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HANDBOOK OF RADON

health, economic and building aspects

Stephen J Wozniak BA PhD

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This Handbook is in three parts: introductory, health & economics and building. The author's perspective of environmental and health issues developed during ten years as a Principal Scientist at the Building Research Establishment, including four as Head of Building Pathology.

Each Section in the Handbook addresses a particular topic and many may be read independently. With this structure, it is inevitable that there is some duplication of basic information, especially in Part 2. It is intended to publish replacement and new Sections in the next few years.

Important Introductory Statement.

"Sections in this Handbook are updated at intervals in the light of research findings in the UK and overseas. Although care is taken to achieve accuracy and a balanced perspective, no responsibility is accepted for any loss or damage arising from actions or decisions based upon information or views contained in any Section or Sections."

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Preface.

Detailed knowledge of ionising radiation has developed only in the last hundred years. In 1895, Roentgen discovered x-rays. In the following year Becquerel discovered radioactivity. Understanding grew rapidly, but by 1900 adverse health effects had already been reported. In 1900 also, Dorn discovered radon, although it was not isolated until 1908.

The discovery of radon as an element followed from Marie Curie's discovery of radium in 1898. However, as early as 1556 radon had (unknowingly) been cited as the cause of lung cancer in miners.

Since the 1900s radium and radon have been used in various and often bogus medical preparations and procedures, including inhalation and bathing in mines and spas, a practice that continues to the present day despite absence of any proven benefit. It was to take many deaths, including those of early radiographers before the dangers of ionising radiation were fully appreciated. The true extent of the radon problem in dwellings has only recently been documented, nearly forty years after the first discoveries.

Contemporary interest in radon as a health risk is based primarily on studies of lung cancer in miners. Since the 1950s radon has become a major topic in several countries. This period coincides almost exactly with the rise and fall of nuclear power throughout the world - France and Japan being notable as exceptions.

The nuclear age started with a promise - limitless cheap energy. It progressed via various misguided and then bogus claims for safety and cost that led inevitably to recognition of economic realities. Billions of dollars were spent, and even in the West civil science became veiled in secrecy.

A generation of scientifically naive politicians became wedded to the idea of dominion over Nature. At last, Man and Technology were to conquer the world. Many nuclear scientists knew that the advice being fed to politicians was flawed. In the USSR and USA alike, grandiose schemes were supported by deceit.

Three Mile Island in 1979 and Chernobyl in 1986 were perhaps inevitable consequences of pretence and secrecy. Of course, the demanding technical problems of reactors and especially those of 'fast' designs that utilise plutonium as a fuel, would have remained to challenge engineers. Yet if scientific reality and open discussion had been valued more highly than vested interests and marketing pretence, present-day perceptions of the industry might be different.

The contemporary history of radon has parallels with the early history of nuclear power. The science is well (albeit imperfectly) understood. Large public programmes, some based more on marketing and myth than on sound science have developed. Control of publicity and funding by a few key personnel ensured reinforcement of chosen perspectives for many years. In the UK, with its Official Secrets Act, much of the radon story cannot be told.

Nuclear energy and radon share also the central difficulty of flawed public perception: relative risk and the need to set nuclear issues in a correct perspective cannot be addressed until radiological protection is demystified. One benefit of radon programmes worldwide may be a better understanding of the risks of moderate exposure to ionising radiation from other sources.

This Handbook is primarily concerned with explaining radon and how to reduce unacceptably high exposure in many types of buildings. It is hoped that it will serve also to encourage wider recognition of the need for analysis when allocating resources.

Stephen J Wozniak

England
August 1992

Acknowledgement.

Assistance given by field-trial householders in Devon & Cornwall is acknowledged. Thanks are owed also to scientists and others in England and the United States of America. [*]

Glossary.

This Glossary is not comprehensive. It is intended only as an aid for readers who never studied science. Many terms used in the Handbook are included.

actinide a small group of elements with high atomic number, including uranium, plutonium and americium.

active system a radon removal system that relies on electrical power or other man-made energy source for its operation.

ALARA As Low As Reasonably Achievable - social and economic factors being taken into account. A principle often quoted to justify expenditure to reduce radiation dose, but with the qualification removed.

alpha particle the nucleus of a helium atom, a sub-atomic particle emitted from some large nuclei when they undergo radioactive decay. Very poorly penetrating in matter, but with a high index of harm per unit of energy. (see quality factor).

atom once thought of as the smallest amount of matter that could not be divided further, now recognised as the smallest amount of matter having the characteristics of a chemical element.

attached fraction applied to radon daughters to describe the fraction of daughters that have become attached to smoke or dust particles.

Becquerel French scientist who discovered radioactivity in 1896 whilst experimenting with uranium salts. The becquerel (Bq) is now the standard unit for activity: one becquerel is one atomic transformation per second.

BEIR as in the BEIR IV report, the term signifies the committee of the US National Academy of Sciences dealing with Biological Effects of Ionising Radiation. The risk factor commonly used for radon of 0.035 deaths per sievert derives from this committee, and from work of ICRP, whose estimates range to 0.05 cancer deaths per sievert for a population of all ages.

beta particle a positively or negatively charged subatomic particle of low mass: positron or electron.

Bq/m^3 ($Bq.m^{-3}$) The recognised units for expressing radon concentration (activity concentration) in air. Not yet in wide use in the USA.

BRE Building Research Establishment. Until recently primarily a research based body and part of the DOE.

collective dose dose totalled for a population. For example the collective dose from radon in the UK is calculated from 57 million people times 1.2 mSv each (on average), giving 68400 Sv per year. If the BEIR IV figure of 0.035 deaths per sievert is applied, the prediction is 2400 deaths annually from radon related lung cancer. Collective dose may easily be calculated for counties or other regions once average indoor radon levels are known.

cosmic radiation a stream of high energy subatomic particles received from the sun and from outer space. The dose from these increases with altitude because there is less absorption by the atmosphere. Typical exposure is 0.2 to 0.3 mSv annually, rising to nearly 2 mSv annually in the world's highest cities.

Curie Husband and wife team of scientists (Pierre and Marie). Received Nobel prizes for discovering radium and polonium. The curie is still used as a unit of radioactivity, but is being replaced by the becquerel. One curie is 3.7×10^{10} events per second.

discounting part of economics and a way of expressing that benefits in the future may be worth less than those in the present, expressed in monetary terms. Parameters such as Net Present Value and Internal Rate of Return are related to Discount Rate, a notional rate of interest on investments.

Glossary/2.

DOE Department of Environment (UK) or Department of Energy (USA).

dose general term for quantity of radiation, often used to mean effective dose equivalent.

early effects a term used to describe death or injury from exposure to ionising radiation where the effect occurs days or weeks after exposure, rather than years or decades later. Only large doses of radiation received over a short time produce early effects, and the severity of the effect is linked to dose. The threshold for onset of mild early effects such as nausea is about 0.5 Sv. However, larger doses from radon over a year produce no early effects. If received in a short time 50 Sv may kill quickly.

economics A pseudo-science popular in the twentieth century. Economic theories were proven correct by selected events. Theories were never disproved by unforeseen events.

EEDC equilibrium equivalent decay product concentration, being the amount of each product necessary to produce the same PAEC as the mixture of decay products that is actually present. Units are Bq/m^3, or equivalent.

effective dose equivalent absorbed dose corrected for both type of radiation and sensitivity of the irradiated tissue. May be thought of as a normalised index of potential harm from ionising radiation. Often abbreviated simply to 'dose'.

EPA A large government body in the USA, based in Washington DC. EPA is responsible for a wide range of environmental matters and has many Divisions.

epidemiology a branch of statistics and medical science concerned with discovering and quantifying the relation between causes and (medical) effects often in cases where no causal link is immediately apparent.

equilibrium factor, (F) the ratio of the EEDC to the existing radon activity concentration. Usually has a value of between 0.2 and 0.6 in houses.

GAC granular activated charcoal, often used to remove radon from water.

Gray Scientist who helped develop medical uses of radiation. The gray is now the standard unit of absorbed dose expressed in J/kg. 1 Gy = 100 rad.

half-life The time taken for the activity of a radioactive species to reduce to half its initial value.

HMIP A part of the DOE in England concerned primarily with pollution from industry, but having the policy remit for some matters connected with ionising radiation.

ICRP International Commission on Radiological Protection. An unincorporated organisation whose aims are to develop an international consensus on the risks from radiation and appropriate safety levels. It has been said that if ICRP did not exist it would be necessary to invent it.

ionising radiation Types of radiation that have sufficient energy to produce ionisation within matter. Examples are alpha particles, beta particles, gamma rays and neutrons, as distinct from visible light, infra-red light and radio waves.

late effects sometimes called delayed effects. A term used to describe the onset of cancers or hereditary defects in future generations years or decades after exposure to radiation. These are stochastic processes - governed by chance - and the severity of a cancer or defect is not linked to the dose received. Only the chance of occurrence is so determined.

LET linear energy transfer, used in the context of low and high LET radiation. High LET radiation such as alpha particles imparts energy to tissue within a short distance, and may therefore produce more concentrated damage. Related to quality factor.

leukaemia a group of rare cancers, sometimes described as cancer of the blood. Some types occur in children and some are linked with exposure to radiation, and perhaps to radon.

mSv millisievert: the recommended unit for expressing radiation dose, usually as effective dose equivalent.

NRPB National Radiological Protection Board in the UK. Advisors to the government on radiation and the risks factors from radiation.

occupational exposure exposure to ionising radiation occurring at a place of work by virtue of one's job.

PAEC potential alpha energy concentration, a measure of the total alpha particle energy that will be emitted by a mixture of radon daughters during their decay. Expressed in joules per cubic metre (J/m^3).

pascal usually seen as Pa, a unit of pressure or pressure difference. One Pa is a very small pressure and can be measured only with sensitive equipment. 101,325 Pa equal one atmosphere.

passive system a radon removal system or technique that does not rely on electricity or other external motive power for its operation.

picocurie per litre (pCi/l) activity concentration of radionuclide(s), similar to becquerel per cubic metre.

plate-out the deposition and attachment of radon daughters onto walls, floors, etc., thus rendering them relatively harmless.

plutonium a radioactive element very rare in nature but produced in nuclear reactors from uranium and used in nuclear weapons and some types of nuclear power stations. It has acquired a reputation for toxicity that verges on the irrational.

ppb parts per billion (one thousand million). A billion is 1,000,000,000.

ppm parts per million.

premature deaths deaths that occur before they need have done. Avoidable premature deaths are those that might have been prevented by (for example) safety precautions being observed, diseases being diagnosed earlier, or exposure to known dangerous substances such as radon avoided or minimised.

quality factor a number usually 1 to 20 to express the different amounts of potential harm to a person caused by unit dose of different types of radiation. Alpha particles have the highest quality factor usually taken as 20, and meaning that the transfer of a given amount of energy to tissue by alpha particles is 20 times as damaging biologically as the same energy absorbed from gamma radiation. Much higher values than 20 have been suggested for alpha particles in induction of leukaemias.

QALY Quality Adjusted Life Year. A parameter used to rationalise the benefit from different medical treatments or procedures, so as to calculate relative cost-benefit. Similar to Well Year in the USA.

rad old unit for absorbed dose, now replaced by the gray. (1 rad = 0.01 Gy = 0.01 J/kg).

radioactivity term used to describe the property of radionuclides of emitting ionising radiation, and of transmuting to other elements.

radon A radioactive gas formed from radium, usually in the earth. Harmful primarily by inhalation of its daughter products. Atomic mass of 222.

radon daughters the atoms of solids such as polonium, bismuth and lead formed when radon undergoes radioactive decay. Often airborne for part of their lives, they can be inhaled and deposited onto lung tissue, and may thus induce lung cancer.

radon progeny radon daughters.

radionuclide an unstable or radioactive nuclide that decays emitting ionising radiation.

radiophobia a term coined to describe the tendency to blame radiation (radioactivity) for any or all ills suffered by people exposed to fallout from Chernobyl or other nuclear incidents. A result probably of psychological trauma combined with inadequate information, secrecy, and mistrust of official statistics.

radium radioactive element of mass 226 and the immediate precursor to radon. Formed from uranium (via intermediate elements) but sometimes found isolated from it in nature owing to very different chemical properties. One of the first radioactive elements to be discovered. Half life of 1622 years.

rbe relative biological effectiveness. Similar to quality factor.

rem roentgen equivalent man. An old unit for dose equivalent and equal to 0.01 Sv or 10 mSv. One rem produces the same biological effect as one roentgen of hard x-rays per kilogram of tissue. A sudden dose of 5000 to 10,000 rem (50 to 100 Sv) is sufficient to kill through damage to the central nervous system.

risk the probability of injury or harm occurring.

risk factor risk per unit dose, usually as deaths per sievert or cancers per sievert.

Roentgen (Rontgen) German scientist who discovered x-rays in 1895. The roentgen is an obsolete unit for an amount of ionising radiation expressed by way of electrical charge produced in air.

Sellafield a nuclear complex in north-west England previously called Windscale and the location in 1952 of the UK's worst nuclear accident. The site now houses facilities for storing and reprocessing nuclear waste. Although synonymous with fears about plutonium, leukaemia and contamination of beaches, the discharges from Sellafield are now at a very low level.

Sievert Scientist who worked with radiation. The sievert is now the standard unit for dose equivalent, but usually as millisievert (1/1000 of a sievert). 1 Sv = 100 rem.

stack effect a term used to describe the gentle buoyancy pressures that are responsible for warm air rising up chimneys and for radon being drawn into houses during cold weather. The pressures involved in the stack effect in houses are typically 0.1 to 5 Pa.

synergism where two or more causes of an effect act together in some way to produce a risk factor greater than the sum of the individual factors. Examples are the enhanced risks from radon *and* smoking and from asbestos *and* smoking.

thoron one of the less common isotopes of radon with mass 220 rather than 222. Its half-life is less than a minute.

unattached fraction applied to radon daughters to describe the fraction of daughters that have not yet attached themselves to a smoke or dust particle. Unattached daughters have high mobility and, it is thought, are potent in causing lung cancer if inhaled.

uranium primordial radioactive element having long-lived isotopes and occurring in rocks and soils as typically a few ppm, or 5 to 50 Bq/kg. A precursor to radium, and therefore to radon.

WL Working Level. A unit dating from study of radon in mines, it is a measure of the energy of alpha particle decays in air, applied to radon daughters only.

WLM Working Level Month. A unit of exposure to radon daughters, one WL for 173 hours.

[*]

1.1 Contents.

Each Section in the Handbook must be read in conjunction with the introductory statement on the title page.

1.2 Contents.

Health, legal & economics Sections (continued)

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2. Forthcoming titles.

Diagrams for radon systems in UK houses.

Cost benefit analysis for radon remediation.

Review of the DOE/BRE radon programme, 1988 to 1993.

Personalities and perspectives of radon.

Air cleaning and filtration for radon remediation.

Radiation and radon exposure from building materials.

More idiosyncrasies of high level houses.

Lung cancer in young people.

Condensation in radon systems.

Further details of cures for solid floors.

Further details of cures for suspended floors.

Heating cost penalties of radon removal systems.

Cures for mixed floor houses.

Some comments on the Ionising Radiation Regulations.

Marginal cost-effectiveness for radon protection.

Review of the Select Committee Report on Indoor Pollution.

Analysis of papers presented at the NRPB 1992 Radon 2000 conference.

Notes from the September 1992 EPA Radon Symposium, Minnesota, USA.

Many of these titles will be available in 1993.

3. Consultancy Services.

The author's major interests and experience lie in the following areas of building and environment.

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Building Environmental Assessment Methods and Environmental Auditing of sites and companies.

Development of environmental assessment methods for all building types; work on Eco-labels, Eco-audits, and Company registration to BS 7750.

Buildings Health.

Sick building syndrome, Legionnaires' disease, Allergies, Radon, Health Economics.

Buildings Energy Use.

Energy calculations, Industrial Building auditing, Domestic Energy Labels, Renewable Energy sources.

Building Pathology.

Investigation of a range of defects and problems, including dampness and timber decay in domestic and other properties.

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Radon consultancy services.

For over three years the author led buildings research to evaluate radon protection measures for new houses and remedial measures for affected houses, mainly in Devon and Cornwall. Experience is based on scores of badly affected houses in the UK, and on work in the USA and Canada.

Services include:

Advice by telephone

(initially free, but charged for detailed work).

Site visits to discuss radon problems and recommend action.

On-site diagnosis including detection of entry routes, inspection of walls and floors and assessment of the interaction between specific radon systems and building fabric.

Specification and (optionally) supervision of remedial work.

Work can be undertaken by a 'preferred' builder working to the author's specifications.

Advice on do-it-yourself systems

for homeowners wishing to pursue their own remedies, but who need expert help.

Inspection and diagnosis and remedy of failed systems

either for the purchaser of the system or for new occupants.

Detailed diagnostic monitoring

to supplement the free service offered via NRPB and Councils, and to assist with system design.

Examination of domestic properties as a part of Sale and Purchase.

Assessments can be undertaken of radon levels and likely remedial prospects and costs, were all or part of the property to be confirmed as badly affected.

Provision of meaningful guarantees.

These are especially valuable for large or complex high-radon houses. Specific problems can be discussed with prospective purchasers, if vendors so wish.

Lectures on radon.

Available for professional groups.

Services as an expert witness,

in many areas of building to include radon.

Services as a Radiation Protection Advisor (RPA).

Employers may need to appoint an advisor under the Ionising Radiation Regulations for premises affected by radon.

[*]

4. Introduction to radon and indoor air quality.

The first point about radon is that although it is considered to be a serious indoor pollutant it is entirely natural and usually no-one's fault. This has tended to limit public concern, in sharp contrast to the anxiety generated over small risks in other areas involving ionising radiation.

Governments have been concerned for many decades with pollution of the outdoor air. Only a few decades ago, London smogs killed hundreds of people before controls were introduced on both industrial and domestic emissions. Urban pollution is still a major problem in some parts of the world, and accounts for probably tens of thousands of deaths and a great deal of respiratory and other illness amongst all age groups. As western countries in particular have cleaned up the outdoor air (in cities if not more widely) they have also begun to embrace energy conservation, and buildings have been made more airtight.

There are two main reasons why Governments and Industry are now more concerned with 'indoor air quality'. First, many modern materials used in building construction and furnishing produce chemical pollutants. The second reason is that with modern scientific equipment, minute concentrations of pollutants can be measured with reasonable accuracy. Only when these facilities are available can either officials or politicians start to show concern, and to consider legislation and apportionment of blame.

Radon is not a new pollutant. It has always existed in buildings, and in the outdoor air. It was discovered as a radionuclide only in 1900, and was suspected of being a cause of ill-health in 1924. Only in 1951 were radon daughters (as opposed to radon gas) suspected of being a cause of lung cancer in miners.

Radon is a naturally occurring radioactive gas produced in minute quantities in most, if not all, soils and rocks. It is a product of the radioactive decay chain of naturally occurring uranium and has no taste, colour or smell. Nevertheless it is an interesting element: despite being a 'noble gas' it will form compounds and if cooled to a solid at the temperature of liquid air (-195 °C) it glows with an orange-red light.

The parent radionuclide is radium, which has a half-life of 1622 years. Therefore, production of radon in the ground is essentially constant. In outdoor air, concentrations are extremely small in all parts of the UK, but higher concentrations occur inside buildings.

Houses in which the radon level is particularly high are a principal concern because many people spend most of their lives at home.

Most of the so-called 'high level houses' in the UK are in the south west, mainly the counties of Devon and Cornwall (see Section 9). Radon is a proven cause, or a proven contributory factor for lung cancer in miners. However, there is little convincing evidence for harm to householders, but this is being sought by way of epidemiological studies in many countries.

It seems likely that radon will be confirmed as a real risk in houses, but nevertheless it should be kept in perspective as a health issue (see Sections 23, 25, 31) and not taken automatically to represent a severe threat simply because it is connected with radiation.

Scientists are divided over whether small doses of radiation cause harm to people or not. Whatever the true position, there are many apparent anomalies, including that people who live in regions of higher than normal background radiation often have a lower overall cancer rate, and that in some experiments, irradiated animals lived longer than those that had not been irradiated. [*]

5. Some basic facts about radiation: a perspective.

There is no disputing that ionising radiation (often just called radiation) can cause cancer. However, there are many causes of cancer, some not well understood. Radiation, including that from radon exposure, seems responsible for only a few per cent of cancers in the UK, perhaps about 3%.

Major causes of cancer include smoking and poor diet. Although the link with diet is not fully understood (or agreed) it is possible that as many as 35% of cancer cases may be linked in some way to food and drink.

Radon daughters are responsible for most of the ionising radiation to which most people are exposed. In 1987, the UK Government acted upon NRPB advice that householders whose homes were found to contain on average more than 400 Bq/m^3 of radon should be advised to treat them in some way so as to reduce their radiation exposure. At that time, Sweden had an advisory level of 800 Bq/m^3 and most other European countries had not formulated guidance.

In January 1990, the so-called 'action level' in the UK (400 Bq/m^3) was reduced to 200, again on NRPB advice. This is not a danger level and it is not a safety level. It is (merely) an advisory threshold where the advice is "above this level consider taking some action in the longer term". In 1991, the EC set an action level of 400 Bq/m^3. Thus, as of 1992, the UK has one of the lowest 'action levels' for radon in homes.

At first sight, houses containing 400 Bq/m^3 of radon and in which the occupants could receive annual doses as high as 20 mSv (see Section 6) might appear to be quite dangerous. 20 mSv is five to ten times the dose that most radiation workers receive. In fact, the risks are not all that great but it needs to be borne in mind that some houses in the UK have been found to contain 5000 Bq/m^3 of radon. This still has to be kept in perspective, because in the United States and Eastern Europe people have lived for decades with 100,000 Bq/m^3 of radon. One house has been reported in East Germany at 300,000 Bq/m^3.

At the other end of the radiation scale, are the minute personal doses to members of the public received routinely from nuclear reactors and reprocessing facilities. These are generally below 0.001 mSv, less even than the dose from cosmic radiation received during a short plane flight.

One illustration of nuclear perspectives is the story of Three Mile Island in the USA (see Section 40 also). A nuclear reactor came close to melt-down, and was severely damaged. Much of the internal cooling water was heavily contaminated with radionuclides (radioactive atoms). This water has long since been decontaminated and it is now so pure that it is less radioactive than the local river water. But it is still stored and has not been discharged to the river, for fear of public outcry. This is one example of the expenditure on minute risks that so characterises much of radiological protection.

Another example is the perhaps understandable overreaction to the accident at Chernobyl (see Section 45 also). In the surrounding countryside, people have been evacuated and compensated because of average annual doses of 5 mSv, and are being compensated for doses as low as 1 mSv. Yet the average radiation dose from natural causes in Cornwall is about 10 mSv per year!

KEY FACTS:

As with some aspects of nuclear power, radon has been taken out of perspective, especially by some public administrators in the United States. One encouraging sign is that both radon experts and health professionals have begun to question past excesses of policy.

Nevertheless, radon can represent a severe risk in the worst affected homes. [*]

6. A note on units used in radon work.

Two special scientific terms need to be understood in radon work. These are Bq/m^3 (becquerels per cubic metre) and mSv (millisieverts).

Bq/m^3 is a unit of activity concentration, a measure of radon per unit volume. This can be thought of as the concentration of radon in the air, whether in a house, a school or outdoors.

Values for activity concentration in Bq/m^3 can range from about 3 (outdoors in the UK), through 50 (reported outdoors in some States of America), to 150,000 or more (found in the worst affected American and East German houses). In soil gas, levels of 20,000 or 30,000 are quite normal.

Over 1,200,000 Bq/m^3 has been recorded by the author in Cornwall, equalling reported concentrations in mines in Czechoslovakia that were at the centre of lung cancer studies decades ago.

The average concentration of radon in UK housing is around 20 Bq/m^3. The average for houses in Cornwall is around 170 and in Devon about 70 Bq/m^3. This compares with an average of between 50 to 60 Bq/m^3 in the USA.

In general, radon levels in UK housing are low: many countries average more than 20 Bq/m^3. However, the radon concentration in a building does not represent the associated risk - because the amount of time spent in the building is of equal importance. To assess potential harm from any type of ionising radiation, a concept called 'dose' is used.

Millisieverts (mSv) are a modern unit for dose, and are used here in the context of effective dose equivalent, a concept introduced by the ICRP in 1977.

Effective dose equivalent takes into account that some organs of the body are more sensitive than others to an assault by unit radiation dose. Formally, the effective dose equivalent is that dose equivalent which if delivered uniformly to the body would result in the same total potential harm as results from the actual dose. Effective dose equivalent can be used directly to compare the chance of harm (usually cancer) resulting from various doses to different organs and by different types of radiation.

There is a conversion between Bq/m^3 of radon and mSv/year for any type of building, determined by the average time that it is occupied. For houses, the conversion factor is 20, so 20 Bq/m^3 in a house will give an annual effective dose equivalent of 1 mSv, assuming that the occupants spend most of their time at home indoors. If the average radon concentration is 800 Bq/m^3, the annual dose will be 40 mSv, (800/20) and so on. It is assumed that house occupancy is around 80 or 90%.

However, the situation in schools and offices is different. School buildings are occupied by classes at work, or during breaks, for around 1000 hours per year, a fraction of only 11 or 12%. For office workers, typical occupancy factors are around 20%. Thus, typically, the radon concentration in a school could be 6 or 7 times as high as in a house before it gave rise to the same concern for an individual, (see Sections 27 and 41) and in an office building 3 or 4 times as high.

KEY FACTS:

High radon levels in houses are of most concern simply because people spend so long at home compared with time in other buildings.

Radon concentrations in air are measured in Bq/m^3, but dose (and thereby potential harm) is expressed in mSv of effective dose equivalent, and usually in mSv per year.

Conversion factors for different types of buildings depend upon the time people spend in them. Radon in schools has proved to be an emotive issue, especially in the USA, but dose to occupants is generally low. [*]

7. Conversion factors for different units.

Many units are used in radon science. The most popular in Europe are explained in Section 6. Other units are also used in radiation work, but not usually for radon.

Activity concentration is measured in Bq/m^3 but may be expressed in pCi/l. (picocuries per litre). The conversion is approximately
$37\ Bq/m^3 = 1$ pCi/l

Absorbed dose: gray, Gy where 1 Gy = 100 rad.

The rad is an old unit. Both rads and grays express energy imparted by radiation to a mass of tissue: 1 Gy = 1 J/kg.

Dose equivalent: rem, where rem stands for roentgen equivalent man. (The roentgen is an obsolete unit).

1 rem = 0.01 Sv = 10 mSv

Dose: (effective dose equivalent, usually) is expressed in Sv, or mSv.

One rem, equal to 10 mSv, is sometimes considered equivalent to "a few hundred cigarettes". Thus a house containing 400 Bq/m^3 of radon and which delivers occupant doses of 20 mSv (2 rem) per year may be producing the same long term risk of premature death as about 2 cigarettes per day, for non smokers.

Older units in common use in the USA are WL and WLM, respectively working level and working level month. These derive from the days when most concern about radon centred on miners. The units represent a certain concentration and integrated concentration of radon daughters in working environments.

Radon itself does not contribute to calculation of the WL.

Some care is needed in using these units, because equilibrium factors have to be taken into account in converting to radon gas concentrations.

Based on decay product (daughter) concentrations,
$1\ WL = 3740\ Bq/m^3$.

Assuming an equilibrium factor of 0.5 (normal for houses) 1 WL = 7480 Bq/m^3 of radon gas.

Also, 1 WL = 200 pCi/l (F = 0.5) or

1 WL = 100 pCi/l (F = 1)

The conversion between pCi/l and Bq/m^3 when applied to radon gas (which is the usual usage) is independent of F, the equilibrium factor.

The WL is actually defined in terms of Potential Alpha Energy Concentration (PAEC) in air. In SI units, 1 WL = $2.08 \times 10^{-5}\ J/m^3$ or 1.3×10^5 MeV of alpha energy.

Quality factors and other units.

For beta and gamma radiation the so-called quality factor is unity, so 1 Sv is produced by absorption of 1 Gy. For alpha radiation however, it is usual to assume a quality factor of 20, so 1 Gy of absorbed dose will represent 20 Sv of dose equivalent. Higher quality factors have been suggested for alpha radiation in bone marrow, whether from radon daughters or from actinides such as plutonium.

Doses from gamma radiation (from rocks, soil and food) are often expressed in nGy per hour. Doses are small compared with those from radon, and range from about 0.1 to 1 mSv annually in the UK. Typical dose rates indoors are between 10 and 250 nGy/h depending upon the location and construction.

A note on Thoron.

Thoron is often produced alongside radon. The two gases are similar, but differ in that the radioactive half-life of thoron (^{220}Rn) is only 54.5 seconds, compared with 3.82 days for ^{222}Rn, usually known simply as radon.

This key difference means that whereas radon can be expected often to enter houses from considerable distances underground (typically 1 to 2 metres), thoron sources need to be either close to the ground surface or to be part of the house construction before they are likely to contribute significantly to airborne radioactivity. However, once in the house, thoron decays to a series of long lived daughters with considerable PAEC. [*]

8. Monitoring for radon: methods and discrepancies.

Measurements of radon in buildings over short periods (even over a few days) may give a poor estimate of the annual average level. Readings taken over minutes or hours are largely meaningless except in research work.

Most domestic radon monitoring in the UK has been undertaken using 'plastic' or 'track-etch' detectors that are capable of integrating radon over periods as long as a year. These cost around £20 each, including analysis, and are used typically for three month periods. They are generally accurate to within 20%, but larger systematic differences between different makes have been observed. An explanation of the working principle is given in Section 36.

Notwithstanding that radon daughters deliver most of the dose to lung tissue it is the long-term average radon gas level in a building that may be monitored to determine health risks and for assessing the effectiveness of most types of remedial measures. For most purposes therefore, track-etch detectors are suitable.

However, in the USA extensive use has been made of a different type of device, the charcoal canister. For several reasons, these are not recommended by many scientists, and inappropriate concern or complacency can result from placing reliance on results from these units. Concern might be even greater in the UK, where naturally ventilated houses would be expected to exhibit greater short period fluctuations than are the norm in many American dwellings.

In old heavyweight houses typical of parts of Devon and Cornwall, summertime readings with track-etch detectors may be suspect. During months of hot weather these houses are often cooler indoors than outdoors, a reversal of the conditions that are responsible for much radon entry (see Section 11). It has been discussed for years that summertime measurements are suspect in some types of houses, but they have been continued. These houses may be worse affected than reported results would suggest.

Another type of detector, the electret ion chamber, has demonstrated good test accuracy and performance on site and is rapidly gaining acceptance amongst scientists. However, it is affected by gamma fields and care needs to be exercised in its use.

The proven deficiencies of some track-etch detectors have included end errors (substantial errors of measurement at low radon exposures) and gradient (calibration) errors. These have affected readings over the whole range of integrated concentration.

Both types of error are relevant in assessment of national statistics, since the fraction of houses estimated to be above any given 'action level' may be markedly affected. Detailed advice is available from the author, and further information is given in Section 36.

KEY FACTS:

Screening using commercially available track-etch or charcoal detectors is poor value compared with the free and confidential service offered by DOE in the affected areas of the UK (see Section 9).

Short term tests using portable radiation monitors can be misleading in respect of assessing either long term average radon levels or the differences room-to-room. Indeed variations room-to-room can depend on which way the wind has been blowing.

Summertime readings in some types of houses may be particularly suspect.

A well known scientific law applies to radon measurements, especially to those using some track-etch detectors:

> if you want to measure something accurately only do it once!

Diagnostics measurements in buildings are discussed in Section 59. [*]

9. Areas of the UK affected by radon.

The principal affected counties are Devon and Cornwall. However, large areas of Devon are only marginally affected.

Areas of Northants, Scotland, Derbyshire and Somerset are also known to contain houses at moderate radon levels and with some above 1000 Bq/m^3. Many small areas have become known because of Press and media attention. However, it does not follow that these are the only or the worst affected in the neighbourhood: often they were merely the first to be discovered. Some streets are well known to be affected, but there can be marked differences both between neighbouring houses and between rows on opposite sides of the street.

The worst-affected postcode sectors in Devon and Cornwall especially have been published in the UK. Earlier publication of radon data by zip code in the USA caused increased interest amongst homeowners because of possible effects on property values. The author may be consulted for details.

Postcodes are a useful way of delineating areas, if only because they are used already by marketing organisations. Each sector contains between 1000 and 4000 addresses. In sparsely populated areas a sector can cover many square kilometres. However, few if any align with known geological features or mine workings, which have been known for years to be one of the methods of identifying areas or villages likely to contain houses with the highest radon levels. Only recently has detailed mapping of radon in soil gas been started in the UK. However, porosity or diffusion parameters are also important (and probably more important in inhomogeneous ground) in predicting areas most at risk.

Over four years ago, a County Council identified the areas most likely to contain its worst affected schools using maps and mining records.

However, it is important to recognise that even in Cornwall only around 20% (1 in 5) of houses contain more than 200 Bq/m^3 of radon, and of these only a small fraction are at levels that need give rise to concern in the short term.

Radon in soil gas could be investigated over wide areas, but it may remain useful only as a broad indicator. This is because of variations over short distances, and the key role of ground permeability. Unfortunately also, airborne measurements of gamma activity (as have been used in seeking uranium deposits) do not correlate well with all known high radon houses. Again, uniformity may be part of the problem.

A few owners of badly affected houses have undertaken detailed study of geological maps, and have confirmed that their home sits astride a fault or junction between rock types.

The combination of broad-scale radon mapping with detailed study of local maps may be a potent and cost-effective method for identifying high-risk areas to fine resolution.

A similar approach was first used in the USA in the mid 1980s and in Sweden well before that: knowledge of local geology was used to predict the location of other high level houses from a few that had been discovered somewhat by chance.

KEY FACTS:

Houses that contain a very high level of radon can be found in many counties, but outside of the principal affected areas are rare.

Within affected counties there can be large areas that are substantially unaffected, but even within a given postcode sector, these can include very small 'hot-spots', owing to changes in the underlying ground.

Neighbouring houses can have genuinely very different radon levels and few houses may exhibit an essentially fixed radon level, independent of occupancy and building factors. [*]

10. The quantity of radon in UK houses.

Amongst the more enduring of folk tales about radon is that it is a dense gas that settles in a layer at floor level.

People sometimes ask whether they should prevent children playing or sleeping on the floor, believing that the concentration at table height will be markedly lower. In fact, radon is rapidly dispersed from cracks in the floor and other entry points into room air, and the quantities are extremely small - so small that they cannot readily be imagined. There is no layering effect because of this small concentration: the density of soil gas (if composed only of air and a little radon) is no different from that of room air at the same temperature. In any case, fresh radon presents little risk if inhaled and complete mixing of soil gas and room air will occur well before equilibrium numbers of radon daughters are formed.

How much radon in an affected home?

The concentration of chemical pollutants is often expressed as parts per million (ppm). One ppm is about a large cupful compared with the volume of the average house. Efforts are made to detect and control highly toxic chemical pollutants to parts per billion (ppb).

(A billion is here defined according to common usage as a thousand million. The English definition of a billion as a million million is now recognised as obsolete). One part per billion (ppb) is about five small drops of water compared with the volume of the average house, or 250 mm^3 in 250 m^3.

However, radon gas is present typically as ten parts in a billion billion (10 in 10^{18}) in an affected house. It is difficult to conceive of such a small volume. It is about 1/100,000 the size of the ball in a ballpoint pen - as small as the tiniest speck of dust. However, even this minute volume of radon still contains nearly seventy billion atoms.

If all the radon that was present at any one time in all the 20,000 worst affected houses in the UK were to be collected together there would be insufficient to sit comfortably in the eye of a sewing needle.

If radon was a 'chemical' contaminant (like substances in tobacco smoke or pesticide residues in food), it would be difficult if not impossible to detect such a low concentration.

Despite that volumes of radon in houses are unimaginably small, radon is highly radioactive, and that is what sets it apart from other pollutants of the indoor environment.

Some useful numbers.

Avogadro's number (atoms or entities in a mole) = 6.02×10^{23}. One mole of a gas will occupy around 22.5 litres under normal conditions.

Half life of radon = 3.82 days (92 hours).

Decay constant of radon = 0.0076 h^{-1} (sometimes called decay rate)

Basic equation for radioactive decay. $\frac{dN}{dt} = -\lambda N$ (λ = decay constant)

At 2000 Bq/m^3, dN/dt = 2000 x 3600, so N equals about 1 billion, or one million atoms of radon per litre. However, one litre of a gas contains in total around 2.6×10^{22} atoms or molecules. Thus the radon concentration is about 1 atom in every 2.6×10^{16}. Devotees of arithmetic should now calculate the volume of a curie of radon, and estimate the activity concentration (in Bq/m^3) in a house containing this quantity. [*]

11.1 How to decide on radon remedial treatment.

1. Don't panic.

   Any radon problem can be solved.

2. Don't spend money in haste.

   Tackling a radon problem sensibly and calmly will result in a satisfactory outcome with minimum inconvenience and cost.

3. Don't believe all you read or hear about radon.

   As in most subjects, there is a wide range of misinformation to tempt the unwary.

4. Remember that not all houses are the same.

   Small houses are often quite simple to cure. Larger houses, especially those built on different levels and with parts dating from different periods can require expert attention to obtain the best results.

5. Remember that not all radon measurements are the same.

   Different rooms often have very different radon levels, even in small houses. Detailed interpretation is sometimes essential.

There are many factors that in real buildings can determine the best type and location of a radon system. By way of introduction, it is helpful to reflect on why and how radon enters houses. This occurs primarily as a result of slight pressure differences between the air inside the building and the air underground. A principal driving force is the buoyancy of warm air indoors when it is cooler outdoors. In theory, if a house or other building is completely sealed, then no warm air can leak out and no cold air from outdoors or the ground can enter, except via diffusion.

Radon will enter through any crack or gap and especially through large holes in floors and (sometimes) walls. Some houses have well sealed concrete floors, others have leaky timber floors, sometimes with decayed joists, and some have a mixture of floor types. Window designs also vary widely, as do heating systems. Little advice has been issued on draught-proofing of floors. Indeed, the aim of most draught-proofing appears to be to seal doors and windows as much as possible, so keeping 'fresh air' out of buildings! Sealing of floors can result in a dramatic decrease in indoor radon levels, but success is uncertain.

How a house is ventilated can be important because it may make a difference of at least a factor of two in annual average indoor radon levels. This may be sufficient to bring many (indeed, most) 'affected' houses below the so-called action level, but a corresponding number of houses classed as 'safe' on the basis of routine screening measurements could of course have their radon levels increased to above the action level by altered ventilation habits. Sometimes sealing windows can REDUCE indoor radon levels!

No reasonable amount of extra ventilation will 'cure' a house that has been assessed at several thousand Bq/m^3, but it may be all that is required in many other cases, and in some houses is necessary to help cure condensation and other problems that have been caused in part by excessive draught-proofing.

11.2 How to decide on radon remedial treatment.

In summary, the interactions between house temperature, ventilation, and occupant behaviour, and house design, can influence not only radon entry rates, but selection of remedial measures.

The key factors determining choice of remedial measures include

The annual average radon level.

This is important because building work that may be justified at 5000 Bq/m^3 may represent a gross overreaction at 400 Bq/m^3. Some high-level houses can be cured quite cheaply.

Whether any member of the family smokes, and how long the family intends to live in the house.

Both these factors determine the extra risk that will be incurred by continuing to live with an elevated radon level. For non-smokers the calculated risks are not great in all but the worst affected UK homes, at least for a few years.

Availability of funds for remedial works.

Often there is merit in undertaking simple measures first, followed later (if necessary) by more expensive steps.

The design of the house.

In large houses of mixed construction especially, some care can be needed to achieve a satisfactory and aesthetically acceptable solution at reasonable cost, and without excessive disruption.

Future scientific developments may produce novel ways of reducing the dose from radon daughters.

Further details of remediation are available from the author, see Section 3. Advice is also contained in Part 3 of this Handbook. Amongst the relevant Sections are:

41. Avoiding undue risk: time-scales for radon remediation.

52. Design & operation of radon sump systems.

53. Who to employ to cure a radon problem: a local builder, a specialist company or a consultant?

56. The role of heating systems in determining radon levels.

57. Influence of radon measures on timber floors.

58. Sealing techniques and their performance.

59. Diagnostics for radon remediation.

60. Experience with radon sumps.

61. Experience with whole house pressurisation.

62. Experience with ventilation provision. [*]

12. Further reading on radon.

This Section presents the author's view of some of the reference books and other publications on radon. The list is not exhaustive. Some books are not mentioned. Much contemporary information can be found only in research papers (and some in this Handbook can be found nowhere else).

Radon and its decay products in indoor air. An expensive reference book edited by scientists from LBL in California. Probably the best single specialist work available for student level studies and advanced topics. International contributors. Edited by Nazaroff and Nero, Wiley Interscience, 1988. ISBN 0-471-62810-7.

IARC Monographs on the evaluation of carcinogenic risks to humans. Volume 43: man-made mineral fibres and radon. IARC, Lyon, France (in English) World Health Organisation. Most of this book is devoted to MMMF but the section on radon forms a useful reference base for epidemiology. ISBN 92-832-1243-6

Air Quality Guidelines for Europe. World Health Organisation, Europe. A summary of risk data and properties for over 30 compounds and elements, including radon. Useful for risk studies. ISBN 92-890-1114-9.

Radiation and Health: the Biological Effects of Low-level Exposure to Ionising Radiation. Conference proceedings edited by Russell-Jones and Southwood. Purely medical/political but recommended for the expertise of the contributors, not all of whom agree with each other. Very readable but now six years old. Wiley & Sons ISBN 0-471-91674-9.

Handbook of Radon in Buildings. Detection Safety and Control. An American multi-authored book produced for the DOE. Comprehensive and scientific but somehow lacks the appeal and readability of the Nazaroff and Nero text, also published in 1988 (see above). Hemisphere Publishing Corp. ISBN 0-89116-823-0

A vast amount of literature is available from NRPB in the UK and especially from EPA in the USA. The range, quality and relevance to all but specialist readers varies widely. Some EPA literature is renowned primarily for its mass. Much is of interest for historical perspective. Dose and risk estimates in all early publications are now out of date.

For schools, the NRPB broadsheets on radiation (nine are now available) are good value, being free of charge. They are a little slanted in places, but authoritative, readable, colourful and well presented. Available direct from NRPB, Chilton, Didcot, Oxon. OX11 ORQ. The NRPB booklet **Living with radiation** may also be recommended for general reading. ISBN 0-85951-320-3, available from HMSO. Another very readable and authoritative booklet is **Radiation: effects and control**, published by the Atomic Energy Authority, Harwell, Oxon. [*]

21. Simplified explanation of the risks from radon.

The risk from living with higher levels of radon over many years is an increased chance of lung cancer in later life. This is well established from studies of miners, although the statistics derive primarily from miners who smoked. This is simply because in the years of interest, before radon levels in mines had been addressed by using better ventilation, smoking was a prevalent habit amongst working class men.

There is less compelling evidence for the risks to non-smokers. Amongst the variables are that conditions in mines are dissimilar to those in homes. Miners are sometimes also exposed to thoron (see Section 7) and because of the long half-lives of thoron daughters, the inhibition of lung clearance that occurs in smokers may be significant. These and other factors complicate the calculation of risk factors for housing.

Links with leukaemia and other cancers may be regarded as 'not-proven'. If these and other effects do occur occasionally, the risk factors are almost certainly much less than for lung cancer - see Section 30 also.

Whilst radon and lung cancer are undoubtedly linked, some perspective can be obtained by comparing the risks with those of smoking.

It is broadly accepted (except of course by some tobacco companies) that smoking one cigarette per day gives a lifetime risk of about 1%. In other words, a person who smoked one cigarette a day all his life would have a 1% chance that he would eventually die from the habit - and a 99% chance that he would die from some other cause. Indeed, his (or her) risk of dying from some form of cancer would be around 20%, so smoking one cigarette a day for life can be thought of as increasing this average prevailing 20% risk by about 1%, to perhaps 21%. Whilst this 1% calculated risk can be avoided, so can larger risks according to some studies (see Section 31).

In contrast to these small risks, a lifetime smoker with a 50-a-day habit has a better than even chance that the addiction will eventually kill him. Of course, not all 100-a-day smokers will die from a smoking related illness - that is not how statistics work - but the risks are very high nevertheless.

The NRPB risk factor for radon at the so-called 'action level' is 1% for a lifetimes' exposure for non-smokers. Recent EPA estimates indicate lower risks, see Section 28.

Whatever the true position, there need be no great concern about a level of 200 Bq/m^3 in homes. People do not panic if they discover that a member of the family is smoking one cigarette per day. Neither should they panic over low levels of radon, or be pressurised into over-hasty action to modify buildings.

The risks are probably much greater for smokers, but in both the UK and USA it is these people who most of all have proved unreceptive to publicity encouraging action for health.

KEY FACTS:

Moderate amounts of radon do not pose much of a risk to non-smokers - perhaps less than the risk of dying in a home accident or on the roads, and a lifetime exposed to radon at the action level (or approximately 10 years at 1400 Bq/m^3 or 5 years at 2800 Bq/m^3) is no greater cause for anxiety than is driving a car or smoking one cigarette a day for decades.

The so-called 'action level' is not a danger level and it is not a safety level. It is (merely) a useful reference point for contemplation of remedial action. In the short term at least, only houses above 2000 (two **thousand**) Bq/m^3 warrant anxiety.

There are many differences between mine environments and room air in homes, between the risks from radon and thoron in mines and homes and between risks from radon and thoron to smokers and non-smokers. Some care in extrapolating risk factors is necessary, and studies are proceeding in several countries. [*]

22.1 Radon: a health, environmental or a nuclear issue?

This Section addresses definition of health, environmental and nuclear issues. The conclusion is that radon is a health issue and that treating it as a nuclear problem is inappropriate.

The terms Environmental & Environment have been much misused, since what distinguishes a true environmental issue is irreversibility over any sensible time-scale. An example is the destruction of tropical forests, and all their associated species. The phrase "Extinction is forever" has been coined by environmentalists.

Concern for "The Environment" should be distinct from that centred upon health issues, where the primary unwelcome effect is upon people. This distinction is only now being recognised.

Confusion is still common when it is something in the local environment (or the indoor air) that gives rise to a real or imagined risk to health, or when there are both environmental and health implications. An example is the use of pesticides on crops. Environmental consequences may be severe (as with DDT, the use of which continues in the Third World) whilst the direct effects of human exposure may be small or zero.

Other chemicals may have no demonstrable effects on the environment, yet pose a slight risk if traces remain in food or water. The judgement in all cases should be on ultimate consequence, but having regard to marginal cost-benefit analysis - or the law of diminishing returns.

Confusion is also evident in peoples' understanding of anything 'nuclear'. These problems may be classified broadly into two groups. The first includes where failure to take suitable precautions could result in sudden release of large amounts of radioactivity, or unauthorised possession of fissile material. Substantial expenditure will continue to be justified.

The other group of problems are those where failure to act or legislate could never result in a security incident or widespread contamination, but where some precautions may be desirable to limit dose to members of the public or in work-places. Here, costs and benefits might more properly be analysed in terms of health expenditure.

A generation of people have good reason to associate radioactivity with fear, secrecy and deceit. Most of the public (here taken to include most politicians) seem thoroughly confused. As a consequence, radiological protection has been able to obtain funding beyond that which might have been granted were the risks from many 'nuclear' problems to have been properly classified and more widely understood.

This is not a unique situation, as the asbestos debacle in the USA shows all too clearly. There, massive (multi-billion dollar) expenditure has resulted in poor cost-benefit at the margins. However, once abatement or protection becomes well established it is politically difficult if not impossible to encourage or regain a proper perspective, especially (these days) if the proponents claim to be 'environmental'.

Perspective has also been lacking within the pesticide debate in the USA, as elsewhere. Over 30 years ago the Food, Drug and Cosmetic Act in the USA required that no traces of any chemical known to exhibit carcinogenic properties in any concentration should be permitted.

The intention was laudable (if rather idealistic) but the legislation did not allow for advances that could have been foreseen in detection of residues, or for improved knowledge of how chemicals caused cancer.

Faced with the problem that strict adherence to the law would effectively prohibit the use of many agricultural chemicals in common use, the US EPA later adopted the reasonable approach of allowing use so long as the calculated risks were very small (rather than zero). One additional cancer per million people exposed was selected as a criterium. This was entirely sensible, since it is unlikely that any chemical poison could present utterly no risk in production, storage or use.

Similarly, the Safe Drinking Water Act (see Section 35) seeks to limit contaminants to extremely low risk levels, and partly as a consequence of concern over man-made pollution of industrial sites and water supplies. There is no requirement for zero risk, perhaps because the impossibility of achieving it was recognised.

In contrast to the one-in-a-million and similar risk factors that have been used within pesticide and water regulation, **advocates of radon control should be content with calculated residual risks 1000 to 10,000 times greater.** This is simply because concentrations of radon in outdoor air range from 2 to perhaps 50 Bq/m^3, giving calculated lifetime risks for non-smokers that may be as high as 1 in 10,000 to 1 in 400.

Levels in tens of millions of dwellings range up to 100 Bq/m^3, giving a possible risk from lifetime exposure of 1 in 200. Risks of this magnitude would be considered unacceptable from 'chemicals' in houses - witness the debate over formaldehyde from chipboard and some types of wall insulation.

However, much of the misunderstanding and dispute surrounding radon has its origins in the aspirations of a few experts and career administrators to treat it as a nuclear issue. Upwards of £10,000 per dwelling and commensurate research funding might then be devoted to remediation, and with the eventual aim (in the USA) of reducing indoor radon levels to no greater than those outdoors. The likely economic consequences of such an idea in terms of marginal cost-benefit may be calculated on the back of an envelope (or perhaps more aptly, on the back of a cigarette packet) but this did not prevent politicians being encouraged to support the necessary legislation. Indeed, some of them may have supported such a national goal without even seeking proper scientific guidance. In its latest Citizens Guide to Radon, EPA admits that this goal is "not yet technologically achievable in all cases". Whether it is logical or economically sensible is not addressed.

In context as a domestic health matter, relevant expenditure would be calculated against a background of other health costs and benefits for the household, or (for public expenditure) for the Nation, see Sections 25, 31 and 39.

Despite the availability of rational and published analysis, radon has been referred to as the greatest environmental problem faced by the United States. However, the frantic and alarmist publicity campaign led by a few administrators (see Sections 34 & 42), has left public concern about radon at a low level. It may be conjectured that people have an innate sense that something entirely natural and that has been present since the world began cannot suddenly constitute an environmental hazard. In this they are correct, but often the 'natural' origin of radon is cited as a reason to dismiss health implications also.

Amid all the contemporary clamour and claims for protection of The Environment, it seems unclear whether proper levels of funding and concern will be applied to real environmental problems. Inevitably, the many vested interests in health and environment will continue their separate battles for funding and public recognition. Within each area, improvements in relative resource allocation will result.

The greater issue, that of deciding allocation between major headings has not yet been properly addressed. The necessary framework - although simple - is not easily discerned amid the mass of risk and risk management literature. Indeed, this may be part of the problem: the mathematics of risk management and economics appear both daunting and inaccessible to all but experts.

In this situation, it may be necessary to adhere to some instinctive beliefs and logical arguments, and to await the production of supporting analysis. It has long been recognised that both politicians and environmental groups lack a unified framework within which to argue for funding, but there are signs that some groups now recognise the requirement. A decade of frenzied and partial programmes (and programs) has produced many projects based only on narrow perspectives.

Within environmental assessment, the need for strategic overview was recognised a decade ago but implementation has been patchy. Many assessments are based only on analysis at a project level. Much the same is true in other areas.

Another part of the problem is that many experts are content to argue and to extend their case only within the bounds of their expertise. Often they are constrained by a belief (or an instruction) that they should mind their own business.

Government Departments are particularly sensitive to staff breaching the sanctity of a rival Department's remit. As a consequence, open debate is largely stifled and partial policies escape proper scrutiny.

Effective pressure for improved analysis may therefore be expected to originate within a few of the less partial environmental or health lobby groups, and with improved official policies following some years later.

Recent debate on the need for (and benefit from) EC regulations on purity of drinking water reflect similar debates in the USA: the funds involved could finance many health programs and to known benefit. It is notable (and probably deliberate) that at few radon conferences are the benefits of marginal intervention assessed in a health context.

More generally, benefits from environmental legislation **at the margins of clean-up** cannot be demonstrated, because there is no reliable risk data for most pollutants - including radon.

Perhaps the best that can be hoped for is that some farsighted and independent politician with an innate sense of what is being lost in the wider environment may seek to address the issue.

The countless billions of dollars spent routinely in the USA on frivolous consumer products have been cited by senior EPA administrators as a rationale for spending far more money on radon. Within the confines of their own subject area they have a good case, but a better argument can be made for spending less money on radon, and yet more on issues of population and world energy consumption.

The world awaits the emergence of an American politician (or an EPA administrator) prepared to oversee an increase of gasoline (petrol) prices in the USA by a factor of three in real terms within five years.

If the principal issues of Environment are not properly addressed they may lead to deaths and misery on an unparalleled scale, and dwarfing all the calculated consequences of inadequate 'health' or 'environmental clean-up' budgets.

In the UK, and as one response to perceived concern over "a healthy environment" it has been suggested that a new body, an Institute for the Environment and Health, be formed. It is proposed that its work might cover risks to both human health and the natural environment from exposure to hazardous chemicals in the environment. To some extent this would be a move in the direction of an American style EPA (as has already been proposed in the UK).

However, given that the risks from hazardous chemicals outside of a few work-place situations are already at a very low level in the West, any funding that is purported to be 'environmental'

22.4 Radon: a health, environmental or a nuclear issue?

might be better spent elsewhere. Residual funding from Health budgets might be directed to areas where major causes of premature death or impairment remain underfunded. There are many of these, and resources need to be targeted at those that can produce the greatest benefits.

The recent proposal to commit yet further funding to chemicals in the (Western) environment as both an environmental concern and a health issue is entirely in line with the political rush to environmental kudos.

If the pattern seen in the USA is followed then thorough analysis may be expected to be applied more in assessing misdirection than in the initial formulation of objectives, a strategy to meet the objectives, and policies and programmes to achieve strategic goals. Furthermore, the analysis is unlikely to be performed (or even the need for it to be recognised) within some of the partial bodies entrusted with public funds.

Real environmental problems are now recognised. As a consequence of public concerns (however misdirected in many cases), funds of unparalleled magnitude may be available to be devoted to understanding and even to resolution of these problems. Unfortunately there can be no quick fixes - which would limit political appeal were public concerns to falter.

However, in order that any opportunity is not lost it must no longer quietly be tolerated for further and substantial funding to be directed at **marginal** cleaning up of the environment (and in the name of The Environment) without marginal cost benefit analysis. This applies both to the outdoor environment and to matters such as radon - a subject that is strictly within the domain of household risks and benefits for all but occupational exposure.

There are many other minor problems that could be addressed via 'popular' technology or that have an appeal to one pressure group or another (or perhaps more often to an individual or two within the group). Examples are extreme purity of drinking water, even better catalysts on large cars, more readily recyclable soft drinks cans, enforced recycling of bacon wrappers and yoghurt pots, and benzene recovery at petrol pumps. These and many others are in essence 'convenience' or 'feel good' projects - easy to classify under a budget heading, amenable to regulation or standardisation by national and international bodies, and yielding the satisfaction of seeing a 'better' product or process within a short time.

In contrast, real environmental problems are centred upon over-population (including of the West), profligate resource usage, global warming, ozone depletion, loss of species, loss of forests, degradation of lands and despoliation of the seas. Most of these are more consequential than causal and no quick solutions are available. Indeed, many detrimental changes that have not yet occurred but that are already perceived and understood may not be avoided, such is the momentum of destruction.

Allocation of central funds and encouragement of the public to be concerned about specific issues should take account of the ultimate consequence of ignoring them. None of the major environmental issues are even slightly influenced by reduction of high indoor radon levels: "the greatest environmental problem faced by the United States". [*]

23. Radon as a public health issue: how important is it?

It is essential to keep the risks from radon in perspective. The risk from increased exposure to radon is essentially that death from lung cancer may occur some years before death from some other cause. However, the risks from radon are not large for non-smokers at the exposures likely to be found in the majority of houses in the UK, even those in Devon and Cornwall. In gauging the risks, it is helpful to consider major causes of death in the UK.

Over 600,000 people die in the UK each year. No amount of medical care could prevent this number of deaths: we all have to die sometime. But what can be prevented to some extent is premature death. A premature death is a death that could have been delayed, perhaps by an accident or illness not occurring, by more prompt diagnosis of illness, or by better medical care.

Out of the over 600,000 deaths in the UK each year, perhaps as many as 200,000 may be classed as premature. The exact number is not important here and cannot be known accurately. It is important to differentiate between avoidable premature death and deaths that, although premature, could not easily have been avoided. Many accidental deaths fall into this category.

The Table below shows major causes where there is some large element of 'preventability'. Alcohol misuse is included, as it plays a part in all the listed causes, except radon.

There are of course many other causes of death in the UK. However, the key fact is that **with healthier living and more care on the roads** more than 100,000 people could have their lives prolonged each year. Of course, if this were to be achieved (and it would take many decades), re-balancing would need to occur in actual causes of death, as the average annual total cannot alter.

In contrast, removing most of the radon from the 2,000 highest-level houses in the UK (those above 1000 Bq/m^3) would reduce the number of calculated non-smoking radon deaths by perhaps 2 or 3. But many thousands of other cancers could be prevented, or cured if diagnosed soon enough. It is all a matter of money, priorities and education.

The Table below does not tell the whole story because it can be more logical to consider the number of years of life extension (rather than the number of lives extended). Thus, a premature death at age 10 is worth more effort to prevent than is one at age 75. Years of life lost (or saved) can be adjusted according to the quality of life during those years. This is the basis of the parameter "Quality Adjusted Life Year", used to assess whether expenditure is 'worthwhile' in one area as against another.

Cause of death	Number each year	Avoidable?
Circulatory diseases	300,000 +	100,000
Cancer (all types)	150,000 +	50,000
Road accidents (all)	5,500	3,000
Road accidents (alcohol linked)	1,500	1,500
Accidents in the home	5,500	2,000
Radon (estimated)	2,500	between 2 and 50

KEY FACTS:

In terms of QALYs, radon is insignificant viewed in an overall perspective of avoidable detriment. It is important in respect of high specific risks in a few buildings. It remains a health problem with no effect on any environmental issue of wider concern. [*]

24. Radon and older people - no cause for concern?

This Section was prepared as a consequence of the author having had to advise several distraught retired people in Devon & Cornwall. They were, variously, afraid for their grandchildren to visit, living with windows open in wintertime and fearful that they would never be able to sell their home. Such anxieties about radon levels found in the UK are absurd, but can be distressing.

The effects of radon on people of various ages are not known with any confidence, and will probably remain uncertain for decades. The reasons include that risk from a typical radon exposure is so much smaller than the risk from smoking.

Probably over 90% of lung cancer deaths are due to smoking and some are suspected to be due to industrial and transport pollution. Against this background, it is difficult to be certain about cause and effect for radon in domestic environments or to determine whether domestic radon exposure later in life ever leads to lung or other cancers.

However, it is highly likely that the effect of any radon exposure only occurs between 5 and 50 years subsequently. Thus, it may not be sensible even to encourage people who are 80 or 90 years old to monitor radon levels in their homes, simply because any further exposure at their time of life is almost certain never to affect them.

There is some evidence that latency periods may decrease as age at exposure increases: thus an assumption of 10 or 15 years rather than 50 may be appropriate for older people. Nevertheless, there is considerable scope for undue stress and anxiety from expensive and disruptive building works, especially if commissioned by 'high-pressure' salesmen. Disruption of a home environment is a known stress factor for elderly people especially.

Some medical doctors have privately expressed the view that more people may die prematurely through radon-induced stress than could ever be saved from lung cancer by treating high-radon houses. However, the fact that some doctors in 'high-radon villages' say they cannot remember seeing a non-smoking patient with lung cancer does not invalidate the calculated risk factors, but it does serve to set a local perspective on the problem.

Unfortunately, a logical approach to radon and elderly people has not been part of advice in the UK. In contrast, some Canadian booklets include encouragement to consider relevant personal factors in evaluating personal risk.

"Does anyone smoke in your home? How much time does any member of the family spend at home? How long will you live in your present home?"

These are all entirely reasonable questions in helping people consider radon in the context of their own personal circumstances.

KEY FACTS:

It is inappropriate for elderly people to be frightened into having expensive or disruptive building work undertaken on their house just because it contains a moderate level of radon. The latency period for radon is probably between 10 and 50 years but unknown (and probably unknowable) for each individual. Any exposure to radon during the last few years of one's life is most unlikely to have any effect.

Nothing can be done to lessen risks already accumulated over 50 or 70 years of living with high levels of radon. These may amount to a few percentage points, but there is little point in becoming worried about possible future events that are beyond any control.

Advice to elderly people, especially if living alone, should take into account their personal circumstances. [*]

25. Preventable radon deaths in the UK.

Amongst the few numbers that the Press have used relating to radon are NRPB's estimates of UK lung cancer deaths in which radon might be implicated. A few years ago the 'best guess' was 1500 per year, but revisions of risk factors (rather than modified estimates of the average level of radon in houses) suggested 2500. Use of this figure enhanced both interest and concern in the affected counties.

More recently, research has suggested that radon in homes may be less dangerous compared to radon in mines as had been supposed. A figure of 1600 deaths is used in the Government's recent White Paper "The Health of the Nation", but this applies only to England. However, eminent scientists concede that radon risk factors for houses may still be uncertain by a factor of five, and EPA in the USA has markedly lowered its projections for non smoking radon deaths.

Most estimates are derived by assuming that the more radon you breathe the more likely it is to kill you. They are based on the so-called linear dose-response model, and on many uncertainties.

However, even assuming that all the calculations are broadly correct, it is deliberately misleading to present the risks from radon utilising a single calculated statistic.

There are two reasons for this. Firstly, the consensus of scientific opinion is that a given dose from radon is possibly 10 or 15 times as dangerous to a smoker as to a non-smoker. Thus, three quarters or more of so-called radon deaths may be linked with smoking. Only a quarter may be in non-smokers. In the 1990 second edition of the DOE Householders' Guide to Radon this point is presented clearly. Likewise, the subject is properly presented in the 1992 edition of EPA's Citizens Guide.

Secondly, most radon deaths are calculated to occur not in Devon and Cornwall, but from the small radon exposures to tens of millions of people living in tens of millions of ordinary houses elsewhere in the UK. Thus, addressing the radon problem in Devon and Cornwall cannot influence 1500 or 2500 premature deaths per year, but perhaps less than 100. Of these, less than 25 may be non-smokers.

Studies are being undertaken in several countries to determine to what extent domestic radon really poses a threat to homeowners. An apparent contradiction is that rates of lung cancer in the 'high radon' counties of Devon & Cornwall are lower than in other regions of the UK. It is thought this arises from a slightly lower incidence of smoking and the later commencement of smoking in rural districts.

In assessing the risk of lung cancer from radon exposure, smoking is called a confounding factor - because it obscures what might otherwise be a clear correlation between regions of higher than average radon and regions having a higher than average incidence of lung cancer. However, beware of simple correlations, see Section 30.

KEY FACTS.

Most radon exposure occurs in a large number of 'ordinary-level' houses. Only about 4% of total UK exposure occurs in 'high-level' houses.

Realistically, around 10 premature non-smoking deaths might be avoided in the UK annually as a consequence of undertaking successful radon remedial action in tens of thousands of houses. Remedy of the 2000 highest level houses (those above 1000 Bq/m^3) might prolong the lives of 2 or 3 non-smokers per year.

In contrast, smoking has been quoted as causing around 100,000 premature deaths per year in the UK, to which may be added around 5000 owing to accidents in the home. In one year 25,000 or more people may die of influenza in the UK, and 2000 from asthma. Many of these may be preventable premature deaths.

In the USA it has been estimated that a multi-billion dollar radon remediation campaign would have the same effect on premature death as a 1% reduction in smoking. [*]

26. Further statistics for radon in the UK.

Following the classification used by NRPB, houses with elevated levels of radon can be grouped into

those over 1,000 Bq/m^3,

those between 400 and 1,000 Bq/m^3 and

those between 200 and 400 Bq/m^3.

If the EC action level of 400 Bq/m^3 is taken as a threshold, about 20,000 houses are 'affected' in the UK, which is about 0.1% of the stock of 22 million homes.

Using the linear dose-response model (see Section 25) it is easy to calculate how many premature deaths may occur each year as a result of exposure to radon in each of these three groups.

However, it is important also to calculate how many premature deaths might be avoided and for what expenditure. It is necessary here to be realistic, just as it is sensible to assume that not all smokers will give up smoking for the good of their health.

In the Table below, it is assumed that in the first group (houses containing more than 1000 Bq/m^3 of radon) action will be taken in over 80%, and to 80% effectiveness. However, it is unlikely that over 80% of these houses will be found in the near term.

In the other groups, it must be assumed that because of the lower risks, there will be less concern and (consequently) less remedial action. Houses below 400 Bq/m^3 do not pose much risk except over decades of occupancy.

In summary, the first group of houses are most urgent in terms of specific risk. The next group are less urgent, more dispersed, and therefore more difficult to find, and so on. Houses above 200 Bq/m^3 are widespread in several counties.

Only by attempting to remove all radon from all buildings could most of the 2500 radon-related deaths be addressed - and this would require truly massive expenditure.

However, this has not prevented some officials from stating that all (presumed) radon deaths could be avoided were a large public programme to be sanctioned to address high level houses. Such statements have been allowed to pass unchallenged and have caused considerable confusion.

KEY FACTS:

Only about 4% of radon dose in the UK is associated with high-level buildings, and mostly with houses. Only a few premature deaths of non-smokers could be prevented by a programme to find and treat many of these houses. For smokers, their higher risks could be reduced simply by stopping smoking, although their risk of lung cancer may remain elevated for a decade or more.

In terms of cost-effectiveness of public finance, only treating the very highest level houses appears to be good value, compared with what could be achieved elsewhere within health budgets, see Section 39.

Bq/m^3.	Above 1000	400 to 1000	200 to 400	Below 200
No. of homes	2000	18,000	60,000	22 million
Deaths/year	10	40	50	1900
Non smokers	2.5	10	13	475
Preventable n/s premature deaths	2	5	3	--

Note: some numbers are rounded. There is little point in presenting radon statistics to high precision because of uncertainties in both radon measurements and risk factors. A perspective of the world radon problem could be obtained from a summation of similar Tables, one for each country. [*]

27. Radon in schools: a major health risk to children?

In both the USA and the UK, much work has been undertaken to reduce radon levels in schools. Emotions have sometimes run high. In a widely distributed broadsheet describing remedial works undertaken in Cornish schools NRPB have claimed that **"exposure to radon at school would have been a major source of risk to these children."**

In the UK, only a few school buildings have been found over 1500 Bq/m^3. The distribution may be expected to follow roughly the well established pattern for housing in the same counties. In analysing the risks to children therefore, a reasonable starting point is a high-level school, at 1500 Bq/m^3.

Children attend a given school for typically 7 years, but the exact figure is not too important. During this time they may be indoors at school for around 7000 hours, which is conveniently 80% of a single year (there are 8760 hours in a year). Thus, exposure to radon indoors at school over a period of 7 years is about equal to the exposure that would be accumulated during a single year by a person living at home at the same average radon level. It is helpful here to recall that for homes the relationship between average activity concentration in Bq/m^3 and dose in mSv is based on about 80% occupancy (see Section 6).

Exposure at school may therefore be set in perspective: in the worst schools it will give an integrated concentration no higher than 1500 Bq/m^3.y which is, coincidentally, the 'acceptable' integrated extra concentration mentioned in NRPB's guidance on time-scales for remediation in houses. Therefore, the dose should not be described as "a major source of risk to these children". Indeed, the extra dose is lower than would be experienced by the same people during their adult lives if these were to be lived in typical Cornish houses, where radon levels may be expected in the range 50 to 200 Bq/m^3, below the so-called action level.

Also, radon has been claimed to be more dangerous to children than to adults, a claim that is almost wholly devoid of any evidence. In the USA, the EPA have been condemned by scientists for trying to use radon risks to children as a 'scare tactic'. A revised view was published in their 1992 Citizens Guide.

Doses in Cornwall over a lifetime are shown in the Table below. The total of 505 mSv may be compared with the Cornish average of about 10 mSv per year, which over the first 65 years of a lifetime, yields 650 mSv.

KEY FACTS:

Claims that radon levels in schools in the affected counties represent a major risk to children are not supported by rational analysis. Despite this, radon remedial work in schools is 'good value' because of the collective dose that can be avoided: a roundabout way of saying that heavily occupied buildings are more worthwhile to treat on public health grounds than are those occupied by only a few people.

Example of possible doses over a lifetime for a person who attended a school at 1500 Bq/m^3 for 7 years, but who lived in typical Cornish houses for 60 years.

Seven years in one of the highest level schools	: 75 mSv
Ten years in a house at 200 Bq/m^3	: 100 mSv
The remaining 60 years of life at 110 Bq/m^3	: 330 mSv
Total	: 505 mSv

Based on 0.01 deaths per Sievert, the accumulated lifetime risk is only 0.5%.
[*]

28. The link with smoking: misrepresentation of radon risks.

Lung cancer was an uncommon cause of death before people started smoking tobacco. It is certain that lung cancer is set to become a major cause of premature death in many Third World countries, just as a steep rise in the number of cases was noted in the 1950s in the West, and following the increased consumption of cigarettes since the 1930s.

In the UK, the annual incidence of lung cancer is now around 35,000 cases, nearly all of which prove fatal. Worldwide, premature deaths from smoking (including lung cancer) are set to rise to ten million per year within 30 years.

It is accepted that radon may be the second leading cause of lung cancer. However, what has not been clearly stated within the radon debate is that whilst ALL tobacco related cancers are easily avoided (by phasing out tobacco as a marketable product) only a fraction of calculated radon deaths could be avoided by treatment of high-level houses. The exact fraction is country specific, as it depends on radon distribution parameters.

For some time NRPB have used a 2 or 3 per cent risk factor to describe lifetime exposure to radon at 200 Bq/m^3. Further studies may lead to revision of this estimate, but the message has been this: if you live for all of your life exposed to 200 Bq/m^3, you have about a 3% risk of dying from radon.

However, if the calculated risks for smokers and non-smokers are assessed separately, the picture changes dramatically. There is some debate over the figures, but 75% or more of so-called radon deaths may be amongst smokers.

In the United States, myths about radon risks have been promulgated since 1986 when the EPA and the CDC (Centers for Disease Control) advised action at 4 pCi/l (see Section 34), stating that homes at this (quite modest) radon level were as dangerous as smoking something less than half a pack of cigarettes per day. Later, the message was shifted to suggest "half a pack a day" and later still, in 1989, to "more than 10 cigarettes per day". Naturally, these statements from Government Agencies caused Press interest and considerable public concern.

However, the publicity was misleading, and has been severely criticised by leading scientists. As a UK body, the NRPB has not commented, but in the 1992 edition of the EPA Citizens Guide substantially revised figures are presented for the risks from lifetime exposure to radon. These suggest that non-smokers may be even less at risk than previously indicated.

For example, the lifetime risk from radon for all persons exposed to 20 pCi/l (750 Bq/m^3) was originally presented by EPA as 6 to 21%. The non-smoker risk used by NRPB is 3.7%. However, in the latest EPA Guide the estimate is even lower at 0.8%. The difference between these figures (0.8% to 21%) is remarkable. For smokers however, the latest EPA Guide shows a 13.5% lifetime risk at 750 Bq/m^3 - nearly 17 times the risk presented for 'never-smokers', although lower in absolute terms than previously.

Thus, at 150 or 200 Bq/m^3, the risk for a lifetime non-smoker is probably closer to one cigarette per day, rather than ten, and may actually be less than the risk from one or two cigarettes per week. At such small risk factors, intervention seems hardly worthwhile if expensive and disruptive.

KEY FACTS:

The consensus of scientific opinion is that smoking and radon act synergistically. This means that the combined effect is more dangerous than being subjected to either pollutant by itself. Thus smokers are more at risk from radon than are non-smokers. This analysis was obscured for years. Sustained pressure from independent scientists forced correction of publicity material in the USA, and production of a much improved EPA Citizens Guide to Radon. [*]

29. Risks from passive smoking: possible links with radon.

The possible role of passive smoking in radon deaths is a complicated issue, and one that is likely to be the subject of further debate. However, irrespective of the exact interactions, two facts are clear enough already.

1. Passive smoking leads to an increased risk of lung cancer and is responsible for much respiratory illness in both children and adults. It is remarkable that there has not been more protest about this suffering, since it is entirely preventable.

2. There is no doubt that a room containing cigarette smoke may have a lower fraction of unattached radon daughters than might otherwise be the case. This could lead to a lower risk from the radon because unattached radon daughters have a better chance of being deposited in the lung in areas thought to be most susceptible to damage by irradiation.

However, because smoke particles have low mobility (compared with smaller aerosol particles) there is less deposition of radon daughters onto surfaces, and correspondingly more airborne radioactivity for a given radon level. On balance, it is thought that an overall reduction in dose may result.

However, breathing the cigarette smoke may give an increased risk of cancer simply because it is a powerful carcinogen. One factor here may be that tobacco itself is radioactive, and some of the activity is deposited onto lung tissue. Whether the reduction in one risk outweighs the increase in the other is a moot point.

Given the other deleterious effects of breathing cigarette smoke, it is probably best avoided. It cannot be recommended that smoking is a good way of reducing health risk by lowering the unattached fraction of radon daughters.

An interesting and related point is that simple desktop fans installed in rooms can markedly effect the concentrations of airborne radon daughters, and if combined with a harmless fine aerosol to reduce the unattached fraction still further, could lead to significant dose reduction for minimal costs. This is one possible route to dose reduction not involving disruptive building works.

Statistics quoted for passive smoking in the UK are typically 'a few hundred deaths per year'. Often 600 is quoted. This is similar to the number of radon deaths postulated to occur annually in non-smokers from lifetime exposure to 20 Bq/m^3 - the UK average radon level in homes: taking 600,000 deaths annually as a base, 0.1% of these is 600.

It is interesting to speculate on commonality: how many lung cancer deaths might be owing to a combination of passive smoking and exposure to low doses of radon? Simple models class radiation as an initiator of cancer and chemicals in cigarette smoke as a promoter. If wholly true then radiation exposure of children may be more serious than for adults, and passive smoking in infants not so serious as in adults, except for respiratory and other problems having no latent period. This is probably a gross simplification, and entirely wrong!

KEY FACTS:

There are competing effects in the interaction of tobacco smoke and radon decay products. On balance, a room containing cigarette smoke may present less of a risk in radon terms than the same room without the smoke. However, the chemical dangers of cigarette smoke may outweigh these benefits. Passive smoking cannot be recommended as a technique to reduce the risks from radon.

Studies of tobacco smoke and radon illustrate the possible benefits of altering both attached fraction and deposition rates as cheap techniques to reduce radon risks in the principally used rooms of a house without resort to extensive building works. [*]

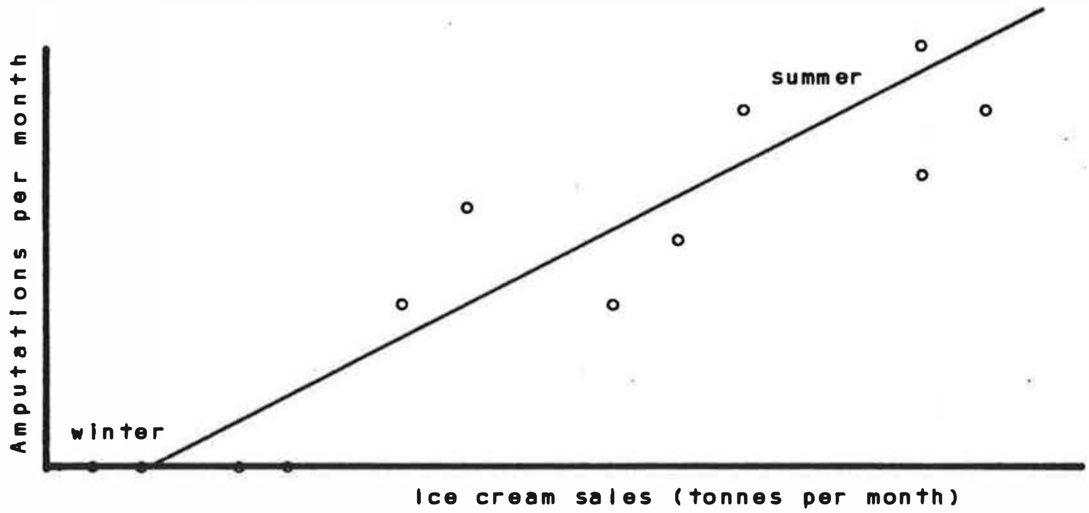
30. Radon and Leukaemia.

One of the most emotive issues concerning radon is a possible link with childhood and other leukaemia. At the present time, there is scant if any evidence for a link between any type of leukaemia and radon exposure. Nevertheless intriguing work published recently has shown that cells may be damaged by alpha particles but that this may be expressed only after cell divisions.

It is important to appreciate both that leukaemia is a very rare disease, and that the causes of many types of leukaemia are not known. In these circumstances, but knowing that some types of leukaemia 'cluster' geographically, some scientists have placed substantial confidence in simple correlation studies. These have been used to suggest a link between average radon exposure and average incidence of leukaemia, both for regions of the UK and for different countries.

However, not only are the correlations weak and some of the data suspect (especially that on radon measurements) but it is a simple but often forgotten scientific fact that "Correlation does not prove Causation." An example to illustrate this is shown below: a correlation clearly exists between the number of people who cut off their toes with lawn-mowers each month, and ice-cream sales. However, few scientists would claim that closing down the ice-cream industry would help prevent garden accidents. Yet based on little more than weak simple correlations, claims have been made that radon causes leukaemia. A firm causal link has not been established.

Whether or not radon is weakly linked with some types of leukaemia, it should be noted that many more patients are now cured than was possible even a decade ago. Further information on all aspects of this group of cancers can be obtained from the Leukaemia Research Fund.



KEY FACTS:

There have been some questionable studies published recently in relation to radon and leukaemia. These have produced a predictable amount of Press speculation, and much anxiety. It may be recommended that future studies be based more around facts rather than principally upon the seductive mythology of weak correlation. Studies showing latent cell damage from alpha particle irradiation have so far only highlighted the question of radon links to leukaemia. Whatever the outcome of further studies, it must be recognised that leukaemia is a rare disease. The scope for prevention may be very limited even if radon is eventually implicated. [*]

31.1 Radon risks within a cancer perspective.

Scientists know that most people have little or no numerical understanding of risk. Often ideas as to what is dangerous are wholly out of line with rational risk assessment.

This has prompted suggestions that work needs to be done on risk evaluation as distinct from risk assessment - where scientists assess risks using available data. Unfortunately, resources for risk avoidance continue to be allocated more by personal perceptions, and radiation is probably the area where there are the least valid perceptions.

For example, parents can become distraught about their child needing five x-rays. Yet they would probably be entirely unconcerned by the greater radiation dose incurred during a flight to Florida, or a week in Cornwall, even if they knew anything about it.

Amongst the key factors that govern risk perception are:

1. If an activity is enjoyable or profitable, risk tends to be disregarded. Avoidable lifetime risk factors of up to 20% seem tolerable to some people.

2. If the source of the risk is natural, less concern is generated than for an equivalent man-made hazard, especially if someone can be found to take the blame.

3. Anything to do with nuclear power is assumed to be dangerous, and anything to do with disposal of nuclear waste is assumed to be doubly dangerous, despite that personal lifetime risks may be below 10^{-6}.

4. Events that cause many deaths at once receive proportionally more publicity.

Confusion stems to some extent from mixing up environmental, health and nuclear issues, and trying to compare them one with another. Section 22 contains a more detailed discussion.

This Section presents the risk from radon within an overall cancer perspective, and using a presentation that has proven comprehensible to many homeowners. All estimates are for non-smokers, since the real magnitude of the radon problem is that remaining once smoking has been phased out.

In the UK, as in many other western countries, the average lifetime risk of dying of cancer is between 1 in 5 and 1 in 4, or between 20 and 25%. This is a greater risk than in many underdeveloped countries simply because many people there die before they have much chance of contracting cancer.

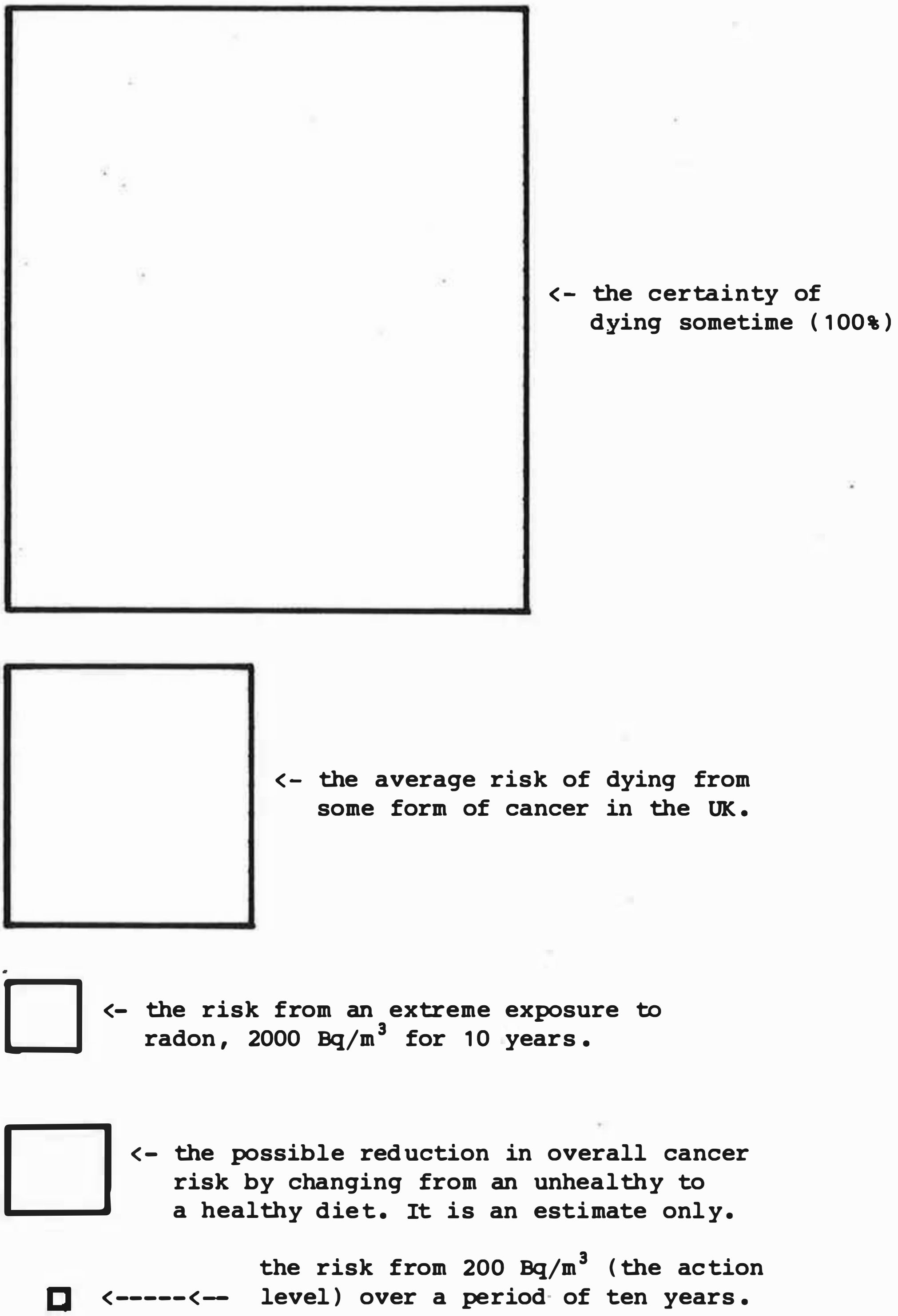
In the UK, the risk of dying from radon after living for 10 years in one of the worst-affected houses (say at 2000 Bq/m^3) may be less than 2%. This severe radon exposure increases total cancer risk from (about) 20 to 22%. However, simply changing from an unhealthy to a healthy diet may well decrease overall cancer risk by 2 or even 4%. There may also be other health benefits from better diet.

However, if "living with 2,000 Bq/m^3" were to be described in terms of a radiation dose 50 to 100 times as great as that received by most workers at nuclear power plants then panic might be the first reaction. The problem here would be that radon had been set in a nuclear context, rather than having been explained as one more health issue amongst many.

Page 31.2 shows what has become one of the most useful presentations of radon risk: the large box represents the overall risk of death at some time (100%, or an absolute certainty). The smaller boxes show the lifetime risks from given exposures to radon, all for non-smokers. Risks to heavy smokers may be more than ten times as great, but with incidence reduced by competing causes of death.

continued.............

31.2 Radon risks within a cancer perspective.



It is clear that despite all the publicity for radon, the risks are modest and except for high exposures, of the same order as for other hazards that are a part of normal daily living.

All data on this page are for non-smokers. [*]

32. Buying or selling a house in a radon affected area.

Radon is unlikely ever to be a widespread concern in sale and purchase of houses in the UK. The reasons include the small scale of the problem, especially compared with that in other countries.

It is acknowledged that short term radon measurements may be misleading, and in any case can easily be 'defeated' by increased house ventilation or similar devious behaviour. A cheap yet reliable measurement may be difficult to obtain during conveyancing.

It is simply unrealistic to place a plaque on the wall of a UK house '257 Bq/m^3' or '675 Bq/m^3'. Change of occupancy or heating system, choice of a different room for the tests, installation of new windows, etc. could all result in a change in measured level.

New houses, approved for construction after 1988 in radon affected areas have had to incorporate membranes and other measures potentially useful for radon protection. Some of these houses are now appearing on the market, and with the simple claim that they are 'radon proofed'.

Unfortunately this is no guarantee of low radon levels. All it means is that the house was built with measures required by the Building Regulations. The author was in charge of much of the research work and may be consulted. (see Sections 3 and 64).

In the USA, there are differences in house design, and in house-sale formalities. These have encouraged the use, in a few States, of radon tests during house sales. Many houses in the northern States have basements, thus permitting a radon test that is less affected by either weather or occupant actions. However, there are problems in translating these results into meaningful values for the main living spaces. Difficulties have arisen also when measurements have been made using charcoal canisters.

A pervasive influence has been that of house relocation companies who, unlike Estate Agents in the UK, purchase unwanted houses for resale. It is standard practice to require certificates for plumbing, termites, etc., and with the aim of handing them to subsequent buyers. These certificates can be used to transfer liability for problems.

Despite the uncertainties of short-term radon testing, remedial works and certification as a condition of sale have become routine in some areas, and sometimes applied to houses that are unremarkable in their radon levels.

Some enthusiasts in local authorities and radon companies in the UK have advocated a public register of houses above the so-called 'action level', seemingly oblivious of measurement inaccuracies and of the fact that naturally ventilated houses can exhibit variable average levels. If logically a register of radon-affected houses were to be thought appropriate on grounds of Public Health and Safety, then so might a register for substandard electrical wiring and fixed kitchen appliances, both known life hazards to children as well as to adults. Again, a sense of perspective may be recommended. Some legal points are discussed in Section 38.

KEY FACTS:

Radon levels in UK houses are not fixed. Houses sold as 'radon proofed' may have high radon levels, as may any other house.

Annual average radon levels in moderately affected houses can vary by factors of 2, and by 5 or even 10 over short periods in different rooms. Much of the variation may be owing to building and occupant response to weather and other influences.

Elevated radon levels can be reduced, just as dry rot can be eliminated. However, there are many possible remedial techniques, and sometimes the choice is not straightforward, see Section 11. [*]

33. Financial implications of installing a radon system: capital costs, maintenance costs, and property values.

Capital costs of radon remediation vary from tens of pounds to several thousand pounds. Much depends on the starting value for the radon concentration, the measures adopted, and on the size and construction of the property. It is a myth that high radon concentrations must always be addressed by expensive and disruptive remedial methods.

The most obvious recurrent costs of radon remediation are for electricity to run fans (typically £50 per year) and extra heating costs that may be incurred consequent upon their operation. These will vary, depending upon the property, system design and fan size, but may be estimated at between a few tens of pounds per year and perhaps over £100.

Additionally, the lifetime of fans when used in typical depressurisation systems may not exceed 5 to 8 years, giving an average annual cost of about £20. Modified fan designs may overcome some of the problems.

Other maintenance costs are most likely to arise as a consequence of re-sealing of entry routes because of ground movements or sealant failure. Again, there is little experience of long term performance.

It may be advised also, depending upon the starting radon level, to undertake a single radon measurement over a few months in a ground floor room every one to five years, to confirm the continuing adequacy of the remediation. This may be less necessary with fan systems than with remediation that relies on sealing alone, simply because it is easier to confirm continuing operation of a fan.

Effects on property values are more difficult to predict and analyse because, as in other markets, confidence and perception can be dominant influences. It is possible that as radon remediation becomes more accepted, systems may be regarded as an asset.

However, because of the low fraction of houses likely to be remedied even in the most affected counties, there is no doubt that houses with radon systems will always represent departures from 'normality'. Aesthetic system design may go some way to help ensure acceptability. Crucially also, property values may be less affected by remediation that is both passive and discreet (such as sealing), since it might be argued that floors were sealed merely to keep out draughts. Section 38 contains cautionary notes for house sellers.

Another factor is the possible development of certificates for radon remediation, as an assurance to purchasers. However, despite commercial attempts to develop these schemes there are many inherently difficult problems, not least of which is the variability of radon levels in UK houses (see Section 55). More worrying however are the possible deleterious effects on building structure of some radon systems.

KEY FACTS:

Capital costs can range from a few tens of pounds to several thousand. Costs may be higher in larger houses, but only if more diagnosis is required and more complex systems specified. It may not be sensible to attempt to cure all rooms in large houses.

Total running costs may range from £10 to £150 per year, excluding unexpected fan replacements.

Effects on property values will be market-determined, and are unpredictable at the present time. In the short term the presence of a radon system may be a disincentive for purchase, except where an authoritative guarantee is available to assure satisfactory design and performance. Guarantees from Limited Companies may be of little value. Guarantees from a Consultant, or underwritten by insurance, are to be preferred.

Large capital costs may be incurred if operation of a radon system results in long-term damage to building fabric. Some problems have been reported in North America. [*]

34. Radon problems in the United States: why so much fuss?

In the USA millions of houses are thought to have indoor radon levels above the action level of 4 pCi/l (150 Bq/m^3). Attributable deaths are estimated at up to 15,000 annually. However, there has been some unease concerning initiatives of the Environmental Protection Agency (EPA) in respect of radon measurements and risk presentation.

Concern over radon monitoring protocols for houses centres on the fact that for years many screening measurements were undertaken in the lowest level, which in the northern States, is often a basement. Houses were declared or classified as affected by radon if one or two basement readings were above 4 pCi/l, despite that this can be a quite normal radon measurement in an underground room.

Average radon levels in the most occupied parts of houses, which are often the ground floor and the first floor, are usually much lower than those in basements.

An additional problem is that there has been undue reliance on short-term tests using charcoal canisters, despite that radon levels may be more constant in basements than in other rooms.

The EPA has been accused of having presented a distorted picture of radon over many years. Indeed, their aims seem to have been consistently to overestimate the problem and to exaggerate the risks. Issue of the 1992 edition of the Citizens Guide to Radon was a lengthy process, but scientists consider that it is a great improvement over early EPA-inspired drafts.

For many years, considerable effort was devoted in Washington to 'hyping up' radon and encouraging concern in houses which could reasonably be left ten or twenty years. Less effort than might seem appropriate was directed to finding and curing houses in some of the real hot-spots and that must be presumed to be a substantial danger.

Radon in houses containing more than 150 Bq/m^3 in the main living areas may be responsible for 2000 premature deaths annually, compared with about 150 in the UK. It has been claimed by EPA that radon levels in 20% of US houses exceed 4 pCi/l, but the true figure appears to be between 7 or 8%. This compares with around 0.3% in the UK (using a threshold of 200 Bq/m^3) but with over 10% in Devon and Cornwall.

Additionally, EPA have claimed that 40% of the estimated total of 15,000 radon-deaths are associated with the high-radon houses, but the true figure may be between 15 and 20%.

In reality, a massive radon remediation program in the USA might prevent around 1500 premature deaths annually. Most of these would be calculated to be amongst smokers, as in the UK.

There is no doubt that the USA has a severe radon problem, but there are many who would question the analyses and motives of some radon administrators. Concern has also been expressed over some State programs- see Section 40. An interesting debate may develop over the next few years, and may extend to Europe.

KEY FACTS:

Radon is accepted to be a major health problem in the USA. Much excellent science has been published in the US to aid understanding and resolution of indoor radon problems. However, EPA's radon division, the body at the centre of radon publicity has been accused of perpetuating myths and bad science in what became a frenzied personalised campaign to have radon accepted as one of the greatest environmental issues of the decade.

Logical analysis of environmental issues does not support the EPA position, see Section 22. State programs have also been criticised, see Section 40.

Readers who doubt the existence of freewheeling billion dollar bandwagons should study the history of other EPA programs, including that on asbestos. [*]

35. Radon in water: health risks in perspective.

Radon is soluble in water, and in some areas ground water contains very high concentrations. In Devon over one million Bq/m^3 was measured in the 1960s, and a couple of central treatment plants are operative.

When water is used for domestic purposes a fraction of the radon in the water will be released into the indoor air. A rule of thumb in the USA is that if water containing 10,000 pCi/l of radon is used in a house it will add 1 pCi/l (37 Bq/m^3) to indoor levels. Water used for drinking is thought to pose little risk.

The issue of radon in water, and how it has been addressed in the USA, illustrates what may happen when legislation drafted to deal with one set of problems is applied elsewhere.

The USA has a Safe Drinking Water Act the aim of which is to limit the concentration of any contaminant in drinking water down to a very low risk level. What was in mind here was chemical contamination of drinking water from toxic waste dumps and industrial plants.

Often the level of risk above which action is taken is of the order of 10^{-4} to 10^{-5}, expressed on a lifetime basis. These are very small risks, but use of the same criteria for radon leads to an action level for radon in water of 200 pCi/l. If water containing 200 pCi/l (7500 Bq/m^3) is used in a house it will add only about 0.75 Bq/m^3 to the radon level in the indoor air. This is 10% or less of the level present in the **outdoor** air in many parts of the USA.

In comparison, the US action level for radon in air from ground sources is 150 Bq/m^3, close to the UK figure of 200 Bq/m^3, although the long term goal set by Congress in the USA is that indoor radon levels should be no higher than those outdoors (which is another story).

What has happened here is that whereas a technology standard has been set for radon in air derived from ground sources, a previously existing health standard has been used for radon in air derived from radon in water. There is something of an apparent paradox, especially for homeowners who draw their water from small private systems and where the cost of meeting a 200 pCi/l level could be quite high on a per-house basis and where money might be better spent in preventing radon entering directly from the ground.

The straightforward logic is that if you can remove a small risk for a small cost, or a moderate risk for a moderate cost, using central funds and a central treatment works, then it may be logical to take action. But for an individual householder, (or a small group of householders) faced with costs of remediation the 300 pCi/l standard recently promulgated in the USA appears ridiculous, despite that it is likely to be limited to wells serving 25 or more people. There has been some debate between the sections of the EPA responsible for setting standards for radon in air and in water.

KEY POINTS:

Care should be taken to classify issues correctly, or there is a danger of mis-allocation of resources to address problems that have been taken out of perspective. In the simplest of terms, the Safe Drinking Water Act in the USA limits chemical pollutants to such a low level that by comparison, radon in fresh air is calculated to be quite dangerous.

There are very few known problems with radon in water in the UK. In one or two areas of Devon, water is held in storage tanks, or subjected to aeration or other treatment, to ensure removal of dissolved radon before supply to consumers. Radon in water need never become an issue for widespread concern in the UK.

Many risk factors are calculated: it may be that there is no risk at all from many pollutants at low levels. Scientists do not know, and some will even admit to their uncertainty. This seems not to prevent inordinate expenditure on some small problems. [*]

36.1 Comparisons of track-etch detectors.

As might be expected, the full details of how track-etch detectors work are complex, especially with regard to the various processing techniques that can be used. What follows is necessarily simplified.

'Track etch' or 'plastic' detectors use a small strip of transparent plastic material to record exposure to radon. This material has a regular crystal structure and upon manufacture has few 'defects' in its atomic lattice.

A property of some materials is that they are resistant to chemical attack by selected reagents, but if attack does occur it may start preferentially at an imperfection. This can be a grain boundary (in a metal), a small region of abnormal composition (in an alloy) or simply somewhere where the regular lattice has been compromised.

In common with many dielectric materials, the plastic strips used for radon measurement can be damaged by alpha particles emitted by radon and its daughters. The materials are selected to have a high sensitivity, but they can exhibit high background counts, and even marked differences between one side of a strip and another.

Damage from radon is invisible when it occurs but if material that has been exposed is treated with a caustic solution it is attacked preferentially at the sites of the alpha particle damage. Each imperfection then shows up under a microscope as a small spot. Counting the spots can give a reliable indication of the average radon level to which the strip has been exposed.

At very high radon exposures, the spots may be so numerous that they start to overlap, but statistics and other ingenuity may be applied to determine the correct result. Thus, plastic detectors may be used over a wide range of radon concentration. Identical strips may be used in rooms at 20 Bq/m^3 as in those at 20,000 Bq/m^3.

However in real life, room air contains both radon and radon daughters and because the relation between their activity concentrations is not fixed, detector material exposed to free room air cannot be used to determine the average radon concentration. This problem is overcome by enclosing the plastic strip in a container (often made of plastic also) and that is designed to admit only radon gas - and not radon daughters. Within the container, radon daughters will form, but their number will bear a fixed relation to the radon concentration in the container, and that in the room. The characteristics of these containers may depend on their shape, size and other factors, but once the relation is known between the average radon exposure and the number of spots that appear on the plastic strips, the device may be said to be calibrated.

These devices are widely used because they are cheap, robust and safe, and because they have such a good 'memory'. Each site of radon damage is preserved within the plastic, and the strip may be processed (chemically etched) months after exposure.

Sometimes, the plastic strips alone are 'calibrated' in test chambers, but different container designs may behave differently in a stable fixed environment than in a real room where there are thousands of fluctuations in pressure caused by wind, movement, and opening and closing of doors. If equilibrium by diffusion alone is assumed, the time constant of some types may be several hours.

Thus, even if only because of the different conditions of calibration and use, it would be wise for scientists to compare results from different types of detectors when they are used in buildings.

In order to confirm similar results from different makes of track etch detectors, the author undertook comparisons of many types within the BRE field trials, and in dozens of houses. Many householders were intrigued to know why three or four different 'radon pots' were variously placed on bookshelves or strung up in cellars. The reason for the work was explained to them quite freely: it was expected that all types would give broadly the same answers.

Thousands of track-etch detectors were used by the author during the winters of 1989/90 and 1990/91. Some were obtained from NRPB (and of several different types), some from TASL in Bristol (again different types), and some from the USA. Early in the work, one type of detector from the USA was rejected for further use after several wholly wrong results were proffered by the laboratory.

At this point, it should be made clear that problems with radon detectors have been widely reported in the USA for many years. No secrecy was found necessary outside of (in the very early days) not identifying the laboratories under scrutiny, so that initial problems of procedure and calibration would not damage reputations unnecessarily.

Also, and to its credit, the US EPA has been open about the problems that were found, as indeed they were bound to be within the Freedom of Information culture. One example of work in which comparisons were made between seven different types of charcoal detectors is that published in mid 1990 in Pennsylvania.

The aim was to test for accuracy and random errors, and with one exception the average result from each set of 15 detectors was within 20%, and with most being closer than 10% to the known average radon level in the houses.

However, one type was in error by over 300% and another showed variations between detectors in the same batch of over 25%. The work followed several other studies in which the accuracy of both charcoal canisters and track etch detectors had been questioned.

Amongst the reasons cited for undertaking the work were that most calibration tests were performed under laboratory conditions, which might not reflect conditions in a home. Similar concerns have been voiced in other published work.

In the UK, there are broadly two reasons why work undertaken for Government Departments is occasionally formally classified under the Official Secrets Act. These are:

1. that the work is or is connected with matters that could harm the security of the State were information to fall into enemy hands.

2. that disclosure of the information could be an embarrassment either to a Minister or other member of the Government, or to a senior Civil Servant. In this context, it would usually be viewed as the Government Department that could be embarrassed.

The contemporary history of radon measurement using track etch detectors in houses may appear to be fully documented. In the USA and in the UK (at NRPB) sophisticated radon test chambers can be used for calibration of detectors. Secondary devices can be used also. For some years, NRPB have operated a device called FRED - Fast Radon Exposure Device, the aim of which is to be able to calibrate batches of radon detectors in a few hours by exposing them to around 100,000 Bq/m^3 of radon. The device is described in NRPB report R190. Other publications are also available and show the excellence of comparisons between track etch detectors and 'active' measurements (those taken using electronic equipment) and in some cases, between different types of track etch detectors.

Several conditions may be essential for full comparison of passive radon detectors in a field trial situation. These are:

1. that a number of detectors of each type must be kept unexposed in order that the background count can be determined,

2. that a group of each type must be exposed side by side to allow the mean and standard deviation of each type to be estimated and

3. that continuous measurement of the radon concentration in each room must be conducted in order to provide an absolute reference.

Other requirements may be considered essential also, including that the age of detectors should be taken into account by processing laboratories.

It is of course inherent within the basic assumptions for long term averaging of radon concentration by track etch detectors that they should respond reasonably linearly to airborne radon concentration - because the variation of radon concentration in buildings can vary over orders of magnitude.

This is quite distinct from concern about any non-linear response to integrated concentration, because this can be more a matter of assessment of overlapping tracks by the scanning equipment.

To take into account known aging behaviour of track etch detectors laboratories need to know their age and time of exposure. Many track etch detectors are exposed for one month only whereas others are exposed for six or seven months.

NRPB have recorded degradation of sensitivity of 18% over six months in test houses, but (apparently) not outdoors. Temperature may be a determining factor, and with warmer houses perhaps yielding lower results. An overall correction factor of 9% would be the 'best guess' for 18% degradation over the monitoring period. It is usual to assume a linear decay.

However, there are no uniquely correct conditions for a successful field comparison. Conditions may be chosen to meet the trial objectives.

Rigorous calibration procedures.

Full comparison of detectors would include assessment of background, calibration and linearity, as well as reproducibility. In these cases, active measurements might be used and background counts could be taken from non-exposed plastic. Each side of each individual sheet of plastic from which strips were cut could be assessed for background count. This is usually in the range 0.1 to 0.5 tracks/mm^2.

The calibration of detector strips is also a simple matter and related to the number of tracks that are detected per unit area per unit of radon exposure. Plastic strip detectors are inherently linear in response over many orders of magnitude as the latent tracks do not normally interact with each other.

Assessment of the standard deviation would be essential for some studies. Standard deviation is a basic statistical concept and may be derived for any group of detectors of the same type by exposing many of them side by side under laboratory or real life conditions and determining the spread of results. The origin of any scatter would depend upon the integrated radon exposure.

At low values it might be determined by the number of tracks per unit area. At high exposures, problems of overlapping tracks and interaction may occur. However, any apparent errors might be as much due to the scanning equipment as to the detectors themselves.

At very low exposures, say below 20 Bq/m^3 for three months, there will only be a small number of tracks on the plastic, and uncertainty due to Poisson statistics may be 10% or greater. The sensitivity is generally lower than 10 tracks per mm^2 for a years' exposure at 20 Bq/m^3. Thus detectors used for 3 months, as is usual, may exhibit fewer than 2 tracks per mm^2 at typical radon levels, against a background of perhaps 0.5 tracks per mm^2. This is why track etch detectors cannot be used reliably for short period measurements at low radon levels. Other types do not suffer these problems (see Section 8).

However, knowing the background and calibration characteristics from laboratory data, a detector used in a building may be processed to determine the average radon level. For each individual measurement there will be a random but unknown error. This is distinct from systematic error between different batches or types of detectors. Systematic error can be investigated by simple comparisons of detectors.

Simple comparison tests.

In these tests, building owners (usually householders) would be asked to place radon detectors in batches within rooms. Typically, three or four different detectors would be placed on a book case, bedside table or kitchen cabinet, and (as is usual) well away from direct sunlight or draughts from doors or windows.

If it were desired to reduce the effect of random error then multiple units of each type could be supplied to each householder. This is not done as a matter of course, and it is inescapable that no number of detectors of a single type can possibly be used to detect or remove systematic error if this is present within one or more batches of detectors, or within some aspect of the processing procedures.

The appeal of track etch detectors is their simplicity of use and low cost. Indeed, it is essential for a domestic measurement programme that householders should not have to concern themselves with any aspect of calibration.

All the householder (or research scientist) need do is to place the detectors in a room, leave them for the specified period, and return them by post to the processing laboratory. The received result should be corrected for the known background and age of the plastic strip, and for its calibration.

Correction of data to yield an estimate of the annual average radon concentration in a house introduces an entirely separate approximation, and one that may be in serious error for some houses. This is not considered further here, but see Section 8.

A reasonable analogy to simple comparisons of radon detectors would be comparison of three or four different voltmeters.

If a scientist purchased ten batteries of unknown voltage and measured their characteristics using the different voltmeters, and if each gave different answers then it would be necessary to question which one or more was reading incorrectly.

It would not be necessary for the scientist to know all about the development and calibration of volt meters, **merely that they gave markedly different answers when used for the purpose for which they were intended and under appropriate conditions.**

Neither would it be necessary to know the exact voltage of each battery in order to say that the voltmeters gave different answers and that something was clearly wrong.

Similarly, if two different types of radon detectors were to give broadly the same result but another type gave different answers then there could be some suggestion - but no proof - as to which type was misreading.

It would be of some concern if substantial systematic differences between detectors were found when they were used for assessing the low integrated radon concentrations found in most houses. This is because of the possible effects upon national statistics were systematic error to have been present in a large number of detectors used for gathering this information.

Systematic or indeed random errors at higher integrated radon concentrations are of less concern, simply because the number of houses yielding such results is much smaller.

For any set of measurements, two types of error may be present:

1. random error and which could be ameliorated to any desired extent by undertaking multiple readings, and

2. systematic error associated with any one detector type and scanning system and which cannot be detected using multiple measurements.

36.5 Comparisons of track-etch detectors.

Validation of detectors, and results.

A validation scheme is now in place in the UK, with the aim of producing confidence in radon measurements. It is interesting nevertheless to consider some of the published data from the United States and work undertaken in the UK.

In the United States, some early measurements using track etch detectors may be open to question. A substantial programme of field trials and test comparisons was undertaken by the EPA but the General Accounting Office has been critical of some commercial and calibration work. Laboratory procedures had to be tightened in order to produce acceptable standards. Consequently, many companies can now achieve within 20% of the correct answer most of the time, and one or two claim within 5%.

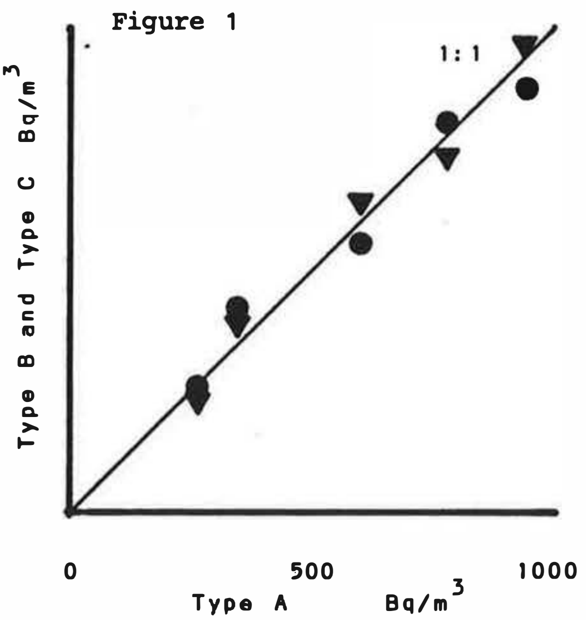
There has been much less work undertaken to compare the results from different types of detectors when used in buildings. In the UK over the winters 1989/90 and 1990/91 thousands of detectors were placed in field trial houses in order to determine radon levels. Hundreds of these were used for comparison purposes and some of the results were to be published in a research paper submitted to the EPA. (see Section 44).

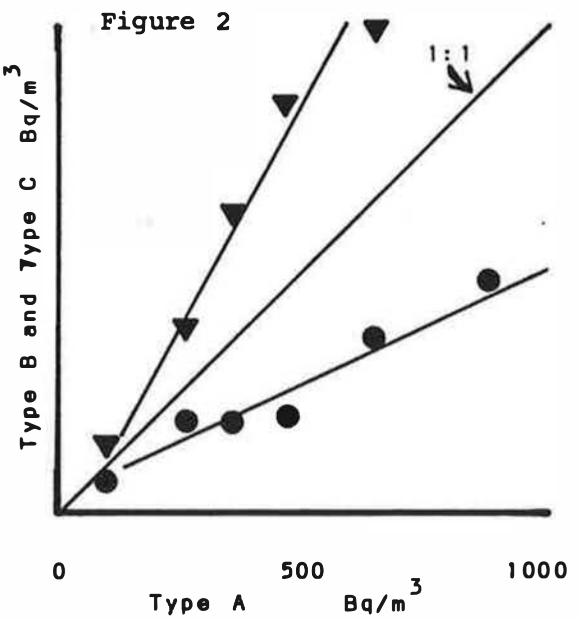
One obvious consequence of different results from different types of detectors is uncertainty as to whether many houses are above or below the action level.

Simple comparisons of two or more sets of detectors may be represented graphically, as shown in figure 1 below. Ideally results would all lie about the 1 : 1 line and with random error being indicated by the scatter of the individual data points. Results similar to those shown in figure 2 would indicate systematic error.

Unfortunately, and despite the scale of the comparisons undertaken in the UK and the fact that many of the results are known to dozens of householders already, they cannot be reported here.

Graphical representation of results from three different types of radon detectors when used in the same rooms.





In comparing three detector types, data from any one may be plotted along the abscissa. Data from the other two is plotted as ordinate. All axes have the same scale. Divergence of the 'best-fit' lines indicates systematic error between detector types. Results as shown in figure 1 indicate only random error. These graphs are for illustration only and do not represent actual data.

36.6 Comparisons of track-etch detectors.

Only a few general scientific comments can be made which are independent of the actual results that were obtained.

If most or all of the results were as shown in figure 1, then there would be very little justification for withholding publication. Indeed, the results would support the credibility of data already notified to tens of thousands of householders.

However, if many or all of the results were as shown in figure 2, then there could be considerable embarrassment especially for any laboratory of national or international standing that was involved in the calibration or scanning work. This would be especially the case if they were responsible for calibrating or validating more than one of several types of detectors that gave systematically different answers.

In view of the results it is interesting to note that soon after the unexpectedly large response to DOE's spring 1991 mail-drop offering free radon tests to all householders in Devon and Cornwall, a large company with nuclear links became involved in radon testing. This was simply because NRPB alone could not cope (and did not wish to cope) with a huge volume of routine measurement work.

The corporate symbol for this company is a hexagon - and a container of this shape was designed and mass produced. To help ensure acceptance of the new product, a similar yellow plastic was used for the container as had been used for NRPB dome detectors over the preceding years. However, there was obviously no time for lengthy testing side by side of the two different types of 'yellow' detectors, those using the familiar dome container and those using the larger hexagonal unit. It remains an interesting question whether some correction between results obtained by the two types may someday have to be applied.

Some householders whose homes were monitored in detail by the author and using many detectors have since been offered re-monitoring - but using only a single NRPB type of detector. Thus, comparisons seem not to be being repeated, and with only one type of detector there can (of course) be no dispute as to the result.

The three types of detectors used by the author in the 1989/90 BRE field trials were:

NRPB yellow domes, as used in regional survey work

TASL medicine pot designs, as used by IEHO in much of their early survey work

NRPB medicine pots, as used in the 2000-house survey of the UK.

In the 1990/91 comparisons, the types used were:

NRPB yellow domes (again)

A new design from TASL of Bristol

A popular type from the USA distributed by Tech Ops.

The Tech Ops design is different from others used in the UK in that it relies on a filter paper rather than on a small crack or diffusion through the plastic container to keep out radon daughters whilst allowing eventual equilibrium of radon gas. Many types sold in the USA have utilised a similar design.

The results obtained by the author included the first substantial international comparison between these American detectors and types used routinely in the UK. It was expected that all would give broadly the same answers.

Finally it may be recorded that in 1987, at an international symposium on the natural radiation environment, held only a few weeks before the author took charge of BRE's radon work for the UK government, it was stated of radon in a UK keynote address:

> **"There is no culprit, no conflict of interest, no cover-up."** [*]

37. The role of the NRPB.

The NRPB was set up by the Radiological Protection Act 1970 primarily to advise Government on the risks of radiation. Its remit was altered under the Health & Safety Act of 1974 to provide for consultation with the Health and Safety Executive. In essence, its role is as a centre of expertise on radiation, and as a source of advice.

The NRPB, like some other organisations centred wholly or principally upon radiation, have a history of being concerned with (and requiring others to be concerned with) doses that would be considered almost harmless by most normal standards.

Indeed, much of radiological protection is focused on doses that are small compared with those received from the natural background. For decades, radiological protection has benefited from a growing fear of man-made radiation. These fears can be reinforced by the occasional well publicised prosecution under the Ionising Radiation Regulations, and by media coverage of minute releases of radioactivity from nuclear installations.

Despite the availability of readable booklets from NRPB and AEA (see Section 12), little progress seems to have been made in setting the whole subject in perspective.

Against this background, the scale of the radon problem in some countries has not been universally welcomed. Whilst it can be argued that doses from high-level houses are so large that heroic efforts should be devoted to reducing them, a different perspective is possible.

Generally, radon risks are similar to other risks of everyday life, and about which people show little concern. Thus, if all 'ordinary' radon doses can reasonably be ignored, why perpetuate an expensive radiological and policy bureaucracy to pontificate over risks that are smaller?

As an illustration of the diversity of radiological expenditure, in the National Health Service around £500 may be thought justified to reduce dose by 1 sievert. In the nuclear industry up to £150,000 may be sanctioned to avoid the same radiation dose. In part, this diversity continues because of the career politics associated with the nuclear industry.

The simple fact is that radon sits uncomfortably between being a health issue (and in the UK it is of minor importance except for a small number of households) and being a nuclear issue where the doses involved can be so large as to dwarf those from all other sources.

The dilemma for radon experts is clear: should modest radiation doses from housing be accorded a low priority (or even be ignored) as presenting little additional risk to the many others to which people are exposed and accept in their daily lives?

Or should the fact that large sums of money are spent routinely in preventing minute doses of radiation in industry or from discharges to the environment now be questioned? A similar debate has begun over the economic cost of meeting some of the more marginal and idealistic 'clean-up' campaigns.

A perspective may be gained from the fact that sunbathing on some Cornish beaches for a week may impart a greater dose of ionising radiation than is received from nuclear discharges that are the subject of protest, demonstration and parental anguish. Any cancer risks from too much sunshine would be in addition to those from the ground.

Central to any debate must be that different magnitudes of expenditure may be appropriate in different areas, thus recognising the logical distinction between health and environmental issues (see Section 22).

The most enduring impact of the UK radon debate may be a more widespread appreciation of the attempts by two senior NRPB staff to see emulated in the UK the massive and in part unprincipled program on radon that has been so contentious in the USA. [*]

38.1 Legal implications of radon in the UK.

All Solicitors and Estate Agents need to become aware at least of the basic facts about radon, so as to be able better to advise Clients moving to affected areas.

Radon for Estate Agents.

Introduction of the Property Misdescriptions Act 1991 is recognised as a milestone by the profession, and requires accurate property descriptions. It would be helpful therefore to be able to measure radon levels to the same accuracy as for room dimensions or size of paddock. The consultation process as to what will be prescribed matters has been lengthy. The easiest to include are obviously physical parameters that change slowly with time, if at all.

Unfortunately, radon levels are sometimes far from uniform. In one house, at one end in a kitchen, long term radon levels were a 'safe' 140 Bq/m^3, yet in the sitting room barely ten metres away, they were 4000 Bq/m^3. This is an extreme example.

To date about 10,000 houses have been notified to their owners (or tenants) to be above the action level of 200 Bq/m^3, but only a few hundred have been remedied. Most of the 'affected' houses will have levels less than 400 Bq/m^3, and action might be advised within a few years. Non-smokers especially may decide to do nothing if they intend moving house within a decade, since overall cancer risks might be reduced more by attention to diet than to the radon.

Eventually however, the house may be put on the market, and Agents instructed. What need the homeowner then divulge, even supposing that he remembers that the house was monitored for radon four or ten years ago?

Anyone who buys a house in an 'affected area' may not have heard of radon, especially if he (or she) is retiring to the countryside after a lifetime in a big city. Local purchasers, within Devon and Cornwall especially, could hardly fail to be aware of radon after nearly a decade of media attention. In Cornwall, the indigenous population have maintained a stoical disinterest, partly because of their disbelief in a gas detectable only in equipment made by foreigners (people from across the Tamar!) and partly because of the well known fact that Cornish rates of lung cancer are below the national average.

Explanations based upon lower rates of smoking in rural areas are often countered by stories of miners who spent a lifetime breathing radon, smoked sixty cigarettes a day and died of poverty at the age of 98. The view of many Cornish folk was well summed up in the Cornishman newspaper in 1990. Two old St Ives fisherman are quoted in conversation. Said one:

> "It's they bloody foreigners comin' down 'ere with their cancers - and they got the cheek to give we locals the fault!"

Also, it may be claimed that local people must have become 'immune' to radon, having lived with it for so long. There are two errors here: high indoor radon levels have been a feature of houses only since the advent of doors and windows, and no mechanism of natural selection could be expected to operate for radon, whose victims usually die long after they bear children.

Many Agents dismiss radon, and while they are right not to exaggerate the issue, reforms of the conveyancing system, and more especially of the caveat emptor rule have been proposed. In the USA there has been implied warranty legislation for years in most States, and even implied duties on Agents to find out more about a possible problem if they had reasonable grounds for supposing that it might exist in any property.

Failure properly to advise a Client might render the Agent liable. The position in the USA is discussed in more detail below.

Liability for reporting radon levels in the UK would be contentious, if only because for many 'affected' houses results can be so variable.

Genuine assertions of a low and therefore 'safe' reading may be 'disproven' and perhaps by a factor of 3 or 4 or even 40 a year or so later, merely by picking a different room for the test.

Recent moves to streamline and speed conveyancing are not helpful for radon testing prior to contract because three months is recommended as the minimum monitoring period. Short term tests will **occasionally** show high levels, sufficient to confirm a problem, but a low result does not prove that the house is unaffected. Of even more concern, but affecting probably fewer houses, is the fact that entry potential testing (see Section 59) can give a false result in some situations. It may therefore be no better as a pre-sale test than using charcoal canisters (see Section 8), and with the disadvantage of being more expensive.

Some notes from the USA.

Coinciding with increased take up of routine testing by relocation companies (see Section 32), the rights and responsibilities of vendors and agents has been discussed. Liability for fraud may be established where either deliberate misrepresentation of radon levels or deliberate concealment of any known level is attempted. State legislation often provides a basis for liability in addition to that under common law, and indeed much radon case law is State specific.

Less serious might be either innocent misrepresentation, where the agent simply relays incorrect information supplied by the vendor, or negligence in checking whether the house was in a known high radon area. Civil liability could be established in most States in all these cases, but the discussion seems rarely to accept that radon measurement is an inexact science, especially in buildings where levels vary between wide limits owing to innocent influences.

The penchant for litigation in the USA is well known, and builders, estate agents and vendors have all been sued in respect of radon in homes. In several States there are established procedures for asking vendors about their past radon results, and standard agreements as to 'who pays what' in cases where the new owner detects more than an 'allowed' amount of radon after moving in.

Alternatively, contracts for sale and purchase can depend upon the result of a short term test - a procedure that amounts to a lottery in moderately affected houses. However, **testing as a part of sale and purchase has proved of such benefit to the radon industry that discussion of matters such as detector accuracy and the credibility of short term testing is discouraged.**

Problems for Solicitors?

In future years, perhaps the problem most likely to tax Solicitors or Counsel will be proving personal injury when there has not been (nor statistically would there be expected to be) any manifest illness that could be ascribed to radon exposure. The problems here are that no-one can ever be sure of the cause of a radiation illness except when dose has been so massive as to induce what are termed early effects. (see Glossary).

Early effects killed many at Hiroshima and Nagasaki, and a few tens of brave, incautious or simply unlucky souls at Chernobyl. For these so called non-stochastic or acute effects, severity of illness is related to dose. Later cancers occur 5 to 50 or more years after exposure, and the probability of occurrence is (in simple terms) proportional to dose, but the severity of the cancer is not: either you get cancer or you do not.

Compensation merely for the risk of future illness would be probably a new concept, especially in respect of a naturally occurring substance such as radon, and when the exposure history was not known. Short of personal dosimetry for all those potentially exposed to air in high-level buildings, there would be no way of knowing reliably the fraction of exposure that occurred in the subject building.

The closest examination of this point to date in the UK may be in the case at Sellafield in which a family claimed damages for contamination that, according to calculation, added very little risk. It was held that contamination even with artificially produced radionuclides, merely increased the risk of cancer (but by a small amount) and did not therefore *per se* amount to injury.

If the calculated risk was perhaps a thousand times greater - as could happen from a few years exposure in a high-radon house - a different view might have been formed. Indeed in the USA, Courts in at least one State have ruled that people can sue for having been exposed to danger, even though no injury has or may probably result. It seems unclear where all this may end, but the portents are that business for members of the legal profession may improve.

Outside of the radon field, compensation has been paid to workers exposed to small doses of ionising radiation and who have contracted cancer - but with no proof that the cancer resulted from other than chance.

Recently also, and in a case recognised as potentially opening the way for many others, an insurance company paid an out-of-court settlement of nearly £100,000 to a worker whose job had exposed him to wood preservatives for over ten years. The settlement was made not on the basis of any proof that his (rare type of) cancer had been caused by exposure to chemicals, but out of fear of the legal costs of an action and because the insurance company did not wish to lose in Court and so create case law unfavourable to its longer term interests.

The prospects for similar awards for lung cancer may be remote - if only because lung cancer is comparatively common even amongst non smokers and even outside of radon counties. It seems an unwelcome development if actions of companies and others become determined by fear of the cost of litigation rather than by the soundness of their case. As in radon as a whole, and in other 'environmental' issues, some common sense seems to be required.

Of importance also would be the position of any professional, or his insurers, who advised ten thousand people not to worry too much about moderate radon levels because the risks were small. The advice would be correct and properly in perspective with other health issues, but more than one in a thousand of those advised would be expected to develop lung cancer in ten or forty years' time even if they lived only with average radon levels of 50 Bq/m^3, and even if all were non-smokers. If many lived for years with a few hundred Bq/m^3 - which is no substantial cause for concern - and many were smokers, perhaps one in thirty could die of lung cancer caused by radon. Could over 300 sets of relatives then sue for damages? Probably so in the USA, and insurers providing Professional Indemnity cover are especially wary of business conducted in North America.

Such considerations have led to extreme safety precautions being taken because ANY departure from excellence and perfection (at whatever cost) could be grounds for an action. In North America building workers are sometimes told to wear protective masks when working in affected houses: a sensible idea in basements at 100,000 Bq/m^3 but unnecessary within houses at a few thousand Bq/m^3 only.

Independent scientists occasionally argue for rationality in expenditure, especially in respect of radiation. But if fear of the Law forces Local Councillors and Officials, and builders and surveyors (and Estate Agents and Solicitors) to err massively on the side of caution in radon, the resources that could be misdirected (read: wasted) could run to hundreds of millions of pounds, and billions of dollars.

38.4 Legal implications of radon in the UK.

Some indication of what may happen (at least in the USA) is provided by progress of the 'Superfund' program. This was created to deal with clean-up of toxic wastes dumped by industry, often around now derelict plants or beneath existing homes.

In essence Superfund is a federal scheme devoted to cleaning up the worst 1200 toxic waste dumps identified in the USA, and with another (estimated) 400,000 sites thought to merit attention. The annual expenditure is apparently $4200 million - to be added to the $6000 million spent annually by other government departments on clean-ups, and with billions of dollars being potentially required at nuclear installations.

There has been criticism for some years that too much effort has been devoted to testing liability in the Courts and too little to addressing the pollution. Environmental clean-up is clearly big business, but sometimes without any trace of harm to health.

Litigation may also play a leading role under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) in the USA. There are similarities with the UK position on contaminated land - in that the owner of a site may be held responsible for the cost of clean-up even if he was not responsible for the pollution. However, CERCLA appears to go further, in that damages may be claimed (so it has been reported) for actual property damage, diminution in the value of property, bodily injury and medical costs. In addition, and with reference to the Sellafield case cited above, damages may be claimed for future medical costs and emotional distress - and they may be punitive. The scope therefore exists for damages in respect of a host of perceived injuries, even if they have not occurred and may not (statistically) be expected to occur.

Not surprisingly, insurance companies in the USA have been unwilling to underwrite cover for pollution: CERCLA is retroactive and not subject to any statute of limitations. If radon becomes a major issue of indoor pollution (as many would wish) it seems likely that massive amounts of remedial work may be undertaken in buildings not to protect workers from any significant hazard but to protect the company from any possible law suits. It is interesting to speculate on how low the post-mitigation level would have to be before the company could feel safe. Could 2 pCi/l (75 Bq/m^3) discovered in an office be a cause of severe emotional distress? Certainly the calculated risks from even this amount of radon are greater than those from computer screens - many of which may soon be replaced to meet tough new Standards for radiation emission.

It may yet transpire that radon levels in buildings in the USA have to be reduced to as low as those in the outdoor air, thus meeting the long term goal set by Congress. Even then however, in many States, the risks may be the largest from any pollutant in the indoor environment.

In the meantime, health budgets are under severe strain, and thousands die of cold (and sometimes of influenza) each time there is a severe winter. This is especially true in the UK. Sections 22 to 26 provide further perspective, with 22 addressing classification of issues, from which may be derived rational limits for expenditure and concern.

The total cost of the clean-ups that may be undertaken at toxic waste dumps in the USA has been estimated to exceed the funds available under present legislation - one reason being that so much has been spent already in litigation. Contaminated land is set to become an issue in the UK too, but in both countries the scale of radon work has yet to be determined. [*]

39.1 Cost-benefit calculations for radon remediation.

It is a useful introduction to economics to acknowledge that many cost effectiveness or cost benefit calculations produce inadequate answers. Calculations are often carried out to great precision.

As a general rule, the credibility of the output can be no better than that of the input data, and in radon even the base figures, for numbers of attributable deaths for example, may still be uncertain by a factor of five. Nevertheless policy must be formulated and the public advised, and it must be left to 'judgement', and to vested interests, to decide priorities.

It is essential to differentiate between public ("public health") and private expenditure. It is also necessary at the outset to recognise what is wrong with some published work on radon.

The first central factor is that **life years** should be used rather than **lives saved** because of the relatively small number of years of life extension per lung cancer patient. However, estimates here seem uncertain. Radon mitigation does not prevent damage and injuries amongst young people especially, as do seat belts and smoke alarms, to mention but two of the subject areas from which statistics have been selected.

The second central factor is that marginal cost benefit must be calculated, if only because of the shape of radon distribution curves. In simple terms, there are few houses at extreme radon levels, many at moderate levels that should not cause concern for a few decades of occupancy, and millions at quite normal levels, but which deliver most of the collective dose. Marginal analysis is quite standard in both health and building physics. In principle the worst of the problem should be dealt with, then the residual problem assessed to determine if further action is worthwhile.

Radon is not straight-forward to analyse if only because smoking may produce more than a factor of ten increase in risk from any given radon exposure. Within Health Economics it has been acknowledged that it is effective to stop people smoking if it is ignored that they may live longer and draw their pensions so adding to the burden on the State.

There are two key questions, and analysis should underpin policy decisions.

If the aim is to reduce lung cancer, how best to allocate resources?

How best to address cancer in any household?

The usual assertion on radon is that up to 2500 people in the UK may suffer a radon-related death annually. Most of these are attributed to radon in houses. Choosing therefore a base figure of 2000, and considering only alteration of the housing stock, as many as 500 non-smokers may die from domestic radon annually in the UK. If all smokers became non smokers, the 1500 would reduce their risks by (say) a factor of 10, thus becoming 150 to add to 500, but this is valid only over decades.

Treating the housing stock to reduce collective dose.

There are about 22 million dwellings in the UK. Radon treatment in ten million of them, selected to be houses rather than high rise flats, for example, might cost £500 to £1000 each (a few houses in Cornwall cost £2000 to cure) but with uncertain effect on fractional reduction in the lower level houses.

If it is assumed that systems and procedures would work on average to good effect and that half of collective dose could be avoided, 250 out of the 500 lung cancers might be avoided for an initial cost of £5000M to £10,000M. More realistically, treatment might be envisaged for the 80,000 to 100,000 houses that are estimated to have radon levels above 200 Bq/m^3, the so-called action level. However, living with this level for 10 years could give a lifetime risk of less than 0.1 to 0.2%, hardly a cause for concern.

39.2 Cost-benefit calculations for radon remediation.

The average life of a house is often taken as 100 years but at current replacement rates many may have to last longer. However, NRPB in some of their calculations have taken 50 years as the remaining life of a house, and this will be used here. It is important to consider running and maintenance costs over this period.

Illustrative calculations

It is assumed that the average REDUCTION in radon level would be 200 Bq/m^3 in 80,000 houses each with 2.5 occupancy. The collective dose avoided per year is therefore 2000 Sv. For an average population the BEIR IV figure of 0.035 deaths per Sv applies, but for non smokers can be rounded to 0.01 deaths per Sv, perhaps 0.015. However, 80,000 houses successfully treated may be optimistic, and an average 200 Bq/m^3 reduction may be too low, but the result is about right: about 3% of collective dose from radon in the UK might be avoided.

So action in 80,000 houses (a part of which would be monitoring probably at public expense in one million homes at a cost of around £30M to £40M) might avoid 2000 x 0.01 or 20 non-smoking cancers per year. The mitigation cost would be 80,000 x £1000 average per house (= £80M) plus running costs over 50 years. Ideally new houses would be 'radon proofed' but that is another interesting story, see Section 32.

Maintenance costs for systems using a 75 watt fan comprise about £50 for electricity per year plus a new fan every 5 to 8 years (the cost of which is assumed to be £120 plus installation). Also, it may be assumed that an **average** annual maintenance cost of £40 would include some allowance for re-monitoring. Extra energy costs for space heating of between £5 and £50 (say £10) would also be incurred, because many systems draw heat from the house as well as radon from the soil. Overall, £40 is less than the maintenance cost of many domestic burglar alarm systems, so seems reasonable. Thus the costs over 50 years are 80,000 x £100 x 50 = £400M.

However, discounting future expenditure could reduce the **total** of £480M in net present terms to £300M or less. This calculation is very sensitive to the real interest rate, and it is probably more helpful for illustrative purposes to assume a fixed value in real terms for the running costs each year, and a fixed dose avoided. Over 50 years, 20 deaths might be avoided annually. Each cancer avoided may represent 3 to 5 life-years only (perhaps more), as lung cancer is a disease of older people.

Thus £300M might produce a benefit of only 3000 and 5000 life years, remembering that the calculation might be in error by a factor of five. The costs are between £100,000 to £60,000 per life-year.

However, and as an example of marginal analysis, the 'high level' houses should be remedied first. Many of these houses are easy to find and from the figures below, £6M would save 500 life-years. The marginal figures for the remainder thus become £294M and between 2500 and 4500 life-years.

According to NRPB statistics there are only around 2000 houses in the UK with indoor radon levels over 1000 Bq/m^3. Their average level may be around 1300 to 1400 Bq/m^3: there are very few houses indeed over 3000 Bq/m^3. The reduction possible may be an average of 80%, undertaken in 80% of the houses (some people will not bother, some systems will fall into disuse, some householders will switch off the fans to save money, etc).

However, dose AVOIDED may be estimated well from 1600 houses, 2.5 people per house, and 50 mSv each per year. The annual total is 200 Sv, or 200 x 0.01 = 2 non smoking death per year.

These houses are 'best value' in public health terms: cost would be perhaps £2M initially and another £100 per year over 50 years for upkeep (see above), or 1600 x £100 x 50 = £8M.

39.3 Cost-benefit calculations for radon remediation.

Overall, this is a maximum of £10M (discounted to £6M or less) to save 2 or 3 non-smoking lives per year over 50 years. The cost per life-year benefit is therefore only £12,000, assuming 500 life years in total.

The cost per Sv avoided may also be calculated. For the high level houses, it is only £600/Sv. This compares well with the NHS where £500/Sv to £600/Sv is a rule of thumb, when they can find the money.

If only the initial costs are considered, as might be the case for public expenditure, cost per life-year falls to perhaps £4000, which is on a par with breast cancer screening or heart transplants for cost per QALY, according to published figures from Health Economics.

In contrast, NRPB have used £210 million costs and £30,000 per 'life saved' as applied to all the affected houses. However this is skewed by including smokers and by not considering life-years, and inadequate because it does not include marginality.

Despite that high radon exposure combined with smoking may lead to an early death, the way to reduce the risk is to stop smoking, and then to address the residual risks from radon.

For readers who are not convinced by this, consider a situation in which dozens of children are killed each year because they walk across roads whilst blindfolded. The high technology solution to reducing deaths might be to fit anti-collision radar to all cars at a cost of many billions of pounds. It is a solution that would appeal to some people.

The more rational solution would be to ensure that blindfolds were removed before children attempted to cross busy roads. This could be done (one supposes) very easily, and 99% or more of the accidents might be avoided. Reducing lung cancer deaths by phasing out smoking is similarly straightforward.

Much of the above is simplistic, but it is more soundly based than are some of the arguments used in the USA to justify extremes of expenditure on radon. The most common type of error is (for example) to avoid recognising that seat belts not only save lives they save large numbers of injuries and much expense on hospital care.

As an aside, radiologists are sometimes furious about the marginal expenditure at Sellafield: up to £150,000 per Sv and "a tragedy of radiological protection", so some say.

The point about radon is that some at NRPB have viewed with jealousy the budgets of EPA in the USA, and closer to home would wish to see even expense on the Sellafield scale applied in houses. This is not sensible on a public health basis.

Perspectives of radiological protection.

For perspective, many people might reduce their calculated total cancer risks more by eating a few pieces of fruit a day than by worrying themselves about radon exposure over the next five years. The highest level houses merit action, but criteria cannot be those of limiting dose to levels set for work-place exposure: recently advised to be reduced from 50 to 15 mSv per year maximum but with very few workers receiving more than 2 mSv.

Radiological protection must be removed from its position of privilege, and be content to compete with medical budgets where the choices are within the home and community.

The key perspective here can be difficult to rationalise: in terms of collective dose avoidable, radon remediation has probably less to offer than better medical procedures and use of more modern equipment. The potential dose savings in the UK from various patient protection measures in diagnostic radiology have been estimated by NRPB at 5000 Sv annually, expressed as effective dose equivalent.

39.4 Cost-benefit calculations for radon remediation.

This estimate assumed a cost per Sv of £500 to £600 - the most the NHS could probably afford whilst not diverting resources from other and more promising areas.

However, much 'preventable' dose in medical radiology occurs at a low dose per patient, in contrast to the severe doses delivered in the highest level radon houses. Calculations using collective dose as the sole criterion are flawed, as the reaction to Chernobyl has illustrated (see Section 45).

One possible approach would be to deal with the highest doses almost irrespective of cost (otherwise identifiable people will remain at high and unacceptable risk) and to question whether low personal doses need to be addressed at all - and irrespective of the magnitude of the collective dose avoidable. Any benefits such as medical diagnosis or keeping a job (for miners) would need also to be considered.

Thus, it may be questioned whether householders living with a domestic radon level above (say) 2000 Bq/m^3 should not benefit from public assistance, and whether purchase of new diagnostic equipment in hospitals is justified if the old units never impart more than a few tens of mSv to any individual. It is no doubt an area for future controversy!

Simplified calculations for radon in houses.

These are probably the most realistic representation of radon economics, as it may be assumed that 'someone else' paid for the system in the past. The homeowner (or tenant) has to decide for each period:

"Do I run the system to avoid this annual dose?"

Thus, initial monitoring and installation costs are ignored, and attention focuses on the 1600 high level houses where 200 Sv is avoided annually for £160,000. This gives £800/Sv or £80,000 per non-smoker death avoided, and illustrates the importance of running costs in real terms.

For all 80,000 houses, 2000 Sv/year may be avoidable for £8M/yr. This is £4000/Sv, or £400,000 per non-smoking death avoided. Even applying a fudge factor of two, cost per life-year would still be £40,000, assuming 5 years per avoided premature death.

It is clear therefore, even from this simple analysis, that radon remediation is not a priority for public investment except perhaps in the few very highest level houses. The position might be different if running costs could be markedly reduced by use either of smaller and cheaper fans or passive systems. Capital costs are less of a concern if the money could somehow be found (or 'lost'!) within the public health budgets of either central or local government.

As discussed elsewhere (Section 43) many of the most seriously affected houses might have been found and dealt with years ago were it not for the decision to make radon into an issue affecting tens of thousands of dwellings, and to create a programme lasting decades.

Finally, this Section has assumed broadly the BEIR IV risk factors. These align with NRPB's 1% risk to a non-smoker for lifetime exposure at 200 Bq/m^3. The latest EPA figures appear to show much lower calculated risks, thus reducing the benefits from radon remediation. In any case, the benefits from being able to live in houses are considerable. The risks from small doses of radon or from falling downstairs (or more occasionally, through the floor) should be seen in this perspective.

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40.1 Radon in New Jersey and other States.

A perspective of New Jersey.

New Jersey is a highly 'regulated' State, and with a commitment to environmental protection. For example, in Newark and Jersey City there are 'recycling police' who patrol the streets checking for correctly sorted rubbish. This aids recycling, and is probably a sign of things to come.

Sensitivity to nuclear issues was heightened in 1979 when the Three Mile Island reactor came close to releasing massive amounts of radioactivity. The reactor is in Pennsylvania, New Jersey's backyard. Despite the severity of the accident, releases were minimal, and the most exposed members of the public received little more radiation than they would have done from a few routine medical examinations. However, this was not how many citizens viewed the matter, and it was predicted that the nuclear industry would take decades to recover - and that was before Chernobyl.

At Three Mile Island, the sloppy management were just lucky. It could have been very much worse, and with populated areas having to be evacuated. Three Mile Island is worth mentioning to illustrate that so much of nuclear legislation, inspection and control is geared specifically to prevention of problems at nuclear facilities. Here, the potential exists for cataclysmic occurrences, or for terrorist acts. Perceptions of anything 'nuclear' owe much to innate fear of disasters.

In the mid 1980s however, this pleasant and environmentally-aware State discovered that it had domestic radon problems. Moreover, some of them were attributed to radium rich spoil heaps from industrial processes, and severe measures were taken to deal with what were often moderate problems.

What happened then and has happened since illustrates how demarcation of official responsibility can determine outcome, and for problems of entirely natural origin also.

The scale of the problem.

New Jersey apparently has around 1.6 million houses that would be expected to be over the US action level based upon basement screening measurements. This might correspond to 600,000 houses above the action level in living areas which was the intent of the original EPA screening protocols, but not how these have often been interpreted.

The definition of a Tier 1 region in New Jersey is that 25% or more of the houses would screen with basement measurements above 4 pCi/l. This is taken to mean approximately 10% above 4 pCi/l in living areas - although it may be less than 10%. This would equate very roughly to Devon and Cornwall combined, although Cornwall alone has higher average levels.

Radon is essentially a health problem in the home. The correct perspectives can be gained by comparing risk and expenditure with other health problems. But in New Jersey, as elsewhere, responsibility for radon was handed to a Department of Environmental Protection that was already heavily concerned with regulation of nuclear materials and work-place exposures, often within the context of nuclear and chemical industry.

The New Jersey reaction to radon.

What follows is an illustration of a widespread problem: how response to an issue can be determined by the choice of responsible persons. Radon in New Jersey is (merely) one example amongst many, and unexceptional.

New Jersey has developed a wide-ranging program for training and certification of radon mitigators, specialists and technicians. This has gone further than probably any other State program, but there has been some vehement criticism both within New Jersey and elsewhere as to the bureaucratic and/or unnecessarily strict nature of laws that have been proposed or enacted.

40.2 Radon in New Jersey and other States.

A series of certification courses have been developed in parallel with those of the EPA. If an individual or a corporate body passes some of the EPA tests or examinations, this does not necessarily qualify them for work in New Jersey because they have to pass the local exams also.

In common with the EPA, RCP (Radon Contractor Proficiency) and RMP (Radon Measurement Proficiency) programmes, the NJ schemes are fee-funded with what have proved to be unpopular rates for examination, testing and submission of documents. Many of the examinations and tests are now performed by private companies under the guidance of NJEPD.

Legislation for control of radon measurement and mitigation companies.

The following extracts from NJ legislation are included to illustrate the scope of the regulations.

"Radon or radon progeny testing may only be performed by certified radon measurement specialists or certified radon measurement technicians."

"A certified radon measurement business shall have its Department radon certification number prominently displayed on each measurement device and/or package it utilises."

"The Department and its representatives may enter and inspect any site, building or equipment or any portion thereof owned or operated by an applicant or by the certified radon measurement or mitigation business, at any time, in order to ascertain compliance or noncompliance with the Radiation Protection Act, N.J.S.A. 26:2D-1 et seq., this subchapter, any certification, or any other agreement or order issued or entered into pursuant thereto."

"All new employees or consultants of a certified radon measurement business or certified radon mitigation business who will be entering structures with unknown radon levels or radon levels above 4 pCi/l for purposes of radon or radon progeny measurement, or designing, installing or repairing radon mitigation systems shall be instructed by the certified radon measurement specialist or certified radon mitigation specialist of the business on proper radiation safety practices prior to entering such a structure, in accordance with the businesses' radiological safety plan. Each new employee shall be required to take and pass a test on radiation safety."

It should be noted that such requirements would apply to many houses in Devon and Cornwall, where the radon level is above 4 pCi/l (150 Bq/m^3).

"Where the radon level is unknown or above 4 pCi/l all radon testers and mitigation workers shall respond to questions or concerns of clients in a low radon area, for example, upper floors or patios during field visits".

"Work breaks/lunches shall not be taken in elevated radon areas"

"Smoking by employees shall not be permitted in buildings being mitigated."

Despite some interest in so doing, New Jersey has not found it possible to legislate against advertising because this would infringe the Freedom of the Press. However, to supplement any commercial material handed to homeowners, mitigating companies are required to give a NJEPD guidance document on screening and follow-up to householders.

Penalties within NJ are severe. Any company who attempts to undertake radon testing or mitigation and who is not licensed to do so will be guilty of a crime of the third degree, which entails up to a $7,500 fine in addition to between 3 to 5 years in jail.

Radon mitigation or testing in NJ seems only for the brave, and of course for the lawyers.

40.3 Radon in New Jersey and other States.

In contrast, in New York it is the Health Department that has the lead responsibility for radon. Increasingly, it is considered that this is more appropriate than assessing radon using the same risk factors as used for environmental issues.

New York has a different view than NJ, and it will be interesting to see how the two approaches develop. To date the NY State Health Department has collected over 30,000 basement screening results and over 30,000 from other floor levels. However, these were obtained over a ten year period, and are not indicative of a panic reaction to radon. Generally results are low with only a few school rooms reported as over 20 pCi/l (740 Bq/m^3).

Other States, for example Florida and Iowa, are to some extent following the example of NJ. Mandatory testing of all schools has been undertaken in Florida, and with 20% of all rooms to be tested each year. It has been reported that over 300,000 radon results have now been obtained from 30,000 Florida buildings, a sizeable fraction of the total of all monitoring to date in the USA!

Other States have performed less than 1000 measurements, but they do not have the known problems of some regions in Florida. Other States have also proposed or enacted certification for radon measurement companies, and some for radon mitigation companies. These include California, Connecticut, Kansas, Maine, Ohio and Washington State.

Overall, the NJ approach is seen by some commentators as being a case of government officials going well beyond what is necessary or desirable. However, once local politicians agree on a course of action and the money is made available then obviously State staff will work within the agreed programme.

Concluding remarks.

The emphasis within NJ may be seen in the context of the Department responsible being that of Environmental Protection, which has the remit also for dealing with radiation risks from nuclear plants. Indeed all their risk calculations seem more biased towards these situations than health issues generally.

A substantial amount of consumer protection legislation has been enacted but this is almost exclusively regulatory as regards the setting up and operation of companies. There is little in the way of inspection of work or of cost effectiveness, despite that provision for inspection is built into the legislation.

It may be noted also that NJ and a few other States are embarking on ambitious educational programs aimed at schoolchildren with the intention of using the pressure that children can bring upon their parents to have homes tested for radon. This is seen to be a more effective route than trying to encourage the parents directly.

Washington State has developed a School Radon Manual to assist in resolution of radon problems, but nowhere in the USA amidst all the clamour and thousands of computerised analyses of results does it seem to be appreciated that the integrated dose at school to any individual is low, even at high radon levels - see Section 27.

Radon programs on the scale of that in NJ are developing in several other States, and often driven largely by real-estate pressures. Again, there seems to be little appreciation of relative risk.

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41. Avoiding undue risk: time-scales for radon remediation.

This Section presents a perspective of radon risks for non-smokers. Not everyone who smokes tobacco dies of lung cancer or heart disease and not everyone who is exposed to high activities of radon will contract lung cancer. There is inevitably an element of chance, of luck. It is known that some people are genetically more predisposed to some types of cancer than others. Advice has to be given in terms of average risks. A suggested scheme is given below in terms of annual dose. However, readers MUST refer to the Bq/m^3 figures to relate the advice to their radon levels, as reported by measurement companies.

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Dose from radon. (mSv/year) and the corresponding average indoor radon levels in housing and schools, during occupied hours.

0 to 10 mSv
(**0-200 Bq/m^3 in housing** or up to 1400 Bq/m^3 in schools).

This is a very low radiation dose. There is no pressing need to do anything. Annual risk is about the same as the average persons risk of being killed on the roads or by an accident in the home.

10 to 20 mSv
(**200-400 Bq/m^3 in housing** or up to 2800 Bq/m^3 in schools).

This is a moderate radiation dose, about equal to what radiation workers are allowed to receive. Action could be considered in the next five to ten years. The annual risk is up to twice that of being killed on the roads, or in the home.

20 to 40 mSv
(**400-800 Bq/m^3 in housing** or up to 5600 Bq/m^3 in schools).

This is more than twice the 'action level' for existing houses and the annual dose is in excess of what nuclear workers are normally allowed to receive. Remedial measures should be considered over the next few years. There is no need to be too alarmed - the risk is only equivalent to smoking a few cigarettes per day unless you are already a smoker, when the risks from radon exposure will be higher.

40 to 75 mSv
(**800-1500 Bq/m^3 in housing** or up to 10,000 Bq/m^3 in schools).

It would be unwise to live for years exposed to these doses from radon. The annual risk is up to 10 times that of being killed on the roads. Annual doses above 50 mSv are illegal if received by way of occupational exposure - during work in the nuclear or any other industry. Remedial action is advised within a year or two.

75 to 125 mSv
(**1500-2500 Bq/m^3 in housing** or over 10,000 Bq/m^3 in schools).

The radiation dose exceeds the maximum permitted level for UK nuclear workers. Remedial action should be taken within a year. There is no need to panic. The risk of lung cancer is still less than that of the average smoker.

125 to 250 mSv
(**2500-5000 Bq/m^3 in housing** or over 15,000 Bq/m^3 in schools).

These radiation doses are very significant - the risk is up to 25 times the average risk of death on the roads.

250 to 375 mSv
(**5000-7500 Bq/m^3 in housing** or over 50,000 Bq/m^3 in schools).

Action is advised well within a year. Only a handful of buildings in the UK have such high levels, although several cellars are known to be affected to this extent. [*]

42. Radon politics in the USA.

In the USA as in the UK, Government Departments have momentum. Respect for (or fear of) vested interests seems sometimes to preclude the intrusion of reason, especially when a subject cuts across cherished and well defended territories. There are few territories so jealously guarded as that of radiological protection. The author has attempted in the UK to bring some perspective to radon, and with some small success has helped to introduce life-years and health economics into North American debates.

Apportionment of funds in US programs is geared strongly to Press or Congressional interest, and the administrators who achieve the highest profile and exposure may get more of next years' budget. This is unexceptional, but radon is not the first subject where the EPA have proposed the expenditure of hundreds of millions of dollars only to have the rationale of their program questioned by eminent scientists.

Recently, EPA rulings on asbestos were overturned by an appeals court, and the National Research Council has suggested that billions of dollars may be being wasted on ill-thought-out environmental clean up programs. Papers at a recent meeting of the Society of Risk Analysis concluded bluntly that the billions of dollars spent in the 1980s on asbestos abatement in public buildings (including schools) could not be justified given the continuance of more serious problems of environment and public health.

The success of the EPA radon program in addressing the central issue of those houses that are so high in radon that they may be classed as dangerous may be judged from the fact that some radon mitigation companies will admit that were it not for the relocation industry (see Section 32) they would be out of business.

Notwithstanding publicity campaigns, the key issue of very high level houses remains substantially unaddressed nearly a decade after their discovery and over five years after scientists outside of EPA first promulgated proposals to effect a rational program of research and application in the United States.

Central to this international problem is that there are too few good scientists in politics, and advocates from the administration can all too easily gain acceptance for policies and programs that have more to do with empire building than good use of public resources.

Politicians should not escape censure either: they need to recognise the inadequacy of their own knowledge, and seek genuinely independent advice.

Financial problems of radon projects.

Across the United States there is a tightening of the availability of State funding for radon. This is especially so for schools, which are at the centre of a larger and acrimonious national debate over funding and educational standards.

Many local School Boards have enough financial problems without bothering about radon. Their views of EPA, at least in part, are coloured by experience with asbestos. In this area large sums of money have sometimes been expended in panic and haste. It is now increasingly recognised that the risks averted (notwithstanding the often higher asbestos levels in mitigated schools) were often much exaggerated especially in the media and amongst local 'activists'. But that is another story, and centred upon politics in Washington DC.

The inadequacy of perspective that seems often to accompany billion dollar bandwagons was summarized in a recent book review:

> "the scientific community can deal very well with scams such as cold fusion where only millions of dollars are at risk, but [that] it collapses over big projects where billions or hundreds of billions of dollars are in question."

[*]

43.1 How radon could have been addressed.

In order to understand why radon has developed into such a sensitive and contentious issue in the UK it is necessary to go back to the early 1980s.

An initial and perhaps superfluous observation is that many vested interests were involved.

In the early 1980s, the first contemporary surveys of houses were being undertaken. The first batch of high-level houses that were to be addressed by the author in 1988/89 were discovered in 1981/82.

Some of the earliest interest in domestic radon came from BRE. A contract was let to NRPB to undertake preliminary work. NRPB were at that time not too interested, despite that radon in houses had been known for decades to be a problem in Sweden and in Canada since the 1970's. Essentially this was a matter of personalities, but all was set to change.

In 1976, eighty UK dwellings were measured for indoor radon levels. By the mid to late 1980s sufficient monitoring, mainly using track etch detectors, had been undertaken in houses to confirm a problem in Devon and Cornwall especially. Similar work was undertaken in Sweden in the 1950s and 1960s and in a few States of the USA in the mid 1980s.

However, policy determination was somewhat in abeyance, having been the responsibility of a Division in DOE concerned more with toxic chemicals. This lack of a focus enabled NRPB to take more of a pivotal role. In the USA, publicity became dominated by EPA, despite the large scientific program funded by the US Department of Energy.

In the UK, NRPB's formal role remained to advise the Government on risk factors for radiological protection. Most of its work was at that time centred upon occupational exposure, nuclear facilities, etc.

Territorial problems occur of course with and within the EPA in Washington, and occasionally provide dramatic stories in the scientific Press: in discussing one argument a senior EPA official conceded "it was all a matter of turf".

A game it might be, but in the UK also it is played by public officials who are rarely held responsible for their spending decisions. Indeed, the mark of a proficient administrator seems often to be that he (or she) can spend all the available funds. Much public money and effort is wasted in ritual dances between rival Departments.

Politicians seem powerless to prevent this, even if they wanted to, because of a lack of scientific training. In any case, the rituals are ingrained into government.

For over three years the author was involved in discussions centred on how radon should be addressed. Several Sections of the Handbook allude to this situation.

Early on in both countries, a decision could have been taken to put radon into perspective, to lay before the public the risks as compared to those from other aspects of daily living, and to acknowledge that perspectives from nuclear industries and pollution of the outdoor environment were inappropriate as the basis for a strategy.

In fairness, little had been published in the UK, but seminal papers from the USA had appeared in the international literature.

The benefit would have been a better informed public. Much confusion and anxiety could have been avoided. That this was not done is in part a tribute to the ability of administrators to magnify difficulties and then to ensure that they need to spend years discussing how best to resolve them.

In particular, contact with the Press could have been open rather than characterised by fear, limited disclosure, and carefully rehearsed scripts. With few exceptions, little perspective on radon (save that from NRPB) was

43.2 How radon could have been addressed.

allowed to be discussed. What is perhaps more remarkable at first sight is the lack of effort devoted to discovering and remedying the very highest level houses.

In pioneering work during 1987/8, and illustrative of what one dedicated person can achieve, Cornwall County Council's Architects' Department identified where most of their high level schools might be found, and using local mining and geological knowledge. Since that early work, few very high level schools have been found - although obviously complete coverage was necessary to identify all of them.

A similar exercise for housing could have been undertaken as early as 1980, or even in the mid 1970's. Targeted areas could have been offered free testing and (perhaps) free remediation. Some areas might have been 'blighted' but local knowledge of old uranium mines is available. It is normal to find a correlation between uranium and radium deposits and radon problems in buildings. Indeed the early regional surveys in the UK were centred upon areas known for high uranium and other relevant geological features, but on a broad scale only.

Many of the worst affected houses in the UK are associated with geological faults or mining activity. Some have mine shafts beneath them, some have mines in the rear garden and some are on known lodes. Of course, not all of the worst affected areas could have been discovered by desk studies and a little judicious monitoring. However, in Cornwall it is probably easier than in other counties to predict likely locations of high radon houses because of the well studied geology.

It is also easier to use geological features to predict the locations of high level buildings (above 1500 Bq/m^3) than those above 200 Bq/m^3, because the latter can be found almost anywhere: with high ground permeability even quite normal concentrations of radon in soil gas can give rise to an elevated level indoors.

A realistic action level for public intervention would have been needed - perhaps 2000 Bq/m^3 rather than 400 Bq/m^3 (the action level in the UK between 1987 and 1990), and with no more than a few hundred houses being found and remedied. Such an initial programme would have needed to concede openly that to address much smaller doses might have been disproportionately expensive within public health budgets.

Central to the analysis would have been Health Economics, a discipline that was not fully developed in the 1970s, and not then even an accepted part of decision making in the National Health Service.

This was essentially the problem: policy was left to those having a radiological interest, and a course was chartered that would enhance and extend the role and remit of radiological protection for decades. Comparisons with other health problems and benefits (kidney machines, cancer and glaucoma screening, CT scanners, and dozens of other causes) were effectively excluded from the early discussions. The Department of Health in the UK only became actively involved in radon at a late stage.

These events and their consequences may be compared with developments in some States of the USA - see Section 40.

In the UK, the preferred radiological options, including definition of 'affected areas' on the basis of a slim (1%) chance of finding a house containing more than 200 Bq/m^3 of radon, and suggesting expenditure for mitigation running into perhaps hundreds of millions of pounds, could not command support at a time of public spending restraint. This was especially the case in view of the uncertain risk factors for radon in housing - a topic that was to be addressed in part via epidemiological studies in several countries and commencing in around 1988/89.

43.3 How radon could have been addressed.

To some extent, the sheer magnitude of possible spending on radon may have increased the appeal of these studies: they could buy time in which to organise a response were the clamouring for a massive public programme to prove ultimately irresistible.

There remains of course every need to clarify the risk factors from indoor radon (and especially to separate out those for non-smokers, see Section 28) prior to embarking on widespread and possibly heroic programmes of building modification.

Thus, the few people who genuinely need expert help - those who may continue to live for years with thousands of Bq/m^3 and who may unknowingly be incurring a risk equal perhaps to smoking five or even ten cigarettes per day - have had to await their turn as part of a wide-ranging programme covering areas that are only marginally affected.

Under the 'targeted' scheme, perhaps 20,000 houses would have been tested, and 500 remedied. The total cost might have been £1M to £2M plus a few man-years of dedicated buildings research costing perhaps £250,000.

It cannot be claimed that this is all hindsight but probably too much has now been invested in the present approach for there to be any admission of an alternative policy.

Any changes will be presented (as is usual) as enhancements built upon the achievements of the past.

Much the same is occurring in the USA. Policies for targeting high risk areas of the country that should (and could) have been adopted five years ago are being claimed as a development from previous policy.

Only a failure properly to comprehend and classify radon as an issue of indoor health and environment divorced from nuclear perspectives seems adequate to explain the extent to which it has been allowed to be pursued on both sides of the Atlantic.

A few scientists have spoken out, and in the USA they have had the benefit of a Freedom of Information Act.

Nevertheless, in terms of specific action, it seems likely that target areas will be identified - as is now being considered in the USA - and houses above a 'super action level' or regulatory standard, chosen perhaps by NRPB, declared in some way as unfit for habitation, or a public health hazard.

Many rented houses have apparently been cured of damp by way of being found to be a statutory nuisance, but it is considered that a test case may find these decisions inappropriate.

There are of course many problems in targeting areas. Houses are the most private of environments, and telling people that they must monitor for radon in order to cure any problem in their home - either for their own good or in the greater public interest - is entirely out of keeping with many peoples' view of the limits of government intervention.

Entirely different perspectives apply in work-places however, where the consensus is to insist on regulations for health and safety that if applied in the home would lead to many prohibition notices. This seems unlikely to change.

Another perspective is that early in the history of domestic radon mitigation in Canada and the USA very stringent standards were set for the residual concentration, because the source of the problem was (or in some cases was thought to be) man-made. Remedial action was officially suggested in the USA above 37 Bq/m^3 (a conversion of 0.01 WL radon daughter concentration, see Section 7, and corresponding to around 80 Bq/m^3 of radon gas). This is not much above the average radon level in homes in the USA, and even at the time was clearly an unrealistic target for cost effective widespread mitigation. [*]

44.1 The abstracts that never were. September 1990.

In August 1990, when working for BRE, the author visited Canada and the USA to study radon and radon remediation. Tentative arrangements were made to present one or more papers at the April 1991 EPA symposium in Philadelphia. Upon return to the UK three research abstracts were dispatched.

All three were accepted. The symposium schedules were printed and distributed to registered delegates, and included these papers. Later, the papers were ordered to be withdrawn. The abstracts should have been available under the US Freedom of Information Act, but were destroyed by the EPA. Therefore, brief summaries are all that can be reproduced.

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Field comparison of Alpha-track detectors from the UK and USA

Various types of alpha-track (track-etch) detectors were exposed for the same periods of time in dozens of houses. The work is amongst the first in which results from sets of track-etch detectors from several suppliers and from various countries have been compared after use in buildings. Most comparisons have been laboratory based.

Initially, three types of detectors from the UK were exposed for around three months. One of each was placed in each of 40 rooms in various houses. Two types from the USA and one from the UK were included in later work. A total of over 200 detectors was used. Exposures ranged from background to about 20,000 kBq.h/m^3, with exposure times from 1000 to 2500 hours. No account was taken of background counts, nor were control blanks used. The detectors were all used exactly as if they had been supplied to householders.

The results show large random and systematic differences between different detectors, sometimes of several hundred percent. The systematic errors were ascribed to:

(a) Use of detectors stored for months before use

(b) Differences in processing techniques between different laboratories

(c) Errors of calibration at low exposures.

Likely explanations are discussed, and recommendations made for better quality assurance.

Experience with radon proofing of new houses in the UK

In June 1988 the UK Government required that all new houses approved for construction after that date in delineated areas of the UK should be built incorporating radon protection measures. These requirements, given as suggested design solutions for achieving radon protection, were contained in 'Interim Guidance under Part C of the Building Regulations, Protection against Radon, June 1988'.

Initial assessments of the effectiveness of the guidance has been undertaken.

Radon levels in 140 new houses in radon prone areas of the UK were measured over three winter months using alpha-track detectors. Thirty-nine of these houses had been built with radon proofing, whilst the remainder had been built earlier and before the new design requirements.

Initial results are inconclusive but in houses built on relatively low activity sites, the measures have made no difference to indoor radon levels.

44.2 The abstracts that never were. September 1990.

The selection and performance of radon remedial measures in UK housing

As part of the UK Government's response to the discovery of high radon levels in certain areas of the country, BRE has undertaken field trials of radon remedial measures in a selection of high-level houses.

A substantial body of information on how householders react to the discovery of high radon levels has been obtained. This is discussed. Simple remediation measures have proved popular, especially where these can have a good chance of success.

Details are given of the installation and performance of a number of remediation measures including simple sealing, house pressurisation and sub-floor ventilation. Results are presented from some of the houses but are variable in many. Therefore, care has to be exercised in claiming success.

UK high level houses cannot be characterised by a fixed radon level since even average levels can be influenced by use of the house. [*]

45.1 A suggested protocol for reporting radiation hazards.

A long-standing affliction of radiological protection and reporting is that lay persons generally have no idea what either experts or journalists are talking about.

Whilst experts may be forgiven failure to comprehend the fears and limitations of ordinary people, journalists should do better.

It is usual in popular articles on radiation to see statements such as:

> uranium fuel was superheated to 3000 degrees,
>
> the accident released a hundred times as much radioactivity as did Hiroshima,
>
> at a hot-spot in the forest, radiation still measured 100 microsieverts,
>
> in some areas of the reactor building, levels were 10,000 Roentgens per hour. To approach meant certain death,
>
> milk contained 20 times the safe level of radioactive iodine,
>
> all of the sheep have been condemned as unsafe to eat. Caesium levels may remain elevated for decades.

Even within the context of the articles from which they were abstracted, the statements are largely meaningless, except to an expert.

This situation, well described as encouraged ignorance, has arisen partly because so many different units are used, but also as a consequence of a desire to maintain mystique.

In the period following the accident at Chernobyl, white coated scientists could be seen engaged in various photo opportunities on windswept hillsides in the UK. Sheep were shown on television being tested (and using equipment that was incomprehensible to the layman), milk was condemned, and advice issued on the safety of eating vegetables.

In reality, everyone involved had a splendid time and no-one was ever at any remotely serious risk from eating or drinking any foodstuff produced in the UK.

Privately, radon experts admitted that had they been offered a few lamb chops from Cumbria or North Wales, or indeed a whole lamb for the home freezer, they would have accepted.

There is a serious point here. In very little of the reporting was any attempt made to set risks properly in perspective and using a single set of units referenced to some 'normal' annual dose. Most of the reporting was based on material from the Departments of Government, and was in terms either of rads, Bq/litre of iodine in milk or Bq/kg of caesium in lamb chops.

It was never properly explained at the time, although it has appeared in various discreet (and discrete) publications since that the doses to members of the public were never remotely dangerous, and certainly not on the scale of a fortnight in some Cornish guest-houses breathing radon.

So what is to be done?

The answer is simple. So simple in fact that a more sinister question needs to be asked: why have journalists for so long accepted and faithfully reproduced what they were told?

There is a concept called <u>effective dose equivalent</u>. It has its faults, but it is simple enough both to understand and to explain on television. Various units can be used, but one, the mSv (see Sections 6 and 7) is recommended.

Effective dose equivalent is simply a calculated quantity that expresses how much harm a given amount of radiation may do, but there is no need even to understand a mSv. It can be thought of as just a very small amount of potential harm. Indeed it has been referred to as a 'basic background unit' of radiation.

In most parts of the UK, people receive between 2 and 3 mSv of dose each year, mainly from natural sources of radiation.

In the USA the average is nearer 4 or 5 mSv, and in Cornwall about 10 mSv.

45.2 A suggested protocol for reporting radiation hazards.

It is clear that a few mSv cannot be much to worry about: people live in Cornwall quite happily and there are no plans to evacuate them.

What then would be the extra annual dose of eating one Chernobyl lamb from the Cumbrian or Welsh hills? What would be the extra risk from drinking every day for a month, a litre of milk containing 200 Bq/l of radioactive iodine?

Would this be 0.01 mSv, or 0.1 mSv, 10 mSv or perhaps 100 mSv? The fact that most readers will have no idea of the answer (and even less idea how to calculate it) illustrates the point perfectly.

In all future public pronouncements on risk from radiation, whether from a aeroplane flight to Spain, a week camping on a particularly radioactive spot in Cornwall or eating three chops from a Chernobyl lamb, the same quantity and units should be used:

> **effective dose equivalent and expressed in mSv over the next year.**

Only then will the public be able to gain a proper perspective. If the answer (as in the case of Chernobyl in the UK) was less than 0.5 mSv (or even 50 mSv) a shrug of the shoulders would have been an adequate response, albeit recognising the dire needs of those closer to the disaster. Variations in natural background over a lifetime can easily exceed 400 mSv depending upon where people live. This is no cause for great concern.

On the other hand, if the anticipated dose from an accident was 1000 mSv per person, prompt precautions (but not panic) would be sensible.

There is one further and related problem. In the Chernobyl accident about 30 people were exposed to massive doses of radiation and died within days or weeks. Latest estimates of deaths amongst those directly involved in the cleanup range from 250 (apparently the official figure) to 5000. These people received only a small fraction of the total radioactivity that was released. Some was spread over a wide area as moderate contamination, (the exclusion zone has a radius of 30 km) and yet more over a vastly larger area but very much diluted.

Perhaps half of the total radiation dose to humans was received by tens of millions of people at such a low level that it becomes questionable whether it should count at all when assessing the merits or problems of nuclear power.

It is iconoclastic to suggest that an occasional release of radioactivity might be an acceptable and small price to pay for energy, so long as large exposures to workers or other individuals could be avoided.

From Chernobyl, most people in the UK received less than 0.04 mSv, broadly equivalent to spending 20 minutes in some Cornish cellars (where the author has spent hours), flying across the Atlantic, or smoking one cigarette.

This was not how most people perceived the consequences, terrible as the accident was (and still is) for those directly involved.

A recent Editorial in the medical press summarized fear of dilute radiation:

> "There are other reasons why some experts may wish to emphasize risk rather than safety. In every country some may have political or fund-raising reasons for their choice of words. Or perhaps, like the media, they want to feel on the same side as those who are alarmed - rather than be accused of being patronizing or unsympathetic".

Quite so, but in the matter of radon also, perspectives have been well known for a decade within those Departments part of whose remit should be seen to include taking a broad perspective to ameliorate the excesses of pressure groups, whether classed as environmental or radiological. A major part of the problem is secrecy, and the obsession with always having to be seen to present a united front. [*]

46. Occupational exposure to radon.

Radiation exposure to workers in the UK is controlled under the Ionising Radiation Regulations, 1985. These follow publication of an EC directive in 1980 and papers by ICRP in 1981 and 1982 giving general principles for the monitoring of workers exposed to radiation, and limits for inhalation of radon daughters.

The Ionising Radiation Regulations are very complicated and in parts difficult to understand. Clarity may not improve if they are updated to take account of revisions in the Euratom Directive on Safety Standards for Radiation Protection.

In simple terms however, the legal limit of exposure is 50 mSv per year (expressed as whole body effective dose), and with a requirement for monitoring individual doses where these exceed 15 mSv annually. In a house this would correspond to only 300 Bq/m^3 but in a school up to 2100 Bq/m^3 (see Section 41). However, not all the requirements of the 1985 Regulations apply where the only source of radiation in the work-place is from radon daughters.

Two classes of work area are defined under the Regulations: supervised and controlled. If calculated dose to a worker is in the region 5 to 15 mSv annually the area becomes 'supervised' and monitoring is required. Above 15 mSv it becomes 'controlled' and personal monitoring is required. It has been proposed that the upper limit of 50 mSv be reduced to 15 mSv, which could have had severe consequences for many Cornish tin mines had not all but one closed already for other economic reasons.

Because it is so much easier to measure average radon gas concentration than any other relevant quantity, the Regulations have been interpreted in terms of this. Thus, if a place of work is assessed at over 400 Bq/m^3 it is deemed to require attention (or it would become a supervised area). A level of 1000 Bq/m^3 or above, if not remedied by building or other methods, would result in controlled area designation.

To date, only a few thousand work-places have been monitored for radon in the UK, and about 300 found to be in breach of the Regulations. Implementation of mitigation measures and any necessary monitoring of workers seems unlikely, at the moment, to involve prosecutions. Much of the monitoring has been undertaken in schools - where the legal requirement is to protect the teachers rather than the children. Schools are discussed in more detail in Section 27.

Unlike artificial sources of radiation which are often well characterised and easily controlled, radon exposure in places of work can involve not only the building problems that have been experienced in houses but the difficulty of personal monitoring if an accurate measure of exposure is required. Any risk to an employer of being sued for not providing a safe working environment would seem slight so long as statutory requirements were met, but even at the lower limit of 5 mSv annually the implied risk is far greater than for many chemicals subjected to control under the COSHH Regulations (Control Of Substances Hazardous to Health).

Section 38 considers some of the legal implications of radon in the UK, including that insurance companies have paid out in claims cases to avoid creating case law, which might have resulted in many more claims. It is to be hoped that the absurdity of routinely measuring radon exposure for each individual in marginally affected buildings so as to defend any future claim can be avoided. [*]

47. Medical uses of radium and radon.

The medical uses of radium and radon have a long history. Indeed, use of spa waters containing radon dates back to Roman times, long before radium was discovered by Marie Curie in 1898 and radon by Dorn in 1900.

Very soon after these discoveries, harmful effects such as skin burns and hair loss were observed amongst early experimenters, many of whom were to die as a result of their work. However, recognition of the carcinogenic properties of radiation was necessarily delayed for many years, because of the latency periods.

Deliberate use of radon and radium in medicine commenced in the early 1900s. It seemed logical to some people, including many doctors, that the power of these newly discovered 'scientific' substances could be turned against disorders within the body.

Nearly a century later and despite advances in knowledge, mines and spas in the USA, Europe, Japan and elsewhere and that contain high levels of radon are still open to members of the public. Breathing the air or bathing in the radon-rich water are believed to help cure arthritis as well as a range of other maladies.

Potential harm may be calculated according to whether the waters are drunk, and if so what they contain, and to what extent the spa or mine is ventilated so as to remove airborne radon.

Drinking radium or radon dissolved in water was popular in the 1920s and 1930s and was widely endorsed. The most radioactive of the commercially available waters were probably dangerous and many deaths may have resulted from their use.

However, ingestion of water containing radon is not a significant risk (see Section 35), and neither is bathing in spas. Likewise, radon water enemas are likely to be more unpleasant than harmful, unless perhaps heavily dosed with radium and administered frequently. This is most unlikely to occur today, but for a couple of decades many people exhibited a reckless enthusiasm for intake of natural radioactivity.

Long term exposure of radon facility attendants could still be a cause for concern but the radon-in-water concentrations would have to be exceptional before the resulting airborne level became significant. Direct emanation of radon from rock and soil in underground therapy centres is a more likely danger. In broad terms, the potential harm from smoking one cigarette is equal to that from one chest x-ray. Breathing a very high concentration of radon for only a few minutes would be equivalent, and is indicative of the risks to workers in spas.

Amongst the more considered uses of radon and radium have been within short-distance radiotherapy - as implants to help cure cancer. Here, it is the gamma emissions that are utilised, rather than the alpha particles that are of principal concern in radon-induced lung cancer.

The great advantage of these treatments was that they enabled concentration of radiation dose to the tumour with minimum dose to surrounding tissue, an especial concern in the early days of radiation therapy when equipment could not produce the finely collimated and directed beams that can be used nowadays. Nevertheless, the length of treatment was often determined by the need to limit dose to healthy tissue.

Man made isotopes of caesium and gold have largely replaced radium and radon in mainstream medicine. They are safer to prepare and use. [*]

51. Radon protection and affected areas: a perspective.

It is known that radon levels in the ground can be misleading as an indicator of possible problems indoors. Radon is ubiquitous in rocks and soils in the UK, as elsewhere, and its discovery at 30,000 Bq/m^3 in soil gas is unremarkable. Thus, it can become necessary to consider application of radon protection methods to new houses within defined areas.

It is an attractive idea for houses and other buildings to be constructed so as to guarantee that they will have low radon levels. Indeed, the Institution of Environmental Health Officers have suggested that radon protection be extended across the UK. Calculations of marginal cost-effectiveness do not support such widespread application, especially in view of the limited data on performance yet available.

However for the key affected counties, or at least those parts that are significantly affected, it may represent good value to incorporate radon protection, since some of the possible methods are far easier to install at time of initial construction.

It must be remembered that even in Devon and Cornwall only around 10 to 15% of new houses would, on average, be expected to exceed 200 Bq/m^3 if built conventionally. The percentage having much higher levels would be expected to be tiny, perhaps 1% overall but concentrated on a few sites.

Many of the highest level radon houses discovered to date are in areas where there will be little new building work, because of protection afforded by National Park or Outstanding Natural Beauty status.

The NRPB have defined as "affected by radon" areas of the country that (from their surveys) they could suggest had a more than 1% chance of a house above 200 Bq/m^3. This now includes all of Devon, Cornwall, and Northants, and parts of Derbyshire and Somerset. Scotland may also have areas delineated.

What is meant by an affected area is that there is a greater than 1% chance of finding a house above the action level of 200 Bq/m^3, or in other words, a house that presents a calculated risk to the occupants about equal to smoking one cigarette per day for non-smokers. Recent EPA figures show an even lower risk factor for people who have never smoked.

Whatever the exact risk, it seems of the same order as sharing an office or home with a smoker. Therefore, it could be suggested that areas of the country be declared as being affected by passive smoking if more than one home or office out of a hundred gave rise to the same risk factor as is calculated for 200 Bq/m^3 of radon. A sense of perspective may be needed in delineating affected areas, because of the costs of radon protection measures.

The essential technique employed to date in the UK for passive radon protection is to lay an airtight membrane, usually a plastic sheet, completely across the site. Effectiveness is achieved if air flow from the ground can be precluded. It is of little significance if the membrane is permeable to radon, since diffusion flow alone will not usually give rise to high indoor radon levels. The difficulties of radon protection as practised to date are simply those of quality control and practicability on site.

No detailed results have yet been published from the UK field trials in 1989/90 and in over 450 houses in 1990/91. The discussion that has appeared seems simplistic in view of the available data set. In the meantime passive stack vents are being evaluated as an adjunct to across-site membranes. Performance is expected to be strongly a function of stack design and location.

What is required is an analysis of the cost and effectiveness of various methods, to include running costs. For new housing these may be lower than for typical older stock because floor designs that are ideal for sub-floor suction can be specified. Small fans or even passive stack vents may suffice. [*]

52.1 Design and operation of radon sump systems.

This Section gives a broad summary of the design and operation of radon sump systems in UK houses. It is based on experience over several years of dozens of systems in both the UK and USA. For some of the more basic details of system design and layout, the publications of DOE (Householders Guide to Radon) and BRE may be consulted. Diagrams will be published later.

Use of radon sumps or sub-slab depressurisation (SSD) is one of the most common methods of reducing radon levels in buildings. The term SSD is used more in North American literature, and fairly represents how the systems work in many American and Canadian houses.

Early expectations for performance were centred around the idea that reversal of pressure difference across the entire floor area would prevent entry of most or all radon gas emanating from the ground. In ideal situations this is exactly what happens. One or more small suction points can be drilled through a concrete basement floor slab, and using only a small fan (30 to 50 watts power) a negative pressure of a few Pa can be maintained around the perimeter of the slab. Since radon entry is often associated only with the edge cracks in full-house concrete basements, the importance attached to pressure reversal in these areas continues to be relevant, in some cases.

In houses that seem almost purpose-designed for SSD systems, a high effectiveness of radon remediation (90 to 95%) can be achieved routinely.

Despite the simplicity of these systems, problems arise as a consequence of air being sucked from the interior of the house or basement. The location of these sources has proved crucially important in understanding detailed system behaviour.

In North America also, some houses were found to be of less than ideal construction. Two key problems are lack of an extensive hard-core layer and the presence of cross-walls. The usual solutions are still a combination of more suction points (16 in one large house, although probably far fewer would have sufficed) and use of higher power fans. In extreme cases of low ground permeability 'vortex blowers' or pressure generating fans have been utilised. These may have power ratings exceeding 200 watts, and problems of noise and running cost have arisen.

In contrast, some early test systems used in houses built on highly permeable ground gave equal or better performance when used with the fan reversed - thus acting to pressurise the ground under the house. However, diagnosis might support the view that the effectiveness owed more to ground dilution than to any pressure effect across floor slabs. Similar arguments can be applied to area-cure systems as reported from Sweden (see Section 60). However, pressurisation systems are not universally successful in these circumstances, and different houses may give different answers depending probably in part upon the closeness of the mitigation system to areas of high local radon entry potential.

More recently, three other factors have begun to concern designers of SSD systems for non-ideal houses. Some of the detailed experience was obtained in the UK. The three factors are:

1. that pressure field extension could not be attained to slab edges, but that nevertheless often the systems worked well,

2. that sometimes the systems did not work and especially not in rooms away from the main (often sole) sump,

3. that leaving edges of rooms unsealed sometimes appeared to produce a better result in some rooms than did the more usual practice of sealing all visible cracks and gaps in the floor.

Further factors have included impaired performance of solid fuel fires served by underfloor air vents (in the UK these are often known by a proprietary name, the Baxi). A more common problem is that noise levels from fans and exhaust points have proved noticeable in quiet rural situations.

52.2 Design and operation of radon sump systems.

Already therefore it is clear that there cannot be any unique most appropriate design for an SSD or radon sump system. This is particularly so in the UK, where variability of house designs and layout are more marked than in standardised 'concrete box basement' houses in the USA.

Design parameters range between wide limits. Examples from the UK are detailed in Section 60.

Fan sizing:

Power requirements can range from 10 watts (a fan small enough to fit in the palm of ones hand) up to the usual 65 to 75 watts of in-line duct fans, and beyond to large pressure developing fans of several hundred watts power and producing many hundreds of pascal depressurisation at low flow rates. Energy costs are typically £7 per year for each 10 watts.

Historically, and on balance, fan sizing appears to have been over-generous, probably because of the (false) assumption that overall depressurisation had to be achieved and because it has been assumed that an ineffective system could be made more effective by increasing the speed or number of fans. Often, only marginal benefits accrued, depending very much upon the source of inlet air.

In ideal situations, very small fans may produce substantial reductions in indoor radon concentration, but unfortunately such conditions are found infrequently in high-level and old UK houses. This problem is likely to limit the use of passive stack vents also (see Section 63).

It seems unlikely that design rules in terms of 'watts per square metre' or similar parameters will ever prove useful. Ideally, fan sizing would be a secondary parameter - to be determined only once basic information about the building and its entry routes had been obtained. In cases where little or no diagnostics is undertaken, multispeed fans may be recommended, if only for a test period. If a low speed proves satisfactory, a smaller fan may be substituted in those cases where appearance is important.

High suction fans should be installed only with care and in situations where diagnostics indicates extensive and low permeability and with few short-circuits. Here they can be effective, and the higher running costs may be justified. Use of these fans to serve an area of floor where there are high radon levels and low permeability may prove disappointing if a higher entry potential exists elsewhere, but at lower radon concentration. Assessment only of radon concentrations underfloor can prove misleading, especially in 'mixed floor' houses.

Sump size:

Successful systems have used very small sumps (simply setting a 110 mm pipe into an existing hard-core layer, and with little or no attempt to form a void beneath the slab) up to about 10 m^3. The latter was not designed as a radon sump, but was found beneath a house in the UK when the floor was excavated on the author's instructions. It had been a rain water store in years past, but had fallen into disuse.

Radon sumps in typical houses and where a large depth of hard-core is present need only be small. Preferably they should be centred upon an area of high entry potential (see Section 59) but these are sometimes difficult to detect, not present or inconvenient to address. Increasing the size of a radon sump will not substantially improve performance except where the limiting factor is low permeability in the neighbourhood of the suction point. In these cases multiple small sumps or edge suction can work better. Care needs to be taken when forming large sumps beneath thin old concrete floors, unless excavation and construction of an old-style 'BRE' sump is specified. These bricks and paving-slab designs are entirely adequate but often unnecessarily large. In situations of infinite source (see Section 59) they are as ineffective as any other design.

52.3 Design and operation of radon sump systems.

Care would also be needed if using high pressure water jets for extending pressure field. The technique has been used with some success in the USA but not under thin and structurally inadequate floors.

Pipe sizing:

Almost universally, pipe sizing in radon systems is not a matter of design. It is a matter of purchasing 110 mm upvc pipe from a builders merchant, and for two good reasons: this is usually in stock, and has been known to work well in the past. This approach actually has much to commend it, as detailed design would require system diagnostics and design of a standard unlikely to be cost-effective for all but the worst affected and difficult-to-cure houses. Nevertheless, it may be mentioned that smaller pipe (50 mm diameter) or rectangular duct work can be satisfactory in systems where low flow rates are predicted by diagnostics. In some houses this can prove much easier to install.

Suction points per unit area:

Again, no design rules exist that are applicable to every house. In the USA emphasis was given in many systems to ensuring that depressurisation reached all points of the floor slab. Indeed, diagnostics equipment is still advertised on the basis of the need to ensure such complete 'coverage' at time of system commissioning. It has proven unnecessary to achieve this.

Another 'rule of thumb' is one sump per 250 m^2, but derives solely from limited experience in schools where often there was a larger than normal hard-core layer, and with few cross walls because of the room sizes. In some small houses, even a large sump has proved inadequate. It is accepted that such 'rules of thumb' should not be relied upon to the extent of being included in design guidance for disparate existing houses. Unfortunately however, once promulgated they persist, and especially if incorporated in guidance from organisations whose past standards of work lend credence to present output.

The problems here are not centred upon the correctness of any arbitrary rule but (simply) upon recognition that radon sump systems can behave in wholly different ways depending upon the house design and construction and upon the underlying ground.

Design rules as existing at present may appear so generalised as to be unhelpful, but this is not the case. There is little point in trying to produce fine-structure designs for systems that by their nature in most real situations will always include an element of 'try it and see'. Additionally, given that components are available only in discrete sizes (50 or 110 mm pipe for example) it would be of little use for a computerised design programme to specify 68.5 mm.

A number of facts are known with certainty:

In houses where the design is ideally suited for an SSD system usually only one small suction point and a small fan may be needed.

To some extent, but without bothering too much with marginal areas, fan size and running speed may be selected either on the basis of vacuum diagnostic tests (see Section 59) or once the fan has been installed. This is an attractive option if multispeed fans are used, especially as at low speeds large fans are commendably quiet, but running costs can be greater than for a smaller fan running at nearer its rated speed.

It is often unnecessary to ensure depressurisation across full slab areas.

The reasons for this include that if key entry sources can be addressed, residual levels may be low enough in principal rooms and of little concern elsewhere. Also, many SSD systems operate not only by reducing pressure underfloor but by lowering radon levels in the ground immediately below the house, but depending much upon air flow pathways.

52.4 Design and operation of radon sump systems.

The problems of determining exactly what is likely to happen in real houses (as opposed to idealised test cells such as are in use at research establishments) are such that detailed diagnosis is unlikely ever to form a part of commercial radon remediation. The exception is where an experienced consultant can be employed.

In houses with solid floors, underfloor radon levels may reduce markedly when a system is installed, may increase, or may remain largely unchanged. There is no simple correlation here with flow rate, since air may be drawn to the fan either from deep underground (and with a maintained high radon level) or essentially from outdoors, but possibly via indoors. Radon concentrations in exhaust streams can provide some guidance as to what is happening, but use of tracer gas equipment is preferred.

To some extent the problems here mirror the difficulties of predicting what will happen when timber floors are depressurised: so much depends on the source of air and on localised entry potentials.

In houses having extensive cross walls it may be necessary to use multiple suction points.

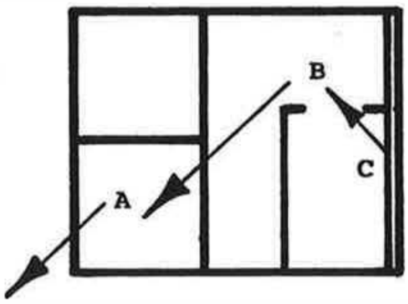
The need for such complications does not depend necessarily upon the starting radon level or indeed upon the results of simple diagnostics, because of 'ground dilution' effects. Also it is relevant to question whether all of the house area needs to be 'cured', given that some rooms may be used only infrequently, and can be kept essentially isolated from the rest of the house by use of internal doors. An analogy would be installation of localised heating, rather than full central heating.

In those cases where simple sump systems fail to work as expected the cure may include a larger fan, but is more likely to centre upon recognition of the compartmentalised underfloor structure, and that air may be being drawn from the house to the system inlet.

Radon sump systems can be highly localised in their remediation, and in extreme situations may actually cause radon levels in adjoining or upstairs rooms to increase.

These effects arise because suction systems can draw large quantities of air not only from underground (or effectively from the outdoors) but from within the house. Occasionally, the systems can be dangerous for this reason (see below). The most curious behaviour of these systems has been seen in houses and schools that sit essentially on top of 'infinite sources' of radon, an old mine shaft for example, and where different parts of the building date from different periods. This is common where substantial alterations and additions have been made. Examples are given in Section 60. Air flow may sometimes be detected moving from room to room (via very sensitive pressure measurements), or whole house depressurisation may be detected when the system is operated. These effects may be manifest at the limits of measurement and tests should only be undertaken by experienced personnel. Unfortunately there are very few days calm enough for convincing results to be obtained.

Cases of radon levels increasing are not common, but may be explained by reference to the diagram below.



Suction is applied in area A (underfloor) but a pathway exists via internal or external walls, or underfloor, to area B. Air is drawn in around area B, but because of closed doors and/or windows is replenished not from elsewhere in the house or from outdoors but from another (but independent) source in communication with radon-rich ground (point C). Points A and C may show no direct communication.

52.5 Design and operation of radon sump systems.

Remarkably, point C may be in a first floor bedroom, and located where joists pass into old thick walls, and may previously not have been a major entry route. The situation as described may be expected to occur most often in old extended or altered properties, or perhaps in semi-detached housing, because of communicating walls.

It is likely there are other, as yet unrecorded examples of 'curious multi-cell behaviour'.

Radon sump systems may influence radon levels in adjoining properties, especially if terraced or semi-detached.

Usually the effect will be beneficial, but may be deleterious. No such effects have yet been observed with certainty, because so little work has been undertaken in semi-detached or terraced houses. In any case results may be site specific and anecdotal. This applies as much in the USA as in the UK. Newer houses are probably less likely to suffer from the idiosyncrasies of some of the older properties investigated in detail by the author, but in all cases greater attention to draught-proofing may increase the importance of 'uncharted' pathways.

Edge sealing may prove unhelpful especially where system air flow is very low.

At first acquaintance, this is a curious phenomenon. It may possibly be explained by the balance between depressurisation and ground dilution. Beneath marginally affected buildings especially, ground permeability may be low. A system installed to depressurise beneath the floor slab may fail to extend to edges of the slab. Remediation may be only partially successful. If some of the edge sealing is removed (as has been done in a few houses in the USA) small volumes of air may be drawn into the underfloor zone from a few points where the pressure field extends to the slab edge. This may reduce the underfloor radon concentration sufficiently effect an improvement in overall system performance.

The trick is probably to seal only those cracks in areas where there is no depressurisation, and to leave a few openings in areas where suction is thought (from diagnostics) to extend to the perimeter.

Dangerous side-effects of radon sump systems can occasionally occur. Whilst uncommon, they need to be appreciated by both installers and householders. Fatalities have already occurred in the USA.

The possible dangers arise from the fact that air can be drawn by the fan from within the building, and that this may affect heating system operation.

It has been known in the international literature of radon for more than a decade that often more than half of the air extracted by radon sump systems can be from the inside of the building. In typical houses in the northern States of the US, timber frame houses are constructed on a poured concrete basement, and radon sump systems have worked well and without deleterious side-effects.

In these houses little if any of the extracted air comes from inside the house, because the poured concrete basement is an almost airtight structure. The performance of these houses and the ease of system installation, has led to suggestions that sumps are the method of choice for all houses.

The construction of many solid-floored radon-affected houses in the UK is markedly different. This should be sufficient to induce caution. Pressure field extension may be blocked by internal walls, and air may be drawn from the building interior or from the roof space down hollow internal walls to the suction point. It is easy to confirm this by using tracer gas. The author remains grateful to householders who tolerated days of his tedious (and to him interesting) experiments.

52.6 Design and operation of radon sump systems.

The consequences of these multiple pathways can include increased condensation in radon systems, increased heating bills, and depressurisation of parts of the building interior.

Especial care may be necessary if applying systems to houses with cob walls because of possible drying out of the probably shallow foundations. However, cob walls are rare, as are buildings of other types having little or no foundation depth.

The most extreme (but least common) problem is that carbon monoxide from a boiler can be drawn into the building. This has occurred in buildings known to the author both in the USA and UK.

Interestingly, the common features have been a combination of a well sealed building and thick old walls. By some curious route, air was drawn from the inhabited volume to the underfloor suction area.

There are several recommendations for systems using large fans especially:

care should be taken to ensure that fossil fuel boilers have an adequate supply of fresh air, and that this supply will not be affected by the radon fan. It will probably be sufficient to ensure that the fresh air requirements for gas or oil appliances are met, but recognising that air bricks will continue to be blocked up by householders concerned by draughts and heating bills.

householders should be warned, and a warning notice should be installed also, to the effect that the fresh air provision for boilers should not be obstructed.

balanced flue heating systems are to be preferred in houses affected by radon.

These cautionary notes apply not only to houses with solid floors and radon sumps but equally to those with unventilated part or full timber flooring under which air is drawn using a fan for radon extract purposes. In the case cited above from the USA, the house had well sealed timber floors, but without provision for air-bricks because of the dry desert climate.

In other States fatalities have occurred apparently related to 'back drafting' - the term used in the USA to describe combustion products being drawn from heating appliance flues into inhabited areas. In some houses the fumes may then be distributed by the air conditioning system.

The author may be consulted in any case of a suspected problem of this type, or reference made to a qualified heating specialist - one who understands radon!

[*]

53. Who to employ to cure a radon problem?

There are many choices facing a building owner or occupier confronted with a radon result. The first question is whether to do anything at all: several Sections in the Handbook should assist with this, especially numbers 11 and 41.

To some extent the choice of remediation route may depend upon whether do-it-yourself work is envisaged. If so, detailed advice may be needed, and may be obtained from a consultant or other specialist advisor. In many cases however, building works may be needed that are outside the competence of a householder.

There are three principal options for commercial remediation. The two guiding principles should be to obtain more than one estimate for building works, and to recognise that, once a suitable course of action has been identified, radon works are generally simple and straightforward. They need be no more expensive than a comparable amount of general building work.

The options are:

1. Obtain estimates from several local builders, including perhaps someone known from previous work to be reliable.

2. Obtain estimates and advice from one of the 'specialist' radon companies. Almost invariably, estimates will be higher than from local builders.

3. Obtain advice and guidance from a consultant, and with the further option of supervision of remedial works undertaken by a selected local builder.

Surprisingly, the third option need be no more expensive than using a specialist limited company. It is the most secure, in that advice from a consultant can be relied upon.

The advantages and disadvantages of each approach are:

1. Local builders.

Local builders often produce good work for moderate prices, and many have considerable knowledge of the particular features of local buildings.

However, because of the limited interest in radon remediation (a situation paralleled in the USA) few local builders have much experience in diagnostics and interpretation of test data.

2. Specialist companies.

Specialist companies may claim to be 'specialists' but on the basis of very little training or expertise. Often their prices are high, and they use only a few standard systems designs. They may be 'tied' to one or more particular manufacturers products. Guarantees should be studied with care - they may be valid only as long as the company remains in business. A few companies may belong to guarantee insurance schemes, which will underwrite the work should the company fail.

3. Consultant supervised works.

Employing an experienced consultant to advise on radon is not expensive, except where detailed tests over many hours are needed to confirm the most appropriate course of remediation.

Often the money spent on consultancy services can be recouped by way of employing a local builder to work as directed by the consultant, rather than employing an expensive specialist company. The key advantage of using a professional consultant is that his work may be expected to carry a personal assurance of competence. [*]

54. Testing of building sites for radon levels.

There is currently no proven method of predicting indoor radon levels from pre-construction tests, and attempts to do this in other countries have produced poor correlations. Indeed, measurements of radon levels in the ground can be quite misleading. Radon is almost ubiquitous in rocks and soils in the UK, as elsewhere.

There are many factors involved, and a reading in the ground that appeared high can be really little indication of a potential problem. A more reliable guide might be the radon levels in many nearby buildings and combined with a knowledge of local geology. However, adjacent buildings can often have different indoor levels, by a factor of 100 or even 300.

At the moment, testing of new-build sites for radon potential does not appear to be useful in the UK. In other countries, classification systems have been developed for ground, based in part on in-situ radon measurements, but these are likely to find wide application only where the ground is fairly uniform over substantial areas, a situation not found in the UK so far as can be judged by the detailed distribution of high radon houses.

In Sweden, a system is used under which ground is classified as being of high, normal or low radon risk. Both permeability and radon in soil gas are considered. Similar schemes are operated in parts of the USA, but based more on broad geological considerations and results from measurements in existing houses than on tests of the ground. (see Section 9 also).

In both countries the requirements for new-build housing may be determined by this classification, with full radon resistant construction being reserved for the 'hottest' areas. A unique set of ground testing or building construction requirements is unlikely to develop in the USA especially, because of the local nature of Building Code enforcement.

It is known that high radon houses can be found at one end of a building site, yet only a few metres away houses of similar construction all have low levels. It seems inescapable that ground tests at one end of a site, at some arbitrary depth, could be useless for predicting what would happen even a few metres away. Also, tests at different depths on the same plot can show marked differences, and there must be doubt as to the most appropriate depth for testing given the variations sometimes necessary in house foundations as a consequence of conditions discovered only at time of construction.

It would be an attractive prospect to be able to predict radon levels in new buildings by inexpensive tests on the pre-construction site. The problems are not those of instrumentation, but of inherent variability of the ground. What may well be possible is to classify sites as low risk, thus avoiding the need to incorporate radon precautions, and based on assessment of homogeneity (deduced from maps) and uniformly low results from soil gas sampling as well as permeability.

KEY FACTS:

Testing of green-field sites for radon cannot be recommended in the UK as a method of predicting high indoor levels. This position may change, but some doubt may always remain in respect of sites where the ground conditions are inhomogeneous. Design and construction standards can also much influence indoor radon levels, as can occupant behaviour, especially in naturally ventilated buildings.

Radon levels in every building may never become predictable to great accuracy, (see Sections 55 and 56) but prediction of high and (especially) low risk sites should certainly be possible in some cases, and with possible savings in construction costs. [*]

55. The influence of house occupancy, weather and building design on indoor radon levels.

It is obvious from basic building physics that radon levels in naturally ventilated houses may vary. In practice, average levels in some houses are remarkably constant, but simply choosing an adjacent room for test can make a substantial difference to the result.

Sometimes the difference between rooms can be as great as a factor of 10, and exceptionally a factor of 40 or more. This is easy enough to rationalise once typical UK houses are compared to American or Swedish designs with central air distribution systems, but see Section 56.

Some interesting questions arise. For example, over which standard year or other set of conditions should radon levels be normalised if it is desired somehow to 'classify' houses as to their radon levels?

Average radon levels can vary from room to room both over short periods of time (hours and days) and over many months.

In mid-summer, windows may be open much of the time, and a low reading may be obtained. Measurements during an unusually severe winter will probably produce a higher result if open fires are used in a moderately airtight house. Thermally massive (heavyweight) buildings with poorly insulated floors are often cooler inside than out during mid-summer conditions - a consequence of thermal mass and thermal coupling to the ground, which maintains a broadly constant temperature. Thus, the pressure gradients that induce radon entry are reversed, and with possibly a large effect upon reported radon levels - see Section 8.

Differences can also be due to how the house is used (the behaviour of its occupants) and thus the same house may exhibit different average radon concentrations when lived in by different families. This fact alone militates against any system of classifying houses as 'safe' or 'dangerous', except of course for the mass of houses that could never be induced to exhibit high indoor radon concentrations however the occupants chose to live.

A good understanding of the facts outlined in this Section could be recommended to those officials who have advocated public registers of 'affected' houses, since both property values and saleability might be much determined by unrepresentative radon measurements.

In reality, a house that registered 150 Bq/m^3 in one 3-month period could register either 80 or 300 Bq/m^3 the next, even when the results have been corrected to annual averages. (This correction to an annual average is also dubious for any one house.) Short term measurements in the same house might produce results between (for example) 20 and 600 Bq/m^3.

Rather than attaching too much importance even to long term results (or to whether a house appears on one test to be above or below 200 Bq/m^3) it would be no more than a recognition of reality to admit that domestic radon measurement is and must remain an inexact science (see Section 36 also).

KEY FACTS:

There is no such thing as a UK house at a fixed radon level, and especially not amongst houses that are moderately or severely affected. Measurement of radon levels in different rooms in the same house can produce genuinely very different answers, even if the measurement devices are reasonably accurate.

Many houses should not be classified simply as 'above 200 Bq/m^3' or 'below 200 Bq/m^3', and especially not on the basis of a few measurements in only a couple of rooms. In the context of broad area statistics such measurements are entirely adequate, but the possible uncertainties in respect of individual houses should be admitted. [*]

56. The role of heating systems in determining radon levels.

There can be strong interactions between heating system design and operation and average indoor radon levels. The effect can be most marked in mechanically ventilated buildings and has been well demonstrated in schools in the USA.

In the UK, the most pronounced interactions have been in houses where old fashioned open fires or 'Baxi' type fires are used on a regular basis. The common factor is substantial suction on the room as a consequence of the large air flow rate up chimneys.

Often, not all the house will be affected by the suction because internal doors may be kept shut (to stop the noticeable draught round the door when the fire is burning!) and in these cases large room-to-room differences in average indoor radon level may be experienced. Short term levels room to room may be different by a factor of 50 or even 100.

In mechanically ventilated buildings, radon levels can be equilibrated by the air mixing that may be an inherent feature of the system design. However, if different rooms run at different pressures some may be pressurised and some depressurised relative to outdoors, and with (consequently) large differences in average indoor radon levels, and these may be reasonably stable in time.

Choice of different monitoring periods and of rooms selected for monitoring may therefore produce large differences in measured average radon levels.

Also, it is entirely possible for subsequent changes in the operation of the heating or air conditioning systems (deliberate or as a result of failures) to induce large changes. This is an example of buildings not having fixed indoor radon levels.

A debate is underway in the USA as to the most appropriate response when mechanically ventilated buildings are found to be affected by radon. Similar considerations apply to some UK houses served by underfloor-ducted warm air heating. Much can depend upon system pressures and whether the ducts are well sealed. The author may be consulted for further details.

Some experts contend that radon removal systems should be installed (almost irrespective of cost) whilst others, supported by the author, argue that faults and imbalances in H&V (heating and ventilation) systems should be remedied and the buildings reassessed for radon. These measurements should be made only during occupied hours if appropriate, before classifying the rooms as requiring conventional radon systems.

This approach is logical since many buildings that are measured as low in radon may be driven to higher levels at some future date by faults in their H&V systems. The logical cure is simply to return the H&V to its previous state, and which, in the case of some faults, may pay dividends in terms of improved indoor air quality (if not energy consumption).

A parallel argument is that smokers should reduce their radon risks by giving up smoking rather than continue with a dangerous habit whilst expending possibly large sums of money on removing a relatively minor hazard.

KEY FACTS:

Heating system design and operation may much affect indoor radon levels throughout mechanically ventilated buildings. Systems may tend to equalise indoor levels, or to exacerbate problems in a few rooms. Simple diagnosis can resolve any uncertainty.

Large effects may occur locally in naturally ventilated houses owing to operation of open fires.

Heating system design or operation may determine whether a building is classified as above or below the so-called action level, and depending upon the room selected for measurement. [*]

57.1 Influence of radon measures on timber floors.

For many years, ground floors of suspended timber construction have been used in houses and other low rise buildings. Often site conditions are such that some type of suspended floor may be preferred throughout, but in housing it was common practice to use solid flooring for kitchens, and hallways. A degree of temperature stability was thereby achieved, especially cooler summertime conditions because of thermal coupling to the ground.

Timber floors usually give good service - typically well over 50 years. Many floors last a hundred years or more, but where decay occurs this is often owing to excessive dampness. Poor design may be to blame in many cases. Timber in modern floors will probably be chemically treated, but good design is still advisable if not essential.

Suspended timber floors in the UK are usually ventilated with outdoor air, via air-bricks This helps ensure a low moisture content, but cannot compensate for timber being laid in contact with damp ground. Joist ends can be most vulnerable because in older houses they were either laid directly into the wall or sometimes onto slates, which acted as a damp-proof layer. Often the end grain of the timber was unprotected.

Devon and Cornwall are amongst the wettest parts of the UK and many floor joists are on the verge of going rotten. Thus, a small change in conditions may be disastrous. Local repair of joists can be effected by building new sleeper walls and resting the still sound sections upon these. More serious problems can occur where the whole floor is decayed.

Traditionally, air-bricks have been provided beneath floor level and on two or more opposite sides of the house so as to encourage cross-ventilation. It is common for these to become restricted, either deliberately or inadvertently. In Devon and Cornwall fewer air-bricks were often installed, because of the strength of prevailing winds. Indeed, generous provision especially of single sided ventilation can result in carpets lifting.

In older houses - those built prior to 1985 when the Building Regulations required over site concrete - timber floors are often still exposed directly to underlying earth which can be quite damp. However, provided underfloor humidity is kept low by ventilation, and unless joist ends are at risk owing to poor design, the floor may still be quite safe from decay. Probably hundreds of thousands of old floors are likely to give good service well into the next century.

Vapour barriers and thermal insulation.

It is not recommended practice to install a vapour barrier over suspended timber floors. This is despite the almost universal provision of such barriers in 'equivalent' situations at roof level. Even with insulated floor designs the vapour barrier is omitted, again apparently at variance with roofing and walling technology.

A possible reason for this divergence of advice is the predominant pressure differences across various building elements. Owing to wind, and with a stack effect operating for most of the year also, floors may have outdoor air drawn through them, whilst walls and roofs may have warm moist indoor air forced into them, thus increasing the risk of interstitial condensation.

With this understanding of how timber floors may operate, the influence of radon systems may be predicted.

In the early days of radon remediation in the UK, it was thought that houses with timber floors were easy to cure. Either the number of air-bricks could simply be increased, or a small fan could be fitted in place of one air-brick to increase air flow and, so it was thought, decrease the radon concentration underfloor.

57.2 Influence of radon measures on timber floors.

Indeed, much advice was issued on the basis of little evidence, so confident were some radon scientists in their understanding of building behaviour. The truth is more complicated.

The behaviour of real floors.

The first mistake is to assume that pressure reversal can be achieved. It has been the experience in the UK, and it is a standard result from the USA also that not only may the radon level underfloor increase because of greater air flow from the exposed ground, but that air can be drawn down cavity walls into the underfloor space, in some cases to such an extent that pressure reversal is not achieved even at very high air flow rates.

A few houses have been treated commercially by using several fans, the idea being apparently that if enough air from somewhere is drawn under the floor the radon level will decrease to a low level. However, under some conditions of 'success' for radon control the floor may be subject to higher humidity levels than previously, despite any greater total flow rate.

Views of how timber floors work in practice should take account of experimental evidence. If there is significant depressurisation of the house caused perhaps by use of an open fire, and if the windows and doors have been sealed, a substantial proportion of ventilation air for the house may enter through the air bricks and then through the cracks and gaps in and around the floor. This mode of ventilation is encouraged by the stack effect within the building and can be responsible for high radon entry rates, albeit at moderate concentrations. This is even more likely to be the case where there is single sided ventilation of the underfloor space.

In all cases, even with the presence of over site concrete, radon can quite readily gain access to the underfloor space and from there into the house. It is a matter of simple experimentation with tracer gas that sealing a timber floor with a plastic sheet can have a dramatic effect on the flow rates. However, results in terms of indoor radon level are sometimes less good.

The reason for this is partially that the reduction in ventilation of the underfloor space, brought about by sealing the floor, leads to a much higher radon concentration under the floor. Also, the slight depressurisation induced by a fan may draw more radon from underground, and radon levels under sealed timber floors may be tens of thousands of Bq/m^3 **despite the fan assisted ventilation.** Even if on average pressure reversal or neutrality is achieved, room radon levels may still be moderate because of pulsed entry during windy conditions.

Another cause of exasperation is that in many old houses especially, sealing the floor does not address all of the possible radon entry routes. Many older houses in the country districts of Devon, Cornwall, Northamptonshire and Derbyshire have thick granite, sandstone or limestone walls, often with rubble or other highly permeable cores.

The other possible (and potentially catastrophic) effect of sealing timber floors in this way may be to increase their average moisture content, since what may have been a principal route for ventilation air has now been blocked off. This has been investigated in a few houses and schools, but measurements of average moisture content take time.

In some cases installation of radon measures has been blamed for decay where it seemed highly likely that defective drains were responsible for increasing local moisture levels. It is essential to understand the reasons for decay before embarking on heroic and perhaps unnecessarily expensive remedial works.

Equipment is available to monitor and report moisture levels in timber: the author may be consulted for details of application.

57.3 Influence of radon measures on timber floors.

Wood block floors.

Wood block is usually laid above concrete, and set in tar or similar material. Plastic sheets or other vapour impermeable material should never be laid over these floors to help cure either radon or dampness. The consequence in only a few months may be severe and irreversible damage to the blocks. The author may be consulted for advice.

In the USA there has been much good experience with 'sub poly' systems used in crawl spaces. Here, a plastic sheet is laid not over the timber floor but over the underlying ground or over site concrete. A fan is installed to draw air from beneath the plastic, which should be sealed as well as possible to the walls. However, in typical 'difficult' UK houses it could be expensive and highly disruptive to install such a system because access is so limited.

The systems are suited to some houses having deep voids - typically those built on steeply sloping sites - but even here there may be easier solutions. Sub poly systems can also help to reduce underfloor moisture levels, but depending much upon the source of the moisture.

Other overseas work.

In Sweden, timber floors are common, and often affected by radon and dampness. Some research interest has centred upon allergies in occupants owing to mould growth underfloor.

Studies have shown that laying a plastic sheet over the ground can have a marked effect on the average yearly moisture content of the timber floor. However, simply laying an over site sheet is unlikely to affect radon levels.

Mould was a problem in around 15% of floors inspected in one study, but in only one case was timber decay sufficiently bad to warrant replacement. This may be a consequence of timber treatments or simply a reflection of the age of the houses, all of which were less than 10 years old. Relative humidity levels in the underfloor air were recorded over a year. During times when the levels were over 80%, the wood could more readily support mould growth, and would be at greater risk of decay.

Effects on heating systems.

Another crucial factor for suspended floor houses is whether pipe-work for household water supply or central heating is located underfloor. If so, an extensive sealing project should be completed only after pipe-work has been inspected and properly insulated: it might be difficult to repair faults later without compromising some of the sealing.

Frost damage to pipe-work is a severe problem in some areas of the USA where crawl space ventilation has been used. In Devon and Cornwall pipe-work is unlikely to freeze beneath uninsulated floors except in severe winters and with high air flow rates. Radon fans may be switched off during unoccupied periods.

In more northern parts of the UK, pipe-work may be at severe risk from frost damage if located in the air stream from a fan or air-brick. Suitable insulation or relocation of pipe-work should be ensured if high flow rates underfloor are envisaged.

Summary for the UK.

Installing a fan to ventilate under a suspended timber floor can increase or decrease radon levels.

Houses are already known to present quite different symptoms depending upon the dampness of the underlying ground and (crucially) upon any local defects in rainwater drainage arrangements.

The underfloor space can still be rich in radon and indoor levels may be determined by 'curious' air flow paths. Use of tracer gas can be essential to understand difficult cases. However, these tests are best left to a consultant: they are required only infrequently and interpretation can be difficult. [*]

58.1 Sealing techniques and their performance.

Sealing cracks and gaps in floors and walls to help cure radon problems is one of the most difficult areas on which to advise. This is because so much can depend on the individual building, and upon standards of work.

Sometimes expectations are not realised, and by a large margin in either direction. The difficulties of using sealing techniques alone to reduce radon levels have been described as like trying to push a piece of string. Another description (also from the USA) is like trying to block a river with a picket fence.

Nevertheless some useful guidance can be given.

Sealing large cracks and gaps in concrete floors, typically where pipe-work or services enter (and not forgetting under the bath in bungalows) can produce substantial reductions in indoor radon concentrations. It can also have little effect, or may cause redistribution of radon around the building.

Truly remarkable reductions in indoor radon concentrations have been achieved by sealing old cracked concrete floors with a cementitious epoxy compound, although whether the effects were genuine or the buildings for some other reason became cured is not understood. Similarly, doubts have been expressed about some early results from passive stack vent systems, see Section 63.

It is useful to remember that occasionally radon levels have been known miraculously to reduce with no action having been taken.

Sealing is often a good 'first stage' measure. If it works, (even if levels are not brought below the 200 Bq/m^3 threshold) the householder may be entirely content. If it does not work, the effort may well not have been wasted because another remedy, perhaps including a fan, may work much better for the sealing having been undertaken. This is especially the case with whole house pressurisation systems (see Section 61) but these require the whole building envelope to be as airtight as possible. Nevertheless, they are the preferred option in some difficult houses, and with performance being improved in stages as sealing is completed. Good diagnostics can be essential to obtain the best results.

It is useful here to stress that whilst radon enters **from the soil**, through **cracks in the building**, these do not have to be visible, and many may be hidden beneath walls, stud partitions etc. In the case of houses built partly underground or into the side of a hill, principal entry routes can include through the walls. Often, these cannot be remedied only by sealing.

In many cases however there will be an element of luck as to the results that are obtained. In only a few houses can sealing be expected to reduce radon activity levels by more than 50-80%. Greater success has been known, but rarely.

Often, sealing of major and obvious cracks in floors and between floors and walls may be all that is needed in rooms that have only a moderate level of radon (below 400 Bq/m^3 is suggested as a guide).

In some houses the amount of disruption in terms of moving furniture and carpets to undertake sealing may well be daunting. Trying a fan system may be cheaper, but perhaps not the preferred option in the long term.

A variety of sealing techniques can be used:

- laying plastic sheeting across the floor surface and taping all joins to a very high standard,

- filling cracks with sealant of a type that remains flexible,

- painting over very small cracks with 'liquid rubber' paints as used to repair flat roofs,

- using 'liquid rubber' paints in combination with strengthening cloth or scrim to bridge over large or deep cracks, such as those often found between floors and skirting boards.

58.2 Sealing techniques and their performance.

To some extent there is a choice of methods, but for suspended timber floors made from strip boarding it is impracticable to try and seal all the gaps. In any case these allow for movement of the wood. This type of floor may be sealed by laying plastic sheeting (of the type used for damp proof membranes) over the floor and securing it well with durable tape or other means to the skirting boards. All joins between sheets should be taped also. The author is able to give more detailed guidance, and see Section 57 also.

For solid floors, a variety of techniques and materials may be used but **if the seal is not airtight, it will probably not be effective.** Success has been achieved using acrylic mastics, cementitious epoxies, and pourable polyurethanes. Silicone sealants are not recommended despite that in suitable situations they are amongst the most durable of products. The problems of silicones include gap filling on rough surfaces, adhesion and sensitivity to application on a even a slightly damp surface.

In all cases success will be more likely if an appropriate material is used and under detailed supervision. This cannot ensure success, but it may preclude almost certain failure.

Houses that are remedied by sealing alone should be checked for radon on a regular basis to ensure continuing effectiveness. The time intervals between checks may sensibly depend on the initial radon concentration. If this was only a few hundred Bq/m^3, and if the sealing produced a marked reduction (confirmed by a couple of three month tests), a check every five years may be thought adequate. Only one radon detector may be used and located in a ground floor room known to have been at a high radon level. A reading corrected for season, of less than 300 Bq/m^3 may well signify that the whole house average is less than 200 Bq/m^3.

However, it is known that whilst a sealed room can become low in radon (having previously been at a high level) adjacent rooms (previously at 'safe' concentrations) can become more badly affected, and as a direct consequence of the sealing work.

Indeed, sealing of one or two leaky timber floors may so much increase the radon levels underfloor that other rooms, previously low in radon may be driven to much higher levels (by a factor of 3 or more).

It is no surprise that sealing can have these effects, and indeed they can be predicted in some cases by diagnostics. If source concentrations can be shown to increase markedly when temporary sealing is effected (as can be done in many cases) permanent sealing may not work too well. If they do not increase markedly, as may occur with an 'infinite source' (see Section 59) there is much more chance of success.

Obviously, any gross redistribution of natural ventilation pathways may completely alter radon distributions within a house, or indeed the distributions between a pair of terraced or semi-detached houses whose floors or wall cavities are substantially interconnected. In older houses especially, this may be the case, and some remarkable results have been obtained.

Despite that sealing is 'obviously' such a central part of radon control it remains a contentious technique and one that:

- may be essential as an adjunct to whole house pressurisation
- may be essential to help limit house depressurisation induced by radon sump systems
- may have adverse effects on timber floors
- is very sensitive to proper design and workmanship
- can succeed alone in many houses, and sometimes in situations where it would not be expected to work
- is discreet and has no running costs. [*]

59.1 Diagnostics for radon remediation.

There are many texts available giving details of radon diagnostics. It is not the intention here to duplicate these or to reproduce material from manufacturers catalogues. Rather, this Section summarizes key points from the authors experience in diagnosis of radon problems in buildings. Emphasis is placed on what has been found to be most useful, and on cautionary tales. Opinions are of course those of the author, and may conflict with those of some other authorities.

The subject of radon diagnostics is complicated by five factors:

- the range of equipment available,
- the claims and counter claims for this equipment,
- general weather conditions, which can lead to little radon being found in a known high-radon house over periods as long as a few days,
- wind direction, which can much influence the radon distribution within a house or other multi-cell building
- the simple (but unwelcome) fact that what may prove useful and conclusive in one house may be a waste of time in the next.

Often tests are designed to suit the building and what is required to be known about it. This is particularly the case with ad-hoc tracer gas studies.

A good starting point is that tests should always be undertaken with a clear idea of what will be the usefulness of the result, assuming that a representative result can be obtained on the day in question. What comprises a representative result may of course not be known!

Diagnostics falls conveniently into several distinct sections:

- Distribution of internal radon concentration
- Air tightness of the building
- Pressure differentials across floor slabs and suspended floors
- Depressurisation of rooms by fires, fans, and radon systems
- Air flow into buildings via uncharted pathways
- Assessment of underfloor conditions: radon concentrations
- Assessment of underfloor conditions: entry potentials
- Vacuum suction testing.

Distribution of internal radon concentration.

It is an unfortunate fact that both short term and long term radon concentrations in UK high-level radon houses are far from constant or reproducible. There is less experience in moderately affected houses, but limited data supports a high degree of variability here also.

There are several factors that conspire to produce this situation:

- UK houses often have a mix of floor constructions and occupancy patterns of each room
- UK houses are almost invariably naturally ventilated
- weather conditions can have a marked effect on short term (days) and instantaneous radon levels
- many buildings in affected areas are old, and have been extended and altered over the years. They are now effectively two or three different buildings, connected together and occupied by a single household.

Some houses are remarkably constant in their radon levels, others are remarkably variable. To some extent this can be explained by local source terms that are highly weather dependent. In other buildings, wind speed (for example) appears to have little effect. Some houses known to the author can almost be guaranteed to be free of radon in a high wind. Others can be guaranteed to exhibit high indoor

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levels. Only when the behaviour of each building is well understood can such effects be predicted.

Long term variations in indoor radon concentrations in given rooms may exceed a factor of 4, without action by occupants or radon specialists. Long term average levels in different rooms in the same house can vary by up to a factor of 40 (see Section 60), and short term levels by almost any factor.

The most constant levels room to room are found in houses having connected timber suspended floors. In these cases the underfloor space forms an effective mixing zone, analogous to the full basement in a typical house in the northern USA. Variations room to room over long periods of time (weeks, months) are typically less than 2. Factors in excess of 3 appear to be unusual.

The most extreme variations are seen typically in houses that have been extended over the years, and where there are different floor types. For example, an old house with part timber floors over an old badly ventilated cellar or crawl space may have added to it an extension with a good quality concrete floor. There is no guarantee of where the highest radon levels will be found but the suspended floor areas are sometimes the worst affected and the most difficult to remedy.

These factors need to be recognised in deciding how to measure radon concentrations and over what time period. If equipment that detects radon daughters is used there are added complications. In free room air, the equilibrium factor (see Section 7) is usually between 0.3 and 0.6. In small spaces however, such as in under-stairs cupboards and beneath baths, the surface/volume ratio is high and radon daughter readings may be much lower than expected for a given radon gas level probably owing to enhanced plate-out.

Recommendations:

In houses with timber floors throughout a single measurement point may adequately characterise the radon level in ground floor living areas if averaged over several weeks and if no abnormal use is made of the windows in the chosen room. Floor coverings such as carpet or vinyl may have only limited effect, except where the vinyl is very well fitting. A departure from the true whole-floor average of more than a factor of 2 or 3 is unlikely. Nevertheless, day to day variations may be extreme.

In houses with solid floors throughout a couple of measurements may be advised in ground floor rooms, especially if rooms have either a different age of floor or are built into a hillside. In extreme cases variations room to room can be a factor of 6 or 7, but 2 or 3 is more usual. The information from these measurements taken over weeks can be used to 'correct' longer term screening results taken only in one of the rooms, and for the purpose of determining average annual levels.

In houses having mixed floor types and especially if of different ages, multiple measurements may be advised, preferably under the control of a consultant if the house is thought to be badly affected. Room to room variations may be extreme, as may day to day variations.

All measurements to determine room to room variations should preferably be taken over a week or more, and it is likely that electret detectors will prove the most popular. Track-etch detectors are insufficiently sensitive for short period exposures, and charcoal canisters cannot average for more than a few days. Nevertheless they can prove useful.

Measurements using 'active' equipment that can produce a read-out of radon level in each room within 10 to 20 minutes must be used with some care. It is sometimes the case that short term measurements show a similar room to room variation as longer term measurements but this cannot be guaranteed, even when the building has been closed up prior to the test period. The reasons include that a closed up condition is atypical of usage, and that wind direction and strength in the hours before a test can markedly influence the respective levels in each room in some houses.

Measurements to determine the long term average radon level in a house should, as is accepted practice, be taken over months, and if possible between autumn and spring. Summertime results can be deceptive, especially in some old houses. Track etch or electret detectors are the most suitable passive devices, with electrets being perhaps less prone to end (background) errors and calibration errors. However, different types can be affected by gamma emissions. Instructions should be followed in all cases.

Air tightness of the building.

This parameter is important for advising on ventilation of a house, and for predicting the likely effectiveness of positive pressurisation systems. When undertaken as a part of research studies a 'blower door' may be utilised. These consist essentially of a large fan set into a framework that can be adapted to fit into a range of door openings. Fan speed can be controlled and the system can operate to pressurise or depressurise a building.

Under suitable weather conditions parameters of a standard air flow equation can be obtained, and the house or other building classified as 'leaky' or 'airtight' as appropriate. In general, UK houses are less airtight than many in Scandinavian countries - a consequence of building construction standards and the greater benefits of energy efficient design in colder climates.

For radon remediation purposes, use of a blower door may be considered unnecessary. Simpler systems based on a commercially available vacuum cleaner or fan can be utilised to introduce air through the letter box or other suitable opening, and the resulting pressure difference across the house structure can be measured using proprietary equipment.

Measurement of flow rate can be by a number of techniques including orifice plates and pitot tubes, but with care to observe the usual precautions when using air flow transducers. By these means, it can rapidly be determined whether a house is likely to be cured wholly or in part by a positive pressurisation system. The effects of sealing selected large openings can also be determined.

In effect, it can be arranged that the test fan introduces into the house a flow rate of air at least equal to what would be introduced by a pressurisation system, but having regard to the pressure/flow characteristics of the proprietary system.

In most houses, even the existing kitchen or bathroom extract fan may be utilised to provide sufficient air flow for test purposes, but the flow will be out of and not into the house. The author's record here is a depressurisation of nearly 15 Pa by a small kitchen fan, but 30 Pa has been known.

One advantage of depressurising the building is that large air leakages into the structure can be found with 'smoke sticks' or 'smoke guns'. Favourite pathways are under sinks, under baths (in bungalows), and where other service pipes and cables enter from the outside. In many houses however, large flows can be detected using no more than a wet finger.

Pressure differentials across floor slabs and suspended floors.

It is important to recognise that these pressure differences are near the limits of measurement using ordinary test equipment. Units are pascal (Pa), and one inch of water column is equivalent to about 250 Pa. Pressures across floors are typically 0.3 to 3 Pa. Sump pressures are in the range 100 to 250 Pa.

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Almost always the most suitable test equipment is an electronic micromanometer. These can be obtained from several sources in the UK. Care must be taken in using these instruments because they can easily be damaged by over-pressure. For averaging purposes, either electronic integrators or a chart recorder may be used, provided that the manometer has a suitable output.

Most of the difficulties arise because wind pressures can be greater than the pressure difference under test. Thus, many days (especially in Cornwall) are entirely unsuitable for testing. Sometimes, it is desired to determine whether suction spreads across a floor slab, and whether it remains sufficient to balance the stack effect - usually about 2 to 3 Pa in a two-storey building.

Depressurisation of rooms by fires, fans, and radon systems.

The equipment used for these tests is similar to that used for across-slab measurements, but with more care being necessary to consider where the reference pressure should be taken. For low pressure differences, it may be important to ensure that the correct difference is being measured: a room to room measurement may be different from a room to underfloor measurement, especially in windy conditions. Where possible a reference pressure from a sheltered location (ie, not directly outdoors) should be selected.

Open fires have been known to induce depressurisation as high as 15 to 20 Pa, and kitchen fans can manage 20 to 40 Pa in extreme conditions. In contrast, radon systems may depressurise the building only by a small fraction of a pascal, but this can be sufficient substantially to alter average flows around the house, and from some minor radon entry routes.

The reason why these small pressures can be significant is that they occur for 24 hours per day, rather than the few minutes or hours per day that is more typical for extract fans and fires. Their measurement is often difficult, and on/off operation of fans is essential. Output should be to an integrator or chart recorder, and the tests need to be undertaken with all windows closed and with no people moving around the house. Calm weather conditions are essential.

Air flows into buildings via uncharted pathways.

These tests can range from difficult to impossible, and much may depend on how much dismantling of the house can be tolerated. Nevertheless, often telltale signs of air entry from curious locations can be observed without test equipment. Classic cases involve stains around the edges of bedroom carpets: air can flow up cavity walls to enter a house via openings around joist hangers or joists. Where a thick white carpet is fitted close to the skirtings, it is not unusual to observe marked staining, indicative of the carpet having acted as an air filter.

Whether these air entry routes are significant in radon terms will depend upon the average radon concentration in the cavity, and average flow rates, and these will depend on a host of constructional details, including whether the house is rendered. (Rendering can reduce the air flow into and out of a wall, and may inhibit clearance of radon via alternating wind pressures.)

Tests of radon concentration in cavities can produce remarkable results, with quite different readings being obtained at different points, indicative of considerable air movement within the cavity or localised sources. Wind conditions can affect these readings to an alarming degree: sometimes cavity levels can be higher than in adjoining rooms (indicative of the cavity as a possible source) whilst on different days tests in exactly the same locations can produce contrary results. The usual glib explanation in terms of 'wind effects' disguises that little is known about how

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air moves from the ground into cavities and from there into and out from buildings: it would be a brave scientist who would predict on-site behaviour given only the design drawings of the house.

Assessment of underfloor conditions: radon concentrations.

Many types of proprietary equipment can be used to measure radon levels in underfloor spaces and within cracks in floors. These can be classified either by technology or according to whether they measure air in bulk or whether they can sample a small volume. This is important, because often the act of taking the sample can markedly influence the result obtained.

Manufacturers catalogues should be consulted for up-to-date details of equipment. Amongst the most popular types are a range of devices that utilise scintillation flasks and photomultiplier tubes to enable measurement of air samples drawn from room air, underfloor air, or air within cracks. The flasks may be used in 'flow-through' or 'grab sample' modes, the latter being almost universally applicable for on-site investigations.

When measuring radon levels within a room or in an underfloor space there is little problem with accuracy as taking the sample does not much influence the source. However, when sampling from a crack or behind a skirting board, the result may be much influenced by the ratio of the effective volume of the air space being sampled to the volume of the sample. Without dismantling the building it is often not possible to determine this effective volume. Thus readings must be interpreted with care, and can form only a rough guide to radon entry routes. The results are meaningless in absolute terms, because even sticking tape over a length of crack can increase a result by a factor of 3 or 4: the explanation is simply that more of the sample is drawn from radon-rich air behind the skirting board, and less from the air in the room.

These effects can introduce considerable confusion if it is attempted to determine by grab sampling which end of a room is 'worst affected' by entry routes. However, it is easy enough to determine whether the sample space is small (and the reading variable) or essentially infinite.

It has to be appreciated that soil gas concentrations of 10,000 Bq/m^3 are not unusual. Concentrations of 50,000 Bq/m^3 behind a skirting board indicate a source for further contemplation, but only readings in excess of 100,000 Bq/m^3 indicate extremely active ground.

The authors record reading for Cornwall is 1,200,000 Bq/m^3, and was obtained beneath a lounge floor in Redruth. Curiously (see Section 60) the lounge was not excessively high in radon despite the poor state of the old concrete floor: far worse had been experienced elsewhere and over less active ground.

It is important to recognise that the average indoor radon levels in a building do not scale well with underground radon concentrations: so much depends on permeability and use of the building. Some of the worst affected radon houses in the UK have underfloor radon concentrations that seem never to exceed 20,000 Bq/m^3, but when combined with an 'infinite source', cracked floors, double glazing and draught-proofing, it is not difficult to accept annual average indoor levels in ground floor rooms in excess of 4000 Bq/m^3.

Radon levels can also be determined by equipment that draws large quantities of air through filters or into chambers. These instruments are unsuitable for many diagnostic purposes, yet are sold as 'universal' measurement devices. Other instruments are based on ion chambers, but in the authors experience can be unsatisfactory.

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Assessment of underfloor conditions: entry potentials.

In an ideal world, radon systems would be designed having regard to a map of radon entry potential of each building. Radon entry potential is the product of the flow rate and radon concentration that can be maintained at any point using a pressure difference typical of the region in which the point is located, and under representative weather conditions. In the real world, measuring entry potential can be difficult under on-site conditions. Also, the techniques are too involved for commercial companies to use since they can involve considerable time on site and investigation of each room in a house. Nevertheless they are useful for research purposes and for consultancy investigations of difficult buildings.

Radon enters buildings because of small pressure differences across floors and other boundaries. In radon potential testing, a small pressure difference is applied using an air pump (or a throttled vacuum cleaner, or a kitchen fan or a blower door) and the flow rate measured. The maintained radon concentration is determined by sampling the air, and the product gives a good indication of the extent to which that part of the underfloor area would be capable of sustaining a radon entry into the room under normal conditions. Of course, the entry potential from the ground has to be matched by entry routes into houses, but often the main flow resistance is the ground itself. Thus the technique gives reasonable answers where applied to typical 'slab on grade' houses built on low permeability soil and without a hard-core layer.

The usefulness of the technique is indicated in the following example:

Where underfloor conditions are those of an infinite source (an old mineshaft) large flow rates are needed to produce measurable pressure differences across the floor. Maintenance of the radon level under these conditions confirms the diagnosis. If the radon reading drops markedly, this indicates not a high entry potential but a substantial short circuit from the test point to outdoor air. Simple testing only of the radon concentration in the absence of flow might produce a similar result in these very dissimilar cases.

Few houses in the UK have been investigated in the detail necessary to explore the full potential of the technique, or more correctly, few householders have been persuaded to tolerate the author's extended experiments.

Also, different results may be obtained on different days: during windy conditions, the source term, as represented by the radon concentration in the subjacent ground, may be significantly reduced.

This can be a severe problem when testing houses built into hillsides, because wind can literally blow the radon 'clear away', leaving no evidence of high levels within all the usual cracks and gaps around the floor. **Radon entry potential testing can therefore give a misleading result, even to the extent of a researcher wondering if he might be investigating the wrong building, so marked can be the discrepancy between entry potential results and notified long term radon levels.**

The remaining difficulty is that the the relatively constant depressurisation that can be imposed by blower doors may not represent how the house behaves in use, especially if open fires are used. Room to room potentials may not match well with notified average radon levels. To some extent mitigation systems can be designed to suit the use of the house as well as its innate characteristics.

59.7 Diagnostics for radon remediation.

Vacuum suction testing.

An established technique is to test the applicability of a radon sump system by mimicing the performance of the system using a vacuum cleaner. The aim is to test the extent of pressure field distribution from the chosen sump location. The test has limited validity in respect of determining whether a system will adequately reduce radon levels because of the number of other factors involved, but is useful in characterising sub-floor communication, especially where there are cross-walls, and in selecting the most suitable type and size of fan given the flow/pressure readings obtained from the suction test.

Vacuum suction testing is often termed communication testing. Poor communication is indicated by regions of maintained positive pressure (or zero pressure) when the simulated sump pressure is set between 100 and 200 Pa, typical for an in-line centrifugal fan. Obviously the flow rate can be measured at the same time, and the technique then becomes somewhat akin to 'entry potential' testing.

If the test indicates good communication and wide distribution of the pressure field, a radon sump system is likely to be successful. If the test appears less promising, the idea of a system need not necessarily be abandoned, since many systems work reasonably in situations where diagnostics suggest only limited effectiveness. [*]

60.1 Experience with radon sumps.

Radon sump systems are one of the most common solutions to radon problems. Unfortunately, their effectiveness may be localised, owing to underground obstructions and short circuiting of pressure fields.

The systems are by no means universally applicable but in the right circumstances they are easy to install and very successful. Section 52 gives details of design.

This Section draws on experience of systems in the UK and USA that have been studied in detail by the author. The emphasis is on anecdotes, to illustrate use of diagnostics and practical difficulties of design and installation. Both internal and external sumps are covered.

In some houses, and especially in bungalows, small radon sumps can be the easiest and potentially most effective solution to a radon problem. Common features are a good depth of hard-core (often owing to the house having been built on a sloping site and where stone fill has been used) and with few cross walls beneath slab level.

In bungalows especially, installation has proven particularly easy where there is a full-height cupboard: the suction pipe can be located in a rear corner and the cupboard contents (often clothes) act as sound deadening material. The fan can be installed in the roof space, in a vertical position, and the outlet taken through the roof. This makes for a very neat design, with all components being hidden, and with all pipe-work within the inhabited volume being under suction.

Where deep hard-core layers exist (and often where they do not) large sumps are unnecessary. Several systems have been installed on a diy basis and for little more than the cost of a fan and a length of pipe. Where bungalows have shallow pitch roofs, obviously there is no need for scaffolding.

In houses, not only is there the complication of roofing work at higher level, but in many cases there is no easy and acceptable route for a 110 mm pipe to pass from ground floor to the roof space. Pipes passing through bedrooms may give rise to complaints about noise, and should preferably be located within wardrobes or airing cupboards, where sound deadening can occur. Use of proprietary ducting rather than 110 mm upvc pipe can ease installation problems but its cross-sectional area may be inadequate for situations where a high flow rate is predicted.

Pipe-work can suffer from external as well as internal condensation, and direct contact with clothing should be avoided except where the pipe is suitably insulated. Glass fibre insulation should not be used because any contamination of stored clothing could produce skin irritation.

Generally, sumps may be located near the centre of houses, or if diagnostics is undertaken, near to areas of high entry potential. The problem with locating sumps near to the edge of buildings is sometimes that there is excessive leakage into the cavity of an external wall, and much of the suction is dissipated. Just to complicate matters, this may be quite effective in limiting radon entry in some houses - but not in most.

In some cases depressurisation of foam filled cavities has acted to spread a ring of suction around the house, and has produced good results. However, there would probably be considerable heating cost penalties with these designs. Old houses are not immune to 'cavity leakage' where the construction is a thick wall with rubble fill. These old walls, common in rural parts of Devon and Cornwall especially, are often highly voided, sometimes inhabited by mice, and more than usually act to block the spread of depressurisation.

Floor constructions have been found to vary from 25 mm of cracked concrete (found still in many older houses in rural counties) to 400 mm of dense concrete. In the latter case, diagnostics enabled a solution not involving excavation of the floor.

60.2 Experience with radon sumps.

The location of an indoor radon sump is often determined only partly by diagnostics: suitable locations of internal pipe-work or objections by the house owner to a certain room being disturbed can be overriding factors.

The difficulty of digging out modern well constructed concrete floors should not be underestimated: several builders have resorted to water cooled disc cutting equipment and complete room redecoration has had to be undertaken. In contrast, many old floors have been replaced with thicker concrete, and incorporating both damp proof membranes and radon sumps, as per the designs for new housing. Removal of the old floor may take less than an hour.

Complete new floors are of course invariably successful in reducing local radon levels, although problems of house depressurisation may occur because the suction extends effectively to slab edges, and to walls.

On more than one occasion it has been found that external as well as internal house walls had virtually no foundations. Use of nylon mesh material in place of hard-core may be recommended where excavation depth has to be kept to a minimum. In all cases the best performance is obtained with uniform size rounded hard-core, since this gives the highest void fraction, other factors being equal.

In houses where there is a large depth of hard-core, owing to a sloping site, it has proven practicable and inexpensive to insert a suction pipe into the hard-core from an outer wall, but beneath floor level. However, short circuiting via cavity leakage is almost inevitable, and although the systems often work well in radon terms, large fans need to operate at maximum power to produce sensible depressurisation even a metre away from the inlet, and noise from exhaust points has proved troublesome.

This is a particular concern in bungalows because the exhaust may be only a few feet above ground level. If pipe-work is taken to ridge height on a chalet bungalow, noise levels can be reduced, but the systems look 'decidedly odd', as it is unusual to see long lengths of pipe running up a gable end wall to above ridge height.

The aesthetic problems are exacerbated if, following design recommendations to limit condensation problems, fans are located at high level. Few householders may be prepared to tolerate such systems once the initial shock of discovering a high radon level dissipates. They may prove unpopular with Estate Agents too.

Additional aesthetic problems may be introduced by recent design recommendations to site the exhaust from radon systems at least 3 metres from any window or door or public path. The intention here is to ensure that none of the exhausted radon/air mixture can enter inhabited areas. Whether this advice is sensible or not depends on local circumstances: many houses have been cured of high radon levels with fan exhausts being within one or two metres. If the exhaust stream is expected to be exceptionally rich in radon (this can be predicted from diagnostics) more care needs to be taken.

The problems experienced with noise from exhaust points in high-flow sump systems are of course similar to those experienced with fans used to ventilate under timber floors, but here the added complication may be noise from the inlet end of the pipe. Systems have had to be modified to overcome these problems.

It has been emphasised in Section 52 that sump systems sometimes work poorly and occasionally do not work at all. Usually these failures may be traced to very low permeability ground, cross walls, failure to undertake entry potential diagnostics, or (at the other end of the scale) to an infinite source. It has proved interesting to resolve some of these problems: the usual solution of "put on a larger fan" may not produce adequate results and noise levels may increase.

60.3 Experience with radon sumps.

In non-domestic buildings multiple fans have been used, again sometimes not to good effect.

It should never be forgotten that pressurisation may offer an easier solution to difficult houses than can multiple sumps, and effort devoted to digging out floors might be better spent in sealing up the house to an extent that would permit successful operation of a pressurising system. Consultancy advice should be obtained in these cases.

The limiting factor may be leakage where joists or hangers are set into walls at first floor level. In the most difficult cases, each house has to be treated on its merits, and a full range of diagnostics may be necessary. Thankfully, such houses have proved to be rare in the UK. The usefulness of diagnostics on simpler houses also is that it can indicate design solutions that entail less disruption and greater effectiveness than more obvious remediation.

Most radon houses respond well to standard treatments, but many might have been mitigated to a better extent were adequate diagnostics to have been utilised. However, here the issue is one of cost and marginal cost effectiveness: if an 80% cure can be achieved simply and easily, it has to be questioned whether it is worth the cost and necessarily uncertain outcome of extensive diagnostics even if some rooms remain over the 200 Bq/m^3 level. (It is usually easy to achieve less than 200 Bq/m^3 in at least one room!)

It is a problem defining the radon level in properties mitigated by sump systems: often the variation room to room may be greater (at least in percentage terms) than before remediation, and with some rooms above and some below the 'action level', but depending upon the period of measurement and obviously upon window opening habits. At the present time, and especially in view of measurement uncertainties (some of which can never be removed because they derive from building imponderables) it would be more honest to ascribe to radon results a degree of uncertainty, rather than to quote blandly in terms of two or three significant figures.

External sumps.

The performance of external sumps in UK housing has proven very variable. Some systems work well and for minimal cost and disruption whilst others do not work at all. Communication testing is the first step of diagnostics, but can prove frustrating. Systems that 'ought' to work do not, because of the presence of high entry potentials that are unaffected by the system. Also, it is not unknown for powerful fans slightly to depressurise a house via wall leakage.

Detailed design of external sumps is important so that the pressure field can extend as far as diagnostics would suggest should be possible, and to avoid cavity short-circuiting - which has proved troublesome. Supervision of the works by a consultant may be recommended in view of the highly variable performance and sensitivity to design parameters and small constructional differences. Similar comments apply of course to side-entry sumps on sloping sites.

The importance of one design parameter may have been underestimated. A large area of concrete or paving around a house may exacerbate the indoor radon levels, but can help facilitate good performance of an external sump. Much then depends on wall design and construction.

These problems are in sharp contrast to early successes reported from Sweden. There, a group of houses built on radium rich but highly permeable ground were apparently cured of their radon problems by using a single large fan and a single deep sump dug tens of metres from the houses.

The key factor would be the permeability of the ground (which would have exacerbated the radon problem for a given source activity concentration) and the good communication across many houses.

60.4 Experience with radon sumps.

The cure may be seen in terms of ventilation of an area of ground, but without the complication of a concentrated source of the type that can prove troublesome if located beneath a house or other building in a mining district. Similar successes in the UK seem unlikely in view of ground conditions in many affected areas.

In cases where it is known or suspected that the water table beneath a building is only a short distance underground an external sump may be preferred, because there is no need to damage damp proof membranes, if present. In a couple of cases, underground pipe-work has become waterlogged, not owing to condensation but to ingress of ground water during periods of higher than normal rainfall. There is no remedy here except to design the system accordingly. For example, fans should not be located at low level because water splash within the inlet pipe can soak the fan motor. It is likely that high water tables are in part responsible for some of the more extreme fluctuations in indoor radon levels. Several houses known to behave in this way are located less than one metre above a local river or stream. [*]

61.1 Experience with whole house pressurisation.

Conceptually, whole house pressurisation systems offer one of the neatest solutions to radon problems, especially in houses with complex construction. The reason for this is that their effect may spread throughout the house volume, unimpeded by obstructions that may be present underground and that might serve to reduce the effectiveness of underfloor suction systems. Unfortunately, the systems are not universally applicable but in the right circumstances they can be very successful.

This Section summarizes experience of these systems in the UK and USA. The emphasis is on principles, diagnostics, and practical experience. Details of particular products can be obtained from manufacturers' literature.

Pressurisation systems operate by introducing a flow of air into a building (usually a house) using a small fan. If a house is totally airtight (which it never is) the fan will build up pressure over a few seconds and then simply maintain over-pressure. Almost inevitably, radon will no longer be able to enter from the ground. At the other extreme, a house may be so leaky owing both to adventitious openings and deliberate use of windows that the fan may be unable to build up any significant pressure. It will then act simply to increase the local or overall ventilation rate, but the reduction in radon concentration may still be noticeable.

Real houses lie often between the two extremes and without testing for airtightness (see Section 59) it may not be possible to predict system effectiveness. However, if the house has draught-proofed windows and doors, and no substantial areas of unsealed timber floor or open chimneys, and if it is usually operated with all windows closed, there is some chance of a system working. A gas fire with a restricted flue has been shown not to affect performance to any great degree.

Usually the systems are installed at first floor level, drawing air from the roof space through a filter. Most systems do not incorporate a heating element, so air is introduced into the house at about ambient or roof space temperature. In wintertime this can lead to complaints of cold draughts, especially where the stairs lead directly into living areas, rather than into a hallway. Several householders have complained about this. Other problems have arisen in houses having secondary glazing. Because the fan may build up a slight over-pressure in the house, more air is caused to flow through gaps into the inter-pane space of secondary glazing systems. This causes a marked increase in condensation on the inner surface of the outer pane during cold weather.

In the USA, concern has been expressed about possible interstitial condensation in buildings not designed to run at an over-pressure: the highest risks may be in well insulated structures in cold climates, and structural elements of timber frame buildings may be at risk from decay. Therefore, some care should be taken when specifying these systems either where the house has secondary glazing or where it has a well insulated timber frame structure.

In summertime, and especially in houses where windows are kept closed most of the time, householders have complained about the increase in temperature in upstairs areas during sunny weather: a consequence of the systems drawing air from the roof space rather than from outdoors. In modern houses, there have also been complaints about the smell of 'tar' from the fan. This results from outgassing of bituminous felts used in roof construction. It should not be a problem in older houses unless they have been re-roofed, or in any house where a high performance felt has been used. Some concern has been expressed about whether the filters supplied with these systems are adequate to remove very small fibres of glass from roof insulation, and that may be present in roof spaces.

61.2 Experience with whole house pressurisation.

Another problem is that in some houses the roof space may be rich in radon owing to air flow from walls. The fan may therefore introduce radon into the indoor air perhaps increasing average levels upstairs whilst decreasing them downstairs.

In summary, problems have included:

- increased inter-pane condensation in secondary glazing systems,
- cold draughts down stairways directly into living areas,
- excessive summertime temperatures in first floor rooms and
- introduction of contaminants, including radon, from roof spaces into indoor air.

One anecdote concerns a system that caused cold draughts in the first floor bedroom. As usual, the fan was installed in the landing area. Unusually, the house had a door at the bottom of the stairs and this was closed at night to keep the cat downstairs. It was found that much of the air flow under these conditions went directly into the bedroom and down through the bare floorboards - presumably to find its way either into downstairs rooms or into the walls (see Section 59 for a discussion of leakage paths.)

Another anecdote (only included here because it again concerned a cat and a door at the bottom of the stairs) is of a house where the ratio of radon levels downstairs to upstairs was a record 20:1 prior to mitigation.

On the positive side, systems have proven successful in houses where these were more than usually airtight and where windows were kept shut, especially upstairs. Tests have indicated that opening windows on the first floor may result in air from a pressurisation fan 'short-circuiting' out of the window and failing to influence radon entry from the ground floor.

Provision of natural ventilation at ground floor level appears to have less effect on system performance. Nevertheless, radon levels in houses fitted with these systems (whether installed for condensation or radon control) may be highly dependent both upon the use of the house and upon any changes to the building envelope that alter its air tightness characteristics.

In spite of these problems, pressurisation systems are likely to remain one of the cheapest, most easily installed and potentially most effective of all options for radon remediation. Sometimes householders will commend systems for making the house 'fresher'. Amelioration of asthma symptoms has also been reported. The underlying problem in these cases may be mould and/or dampness, and could be addressed directly.

It is advisable to test houses prior to installation and to warn householders of the possible effect of innocent changes in window opening behaviour.

Running costs of the systems will be a few tens of pounds per year for electricity and between a few tens and over a hundred pounds per year in extra heating costs. It should be remembered that radon sump systems can incur similar costs.

More accurate estimates require knowledge of the fan flow rate 'in situ', the type of heating, and the severity of local winters. A minimum flow rate may be 100 m^3 per hour, representing perhaps 0.3 ach. During a wintertime with a temperature difference of 18 K the marginal cost using on-peak electricity would be about £1 per day, falling to around 35p per day with gas central heating. A typical heating season may be 1500 or 1800 degree-days, thus the seasonal cost could exceed £100, or be as low as £30. Some fans run at much higher flow rates. In all positive pressure systems, the net change in house ventilation may be less than the system flow rate because incoming draughts are excluded. [*]

62. Experience with ventilation provision.

This Section deals primarily with altering natural ventilation - the special case of positive pressurisation is covered in Section 61.

Reduction of indoor radon levels by altering building ventilation has been misreported and misunderstood in the UK. Amongst the key facts are:

Draughty houses can have high radon levels.

Well sealed houses can have low radon levels, even in high radon areas.

Application of draught-proofing and double glazing may increase or decrease indoor radon levels, depending upon the building design and the measurement location.

Opening windows or removing draught-proofing on different sides of a building may have different effects.

The most important effect of increased ventilation may be pressure equalisation, rather than increased ventilation rate. Reduction in indoor radon levels may reflect decreased radon entry rate.

Reduction of indoor radon levels by altering house ventilation is a viable mitigation method but is most applicable where initial levels are moderate and the building needs improved ventilation for condensation or odour control, having previously been too well sealed or where unused chimneys that were causing depressurisation can be blocked off. Factors of between 1 (no change) and 2 can be expected in many cases, but need to be confirmed.

Improved ventilation can obviously be used as a temporary method of reducing high radon levels until permanent action is taken, but again it needs to be confirmed that a useful reduction has occurred: simply leaving a window slightly open for a few hours every day may not significantly affect the 24 hour average level.

Nevertheless, dramatic short term reductions in indoor radon levels can sometimes be effected by opening a window a few mm (half an inch), but this cannot be recommended as a universal cure, if only because no change may occur in some buildings.

The most marked improvements effected by ventilation alone have involved cellar spaces and (more commonly) provision of more air-bricks under timber floors. Much depends on individual house details, especially the problems of timber floors (see Section 57). Large reductions (up to a factor of 10) have also been seen where heating systems have been changed (see Section 56) and where the principal effect has been in the mode of room ventilation.

However, the most pervasive influence of altering house ventilation rates is sometimes not so much on the whole house average radon level (averaged over all rooms) but on the room to room variation. Since radon levels are often assessed only by pairs of detectors (one upstairs, one downstairs), the result can be determined by window opening habits.

Bedroom radon levels may be more uniform than those in ground floor rooms. Large differences can often be ascribed to opening of one bedroom window for many hours per day (or night) as is common practice.

Key facts:

Improved ventilation may be acceptable as a permanent mitigation technique in some circumstances.

The most encouraging results may be expected where previously sealed underfloor spaces can be ventilated and where windows on the windward side of the house are selected for ventilation provision.

In many houses, changes in ventilation habits may shift the long term average radon level in a room either side of the action level.

[*]

63.1 Passive stack ventilation and the story of a radon project in the USA.

Passive stack vents may play an important role in radon remediation in the UK, but to date their potential has not been fully investigated. Their advantages include ease of installation (in many new houses and some existing dwellings) and low running costs. Only a small heating cost penalty may be incurred.

Passive stack vents may work best in situations where a previously unventilated underfloor area at a high radon concentration can be subjected to considerable dilution. This may occur in the case of 'solid' concrete floors also, but not where underfloor permeability is poor or where there is a large entry potential. In the first case the flow rate will be too small and in the second radon entry into the room will be little changed despite a moderate flow induced by a well designed vent.

Similar problems occur routinely even with large fans - see Section 52. The effectiveness of passive stack vent systems can therefore range from excellent to insignificant, even when applied to different rooms within the same house. If applied to a ventilated suspended floor they may show poor results because the fractional change in ventilation rate may be small.

Curious effects, and even an increase in indoor radon levels (although not yet observed) may be experienced if a system is installed to ventilate a sealed underfloor space such as a cellar, or a void beneath a suspended concrete floor. Much may depend on air flow paths into the space, as for timber floors which are known sometimes to exhibit perplexing behaviour.

However, performance in new houses with solid floors may be expected to be more consistent in those cases where dilution of radon levels can be produced at low flow rates. Performance may be determined to a large extent by the outlet design and position. This is because the other significant parameter, underfloor communication, may be arranged to be uniformly favourable, and new houses are not likely to be built above mine shafts.

It is unfortunate that these systems may deliver their full potential only occasionally, and only when installed with the benefit of good design. Despite almost insignificant application to date, it is likely that new houses may have them installed as standard in radon prone areas within a few years. In existing houses so much depends on diagnosis that fan systems may be preferred, and will remain essential in the worst cases.

In all cases, passive stack vent performance will be determined in part by outlet design, and insufficient may be known about this. The potential for improved performance may be greatest in windy areas - with Cornwall being an ideal location.

The rest of this Section describes the background to a passive stack project in the USA, if only to illustrate that bureaucracy is not unique to the UK.

In January 1990 Washington State legislature mandated radon control measures be implemented in key areas. These were determined by monitoring data obtained largely from existing houses. A county is now designated as 'affected by radon' if results averaged over 2 pCi/l - only 75 Bq/m^3.

During 1990 the State Building Code Council developed radon resistive construction standards to be incorporated in the interim State ventilation and indoor air quality code, a sub-code of the 1991 State Energy Code.

The proposed project sought a strengthened basis for determining future radon code requirements. In particular it sought evaluation of the effectiveness of passive systems, as these were already a prescriptive requirement for basement and slab-on-grade (solid floor) houses.

63.2 Passive stack ventilation and the story of a radon project in the USA.

It was recognised that passive stack vents have several important advantages that should be of interest to States developing radon control requirements. They are easier to install - and indeed to mandate - than active systems, they cost less to install, have no operating costs (see Section 39 for a discussion) and perhaps may provide significant radon reductions for the lifetime of the dwelling without any risk of being disabled by home owners.

However, there was limited data on the performance of passive stack vents especially with regard to their operation in existing dwellings. It was recognised (probably correctly) that their performance might vary markedly because of small design differences.

It was the aim to provide better technical guidance before ideas became crystallised within final State radon codes - and by implication for many other radon areas within the United States, many of which have quite different building designs and local construction preferences.

To this extent therefore, the position is more complicated than in the UK where a unified approach may develop.

Out of nearly 40 counties within the State, 8 had been identified as potentially high in radon. Within these, new build construction had to include a passive stack vent with suitable sub-slab aggregate. The interim Code provides for building inspectors to provide a track-etch detector with each new home - but it is left to the homeowner to decide whether to use it.

This approach is not recommended unless a delay period is used because house usage and performance may be atypical in the first few months of occupancy, including use of enhanced ventilation to remove fumes from paint and furnishings.

A comparison study was envisaged, to study passive stack vents in houses with a control group of houses without such devices. The number of variables involved was considerable, and included the substructure type (slab on grade, finished basement or an unfinished basement typical of speculative construction), geographical location and heating system degree days.

In addition, soil permeabilities were known to vary widely even across one building site or county, as were constructional details of individual houses, especially having regard to the type of primary heating system, with or without air conditioning.

However, at a crucial stage of the project, internal funding for State radon work was cut by around 50%. Partly as a result of these and other cuts the project was put at risk. An added complication was that the radon code was incorporated into the State Energy Code - one of the most progressive in the USA. Various pressure groups did not approve of the Energy Code, and they schemed to have the whole Code vetoed, or reworked (which would have introduced the delays many in the building industry wanted to see.)

Prior to 1991 approved radon demonstration projects only required about 25% of local (ie State) funding with around 75% being provided centrally by the EPA. However, almost coincidentally with the reduction in local funding for radon work, the EPA moved from a position of minority State funding for projects to requiring that typically 40% (1991) and 60% (1992) of funds for joint projects be provided locally.

EPA had become more conscious of handing out large sums of money around the United States and with very little local commitment to joint projects.

An update on the US radon position is likely to be published in 1993: see Section 2. [*]

64.1 Building Codes in the USA: the delegation of control.

Despite years of research, nationally derived radon codes for new residential construction have not been implemented in the United States. However, many large builders in the radon areas are voluntarily installing simple measures such as subslab aggregate and a membrane together with a passive stack vent.

This enables them to tell customers that if they wish to have the house checked for radon and if it is found to be affected, they can easily modify the passive system by means of a small fan in order almost certainly to reduce the levels significantly.

In the United States, there are three distinct sets of building codes and to some extent these are applied in different regions.

The Standard Code (The Southern Standard Building Code) has more emphasis on wind loading because it is used primarily in the parts of the US where storms are more prevalent.

The Uniform Building Code (International Conference of Building Officials) and the National Building Code (BOCA or Building Officials and Code Administrators) have emphasis on snow loads for the northern states and on seismic or building structure provisions for use in the western USA.

For one and two family dwellings, there is a fourth code which is subscribed to by the other three and represents essentially the only nationally accepted Building Code. There is a great deal of overlap between the provisions of these Codes, but there are differences.

A house in many regions may be constructed to one or another of the Codes depending much upon the preferences of the local building inspectors. Building inspection in some States is closely controlled, in other States is haphazard. Often this is a problem of staffing levels.

In the more outlying districts it is generally three years before Code requirements are widely enacted and it may be fifteen years before there is full implementation of building changes because inspectors have wide discretion, and there are usually let-out clauses within at least the first drafts of additions to any Code to allow for local discretion and for particular building practices.

EPA are working on a proposed Model Standard for new houses which could be considered for adoption by all the County and State bodies. However, there is no prospect of EPA being able to regulate across the United States for radon, no matter how much they might wish to do so. The Model Code that was published in draft form (for comment) is intended for use by code development organisations, States and local jurisdictions as they develop and enforce their local building codes. To some extent the EPA draft will be like the old Model Water Bye-laws in the UK with many parts being widely adopted but with freedom to implement local preferences.

It is often said that about 25% of the houses in the United States may have elevated radon levels; this may be owing to reliance on basement radon measurements and the true figure may be nearer to 7 or 8% based upon radon levels in the principal inhabited rooms.

There are around 60 million single family residences in the USA together with about 20 million apartments, giving a total of around 80 million. The build rate is traditionally around 1 million per year but seems likely to be below this for the next few years because of a recession.

The EPA will be delineating Counties and States within the US on the basis of expected radon levels in typical dwellings based very much upon geology and a knowledge of radon levels already found within existing dwellings. This is similar to the UK scheme, but see Section 54.

64.2 Building Codes in the USA: the delegation of control.

Within what are called Priority 1 areas it is envisaged that active systems will be required (but this does not mean that any County need abide by this ruling). The proposed Code will be a prescriptive standard but with no need for checking of radon levels after construction: it will simply be assumed that the active system will work adequately to reduce the radon levels to a very low value. If systems are installed correctly there is little reason to doubt this.

Within these Priority 1 areas (areas in which houses have above 75 Bq/m^3 in the living areas on average, and therefore broadly equivalent to Devon) would be delineated hot-spot areas in which houses were known to average over 150 Bq/m^3. No further requirements are envisaged in these areas, but they may be highlighted on the EPA colour coded maps and local officials encouraged to give particular attention to radon measures.

Within Priority 2 areas there will be no requirement to install active systems in new houses. However, there will be provision for testing of the passive systems (by monitoring indoor levels). Builders will be required to install a fan and (presumably) to re-test the system if levels are high.

In the Model Code the liability of the builder and local building officials will terminate at the end of these stages whether or not the indoor radon levels are low.

There is some discussion as to whether the prescriptive approach within the Priority 1 areas is correct because it may result in the installation of tens of thousands of fans in dwellings where they were not really necessary - because a passive system might have produced radon concentrations at an acceptable level.

The danger is that it may become a part of folklore that radon fans are often not necessary. Then the temptation may be not to operate them in all homes.

There is some support for the view that fans should only be installed where required, and with the possible long term advantage that people will come to associate them with a genuine need.

However, up to 100,000 houses may be constructed every year with radon fans simply because they are within Priority 1 areas. (This approach is favoured by fan manufacturers.)

EPA have undertaken cost-benefit analysis in respect of new build radon resistant construction. In some schemes, the installed cost of all the measures is only $200 to $400 per house.

A figure of $140,000 per life saved has resulted from some studies, but needs to be multiplied by a factor of at least 4 to give the non-smoker cost-benefit. The costs are then within the normal range of $300,000 to $9M per life saved that EPA have suggested that the public is willing to pay to reduce risks. It would be interesting to relate this to health costs and benefits in the USA: it has been reported that the Office of Management and Budget calculated the benefit of some EPA rules to be as extreme as $57 trillion per life saved!

Another interesting statistic is that EPA claim around 140 lives saved per year from one million new houses built to radon proof standards. Thus, were the entire housing stock of Devon and Cornwall (about 700,000) to be replaced by radon resistant construction (an assuming roughly equal average commencing radon levels) then perhaps around 80 lives per year could be prolonged, including around 15 to 20 non smokers.

Proper calculations need to consider realised average radon levels with and without radon resistant construction. Despite the emphasis within the EPA guidance on passive stack vents (so as to avoid undue use of fans) there is little evidence as yet of system effectiveness. This is being addressed under several research programs, but some have suffered cutbacks owing to lack of State funding. (see Section 63).

64.3 Building Codes in the USA: the delegation of control.

In what seems an act of marketing desperation, some radon reduction packages are being 'sold' on the basis of their providing better energy standards, because of the sealing work that is being undertaken. However, this may not be necessary for successful operation of passive and active systems.

Another way of selling the benefits of radon resistant construction is to claim that better fire resistance results - from the stopping up of gaps between ground and first floor levels. However, installation of a plastic pipe through a ceiling and without use of a fire damper would introduce an extra route for flame and smoke. This is not an idle point: in New Jersey a fatality occurred recently in a house known to the author and fitted with a radon system. Smouldering papers in the basement caught alight, the smoke detectors failed to work, the plastic pipes melted and the owner was asphyxiated. The radon system was not implicated as a prime cause of death.

There is considerable emphasis within the draft Code on construction methods to minimise pathways for soil gas to enter, reducing or negating any pressure differentials between indoors and outdoors, and on care in selection and use of HVAC systems. The guidance is in general terms only.

It is stressed that the EPA Model Code is only the basis for developing building codes for radon resistant construction that are appropriate to particular localities, and that these must be developed and implemented by Counties and States having jurisdiction.

It may be many years before radon resistant construction is the norm in radon-affected areas of the USA, and many years more before its effectiveness and cost-effectiveness is properly evaluated. [*]