radon problem and many studies of radon indoors are now in progress.

Most countries in the world follow the recommendations of the International Commission on Radiological Protection (ICRP) when working out national norms for radiation protection. These dose limits have explicitly been valid only for those radiation sources which have been the subject of licensing requirements and supervision by national authorities. Exceptions from these requirements have been the radiation doses to patients from medical uses of radiation and the radiation from natural sources of radiation.

It was not until 1977 that new recommendations of ICRP (6) gave a clear account of the philosophy behind these exceptions.

One condition for applying the dose limits only to some types of radiation exposures and not to others is that the relationship between the detriment and the radiation dose does not show any threshold. If this were not so it would have been necessary to limit the sum of all radiation doses to values below the threshold value.

For the low radiation doses, e.g. in dwellings, the assumption is that the risk increases in direct proportion to the radiation dose. Each small additional dose therefore causes a correspondingly small additional risk, independent of all other irradiations. The justification of each exposure can therefore be assessed without taking any other exposures into account.

The basic recommendations of ICRP are that (1) each radiation source should be justified from the point of view of society with regard to the risks, (2) that any necessary exposures are kept as low as it is reasonably achievable (optimization), and (3) that the dose equivalent to individuals shall not exceed certain specified limits.

For technologically enhanced natural radiation, e.g. that from a new radioactive building material, the source might be considered as one for which the specified limits are valid.

For already existing situations, e.g. existing building materials or water supplies, the situation is different. It is not primarily a question of administrative decisions for planning. Whether any remedial action to reduce radiation exposures is justified depends on the consequences and social cost of the action.

In the international discussions it has been said that it might be possible to agree upon non-action levels for new building materials. With regard to existing materials and buildings, the international community may also advise that non-action levels be established, but in this case the choice of level may only be decided within each country because of widely different conditions in the various countries.

On a national basis it might be appropriate to go further and introduce authorized limits for new materials and action levels for existing materials and buildings under specified circumstances.

According to ICRP one tenth of the occupational limit is applied for the population. If one tenth of the occupational limit for radon daughter concentration were applied to the home situation, considering occupancy time, inhalation rates etc, the implied upper limit for planning purposes would be 74 Bq/m^3 (2 pCi/l) of radon. Even for the most common houses in Sweden built of normal concrete or brick it has been shown that this level is reached already at an air exchange rate of approximately 0.5 h^{-1} if no special arrangements are made such as filtering of the air.

However, the derived limit should comprise the total exposure from all radiation sources with the exception of the "normal" natural background and medical exposures and not just the exposure from one particular source such as building materials. It would also imply no additional exposure of other body organs. How to define the "normal" background for the radon concentrations in dwellings is under discussion. It could be taken as the concentration outdoors. It is, however, impossible to build a house with a limited air exchange rate without an enhanced radon concentration indoors compared with outdoors. Therefore it might be reasonable to assume a background higher than the radon concentration outdoors.

For existing dwellings in Sweden built during the ten last years the average concentration is higher than the derived limit partly because of the low air exchange rates. Newly built houses have about 0.3 - 0.4

exchanges per hour although this is below the minimum value given in the 1975 Swedish Building Code. It therefore seems possible to expect a some-what better situation from the radiation protection view on the basis of air exchange rates at or above the minimum value given in the Building Code. It might also be possible to reduce the radon daughter concentration by applying technical solutions for reducing the emanation rate of radon or by filtering the air, but the reducing effect of such solutions is not yet known well enough.

However, the derived limit of 74 Bq/m^3 of radon can not be considered to apply to existing dwellings for which it should rather be assessed whether remedial actions are justified. It might be possible to derive an action level for existing dwellings on a national basis by optimizing protective measures, taking into account the consequences and social cost of the action.

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DISCUSSION

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1. For the health hazard it is the average radon daughters level which is of interest. Is the fraction of radon daughters the same for mines and dwellings?
2. The radiation induced cancer is derived from relatively high level radiation. Does the linear dose-effect relationship hold for long-time exposure to low-level radiation?
3. Is it possible that the latency time exceeds the normal lifetime?

G.A. Swedjemark

1. The equilibrium factor between the radon daughters and the radon varies with the ventilation rate both in mines and in dwellings. The approximate average for both mines and dwellings is 0.5.
2. The estimation of the radiation induced cancer is derived from higher dose rates than is found from the

γ-radiation from the building materials. The reliability of the linear dose-effect relationship is much discussed. It is not possible to give evidence for or against this theory because the difficulty in studying an irradiated and a control group of the population large enough to distinguish an excessive cancer frequency. It is probable that a long-term exposure gives a lower effect than the same dose given on one occasion. For the radon daughter exposition, however, the risk estimation is based on epidemiological investigations of miners, who have been exposed to radon daughters over many years. For most dwellings the radon daughter concentration is lower than the level, found to give excessive frequency of lung cancer in miners. There are, however,dwellings in Sweden, where the radium content of the building materials in combination with low air exchange rates has given radon daughter levels indoors of the same magnitude as the lowest levels in mines which have given excessive frequency of lung cancer. Further more, the investigations of miners indicate a linear dose-effect relationship. There are, however, several factors which differ between miners and the population as a whole - e.g. non-radiological air pollutants, smoking habits, age and sex - and these factors might influence the frequency of radiation induced cancer.

3. As far as we now know the latency time for lung cancer seems to be 20-40 years, the longer period value applying to non-smokers.

K.Bækmark
Aalborg Portland
Cement Factory, DK

Is it possible to reduce the emanation rate of radon from concrete walls by using other types of aggregate in the concrete, for instance using chalk flintstone instead of granite?

G.A. Swedjemark

Yes. However, this might have excessive economic consequencies in some regions.

D.J.Nevrala
British Gas
Corporation

Could you give an indication why there is such a variation between individual countries and whether ventilation rate or material properties predominate.

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G.A. Swedjemark

Both the ventilation rate and the material properties are of importance. The radon content in various rocks varies very much from the very low radon content in sandstone to rather high contents in granite and even higher for example in alum shale. The ventilation rates also vary very much between countries. In the Scandinavian countries the air exchange rates are about 0.5 h^{-1} and below in newly built houses. However, in England, for example, they seem to be from 1 to a few air exchanges per hour. In particular if low radon contents in the ground and in the building materials are combined with high air exchange rates, the radon concentrations indoors will be very low, as in England. The reverse is the case for example in Sweden, where the radon concentrations indoors tend to be rather high, because of the combination of radium-rich minerals in the ground and in building materials and low air exchange rates.

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The data presented in fig. 2 and 3 show a dramatic change in radon concentrations in relation to wind directions. 180° changes in wind directions are normally due to the passage of meteorological weather fronts, and are, therefore, normally followed by steep changes in atmospheric air pressure.

My question is, therefore,to what extent the changes in radon concentrations is due to the pumping effect caused by rapid changes in air pressure.

G.A. Swedjemark

Rapid changes in air pressure strongly influence the diffusion of the radon from the material as has been shown by Jonassen. However, in measurements in dwellings we have no way of distinguishing between the effect of ventilation rate and the effect of pumping.