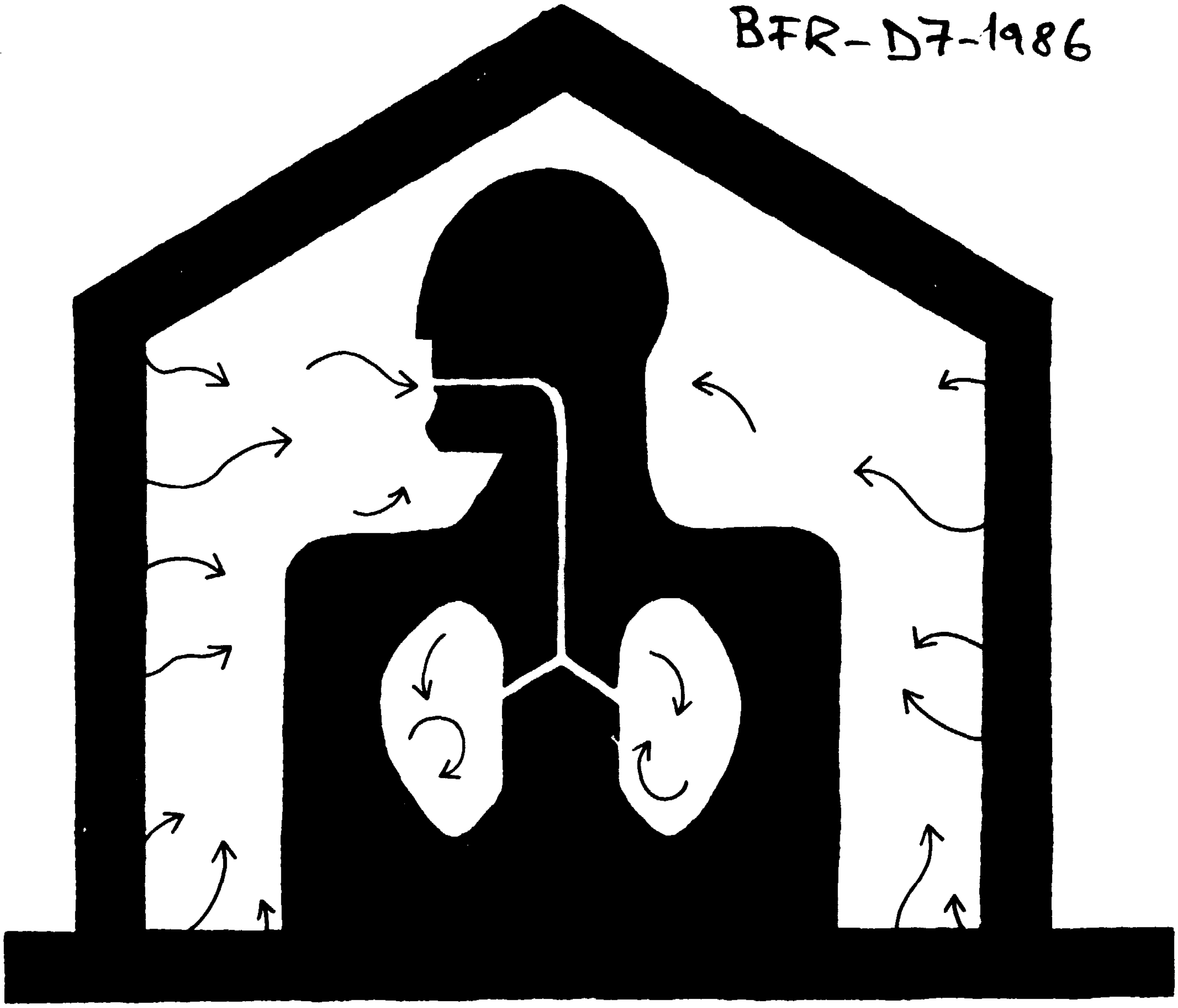
BFR-D7-1986



Technical Solutions and Remedial Strategy

BFR – D7:1986

INDOOR IONIZING RADIATION

Technical solutions and remedial strategy

Sven-Olov Ericson
Thomas Lindvall
Lars-Göran Månsson

This document refers to research grant No. 810531-2
from the Swedish Council for Building Research, Stockholm.

ABSTRACT

Radon in indoor air is discussed in the perspective of the effective dose equivalents from other sources of radiation. Estimates of effective dose equivalents from indoor radon and its contribution to lung cancer incidence are reviewed. Swedish experiences with cost effective remedial actions are presented. The authors present optimal strategies for screening measurements and remedial actions in a cost-benefit perspective.

D7:1986

ISBN 91-540-4554-1
Swedish Council for Building Research, Stockholm, Sweden

Spångbergs Tryckerier AB, Stockholm 1986

TABLE OF CONTENTS

PREFACE

This report has been prepared as a Swedish contribution to the work within the **Energy Conservation in Buildings and Community Systems Programme**, Annex IX "Minimum Ventilation Rates" of the International Energy Agency (IEA). The purpose of this report is to present a state of the art review of present knowledge on indoor ionizing radiation with special emphasis on the possibility to prevent excessive concentration of radon in new constructions and cost effective remedies for present buildings. The report also includes the authors' view on the issues of optimal strategies and cost-benefit considerations.

This report has been approved for publication by the Swedish Council for Building Research. Approval does not signify that the contents necessarily reflect the views and policy of the Council or of other Swedish agencies, nor does mention of trade names, commercial products, or methods constitute endorsement or recommendation for use.

The authors are solely responsible for the conclusions and statements in the report. Valuable comments have been received from Dr Hans Ehdwall, Dr Niels Jonassen, Dr Göran Pershagen, Dr Erling Stranden, Dr Gun Astri Swedjemark, and Dr Håkan Wahren.

Sven-Olov Ericson
Radon Consultants, Danderyd, Sweden
Thomas Lindvall
Karolinska Institute and National Institute
of Environmental Medicine, Stockholm, Sweden
Lars-Göran Månsson
Swedish Council for Building Research,
Stockholm, Sweden

March 1986

1. INTRODUCTION

Toxic or otherwise potentially harmful substances are natural and inevitable components of our environment. Many of these substances, i e some trace elements and vitamins, are essential to life in trace quantities and harmful or even lethal in higher concentrations. Others are only toxic without any known beneficial function. The toxic properties are sometimes related to the arrangement of harmless elements into a biologically active chemical compound, examples of which are toxins produced by bacteria and the arrangement of oxygen, carbon and hydrogen into alcohol. The toxic effect can also be carried by the atom itself, i e toxic heavy metals such as mercury and cadmium. Radioactive nuclides can cause health effects through the emitted radiation.

Trace amounts of naturally radioactive nuclides are present in soil, rock and building materials, as well as in living organisms including human beings. Through the emitted radiation these nuclides can cause harm when present in concentrations so low that even the strongest poison would be completely harmless. Living organisms also receive some radiation, cosmic rays, from sources outside the earth. The combined effect of all natural radioactivity contributes more to the total radiation burden than do all artificial sources of radiation including medical diagnostics, nuclear energy and fall out from nuclear weapon testing. It is not surprising that natural radiation has been attracting increasing attention from the radiation protection community. The most important factor contributing to the total dose burden from natural radioactivity is radon and its short-lived decay products present in indoor air.

Table 1 illustrates the contribution from various sources to the collective effective dose equivalent to the Swedish population /25/.

The table shows that in Sweden radon in dwellings is not only the single most important contributor to radiation dose burden, but is even twice as important as the sum of all other sources, nuclear energy and medical diagnostics included. In the table the doses from radon daughters in indoor air have been calculated according to the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) /89/ as 0.08 $mSvy^{-1}$ per Bqm^{-3}. The relationships in Table 1 are not unique for Sweden but representative also for Finland and Norway and some areas in other countries. One example is South-eastern Graubünden in Switzerland, where cristalline precambrian rock with a high uranium and thorium content reaches the surface. In this area measurements indicate a geometric mean radon concentration in the living quarters of 255 Bq/m^3 (approximately 10 $mSvy^{-1}$ assuming equilibrium factor equal to 0.5) /19/.

Table 1. Collective effective dose equivalents from different sources of radiation to the Swedish population, personSieverts and year; absolute and relative numbers (%) /25/.

Sources of radiation	personSv/year	%
Cosmic rays	2400	4.7
Natural radioactivity in the body	3500	6.9
Radiation from the ground (4000 personSv/ year corrected for 20% occupancy outdoors)	800	1.6
Nuclear energy, dose to the public	0.3	0.0006
Nuclear energy, occupational dose	15	0.03
Nuclear weapons fall out	100	0.2
Radon in dwellings	**34000**	**67**
Gamma radiation indoors, (80% occupancy)	4000	7.8
Consumer articles, watches, fire alarms, TV, screens etc	1	0.002
Other industry, occupational dose	2.5	0.005
Research and education	10	0.02
Dental X-ray, patients	600	1
" , occupational	0.3	0.0006
Radiation therapy, patients	irrelevant	
" , occupational	1	0.002
Medical X-ray, patients	5000	10
" , occupational	2.3	0.005
Medical isotope examination, patients	580	1
" , occupational	2.2	0.004
Veterinary X-ray, owner of animal	0.4	0.0008
" , occupational	0.3	0.0006

In most countries, however, radon in indoor air contributes less than 50% of the total dose burden. For example, in the United Kingdom radon decay products in indoor air has a mean concentration of 12 Bq/m^3 and is the most important contributing factor responsible for 33% of the total dose burden /65/. The situation in the Federal Republic of Germany is similar with a mean indoor air concentration of radon daughters of 17 Bq/m^3. UNSCEAR /4/ has estimated that the average indoor concentration of radon daughters is 15 Bq/m^3 in the temperate regions of the world.

Through radiation protection activities the total dose burden from artificial sources of radiation has been reduced or remained constant. However, doses from radon in indoor air have increased considerably during recent decades. Measurements of radon in Sweden 30 years ago indicate an average concentration of radon daughters of 12 Bqm^{-3} (the average potential alpha energy concentration corresponding to an equilibrium equivalent concentration (EEC) of radon daughters). Recent radon measurements in randomly sampled dwellings indicate that the corresponding figure today is 53 ±16 Bqm^{-3} /58/, /69/, /83/, equivalent to a four to fivefold increase in the potential alpha energy concentration in 30 years. But this may be an overestimate because the measurements did not cover the same areas.

2. SOME FACTS ABOUT RADON

Uranium-238 and thorium-232 are radioactive with very long half-lives, $4.5 \cdot 10^9$ and $1.4 \cdot 10^{10}$ years respectively. These elements are slowly transformed into stable lead-206 and lead-208 respectively. The transformation takes place by consecutive decays in a chain of several unstable intermediate nuclides. At equilibrium the relative amount of each nuclide is inversely proportional to its half-life. With one exception, the intermediate nuclides are isotopes of metals and thus immobile in the matrix. The one exception is radon, which is produced by decay of its parent nuclide radium. It is a noble gas and thus free to move by diffusion as well as by convection, if not trapped by the surrounding matrix. The isotope of radon produced in the thorium decay chain, ^{220}Rn, has a half-life of only 54.5 seconds. Due to the short half-life only a very small fraction of this isotope emanates from building materials or infiltrates from the ground subjacent to the building, and mixes with the indoor air. In the uranium decay chain one intermediate nuclide is ^{222}Rn with a half-life of 3.8 days. This time is long enough to allow for a partial release from building materials and soil. The half-life is short enough to restrict transport by pure diffusion to short distances only, but once the radon has left the solid material and become mixed with air, convective transport over longer distances (several meters) from the soil into a building is possible.

From the half-life of a nuclide it is possible to calculate how many atoms it takes to get one decay per second, which is the definition of one bequerel (Bq). 476 000 atoms are needed to get one bequerel of ^{222}Rn. A decay of one atom of radon is followed within a short time by the consecutive decay of the shortlived radon daughters, polonium-218 with a half-life of 3 min and 260 atoms/Bq, lead-214 with 27 min and 2300 atoms/Bq, bismuth-214 with 20 min and 1700 atoms/Bq, and polonium-214 with $2 \cdot 10^{-4}$ sec. One Bq of radon daughters (EEC) is thus altogether only approximately 4300 atoms.

In air the nuclides originating from radon are present in varying proportions. An exact characterisation is complex and must involve quantification of their individual concentrations. As a simplification, the concept of potential alpha energy concentration or equilibrium equivalent concentration of radon (EEC) is used for any combination of these nuclides having the same potential of emitting energy as alpha particles under complete decay to lead-210 as if they were all present in the same activity concentration (Bqm^3). Thus one Bq/m^3 of radon daughters (EEC) refers to any combination of the individual radon daughters having the same potential of emitting alpha particles as one Bq/m^3 of each of the nuclides.

A fraction of the radon daughters can occur as free ions or small neutral clusters of atoms (approximately 5 nm) in the air. In normal conditions, however, the majority is attached to particles in the air. This is usually referred to as the attached and the unattached fractions. However, the airborne radon daughters may exist in a size continuum from small clusters of atoms up to the size of the indoor aerosol /44/, /70/.

Experiments have shown that moderate concentrations of radon daughters indoors can increase considerably and even more than double in the presence of cigarette smoke /104/.

In outdoor air a typical concentration of radon is 5 Bq/m^3, corresponding to an average distance of 7 mm between atoms of radon. In average indoor air with 20 Bq/m^3 the average interdistance is 4 mm. In the minority of dwellings with >1000 Bq/m^3 the distance between radon atoms is less than 1 mm. This corresponds to an almost incredibly low fraction of the atoms being radon. For each atom of radon there are $2 \cdot 10^{16}$, $3 \cdot 10^{15}$ and $6 \cdot 10^{13}$ atoms respectively of other elements.

At about 400 Bq/m^3 of radon daughters in indoor air the risk for human adverse effects commonly calls for the intervention of society. This concentration corresponds to only $1.7 \cdot 10^6$ atoms per m^3 or $6 \cdot 10^{-16}$ gram/m^3. No chemical compound or element would show toxic effects at such a low concentration.

The radioactive nuclides in the decay chains of uranium and thorium emit different types of radiation, of which gamma and alpha radiation are the most important. The two types of radiation have very different properties. Gamma radiation is penetrative and made up of energetic photons. This type of radiation, emitted by nuclides in the building materials, results in a field of gamma radiation in the dwelling and an almost uniform dose to the whole body. Alpha radiation is made up of particles, i.e., nuclei of helium consisting of two neutrons and two protons. This type of radiation penetrates a few centimetres through air and only 40 to 70 micrometres through tissues. Thus this type of radiation can only reach living cells through decay of radioactive nuclides within or on the body. The health hazard derived from the resultant effective dose equivalent is generally assumed to be a factor of 20 higher than from the same energy absorbed as gamma radiation in tissues. The basic reason for this is that alpha radiation has a high linear energy transfer (high LET-radiation), giving an intense impact on the small volume of tissue affected. When gamma radiation penetrates tissues the energy in the gamma photon is distributed along its long path of penetration (low LET-radiation).

3. RISK ANALYSIS AND HEALTH EFFECTS

Exposure to radiation is generally assumed to result in a linear increase in the probability of developing fatal cancer.

Different types of radiation and doses received by different parts of the body can be compared only after transformation into a common dimension, the effective dose equivalent with SI unit Sievert (Sv). The internationally adopted weighting factors for this transformation for different types of radiation and various organs are continously subject to revision in the light of new data evaluated by the International Commission on Radiological Protection, ICRP.

The amount of radiation energy, SI unit Gray (Gy), joule/kg, absorbed in a tissue is transformed to dose equivalent, unit Sievert, to that tissue by a quality factor specific to the type of radiation. For gamma radiation this factor is one and for alpha radiation it is 20.

The dose equivalents for a specific organ are transferred to effective dose equivalents by internationally adopted weighting factors for each organ. After these transformations it is possible to compare consistently health hazards from alpha radiation to the lungs with gamma radiation to the whole body. It is then generally assumed that the dose equivalent 1 Sv to the lungs corresponds to 0.12 Sv effective dose equivalent or to a uniform dose of 0.12 Sv to the entire body.

According to the ICRP it is commonly assumed that the effective dose equivalents can be indicators of the probability of developing fatal cancer induced by radiation. The probability is often quantified as about 2 fatal cancers per 100 personSievert.

Present estimates of the relationship between exposure to radon daughters in indoor air and the added risk of developing lung cancer are derived from dosimetric modelling or by analogies or from extrapolations from epidemiological studies on the excess prevalence of lung cancer among miners. The dosimetric models calculate the distribution and movement of radon daughters in the body. From this the doses received by different tissues are calculated and subsequently the effective dose equivalent modelled. Such modelling inevitably involves several assumptions and a considerable uncertainty. Several epidemiological studies have been reported /1/, /2/, /15/, /26/, /53/, /59/, /75/, resulting in a fair consensus on the relationship between increased lung cancer incidence and exposure to radon daughters in mines .

When applying results from miners to the general population some differences can be compensated for, i e breathing rate and duration of exposure. Other differences can be compensated for only with assumptions which result in considerable uncertainty. Among these differences are:

- miners are healthy adult males whereas in dwellings the whole population is exposed,
- the higher breathing rate during work in mines can result in a distribution of the radon daughters in the respiratory tract different from the distribution after the slower breathing rate in dwellings,
- the exposures in mines are characterized by high concentration of short duration limited to 40 hours a week for 40 years; in dwellings the exposure is extended over longer times but at lower concentrations.

During recent years several scientific bodies have evaluated the results from dosimetric modelling and epidemiological studies attempting to reach consensus on an acceptable relationship between exposure to radon daughters in dwellings, expressed as a conversion factor between exposure, concentration and the resultant effective dose equivalent. UNSCEAR gave as a reference conversion factor 0.061 mSv/year per Bq/m^3, assuming that 80% of the time was spent indoors /89/. This corresponds to 0.08 mSv/year per Bq/m^3, assuming 100% indoor occupancy. The range of uncertainty was expressed as 0.04 - 0.1. The OECD assumed a conversion factor of 0.065 mSv/year per Bq/m^3 of radon EEC in buildings with low ventilation rates, and of 0.095 mSv/year per Bq/m^3 in buildings with average ventilation rates /63/. The National Radiological Protection Board in the UK has adopted 0.05 mSv/year per Bq/m^3 (5 mSv/WLM) as a reference conversion factor between exposure under 75% occupancy /65/. In the USA the National Commission on Radiation Protection and Measurement (NCRP) estimated the lifetime excess risk for domestic exposure as equivalent to a conversion coefficient of 0.13 mSv/year per Bq/m^3 (12 mSv/WLM) /42/.

In its preliminary report the Swedish Radon Commission (SRC) used 0.135 mSv/year per Bq/m^3 equilibrium equivalent concentration of radon as a reference value for 100% indoor occupancy /68/. In its final report, the SRC did not take any stand, referring only to the figures given by the ICRP, UNSCEAR and OECD. The SRC stressed that on the present scientific base every quantification of the relationship between exposure and risk must be deemed very uncertain /69/.

The good agreement between the conversion factors given by the different groups probably reflects a fair consensus on reasonable assumptions in the process of allocating resources to this field in competition with other demands for health protection. The uncertainty in the scientific database is probably wider than illustrated by the small difference in conversion factors.

It is, however, rather a rule than an exception that estimates of exposure-risk relationships are uncertain. Although the estimates sometimes are very uncertain they probably are better than nothing when setting priorities in environment and health protection.

In the following the conversion factor of 0.061 mSv/year per Bq/m^3 for 80% indoor occupancy is used in combination with the risk estimate 0.02 fatal cancers per personSv given by the ICRP. Thus one Bq/m^3 of radon daughters is assumed to result in 0.061 mSv/year or in the risk $0.061 \times 10^{-3} \times 0.02 = 1.2 \cdot 10^{-6}$ fatal cancers per year, or in the lifetime risk over 70 years of $9 \cdot 10^{-5}$ fatal cancers. If this risk estimate is correct it would mean that 400 out of the present 2500 cases of lung cancer per year in Sweden are related to inhalation of radon daughters in indoor air. Effective dose equivalent figures and lifetime risk estimates for representative concentrations of radon daughters in indoor air are presented in Table 2.

Table 2 Effective dose equivalent and lifetime risk for representative concentrations of radon daughters (equilibrium equivalent concentrations of radon) in indoor air.

Indoor radon daughter concentration	mSv/years	lifetime risk
Estimated indoor mean for temperate regions 15 Bq/m^3 /UNSCEAR 82/	0.9	0.1%
Finnish, Norwegian and Swedish indoor mean, about 50 Bq/m^3	3	0.4%
Swedish action level 400 Bq/m^3	24	3.4%
Swedish action level 2000 Bq/m^3, remedial action recommended within one year	120	17%

The risk estimates of lifelong exposure to 2 000 Bq/m^3, Table 2, might overestimate the true risk, since the linear relationship between exposure and risk cannot be extrapolated to very high levels of individual risk.

All risk estimates referred to in Table 2 are based on the so-called absolute risk concept. This concept considers only the excess radiation risk as a function of the cumulative dose or exposure. However, analysis of the increase with time of the lung cancer death rates in exposed populations suggests that a relative risk model may apply. According to this model the incidence of lung cancer in exposed populations, after an initial latency period, follows that of non-exposed populations, but at a higher level by a factor constant in time after exposure. The model implicitly accounts for an influence of smoking provided there is a multiplicative interaction with exposure to radon daughters. With the relative risk model it has been estimated that about 10+5% of the lung cancer death rates among people living in "normal" areas with 8-25 Bq/m^3 of radon daughters in the indoor air might be attributable to radon daughters exposure. For chronic exposures at about 300-500 Bq/m^3 the lung cancer death rate might be twice as high as it would be in the same population with no excess exposure to radon. According to the relative risk-model, exposure to radon in absolute terms would be much more dangerous for smokers or people with otherwise enhanced risk of developing lung cancer /39/, /40/.

A working group of the World Health Organization (WHO) has evaluated radon in indoor air and concluded, in accordance with the relative risk concept, "that estimated risk of lung cancer, attributable to inhaled radon daughter concentrations indoors, is a significant fraction of the total lung cancer risk. It is estimated that at the observed mean levels indoors, about 10% of all lung cancer cases might be caused by radon daughters. ... At the high end of the concentration distribution, the risk is of the order of that caused by cigarette smoking. ... Reducing exposure to radon daughters is an effective approach to reducing lung cancer risks" /98/.

A more accurate estimate of the true relationship between exposure to radon daughters in indoor air and lung cancer incidence is urgently needed and can only be established by epidemiological studies in dwellings. Research in this field is difficult because of:

- long latency time; 10 - 30 years between exposure and manifested lung cancer,
- several factors other than radon can result in lung cancer, and
- except in the small number of dwellings with extremely high concentration of radon daughters the expected increase in morbidity is small, so that a very large sample is required to give a statistically significant result.

In Sweden, epidemiologists have been investigating the health effects of indoor radon for some years. Published results of a few pilot studies indicate a statistically significant association between bronchial cancer and estimated exposure to radon in dwellings /2/. In one study 53 cases of lung cancer and an equal number of controls, matched for sex, year of birth and smoking habits, were extracted from the Swedish twin registry, and from a material of lung cancer cases and controls in Northern Sweden. Exposure was estimated from data on house characteristics of relevance for indoor radon levels, e. g. building material and type of ventilation. The results indicated a higher exposure to radon for the lung cancer cases than for the controls among smokers but not among non-smokers /66/.

Recently, a case-referent study on the possible association between radon emanating from the ground and bronchial cancer has been performed among 292 female lung cancer cases and 584 matched population referents. Both groups had lived at least 30 years in the City of Stockholm. Indoor radon and radon daughter measurements were made in a 10% sample of the dwellings where the cases and referents had lived. A relative risk of 2.2 (p=0.01) was found for lung cancer associated with living in dwellings close to ground in areas with an increased risk of radon emanation /84/.

Larger studies with potential to quantify any relationship between exposure to radon in indoor air and lung cancer with statistical significance are being planned in Sweden and in Norway. A pilot study in Norway has shown that it is feasible to conduct epidemiological studies in the Norwegian population since there are a reliable lung cancer incidence database, large regional variations in indoor radon concentrations, a reliable database on building stock, and a reliable database on smoking habits among different parts of the population /80/.

4 SOURCES OF INDOOR RADON

Radon enters a building
- from soil, fill or capillarity breaking layer,
- by exhalation of a fraction of the radon which is produced by decay of radium in the building materials,
- with drinking water, and
- with supply air or infiltrating ambient air.

In detached houses and in flats at ground level, infiltration of soil gas can act as a carrier for radon from subjacent soil, fill or the capillarity breaking layer. This is the most important and problematic of the different sources because it can result in extremely high indoor concentration of radon. Infiltration by this route gives radon daughter concentrations an order of magnitude higher than by using Swedish aerated alum shale concrete in efficiently weather-stripped buildings. Infiltration of soil radon can occur on soil with quite "normal" radium activity if the soil is permeable, like gravel.

The exhalation from building materials for practical purposes can be regarded as constant over time. Thus the contribution from building materials to the concentration of radon in the indoor air is inversely related to the ventilation rate. In flats with no contact with the ground exhalation from building material is typically the major source of indoor radon.

Significant contributions to the indoor concentration of radon can be released from drinking water if this is taken from a well drilled in certain types of rock, for example granite.

It is generally accepted that type of building and basic design has a great influence on indoor radon concentration. Flats without ground contact and detached houses on spot footings are resistent to infiltration of soil radon. Dwellings with open contact to a basement, on the other hand, are most prone to infiltration of soil radon. Foundation walls made of in situ concrete are normally tight while walls made of concrete blocks can present a route of entry for radon. Monolitic reinforced basement slabs can be made tight enough while foundation on footings and separate slabs in each room in the basement is a common design in houses with excessive infiltration of soil radon.

4.1 Radon from the soil

The production rate of radon in rocks and soil varies with the concentration of radium. Each bequerel of radium gives one atom of radon per second. And as one bequerel of radon equals 476 000 atoms one bequerel of radium produces 3 600/476 000 = 0.0076 bequerel of radon per hour. Most of the radon is produced in the solid grains of soil or in the interior of crystals in rock and is immobile. A fraction, however, enters the gas-filled pores in the rock or soil. This fraction, typically 5-30% but sometimes in clay up to 60 % /69/, can be produced by the decay of radium precipitated in cracks or expelled from crystals by the recoil from the alpha particle emitted when the radium atom decayed.

The resulting concentration of radon in the interstices between particles in soil or in cracks of a rock always is of orders of magnitude higher than can be accepted in a dwelling. The reason for this is that

- the surface to volume ratio in soil is much higher than in dwellings,

- there is much more mineral matter per unit of gas volume, and
- the exchange rate with the atmosphere is lower.

The concentration is a function of

- radium content,
- fraction of free radon emanating from the particles into the soil gas,
- the pore volume,
- fraction of pore volume filled with water, and
- air exchange rate with the atmosphere.

The following example illustrates the situation: Assuming 1600 kg of soil per cubic metre, 30% pore volume, 10% of radon emanating from particles to the pores, radioactive equilibrium between radium and radon, and world average concentration of radium in the soil, 25 Bq/kg /89/, the concentration of radon in the soil gas would be 1600/0.3x0.1x25 = 13 000 Bq/m^3.

In Sweden, concentrations in soil gas of 20 000 Bq/m^3 are regarded as "normal". At a depth of 1 metre in eskers the concentration of radon is often 70 000 - 120 000 Bq/m^3 indicating that 25% of the radon is free and emanates to the soil gas /69/.

The concentration of radon in the soil gas is not constant. At the Swedish Geotechnical Institute the concentration of radon in soil gas was monitored over a period of 19 months in six localities in clay, sand, and gravel over granite and alum shale /56/,/57/. The measured concentration of radon was correlated to geohydrological and meteorological parameters. In wintertime frozen soil and snow acts as a tight cover, resulting in high concentrations. Heavy rainfallls can seal the surface temporarily resulting in a peak in concentration. Under dry conditions in permeable soil the emanation from the soil particles is reduced and at the same time the air exchange rate with the atmospere is increased. The combined effect is unusually low concentrations of radon. In clay, dry periods can have the opposite effect on concentration of radon, giving unusually high concentrations. A small reduction in water content can increase the permeability dramatically by creation of cracks.

Similar results have been obtained in Finland, where the radon concentration in an esker was found to be several times higher in wintertime than during spring and summer /85/. In this case, the concentration of indoor radon showed seasonal variations similar to the soil gas. As an average, the concentration in the soil was about twenty times higher than indoors, indicating that 5% of the leakage of the building was towards the soil and thus 5% of the air exchange was by infiltrating soil gas. The study also demonstrated the effect of the variable structure of an esker consisting of layers, and the inhomogeneous activity of the ground. In one location the concentration of radon was much higher and showed much stronger seasonal variations under a layer of clay than above this layer.

There is by now sufficient evidence to conclude that seasonal variations and possible inhomogenities in the soil must be taken into consideration when the risk of infiltration of radon into future constructions is evaluated.

It is generally accepted that radon enters a building from the subjacent soil, being carried by a convective flow of soil gas infiltrating through cracks, holes or other openings between the soil and the interior of the building. Transport by diffusion is nearly always insignificant. Only when the concentration of radon under a concrete slab is extremely high can the transport by diffusion through the concrete exceed the exhalation from normal concrete /13/, /93/.

The diffusion of radon through an open connection is much stronger than the diffusion through the same area of concrete slab /92/. For example, if there is one crack of one cm width for each metre of slab the influx of radon by diffusion will be 25% of the influx without the slab. This is a 25-fold increase in influx compared to a tight concrete slab /54/.The possible transport of radon through an opening, however, is still much greater if there is a convective flow driven by a pressure difference.

There are in general three requisites necessary for excessive building infiltration of radon from the soil:

- there must be an open connection for convective gas transport into the building,
- there must be a driving force supporting a convective flow through the opening, i.e. a pressure gradient with negative pressure in the building relative to the soil, and
- there must be a large enough volume of permeable soil subjacent to the building.

Since the concentration of radon in infiltrating soil gas is very high, even a small fraction of the total untightness of a building envelope facing the soil will

Table 3 Infiltration of soil gas (m^3/h) with 1, 5, 10, 50 and 500 kBq/^{3} radon contributing 10, 50, 200 and 1000 Bq/m^3 to indoor radon.

Radon concentration in soil gas, kBq/m^3	Indoor radon concentration from soil gas infiltration, 10 Bq/m3	50 Bq/m3	200 Bq/m3	1000 Bq/m3
1	1 m3/h	5 m3/h	20 m3/h	100 m3/h
5	0.2	1	4	20
10	0.1	0.5	2	10
50	0.02	0.1	0.4	2
500	0.002	0.01	0.04	0.2

result in a significant increase in indoor radon concentration. Table 3 illustrates the infiltration of soil gas which will give a certain contribution in a dwelling ventilated by 100 m^3/h.

Table 3 shows that on a normal soil with 5 - 10 kBq/m^3 of radon in the soil, soil gas infiltration will contribute 50 Bq/m^3 to the indoor radon concentration if 0.5 - 1% of the air exchange is infiltrating soil gas. To avoid significant soil gas contributions on soil with unusually high concentrations of radon it is necessary for less than 0.1% of the air exchange to be by infiltrated soil gas. Consequently, 0.1% at the most of the total untightness of the building envelope should relate to surfaces in contact with soil.

Inside buildings the air pressure is often lower than outdoors or in the soil. This pressure difference is the net effect of temperature differences, wind pressure, and any mechanical extraction of air by exhaust ventilation from the building. The pressure difference over the slab between the interior of the building and the subjacent soil can also be influenced by a stack effect in the soil. This phenomenon has been studied on an esker /74/ and in a cliff /91/.

Reducing ventilation rate by weatherstripping and other tightening measures has during the latest decade been a very cost-effective and widely applied energy conservation measure. Hereby the infiltration of radon from the soil has increaed unless when due consideration to untightnesses to the ground has been taken.

4.2 Radon from building materials

The mobile fraction of radon, often called emanating radium, in the pores of building material migrates by diffusion to the lower concentration at the surface of the material where some is exhaled to the surrounding air. The exhalation from the surface is reduced by any tight covering.

The exhalation rate of radon from building materials has been studied extensively. However, the values obtained are not always consistent and large variations are found for the same material and surface. There are obviously great experimental difficulties and the factors influencing the exhalation are not fully understood.

The exhalation is strongly influenced by the moisture content of the material. Very dry material has a low exhalation and when it is soaked wet as well. The exhalation has a maximum between these, for buildings, extreme conditions. The exhalation from concrete was shown to increase many times over when the moisture content was increased to 2% of the dry weight. Between 2% and 4% moisture content the exhalation was almost constant, about 20%. A further increase in water content resulted in increased exhalation /67/. The maximal exhalation is often 2-5 times the exhalation from dry material, but can be as high as 30 times /57/.

For concrete, exhalations corresponding to 1-35% of the amount produced have been reported /36/, /90/. The majority of measurements reported in literature indicate exhalation of 1 -10 Bq/m^2,h from normal building materials. Exhalations exceeding 20 Bq/m^2,h are very uncommon. A concrete wall 20 cm thick with average radium activity (25 Bq/kg) can be taken as representative. Exhalation of 10% of the radon content is 4 Bq/m^2,h, which can contribute 15 Bq/m^3 to the indoor radon concentration only if the air exchange rate is 0.5/h.

There are some examples of building materials with unusually high radium activities and correspondingly high exhalations of radon. The most well known are mill tailings used as concrete ballast, for example in Grand Junction, Colorado /14/, and aerated concrete based on alum shale which was widely used in Sweden until 1975. Other examples are granite stones in some parts of the UK /11/, phosphate slag in Alabama /4/, and byproduct gypsum from production of phosphoric acid /64/. Swedish aerated concrete based on alum shale has radium activity ranging up to 2700 Bq/kg with 1300 as an average /61/. The exhalation of radon is a function of the radium activity, e.g., a sample with 2500 Bq/kg exhaled 200 Bq/m^2,h /69/.

Generally the exhalation of radon from building materials can be regarded as constant over time. The contribution from this exhalation to the indoor radon concentration is inversely proportional to the amount of air passing through the building as intentional ventilation and as infiltration through leakages. A doubling of the air exchange rate will thus result in a 50% reduction in the radon concentration emanating from building materials.

The most cost-effective measure for energy conservation in existing buildings is probably the reduction of unintentional air infiltration achieved by weather stripping and other sealing measures. But successful sealing will result in an increased radon concentration. With present energy costs it has been shown, however, that for common building materials the marginal costs for increased energy demand cannot justify any increase in ventilation rate simply because of its effect on radon concentration, except in cases when the ventilation rate is below or equals 0.3 air changes per hour /16/. In "normal"buildings, therefore, other aspects of the indoor air quality will determine the recommendations on minimum air change rates.

4.3 Radon from drinking water

In cities the municipal water supply systems normally use surface water from lakes and rivers which have a very low concentration of radon. As a rule, waters from aquifers in sand and gravel also have low concentrations of radon. Very high concentration of radon have been measured in waters from wells drilled in solid rock. Groundwater in granites in Finland /46/, /7/, Sweden /48/, and Maine (US) /22/, /31/, /32/ can sometimes contain extremely high concentrations of radon.

The radon in water is released to the air when the water is heated or is dispersed in the air. Radon in drinking water seemingly contributes to the long-term average concentration in indoor air with 10^{-4} times its concentration in the water. Each 10 Bq of radon per litre of water will thus increase the concentration of radon in the indoor air by approximately 1 Bq/m^3 /6/, /22/, /30/, /94/.

The concentration in a bathroom can be very high after a shower, for example. In Canada 6700 Bq/m^3 radon was measured in the bathroom immediately after a shower with 2 000 000 Bq of radon per litre of water /94/. For example a housewife can be subject to significant exposure, well above the long time average for the dwelling, while doing her household chores /6 /. On the other hand, it has been shown that a slight change in habits can reduce the emission of radon from water /6/. If the bathroom door is kept closed the radon will mostly leave the building through the air in the bathroom exhaust. It is very likely that mechanical exhaust ventilation from spaces where water is used will extract most of the radon released from water and reduce the contribution to the average concentration in the dwelling.

5. OVERVIEW OF RADIATION LEVELS IN DWELLINGS

5.1. Radon in indoor air

Large-scale surveys of indoor radon concentration, involving more than 100 dwellings, have recently been completed or are in progress in several countries. The purpose of these surveys is to describe the distribution of population exposures, to identify problem areas, or to study the effects of remedial actions of manmade contamination and of cases of excessive radon infiltration from soil gas. The radon and radon decay product concentrations in all cases seem to be well represented by a log normal distribution. The mean indoor equilibrium equivalent concentration (EEC) of radon has been estimated to be 15 Bqm^{-3} in the temperate regions of the world /89/. There are some areas where the distribution deviates significantly from this mean, some with extremely high concentrations. The commonest reason is infiltration of soil gas from permeable soil. Building materials with high radium activity contribute significantly in some cases.

In Sweden, the combination of infiltration of radon from the soil and the use of aerated concrete based on alum shale has resulted in a mean indoor concentration of radon daughters estimated to be 53 ± 16 Bq/m^3 /69/. The population exposure distribution has been estimated as:

>	0 Bq/m^3	8 200 000 persons
>	100 "	800 000 "
>	200 "	300 000 "
>	400 "	90 000 "

As an effect of the log-normal concentration distribution, the main contribution to the collective effective dose equivalent to the whole population is not from the small fraction of houses with elevated radon concentrations. In Sweden, the one percent of the building stock with > 400 Bq/m3 has been estimated to cause 16% of the collective exposure, while 90% of the dwellings with <100 Bq/m3 determine almost 50% of the collective exposure.

Until June 1982 local communities had made screening measurements in 32 000 dwellings selected because they could be expected to have high concentrations of indoor radon. Approximately 10% of the measurements showed more than 400 Bq/m^3 of radon daughters. More than 2.000 $Bq/^3$ was measured in 0.3% of the dwellings /105/.

In Finland, the present estimate for the national mean indoor radon concentration is 90 Bq/m3. In a problem area in Southern Finland, the mean for 754 measured houses was 370 Bq/m3 while in the most extreme subarea the mean radon concentration was 1.200 /8/.

In Norway, the mean indoor radon concentration has been estimated as 80 Bq/m^3. About 3% of the dwellings in Norway are believed to have radon daughter concentrations above 200 Bq/m^3 and for about 1% of the dwellings the concentration is believed to exceed 400 Bq/m^3. The highest indoor concentrations of radon occur in areas with alum shale in the ground. In one municipality with such ground, 38% of the measured dwellings had > 400 Bq/m3 of radon /79/.

In the UK, about 800 measurements have been made in areas with igneous geology and uranium mineralisations. The results indicate the existence of small areas where the mean radon concentration is of an order of magnitude above the national average. A few houses have been identified with approximately 2 000 Bq/m3 radon daughter EEC /12/.

In the USA high indoor concentrations have been reported from a part of Eastern Pennsylvania and from Maine. In six electrically heated homes in Pennsylvania, the concentration of radon in the living area ranged from 160 to 1800 Bq/m3 /96/. In 122 Pittsburgh area houses measurements on the first floor gave an average radon concentration of 90 Bq/m^3. The highest measured concentration was 900 Bq/m^3 /102/. In a national survey in the USA radon concentrations have been measured in 453 houses of physics professors from 101 universities in 42 states /103/. The geometric mean was 38 Bq/m^3 and the aritmetic average was 54 Bq/m^3.

5.2. Gamma radiation in dwellings

There are three major components determining the gamma radiation in a dwelling:

- gamma radiation from building materials, which is the single most important contributing factor,
- cosmic rays, the intensity of which is a function of latitude, altitude above sea level and any shielding effect from heavy building materials such as concrete, and
- gamma radiation from the ground, terrestrial radiation, which is a function of activity of natural radioactive nuclides in the ground under the house and shielding by building materials such as concrete slab.

Outdoors, at sea level, the cosmic radiation contributes 0.3 mSv/year /89/. The world average for effective dose equivalent from gamma terrestrial radiation has been estimated to be 0.3 mSv/year /89/. The average for individual countries deviates from this figure. For Sweden the average has been estimated as 0.5 mSv/year /68/.

Since heavy building materials act as a shield for radiation from the ground and cosmic rays, it is possible to find situations where the intensity of gamma radiation inside a dwelling is lower than outside. The prerequisite for such a situation is the use of wood as the main building material and of concrete with low activity concentration of radioactive nuclides. This is the basis for construction of storage rooms for X-ray film and laboratories for measuring extremely low concentrations of radionuclides, i e in humans, where efficient shielding of radiation is essential. Such rooms are built with thick walls of a material with unusually low activity of naturally radioactive nuclides.

On the other hand, it is normal for building materials like ordinary concrete produced from local gravel to result in a small increase in the field of gamma radiation inside dwellings. If the building materials have the same activity concentration of naturally radioactive nuclides as the surrounding soil, a normal representation of building materials (wood, brick and concrete) gives an average indoor to outdoor ratio of 1.2 in absorbed dose /89/.

The relationship between activity of naturally radioactive nuclides in the building materials and the resultant contribution to gamma radiation indoors have been studied by several investigators /3/, /33/, /47/, /49/, /50/, /51/, /52/, /60/, /62/, /76/, /77/, /78/, /82/, /87/, /88/. This database can be considered a fair consensus of the conclusions reached by different researchers. In normal houses with a combination of different building materials, the activity of potassium, radium and thorium in the main materials will result in 0.2-0.3, 2-3 and 3-4 uSv/year respectively per Bq/kg. In the extreme, more theoretical situation where floor, ceiling and all four walls are made of 20 cm thick concrete the increase in the effective dose equivalent will be 0.6 uSv/year per Bq/kg for ^{40}K, 7 uSv/year per Bq/kg for ^{226}Ra and 8 uSv/year per Bq/kg for ^{232}Th. Based on these figures it is possible to estimate the dose commitment following the incorporation of ^{40}K, ^{226}Ra, and ^{232}Th in the structures of dwellings as 0.6, 7 and 8 mSv per MBq respectively.

Aerated concrete based on alum shale, widely used in Sweden from 1930 to 1975, is perhaps the most outstanding example of a building material with very high activity concentration of naturally radioactive nuclides. In buildings made of this material the effective dose equivalent from indoor gamma radiation in rare cases can reach 4 mSv/year /68/. Thus, the contribution from gamma radiation from building materials to the effective dose equivalent can range from a small negative value to approximately 4 mSv/year. The average can be estimated to be not far from 0.1 mSv/year.

Changes in ventilation rate, infiltration rate or other energy conservation measures can never have any impact on gamma radiation inside dwellings.

6. REMEDIAL ACTIONS

Methods for remedial actions against excessive concentration of radon in indoor air have been developed and applied, i.a. in Canada, Sweden and the USA. When selecting a remedial action method suitable for a specific building several factors have to be considered. The most important ones are:

- the source (soil, building materials or water),
- the route of entry,
- the type of building, and
- the required reduction (is 50% enough or is >90% required?).

The most common sources and routes of entry for radon into a building are illustrated in figure 1. The same building after possible remedial actions have been taken is presented in figure 2.

6.1. Radon from the soil

As stated above, the soil subjacent to buildings is probably the most important contributor to indoor radon. No other source can result in as extremely high concentrations as radon from the soil.

Only insignificant amounts of radon can enter a building by diffusion through building materials. Infiltrating soil gas acts as a carrier for radon from the subsoil into buildings. Thus there are three essential prerequisites for infiltration of radon from the soil:

- the subsoil must be permeable, allowing a convective flow of air,
- there must be some leakage between the soil and the interior of the building, and
- there must be a driving force, i.e., a pressure gradient sucking air through untightnesses into the building

The three parameters given above are possible targets for remedial actions against infiltration of soil gas. It is, however, not possible to change the properties of the soil under the house and by this means prevent infiltration of soil gas. It is also necessary to have a permeable material as capillarity breaking layer under any concrete slab.

If the untightnes where radon enters the building can be identified and sealed this can be a very cost effective remedial action. For example, indoors in a group of terrace-houses built on young uraniferous granite and blast debris an average of 500 Bq/m^3 of radon was found. The building material was concrete with a probable exhalation of 10 - 15 Bq/m^2,h. Although the air exchange rate was low (well below 0.5 air exchanges per hour), the building materials could not be expected to contribute more than 100 Bq/m^3. It was found that

Figure 1. Illustration of the most common sources of indoor radon (soil, building materials and water) and its normal routes of entry. (Reproduced with permission from AIB Consulting Engineers, Solna, Sweden)

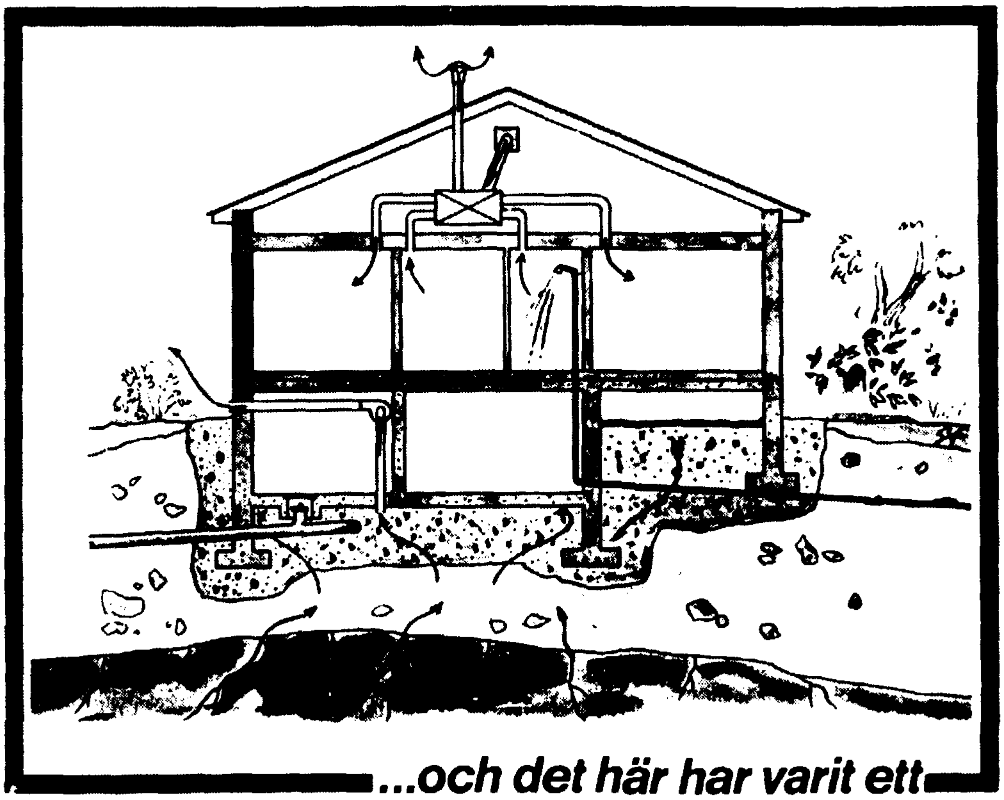


Figure 2. Illustration of normally succesful remedial actions in existing buildings with indoor radon from soil, building materials and water; sealing of untightnesses in the basement, depressurization of the capillarity breaking layer and installation of a balanced ventilation system. (Reproduced with permission from AIB Consulting Engineers, Solna, Sweden)

the main waterpipe entered the houses through a hole in the concrete with a diameter some 40 mm wider than the water pipe. The air which infiltrated this route had an average radon concentration of 20 000 Bq/m^3. From the soil gas contribution to the concentration of indoor radon it follows that the soil gas was diluted 50 times and that 2% of the air passing through the building was soil gas. The water pipe entrance was sealed with a plastic caulk at negligible cost. Hereby the concentration of indoor radon was shown to be reduced to normal levels /17/.

It is concluded that, as a general principle, infiltration of soil gas in new construction must be prevented by designing as tight a construction as possible. Normal concrete with no cracks and holes is tight enough, and a concrete slab of conventional quality presents sufficient resistance to radon even if the concentration is 300 000 Bq/m^3 in the soil gas immediately beneath the slab /20/.

Often the untightness of a building to the ground is inaccessible or diffuse. Attempts have been made to seal all the interior surfaces of concrete floors and basement foundation walls with several layers of epoxy sealants. Although epoxy sealants provide an impervious layer the effect is not normally permanent. The sealant tends to crack over cracks in the concrete slab /14/. This phenomenon could probably be counteracted by using a permanently elastic surface sealant such as rubberized asphalt, which has been evaluated as a possible surface cover for dumps of uranium mill tailings in the USA /28/,/29/. In a furnished basement, the cost of restoring panelling and floor makes the method rather expensive.

The most commonly applied way of coping with infiltration of soil gas has been to eliminate the pressure gradient between the soil and the building. This can be achieved by balancing the negative pressure caused by the stack effect by pressurising the building. This method, however, cannot be recommended. It would have the desired effect on infiltration of soil gas but would simultaneously press warm humid indoor air into the cold parts of the walls with water vapour condensation and possibly development of mould as adverse side effects. Instead, it is recommended that the pressure gradient over the slab be changed by sucking air from the soil under the slab, thus maintaining a stronger negative pressure under the slab relative to the interior of the building. This technique has been successfully applied in Canada /94/, in the remedial action program in Grand Junction, Colorado and in Sweden.

In Sweden, 39 installations for creating a negative sub-slab pressure have been evaluated. The average reduction in radon concentration in indoor air was 88% or 2 600 Bq/m^3. A limited flow of gas is extracted, just enough to prevent infiltration through any cracks.

Sometimes it is sufficient to apply suction in one point only, but if the capillarity breaking layer is sectioned by footings, suction in every section is recommended. It is essential to apply the suction in a small cavity under the slab. With no such cavity the pressure drop will often be too high close to the point of suction, preventing horisontal spreading of negative pressure under the slab /17/.

Application of strong suction at one point in an esker has been demonstrated as a possible remedy for a group of adjacent buildings (personal communication from Dr Bengt Eriksson, National Institute for Building Research, Gävle, Sweden, /10/).

In certain conditions it is also possible to prevent infiltration of soil radon by blowing air down under the slab. Such an installation will be effective if the concentration of radon under the slab is reduced to a low value by this ventilation. Optimal alternatives must be selected with due consideration to building physics and local conditions.

Increased indoor ventilation is uaually not an effective remedial action against infiltration of soil gas. If soil gas infiltrates the building, the resulant indoor air concentration may become extremely high. The source term emission then has to be reduced, since no realistic ventilation rate will suffice to dilute the radon to an acceptable concentration. Mechanical exhaust air ventilation of the building will increase the negative pressure in the building and possibly increase the infiltration of radon from the soil. In one house, operation of the exhaust fan over the kitchen stove was shown to increase the ventilation rate of the house considerably, but so did the flow of air from the crawl space into the kitchen. This resulted in a several-fold increase in radon concentration /9/. Operation of an exhaust air ventilation system in a house with slab on grade has had a similar effect /20/. Whenever mechanical ventilation is applied in a house with suspected infiltration of radon from the soil the system should be of the balanced supply-exhaust type. Balancing the system to a neutral pressure, and regular maintenance, will be essential. Considering these demands, ventilation can be a good supplementary remedial tool, especially in cases where the building materials contribute significantly to the remaining concentration of radon. Installation of mechanical balanced ventilation in 10 dwellings with infiltration of soil radon resulted in 40 - 90% reduction in indoor concentration /20/.

6.2 Radon from building materials

Building materials can be regarded, by and large, as a constant source term for indoor radon. Common building materials have such low exhalation rates, less than 20 Bq/(m^2,h), that retrofitting with a mechanical ventilation system will not be cost-effective. The most well known building material with excessive exhalation of radon is probably a type of Swedish aerated concrete with alum shale. The typical exhalation from this material is 50-200 Bq/(m^2,h). In houses where aerated alum shale concrete is the main building material,

weather stripping can result in a rise of the radon concentration up to 1000 Bq/m^3. In such situations retrofitting with a mechanical balanced ventilation system is the best remedial action. The adequate air exchange rates can not be achieved simply by increasing the general untightness of the building envelope. In cold climates the result would be an uncomfortable indoor thermal climate and excessive heating costs. In Sweden, the installation cost of a retrofitted ventilation system is approximately 5% of that of a new construction.

The effect of a retrofitted balanced ventilation system on indoor radon concentrations often deviates from what is calculated assuming complete air mixing and dilution of a constant source for radon.

Improperly designed or located air inlets and outlets may cause the ventilation air to pass straight from air inlet to air outlet, not mixing with the room air. This can result in a surprisingly small reduction in radon concentration.

Clean air is often supplied to "clean rooms" where people spend most of their time, and then passes through transfer air devices into other parts of the house where the air outlets are located. The dilution rate with non-polluted air in the "clean rooms" will be higher than the average for the whole building and consequently in these rooms the reduction in radon concentration will be larger than expected.

The increased air movements in a house with mechanical ventilation may increase the adsorbtion of radon daughters to surfaces, plate out.

A reduced dwell time of the radon in indoor air tends to reduce the equilibrium factor. When the effect of ventilation is characterized by measuring the concentration of radon daughters, this adds to the reduction in concentration of radon.

If the ventilation systems are equipped with efficient air-to-air heat exchangers or the heat in the exhaust air is recovered with a heat pump, the ventilation systems neither increase nor decrease the energy demand in the building. With retrofitted mechanical and balanced ventilation systems, houses built from aerated concrete based on alum shale can be remedied efficiently. In 7 dwellings the concentration of radon daughters was reduced by 95% down to 16 - 60 Bq/m^3 /18/.

6.3 Air cleaning

When air passes through a mechanical filter or an electrostatic precipitator, particulates with particle-bound radon daughters, as well as the unattached fraction of the radon daughters, are removed efficiently. These filters, however, do not remove any radon from the air and thus the production of radon daughters through the decay of radon is not affected. The radioactive half-lives of the radon daughters are fairly short and limit the duration of the effect of filtration. A drastic reduction in concentration of radon daughters therefore requires a high volumetric capacity in the filter, with more than one turnover h^{-1}. A lower filtration rate will result in a non-significant dose reduction only /73/.

Filtration removes radon daughters from the air by two more mechanisms over and above the removal in the filter itself. The radon daughters produced by radon decay in filtered air, which has a low concentration of particulates, will have less chance to attach to particulates, leaving a large fraction of the radon daughters in the unattached form. Unattached radon daughters are more mobile and more likely to plate out on walls and other surfaces. The forced circulation of air which is a side-effect of filtration also increases the plate out on surfaces.

The overall reduction in concentration of radon daughters by air cleaning is partly outweighed by the fact that the unattached fraction of radon daughters is increased. The unattached fraction is generally assumed to be more harmful and to give a higher radiation dose per inhaled unit of activity /44/, /73 /. Radiation doses from inhalation of radon and radon daughters are calculated by models incorporating several assumptions. The most frequently used models are the Harley-Pasternak /27/, the James-Birchall /41/, and the Jacobi-Eisfeld /37/, /38/ models. These models differ, i.a., by the different weighting factors given the unattached fraction of the radon daughters.

The efficiency of electrostatic precipitators largely depends on which combinations of age and dose models are being used in the inter-equipment comparisons /43/, /44/, /45/, /71/. The activity concentration of radon daughters was found to be reduced by 50 - 75% in air with a low and by 31 - 65% in air with a high initial concentration of particulates. The reduction in calculated dose, however, was limited to 30 - 40% of the value of unfiltered air. Similar results have been obtained in other investigations of electrostatic filters /24/, /86/. All the models showed some reduction of dose during filter use. It is calculated that filtration at a turnover rate of 4 h^{-1} will result in 50% reduction of the effective dose equivalent /73/.

As the more harmful unattached fraction is increased by filtration, it has been argued that filtration might even increase the dose. From the studies referred to above this seems not to be the case, although the reduction in radiation dose is less than is indicated by the overall reduction in activity concentration of radon daughters.

In the USA the EPA assumed air cleaners to be one of a few economically feasible remedial actions for existing structures on phosphate land in Florida /23/. For HEPA filters, the capital cost was estimated at $400 and average annual operating cost at $100. For electrostatic precipitators, the capital cost and the annual operating cost were estimated at $350 and ≥$35 respectively.

In conclusion, it seems that air filtration would result in only a small reduction in dose. The technique can not be recommended as a remedial action against excessive concentrations of radon daughters except in combination with other more efficient actions. In cases of moderately enhanced concentrations of radon daughters, filtration can result in an acceptable air quality. The absolute dose reduction, however, will not be sufficient to justify the costs involved. The reduction of the radiation dose from radon daughters can nevertheless be a positive side effect when filters are installed to cope with some other indoor air quality problem.

7. STRATEGY

An optimal strategy for coping with radon in indoor air should

- minimize cost,
- provide a level of ambition compatible with other fields of radiation protection and of public health, and
- give special consideration to the small minority of the population possibly exposed to extremely high concentrations posing an unacceptable individual risk.

The International Commission on Radiological Protection /35/ has given general advice on fundamental principles in radiation protection to natural sources of radiation. Radon in dwellings has, as the most important exposure to natural radiation, been used for illustration of the general recommendations.

The tradition in radiation protection has been to set very stringent limits on doses from artificial sources of radiation. Natural radiation, including radon in indoor air, has traditionally not been covered by any regulations.

The dose limit for occupational exposure has been set at 50 mSv in one year. This limit is applicable for a single year, but yearly doses of 50 mSv would not be acceptable over a long period of the working life of an individual. With the limit of 50 mSv/year per year for 40 years' working life, the individual would accumulate 2 Sv. Using the assumption of ICRP that each personSv corresponds statistically to 0.02 fatalities induced by radiation, this is equivalent to a 4 % individual risk. This figure is regarded as the upper limit of individual risk that the individual generally will accept. With no regard to the costs involved, each individual is guaranteed not to receive higher doses from occupational exposure.

For the general public the ICRP has recommended that the committed effective dose equivalent from exposure to artificial sources of radiation in any year be limited to 5 mSv. For repeated exposures the Commission has stated that 5 mSv/year is a bit high and that it would be prudent to restrict the dose further to 1 mSv/year from lifelong exposure. This would limit the dose from artificial sources to each member of the public to 70 mSv, which statistically would correspond to an individual risk of 0.14%.

The setting of upper limits of accepted doses is one of three principles for radiation protection. Another principle is that a practice which causes exposure to radiation should be justified by providing a positive net benefit to mankind. The third principle discussed by ICRP /35/ is the rule of ALARA. ALARA stands for **As Low As Reasonably Achievable**, economic and social factors being taken into account. The meaning of this principle is optimisation of the use of resources allocated to further reduce the doses below the upper limits. The underlying philosophy is that every increment in dose is equally urgent to reduce. Thus, it would be contrary to this rule to take action at a very high cost per unit of dose reduction if at the same time more cost-effective actions are neglected.

The ALARA principle is not intended to protect any single identified individual but to be used as a guideline for what are and are not reasonable costs in allocation of resources. In Sweden, the limit of reasonable cost has been suggested as SEK 100 000 per personSv of collective dose reduction /55/. This figure is not meant as a strict value to be used in a mathematical calculation of the cost-efficiency, e.g. in analogy with the accepted pay-off time in investment calculations. The figure is rather to be seen as one of several indicators used in allocating resources available for radiation protection. The figure is given as an interval ranging from SEK 10 000 to SEK 500 000 per personSv. The limit of reasonable cost can be transformed into a figure on the willingness of society to pay for one statistically avoided fatality caused by radiation. SEK 100 000 then corresponds to SEK $5 \cdot 10^6$ for one fatality. This may be compared with the figure of SEK $4.3 \cdot 10^6$ per life saved which can be deduced from the policy in traffic accident prevention. It might be argued that there is a higher ambition in radiation protection than in traffic accident prevention, since every fatality in traffic accidents is accompanied by a larger number of non-fatal injuries, some of which are disabling for a very long period of time. Traffic accidents also involve the young portion of the population, in contrast to lung cancer from radon.

The cost limits mentioned above refer to the marginal cost, implying that urgent programs generally start with the most cost-effective actions and stop at a more or less outspoken increase in marginal cost. The average cost to society will thus be lower than the "limit for reasonable costs" examplified above.

Until recently the annual "whole body" effective dose equivalent from natural sources of radiation was estimated to be approximately 1 mSv as a worldwide average. In the 1982 UNSCEAR report /89/, however, this estimate was doubled to 2 mSv. The change was caused mainly by an increase in the estimated effective dose equivalent referring to the dose to the lung of radon decay products, mainly in indoor air.

An important recent discovery is that soil gas infiltrating into a building can act as a carrier for radon resulting in extremely high concentrations of radon in the indoor air /72/, /95/. Very high concentrations indoors have been measured on ground where the activity of radium is not very different from the world average. The combination of a very permeable soil, such as gravel, allowing soil gas to move freely to the building envelope, and open contact between the soil and the interior of the building, has been proven to be a sufficient cause of unacceptably high concentrations of indoor radon. The resultant effective dose equivalents may be very high, ranging up to 1 Sv each year. This is at least 20 times the upper limit for permitted occupational exposure and constitutes an individual risk not likely to be accepted, either by the exposed individuals or by society. Life-long exposure would, according to risk estimates presented by the ICRP and others, result in a probability of developing lung cancer which is higher than from tobacco smoking.

It has been shown that many soil gas infiltrated buildings can be remedied in a cost-effective manner /17/. The costs involved can be as low as a factor of 100 below what would be regarded as justifiable if the source of the radiation was artificial.

Discussions have been going on as to whether it is prudent to distinguish between purely unaffected natural radiation and natural radiation enhanced by some action of man, Technologically Enhanced Natural Radiation (TENR). The ICRP, however, recognised back in 1977 that it is very difficult to make such a distinction /34/. The ICRP stated /35/: "The Commission had already drawn attention to the difficulty of distinguishing between normal and enhanced levels of exposure. It has now concluded that this distinction is unhelpful and bases its new advice on a different approach in which the emphasis is on the extent to which the exposure to the source is controllable".

The parameter of interest is the long-term average concentration of radon daughters. This parameter, however, is very hard to determine as the concentration is not at all constant but varies considerably. The variations are the net combined effect of several factors. Some of these factors have short time constants, among them the effect of instant airing of a room by window opening, while others act slowly, such as seasonal variations or effects of humidity linked to the initial drying in a new structure. In practice it is impossible to determine with a high degree of accuracy a representative long-term average for radon daughter concentration in a building. Available methods measure either the concentration at a certain moment of sampling or the average concentration during the time the detector is exposed in the building. A longer integration time gives a more representative value, but the devices which can measure for 6 months to one year tend to be less accurate than measurements based on grab sampling techniques. Even a hypothetically perfect measurement will leave som uncertainty regarding life-time exposure. It is possible, for example, that new installations or retrofittings in a building will lead to the opening or sealing of connections between soil and the building interior, or affect the ventilation rate.

As the concentration of radon in indoor air ranges over more than three powers of ten, a moderate uncertainty in the characterization of a specific house should be accepted. It would seem practical to regard the action level implemented by society as a guide to the range whithin which remedial actions commonly become justifiable from a cost and health protection point of view. The estimation of radon daughter concentration is only part of the basis for a decision on remedial action. Other factors to be considered are the need for a reduction of the collective dose in the population, the nature of the remedial actions in question, and the attitude and willingness/ability of the inhabitants to pay for the costs. For cases where fairly simple remedial actions can be taken the ICRP suggests /35/ that an action level for equilibrium equivalent radon concentration in the region of 200 Bq/m^3 (annual effective dose equivalent of about 12 mSv) might be considered. For severe and disrupting remedial action, a value several times higher might be more appropriate, the Commission says.

In Sweden, there have been regulations in force for some years which stipulate that an average concentration of 400 Bq/m^3 and more of radon daughters in the inhabited space shall be regarded as a sanitary nuisance /99/, /100/. In theory, this makes remedial actions mandatory. This action level was introduced as a temporary limit, giving priority to the few buildings with very high concentrations. The limit was deduced from the recommendation given by the Swedish Radon Commission that the exposure during the next five years should be limited to 2 000 Bqyears/m^3 /68/. Measurements were recommended to be made in two rooms in the dwelling, one of which the bedroom, where the highest concentration was expected. In the calculation of the average, double weight was given to the higher of the two measurement values. The limit was meant both as a tool for directing actions to buildings with very high concentrations and as a limit between cases where remedial actions should be taken or not.

As has already been emphasised in this report, a more accurate estimate of the precise relationship between exposure to radon daughters in indoor air and lung cancer incidence is needed, through epidemiological studies in dwellings. Although conclusive evidence is still lacking for reliable judgement of the critical effect levels, we believe the database permits us to mount a reasonably adequate action program. In our opinion, a practical and cost-effective action strategy based on both the statements in the ICRP publication No 39 /35/ and the present Swedish regulations for existing buildings /68/, /99/, /100/ could be for Sweden:

- Measurements indicating less than approximately 150 Bq/m^3 of radon daughters suggest only simple and low-cost remedial actions such as maintenance of the existing ventilation system or sealing of obvious and easily accessible routes of entry for soil gas.

- When initial measurements indicate concentrations in the middle range 150 - 500 Bq/m^3 of radon daughters (the latter figure corresponding to 400 Bq/m^3 with allowance for a 25% variation in screening measurement data) remedial actions are recommended, but the decision on the specific remedial actions should be taken by the houseowner. A recommendation on the action of choice should be given by the health or building authorities after having considered the estimated cost and effectiveness of possible actions, and the uncertainties inherent in the measurements.

- Measurements in screening programs indicating concentrations higher than 500 Bq/m^3, i.e. several times higher than 200 Bq/m^3 /101/, justify immediate simple remedial actions without waiting for confirming measurements. If simple remedial actions cannot be taken, repeated measurements are to be made, designed to verify the situation and to help design the remedial actions. If the high concentrations are verified, even quite expensive remedial actions must be accepted. If the houseowner can-not afford the action and it has been established that simpler actions are not likely to be effective, public financial support should be considered.

In some situations remedial actions should probably be mandatory. In our opinion, the exposure limit above which society may prescribe remedial actions should be high for adult persons living in a house of their own. If there are children in the building, in our opinion, the mandatory limit should not be very much above 400 Bq/m^3 radon daughters. If the dwelling is rented, or it is e.g. a public day-care centre for children, remedial actions, to be consistent with other sectors of public health protection, should be mandatory at even lower levels.

A key problem is the design of screening programs for identifying buildings eligible for remedial actions. The ICRP recommends /35/ that "competent national authorities establish investigation levels to separate exposures that require investigation from those that do not". This procedure is meant to separate, in the least costly way, the majority of buildings with low radon concentration from the few with an elevated concentration of radon daughters above or near the action level. The ICRP recommends that not every building be subject to measurements but that characteristics such as type of building material, local geology, and ventilation principle be used in attempts to separate the small fraction of the building stock where the vast majority of buildings with radon daughter concentration above the action level can be found.

Modern detectors based on track techniques integrating the concentration over 3 months or more, give a fairly exact figure on the radon concentration at fairly low cost. It is often more expensive to characterize a building by inspection as to the status of the ventilation systems and the presence of openings to the soil. Distribution of modern track detectors, or other low cost dosemeters, by mail will probably present the least expensive and most accurate determination of the long term average concentration. The accuracy of such measurements is sufficient to separate the small group of buildings with elevated concentrations from the majority with "normal" concentrations, and will in most cases be sufficient for making the decision as to whether or not remedial actions at a reasonable cost are indicated. Some parts of the building stock, however, can be excluded from measurements already at the planning stage. In areas where no high radium activity building materials have been used, all apartments with no direct contact with the ground may be excluded from the screening. Wooden houses at locations where the soil is known to be impermeable or to have low activity of radium may also be excluded.

For new buildings the ICRP /35/ states that there are much better possibilities than in old buildings to achieve a low indoor radon concentration. It is recommended that "the exposure of the most highly exposed individuals should be limited by the application of an upper bound of individual dose in the optimization assessment". This upper bound should be established taking into consideration the local possibilities of minimising the infiltration of soil gas and the possibility of avoiding the use of building materials with elevated activity of radium. As a result of the necessary modifications being easier to implement in new buildings, the upper bound for these will be lower than the action level for existing situations. The ICRP believes that a reasonable upper bound for the equilibrium equivalent radon concentration is of the order of 100 Bq/m^3. Application of an upper bound of 100 Bq/m^3 to us also seems reasonable to comply with in every known situation. This is also in agreement with the recommendations from a task group of the World Health Organization. On the most "radon dangerous" soil this might require restrictions on type of building if the added costs are to be kept low e.g. by avoiding inhabited basements in open contact with the main living space.

In Sweden, it is prescribed in the Building Code that in new buildings the long-term average concentration of radon EEC must not exceed 70 Bq/m^3. In the Comments to the Code it is stated, however, that as a consequence of the uncertainty in measurements it is reasonable to approve measurements up to 140 Bq/m^3. Higher values can be approved only if the remedial measures that would be required to reduce the concentration are unreasonably expensive in relation to what can be gained in reduced exposure. It is believed, the Comments read, that the limit value for new buildings, together with the remedial actions taken based on the action level for existing buildings, will reduce the collective average population exposure from the current level of approximately 50 Bq/m^3 to approximately 25 Bq/m^3 in 100 years.

8. COST-BENEFIT CONSIDERATIONS

If $10 000 per personSv is used as a criterion for cost efficiency in radiation protection (see also section 7) it follows that:

- Common building materials used in a realistic building design and with common surface treatments give, on the average, an exhalation of radon of less than 20 Bq/m^2,h. With present energy costs and in a cold climate (number of degree days $\geq$50% of the Swedish situation) other aspects of the indoor air quality than the radon emission from building materials will set the limits for energy conservation by weatherisation of the building /16/. Only in exceptional situations is it necessary to refrain from energy conservation by weatherisation because of the exhalation of radon from building materials. Other aspects of indoor air quality and building physics set the limit for minimum recommendable ventilation rate. Ventilation rates below the generally recommended minimum rate will obviously increase the radon concentration as will the concentration of a number of other pollutants in the indoor air.

- Once an existing structure with infiltration of radon from the ground has been identified, remedial actions seem cost-effective if the contribution from the soil to the indoor radon concentration is more than 50 - 100 Bq/m^3. If the low-cost remedial actions are not successful the cost efficiency of more expensive remedial actions should be evaluated on a case by case basis.

- More expensive remedial actions in existing buildings, such as retrofitting a mechanical balanced ventilation system, seem to be cost efffective by its sole effect on the radon concentration if the expected reduction is about 200-400 Bq/m^3.

- Radon from the soil enters buildings by a convective flow of air driven by a pressure gradient. Transport by diffusion is insignificant. Thus the pressure difference between indoor air and soil gas subjacent to the building has a decisive impact on the radon concentration. In buildings on permeable soil, ventilation systems should be designed to avoid a negative pressure indoors relative to the basement and the ground.

- In new buildings small modifications in the design will in most cases prevent infiltration of soil gas. When buildings are constructed on "radon dangerous" land, infiltration of radon from the soil can be prevented by adequate building design and construction principles that are either inherently radon safe or require only minor modifications. Other types of basic building design will require more expensive modifications. If inhabited basements are avoided, any ground can be built upon with strict design levels at an added cost of not more than approximately 4% of the base cost for a detached one-family house.

- Our experience shows that the average cost will be minimised if the owner of the house has an incentive to look for the most cost-effective solution to any problem with radon. If the costs are fully covered by society the owner will not have this incentive and will often argue for a more expensive action.

Even if the costs of remedial actions in a house are fully or partially covered by the owner society still has to carry the full responsibility for other parts of the protection program against radon in indoor air. Local or central agencies should perform research and surveys concerning
- adaption and demonstration of remedial actions in existing structures,
- adaption, demonstration, and verification under local conditions of modifications in design suitable for preventing infiltration of radon from subjacent soil, and
- documentation of where geological conditions indicate a risk for infiltration of soil gas.

The society also must carry the responsibility for including relevant information on radon in the training of building engineers, geotechnicians, and health protectionists.

9. REFERENCES

1 Archer, V.E., J.D. Gillam, and J.K. Wagoner, "Respiratory Disease Mortality among Uranium Miners", Ann. N.Y. Acad. Sci. 271;280-293 (1976).

2 Axelson, O., Edling, C., Kling, H, Andersson, L., and Rignér, Å, "Lung Cancer and Radon in Dwellings", Lancet, 1981, ,995-996.

3 Beck, H.L., "The Physics of environmental gamma radiation fields", in The Natural Radiation Environment II, p. 101-133, Oak Ridge, United States Atomic Energy Commission, 1975

4 Belvin, E.A., Chairman, A study of Phosphate Slag in Building Materials, A report on the Phase I survey, Report of the Interagency Phosphate Slag Task Force, June 1979

5 Burkart, W., Wernli, C., and Brunner H., "Radiation Exposures and Risks due to Airtightening of Homes in an Alpine Area with High Radon Emanation", Sozial- und Präventivmedizin, 30(1985)266-267.

6 Castrén, O. et al., " High Natural Radioactivity of Bored Wells as a Radiation Hygienic Problem in Finland", presented at the 4th International Congress of IRPA, Paris, April 1977.

7 Castrén, O., "The Contribution of Bored Wells to Respiratory Radon Daughter Exposure in Finland", Natural Radiation Environment III, p.1364-1370, U.S. Symposium Series 51, Houston, Texas, April 23-28, 1978, CONF-780422 vol 2, ISBN 0-87079-119-2

8 Castrén, O., Voutilainen, A., Winqvist, K., and Mäkeläinen, I., "Studies of High Indoor Radon Areas in Finland", the Science of the Total Environment, 45(1985), 311-318

9 Clavensjö, B., Ericson, S-O, Eriksson, B.E., Håkansson, B, and Swedjemark, G.A., "Radon in Dwellings - remedial actions against radon in indoor air"(Radon in Bostäder - Byggnadstekniska åtgärder för att minska radonhalten i inomhusluft), Swedish Council for Building Research R28:1982, ISBN 91-540-3658-5 (In Swedish).

10 Clavensjö, B., report to the Swedish Building Research Council 1986, in preparation.

11 Cliff, K.D., "Assessment of Airborne Radon Daughter Concentration in Dwellings in Great Britain", Phys. Med. Biol. 23(1978) 4, p. 696-711.

12 Cliff, K.D., et al., "The Incidence and Origin of Radon and Its Decay Products in Buildings", National Radiologhical Protection Board, NRPB-R159, ISBN 0-85951-219-3, February 1984.

13 Collé, R. et al, "Radon Transport through and Exhalation from Building Materials. A review and Assessment", U.s. Department of Commerce, Sept 1981

14 U.S. Department of Energy, "Progress Report on the Grand Junction Uranium Mill Tailings Remedial Action Program, Feb 1979, DOE/EV-0033.

15 Edling C, "Lung cancer and Radon Daughter Exposure in mines and Dwellings", Linköping: Linköping University, Medical Dissertations, Sweden, No 157, 1983

16 Ericson, S-O., "Cost-benefit analysis of decreased ventilation rates and radon exhalation from building materials", vol 5 p. 271-276 in Berglund, B. et al., Proceedings of the 3rd International Coinference on Indoor Air Quality and Climate, Stockholm August 20-24, 1984, Swedish Council for Building Research, ISBN 91-540-4197-X.

17 Ericson, S-O, and Schmied, H., "Modified Technology in new constructions, and cost effective remedial action in existing structures, to prevent infiltration of soil gas carrying radon", vol 5, p. 153-158 in Berglund, B. et al., Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm August 20-24, 1984, Swedish Council for Building Research, ISBN 91-540-4197-X.

18 Ericson, S-O., and Schmied, H., "Installation of Supply/exhaust Ventilation as a Remedial Action against Radon from soil and/or Building Materials", The Science of the Total Environment, 45(1985) 499-505

19 Ericson, S-O, and Schmied, H., "The first long time comparison of techniques for passive integrated measurement of radon and radon daughter concentration performed in an occupied dwelling", The Science of the Total Environment, 45(1985) 405-415

20 Ericson, S-O., and Schmied, H, report for the Swedish Building Research Council 1986, inpreparation (In Swedish)

21 Ericson, S-O, "Byggnadstekniska Åtgärder - Kostnader och Nytta för Fastighetsägare", presented at Nordic Society for Radiation Protection seminar in Helsinki February 13-14, 1986 (In Swedish)

22 U.S. Environmental Protection Agency, "Radiological Quality of the Environment in the United States", 1977, EPA 520/1-77-009

23 Indoor Radiation Exposure Due to Radium-226 in Florida Phosphate Lands, U.S. EPA 520/4-78-013, February 1979

24 Rajala, M., Janka, L., Lehtimäki, M., Kulmala, V., and Graeffe, G.,"On the Influence of an Electrostatic Precipitator and a Mechanical Filter on Radon Decay Products", submitted for publication in Health Physics

25 Grapengiesser, S., "Review of Collective Effective Dose Equivalents to the Swedish Population" (Översikt över svenska kollektivstråldoser) report to rthe Swedish Cancer Committee, Ds S 1984:2 ISBN 91-38-08500-3.

26 Ham, J.M., Report of the Royal Commission on the Health and Safety of Workers in Mines, Toronto Ministry of the Attorney General, Province of Ontario, 1976.

27 Harley, N.H., and Pasternack, B.S., "Environmental Radon Daughter Alpha Dose factors in a five lobed human lung", Helth Physics, 1981

28 Hartley, J.N., Koehmstedt, P.L., Esterl, D.J., and Freeman, H.D., "Asphalt Emulsion Sealing of Uranium Mill Tailings 1979 Annual Report", Battelle Pacific North West Laboratory, for U.S. Department of Energy Contract DE-AC06-76RLO 1830, PNL-3290

29 Hartley, J.N., Koehmstedt, P.L., Esterl, D.J., Freeman, H.D., and Clark, R.L., "Application of Asphalt Emulsion Seals to Uranium Mill Tailings", Battelle Pacific Northwest Laboratory, presented at the Third Symposium on Uranium Tailings Management, Fort Collins, Colorado, November 24-25, 1980.

30 Hess, C.T., Caspariuys, R.E., Norton, S.A., and Brutsaert, W.F., "Investigation of Natural Levels of Radon-222 in Groundwater in Maine for Assessment of related Health Effects", in Natural Radiation Environment III, Proceedings of a symposium held at Houston. April 1978, CONF-780422, vol 1, p. 529-546, ISBN 0-87079-119-2

31 Hess, C.T., "Radon-222 in Potable Water Supplies in Maine. The Geology, Hydrology, Physics and Health effects", Land and Water Resource Center, University of Maine at Orono, Sept 1979.

32 Hess, C.T., Weiffenbach, C.V., Norton, S.A., Brutsaert, W.F., and Hess, A.L., "Radon-222 in Potable Water Supplies in Maine. The Geology, Hydrology, Physics and Health Effects", in Natural Radiation Environment, Vohra, K.G. et al Eds, Bombay, January 19-23, 1981, p.216-220.

33 Hultqvist, B:, "Studies on naturally occurring ionizing radiations with special reference to radiation doses in Swedish houses of various types" Kungl. Sv. Vet. Handl. Ser 4, Vol 6, N:o 3, 1956

34 International Commission on Radiological Protection Publication No 26, Annals of the ICRP Vol 1:3 1977

35 International Commission on Radiological Protection, ICRP Publication 39, "Principles for Limiting Exposure of the Public to Natural Sources of Radiation", 1984, ISBN 0 08 031503 8.

36 Ingersoll, J.G., A Survey of Radionuclide Contents and Radon Emanation Rates in Building Materials used in the U.S., Health Physics Vol 45:2 p 363-368, 1983

37 Jacobi, W., and Eisfeld, K., "Internal dosimetry of radon-222, radon-220 and their short-lived daughters", GSF report S-626 (1980).

38 Jacobi, W., and Eisfeld, K., "Internal dosimetry of inhaled radon daughters", p 31-35 in: Proceedings of International Conference on Radiation Hazards in Mining: Control, Measurement and Medical Aspects. Golden, Colorado, 1981. Society of Mining Engineers, New York, 1981.

39 Jacobi, W., "Expected Lung Cancer Risk From Radon Daughter Exposure in Dwellings", p. 31-42 in Berglund, B. et al Eds Indoor Air, Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm August 20-24, 1984, Swedish Council for Building Research, ISBN 91-540-4191-0

40 Jacobi, W., and Paretzke, H.G., "Risk Assessment for Indoor Exposure to Radon Daughters", The Science of the Total Environment, 45(1985), p. 551-562

41 James, A.C., Jacobi, W., and Steihäusler, F., "Respiratory tract dosimetry of radon and thoron daughters. The state-of-the-art and implications for epidemiology and radiobiology, p. 42-54 in: Proceedings of International Conference on Radiation hazards in Mining: Control, Measrurement and Medical Aspects, Golden, Colorado, 1981, Society of Mining Engineers, New York, 1981.

42 James, A.C., "Dosimetric Approaches to Risk Assessment for Indoor Exposure to Rdaon Daughters", Radiation Protection Dosimetry, 7(1984)N:o 1-4, p. 353-366.

43 Jonassen, Niels, "Radon Daughter Levels in Indoor Air; Effects of Filtration and Circulation", Progressreport VII, Grant AMI-52189-Ö from Statens Vattenfallsverk (Stockholm), May 1984.

44 Jonassen, Niels, "Radon Daughter Levels in Indoor Air: Effects of Filtration and Circulation", Progressreport IX, Grant AMI-52189-Ö from Statens Vattenfallsverk (Stockholm), November 1985.

45 Jonassen, N., and J.P. McLaughlin, "The Reduction of Indoor Air Concentrations of Radon Daughters without the Use of Ventilation", The Sience of the Total Environment 45(1985)485-492.

46 Kahlos, H. and Asikainen, M., "Natural Radioactivity of Ground Water in the Helsinki Area", Institute of Radiation Physics, Helsinki, report SFL-A19, Nov 1973

47 Keller, G., and Folkerts, K-H., "A study on indoor radon", Vol 2 p. 149-154 in proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm August 20-24, 1984, Swedish Council for Building Research, ISBN 91-540-4193-7

48 Knutsson, G., "Radon content in various types of groundwater in Southeastern Sweden. A preliminary report", Striae 4(1977) p. 55-59, ISBN 91-7388-003-5

49 Koblinger, L., "Calculations on the gamma levels in rooms due to radioactive sources in the walls", Paper G2, 3rd European Congress of the International Radiological Protection association, Amsterdam, May 1975.

50 Koblinger, L., "Calculation of Exposure Rates from Gamma Sources in Walls of Dwelling Rooms", Health Physics, Vol 34, p. 459-463, 1978.

51 Kolb, W., and Schier, H., "Building Material induced radiation exposure of the population", Paper G3, 3rd European Congress of the International Radiological Protection association, Amsterdam, May 1975.

52 Krisiuk, E.M. et al., "A study on radioactivity in building materials", Leningrad Research Institute for Radiation Hygiene, 1971.

53 Kunz, E, J. Sevc, V. Placek, and L Horacek, "Lung Cancer in Man in Relation to Different Time Distribution of Radiation Exposure", Health Physics 36:699-706 (1979).

54 Landman, K.A., and D.S. Cohen, "Transport of Radon through Cracks in a Concrete Slab", Health Physics, Vol 44:3, p 249-257, 1983

55 Lindell, Bo, "Risk Philosophy within Radiation Protection" (Riskfilosofi inom strålskyddsverksamheten), SSI:1980-38 (In Swedish)

56 Lindmark, Alf and Rosén, Bengt, Radon i jord, Swedish Geotechnical Institute, Report No 24, 1984, ISSN 0348-0755 (In Swedish).

57 Lindmark, A., and B. Rosen, "Radon in Soil Gas - Exhalation Tests and in situ Measurements", The Science of the Total Environment, 45(1985) 397-404.

58 Mjönes, L, A Bur´en, and G.A. Swedjemark, "Concentration of radon in Swedish Dwellings" (Radonhalter i svenska bostäder), Swedish Radiation Protection Institute Document a84-23, (In Swedish).

59 Muller, J., W.C. Wheeler, J.F. Gentleman, G. Surangi, and R.A. Kusiak, "Study of Mortality of Ontario Miners 1955-1977 Part 1", Report Ontario Ministry of Labour, Atomic Energy Control Board of Canada, May 1983.

60 Mustonen, R., "Natural Radioactivity in and Radon exhalation from Finnish Building Materials", Health Physics vol 46, N:o 6 p. 1195-1203, 1984

61 Möre, Hans,"Radioaktiva ämnen i Byggnadsmaterial", SSI-rapport 85-08, ISSN 0282-4434 (InSwedish).

62 Nuclear Energy Agency/OECD, "Exposure to radiation from the natural radioactivity in building materials", May 1979

63 Nuclear Energy Agency, Dosimetry aspects of exposure to radon and thoron daughters", report by a group of experts, Paris, OECD, 1982

64 O'Riordan, M.C., et al., "The Radiological Implications of using by-product Gypsum as a Building Material", National Radiological Protection Board, NRPB-R7, Dec 1972.

65 O'Riordan, M.C. et al., "Human Exposure to Radon Decay Products Inside Dwellings in the United Kingdom", Nationalx Radiological Protection Board, NRPB-R152, February 1983.

66 Pershagen, G., Damber, L., and Falk, R. "Exposure to Radon in Dwellings and Lungcancer: A pilot Study", in B. Berglund, T. Lindvall, and J. Sundell(Eds.) Indoor Air Volume 2: Radon, passive smoking, particulates and housing epidemiology, Stockholm. Swedish Council for Building Research, D17:1984, p. 73-78.

67 Pettersson, Håkan; Hildingson, Olov; Samuelsson, Christer, and Hedvall, Robert, Radon Exhalation from Building Materials (Radonexhalation från Byggnadsmaterial), Statens Provningsanstalt Teknisk Rapport SDP-RAPP 1982:32 ISSN 0280-2503. (In Swedish)

68 Swedish Radon Commission, A tentative proposal for remedial actions against radiation hazards in dwellings" (Preliminärt förslag till åtgärder mot strålrisker i byggnader), DsJo 1979:9, ISBN 91-38-05010-2 (InSwedish)

69 Swedish Radon Commission, final report "Radon in dwellings", (Radon i bostäder), SOU 1983:6, ISBN 91-38-07433-8 (In Swedish).

70 Raes, F., A. Janssens, and H. Vanmarcke, "A closer Look at the Behaviour of Radioactive Decay Products in Air", The Science of the Total Environment, 45(1985), 205-218.

71 Rajala, M., K. Janka, M. Lehtimäki, V. Kulmala, G. Graeffe, and J. Keskinen, "The Control of Radon Progeny by Air Treatment Devices", the Science of the Total Environment, 45(1985) 493-498.

72 Rundo, J., Markun, F., and Plondke, N.J., Observation of High Concentrations of Radon in Certain Houses, Health Physics 36(1979) 729-730

73 Samuelsson, Christer, "Filtrering av Radondotterhaltig luft", Swedish Council for Building Research grant 810053-4, (In Swedish).

74 Schmied, H, "Combined Stack Effect in Houses and Eskers Explaining transients in Radon Source", the Science of the Total Environment 45(1985) 195-201.

75 Sevc, J., E. Kunz, and V. Placek, "Lung Cancer in Uranium Miners and long-term Exposure to Radon Daughter Products", Health Physics 30:433-437, 1976.

76 Spiers, F.W., "Gamm-ray dose-rates to human tissues from natural external sources in Great Britain", in The Hazards to man of nuclear and allied radiations. A second report to the Medical Research Council, London, Her Majesty's Stationery Office, 1960

77 Stranden, E., "Some Aspects on Radioactivity of building materiuals", Physica Norvegica, 8, p. 167-173, 1976

78 Stranden, E., "Radioactivity of Building Materials and the gamma radiation in mdwellings", Phys. Med. Biol. 24(1979) p. 921-930

79 Stranden, E., Kolstad, A.K., and Lind, B., Radon in Dwellings (Radon i boliger), Arbeidsdokument 1984:5, National Intitute of Radiation Hygiene, Norway, 1984. (In Norwegian).

80 Stranden, Erling, "Radon in Norwegian Dwellings and the Feasibility of Epidemiological Studies", Accepted for publication in Radiation and Environmental Biophysics.

81 Stranden, Erling, "^{222}Rn in Norwegian Dwellings: Occurrence, Primary Sources and Possible Health Effects", Submitted to Health Physics 1986

82 Swedjemark, G.A., "The Ionizing radiation in dwellings related to the building materials", SSI:1977-004, Stockholm, National Institute of Radiation Protection.

83 Swedjemark, G.A. "Radon and its Decay Products in Housing - Estimation of the Radon Daughters Exposure to the Swedish Population and Methods for Evaluation of the Uncertainties in Annual Averages" Doctoral Dissertaition, Department of Radiation Physics, University of Stockholm, Stockholm 1985, ISBN91-7146-634-7

84 Svensson, C., Eklund, G., and Pershagen, G. "Indoor Exposure to Radon from the Ground and Bronchial Cancer Among Women", Submitted for publication in Radiotherapy and Oncology, 1985

85 Taipale, T.T. and Winqvist, K., Seasonal Variations in Soil Gas Radon Concentration, The Science of the Total Environment, 45(1985)121-126

86 Tappan, J.T., Phase II demonstration of electrostatic filtration systems as a uranium mill tailings remedial action, Feb 9, 1979, report to Colorado department of Health.

87 Toth, A., "Natural radiation burden of the population", Akademiai Kido, Budapest, 1983, ISBN 963 05 3161 6 (In Hungarian)

88 Natürliche Radioaktivität in Baumaterialien:Zwischenbericht zu Ergebnissen, der vom BMI mit WErhebungsmessungen bneauftragten Institut. Umwelt Nr 32, 5.6.74, p. 14-18.

89 Ionizing Radiation: Sources and Biological Effects, 1982 Report of UNSCEAR to the General Assembly.

90 Wicke, A., "Untersuchungen zur Frage der natürlichen Radioaktivität der Luft in Wohn- und Aufenthaltsräumen - Grundlagen zur Abschätzung der Strahlenexposition durch Inhalation von Radon- und Thoron-zerfallsprodukten", Dissertation der Justus-Liebig-Universität, Giessen, 1979.

91 Wilkening, M., "Radon Transport in Soil and its Relation to indoor Radioactivity", the Science of the Total Environment 45(1985)219-226.

92 Wilkinson, P., and P.J. Dimbylow, "Radon Diffusion Modelling", the Science of the Total Environment 45(1985)227-232.

93 Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, sponsored by The Atomic Energy Control Board, Elliot Lake, Ontario, Mrach 7-8, 1978

94 2nd Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Atomic Energy Control Board AECB-1164, Bancroft, Ontario, March 12-14, 1979

95 Åkerblom, Gustav, "Environmental Radon Investigations in Sweden", paper presented at The International Meeting on Radon-Radon Progeny Measurements, Montgomery, Alabama, August 27-28, 1981.

96 George, A.C., M. Duncan, and H. Franklin, "Measurements of Radon in residential Buildings in Maryland and Pennsylvania, U.S.A.", Rad. Prot. Dos. Vol 7 No 1-4. p 291-294, 1984.

97 National Council on Radiation Protection and Measurements, "Evaluation of occupational and environmental exposures to radon and radon daughters in the United States", NCRP Report No 78, NCRP Bethesda Md 1984.

98 World Health Organization WHO, Working Group on Indoor Air Quality: Radon and Formaldehyde. ICP/CEH 002/m70(S) 86491, 20 September 1985.

99 Swedjemark, Gun Astri, "Limitation schemes to decrease the radon daughters in indoor air", Natinal Institute of Radiation Protection, Box 6204, S-104 01 Stockholm, SSI-rapport 86-01, ISSN 0282-4434, 1986.

100 National Institute of Radiation Protection: "Radon in housing, the deliberations of the Swedish Radon Commisssion: Introduction, Summary and Considerations and proposals, Comments on the report provided by the National Institute of Radiation Protection. Report a 84-10, National Institute of Radiation Protection, Stockholm, 1984.

101 Bouville, A., J.O. Snihs, and M.C. O'Riordan, "Principles of protection against natural radiation", The Science of the Total Environment, 45(1985)565-577.

102 Cohen, Bernhard L., "Survey of one-year average Rn levels in Pittsburgh area homes", Health Physics Vol 49, No 6, pp 1053-1059, 1985.

103 Cohen, Bernhard L., Department of Physics, University of Pittsburgh, Pittsburgh, PA 15260, personal communication.

104 Bergman, Hans, Christer Edling, and Olav Axelson, "Indoor radon daughter concentrations and passive smoking", in Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Berglund, B., et al eds. Vol 2 p 79-84, ISBN 91-540-4193-7, Stockholm, August 20-24, 1984.

105 Swedjemark, Gun Astri and Lars Mjönes, "Exposure of the Swedish population to radon daughters", in Berglund B. et al eds. Proceedings of the 3rd International Conference on indoor Air Quality and Climate, Stockholm, August 20-24, 1984, Vol 2 p 37-44, ISBN 91-540-4193-7.

Art. No: 6702607

D7:1986
ISBN 91-540-4554-1
Swedish Council for Building Research,
Stockholm, Sweden

Distribution:
Svensk Byggtjänst, Box 7853
S-103 99 Stockholm, Sweden

Approx. price: SEK 40