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Radon Pollution Control

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1. INTRODUCTION

Human beings are exposed to two sources of radiation in the environment: natural and man-made. Natural sources include radioactive radon, radioisotopes with a long half-life, such as potassium in the body, cosmic rays (energetic γ-rays and particles from the sun and interstellar space), and some rocks. Various sources of artificial radiation include medical X-rays, nuclear medicine for cancer treatment, and some consumer products containing radioisotopes. Natural sources of radiation account for 82% of total exposure for humans. A common radioactive element is radium, one of whose decay products, radon, poses health concerns. Radon emanates from rock, soil, and underground water as a gas. In the solar system, various radioisotopes of radon gas form from decay of radioactive uranium and thorium elements found naturally. The contributing effects from natural and man-made radiation sources on human beings is shown in Fig. 1.

Radon emanating from soil fills the atmosphere but eventually transmutes to other elements and is removed. The concentration of radon gas reaches equilibrium because of this influx and outflux of gas in the atmosphere. However, the concentration of radon may show significant variation in closed living places. Inhalation of radioactive radon gas is a threat to public health. Homes built on granite and phosphate rocks containing uranium ore may expose their owners to health risks resulting from high radon concentrations. Homes with improved thermal insulation and minimum air circulation can be even more significant candidates for radon buildup.

Several important issues related to radon are introduced in the four sections of this chapter. Section 1 discusses radon and its decay products. Section 2 presents various instrumental methods of radon measurement. Section 3 focuses on the health effects of

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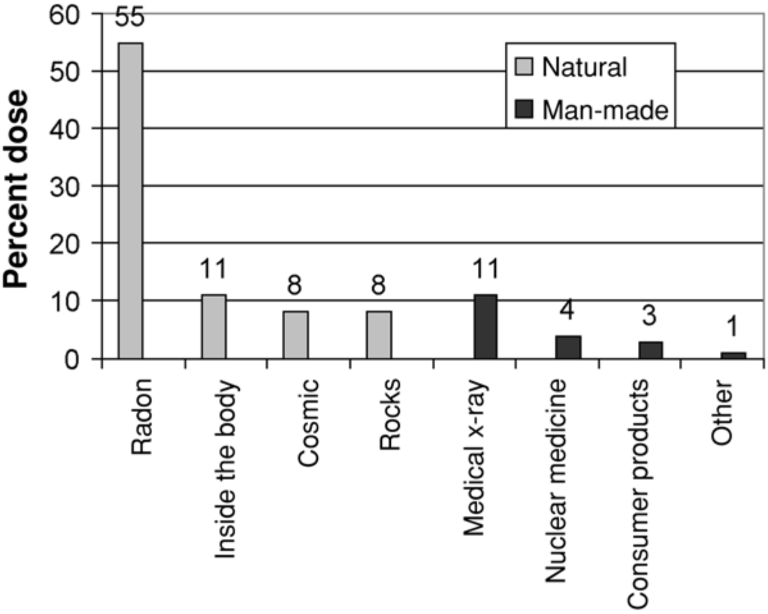

Fig. 1. Percent distribution radiation doses to humans from various sources (Cobb, C.E. (1989) Living with Radiation, *National Geographic*, **175**(4), pp 403–437).

low-level radioactivity of radon and its decay products. Finally, Section 4 discusses radon mitigation in buildings.

Radon (Rn) is a colorless, odorless, and tasteless inert gas, which decays to form a series of radioactive particles. An "isotope" of an element has the same number of protons (same atomic number) but a different number of neutrons and different mass number (total number of neutrons and protons). Some isotopes of an element may be radioactive and emit radiation from their nuclei. There are three principal kinds of radiation emission: α-, β-, γ-rays. γ-Rays are highly penetrating rays similar to X-rays. β-Rays are electrons traveling at high speeds. α-Rays are also particles; each α particle is composed of two protons and two neutrons—equivalent to a helium nucleus. Each time an α-ray is expelled from an atomic nucleus, the atom changes to a lighter, new element and the α-particle becomes a helium atom. If the new element is also radioactive, emission of radiation will continue until, eventually, stable, nonradioactive nuclides are formed.

1.1. *Units of Radioactivity*

The unit of radioactivity is expressed as disintegrations per second, in becquerel (Bq). The older, but commonly used unit of radioactivity is Curie (Ci). It is defined as the activity of 1 g of pure Ra-226 obtained from uranium. The activity in Ci is equal to 1 $\mathrm{Ci} = 3.7 \times 10^{10}$ Bq.

The decay of a radioisotope is described by an exponential law for first-order reaction:

$$A = -dN/dt = \lambda N \tag{1}$$

Here, A is the activity (in Bq), N is the number of radioactive atoms, λ is the decay constant, related to the half-life, and t is the time. The solution of this first-order rate equation yields an exponential relation:

$$N = N_0 e^{-\lambda t} \tag{2}$$

Here, N_0 is the number of atoms present initially at time $t=0$ and N is the number of atoms present at time t. The half-life of an isotope, $t_{1/2}$, is defined as the time necessary for the initial number of radioisotopes to decay into half of the initial number; that is, when the time is equal to the half-life $t=t_{1/2}$, the number of particles N will be equal to the half of the initial number of particles, $N= N_0/2$. The relation between the decay constant λ and the half-life $t_{1/2}$ is

$$\lambda = 0.693/t_{1/2} \tag{3}$$

The specific activity of the radioisotope is defined as the activity of 1 g of pure radioisotope. The specific activity of any radioisotope can easily be calculated from Eq. (1) provided its half-life is known. As an illustration, the specific activity of 1 g of U-238 can be calculated using its half-life of 4.47×10^9 yr, which is converted into seconds in the following calculation:

$$A = \lambda N = \frac{0.693}{4.47\times10^9\times365\times24\times3600}\left(\mathrm{s}^{-1}\right)\frac{1\times6.02\times10^{23}}{238}(\text{atoms})$$

$$A = 1.24\times10^5\ \mathrm{Bq/g\ U\text{-}238},\ \text{specific activity (activity of 1 g U-238)},$$

Here, 6.02×10^{23} is Avogadro's number, the number of atoms in 238 g (1 mol) of U. The activity of a trace amount of uranium in soil can be expressed in 1 kg soil if the abundance of uranium in the soil is known. The concentration of uranium in the soil is on the order of several parts per million (ppm, or gram of radioactive isotope in 1 ton of soil sample). Thus, the activity of uranium in 1 kg of soil, assuming 1 ppm uranium concentration, can be predicted as

$$A = 1.24\times10^5(\mathrm{Bq/g\ U})\times1\times10^{-6}(\mathrm{g\ U/g\ soil})\times1000\ (\mathrm{g\ soil/kg\ soil})$$

$$A = 124\ \mathrm{Bq/kg\ soil}$$

1.2. Growth of Radioactive Products in a Decay Series

Different radon isotopes are produced by the radioactive decay of radium, which results from the decay of uranium, U-238, U-235, and thorium, Th-232, which occur naturally in some rocks. Some examples of these reactions can be written as follows (· · · indicates the presence of other decay products):

Uranium series:

$$^{238}\mathrm{U}\rightarrow\ldots\ ^{226}\mathrm{Ra}\rightarrow{}^{4}\mathrm{He}+{}^{222}\mathrm{Rn}\rightarrow\ldots\ ^{206}\mathrm{Pb}\ \text{(stable)}$$

Thorium series:

$$^{232}\mathrm{Th}\rightarrow\ldots\ ^{224}\mathrm{Ra}\rightarrow{}^{4}\mathrm{He}+{}^{220}\mathrm{Rn}\rightarrow\ldots\ ^{208}\mathrm{Pb}\ \text{(stable)}$$

Actinium series:

$$^{235}\mathrm{U}\rightarrow\ldots\ ^{223}\mathrm{Ra}\rightarrow{}^{4}\mathrm{He}+{}^{219}\mathrm{Rn}\rightarrow\ldots\ ^{207}\mathrm{Pb}\ \text{(stable)}$$

Table 1
Isotopes in the U-238 Decay Series

Nuclide	Half-life	Decay particle
U-238	4.5×10^9 yr	α
Th-234	24 d	β
Pa-234	1.2 min	β
U-234	2.5×10^5 yr	α
Th-230	8×10^4 yr	α
Ra-226	1.6×10^3 yr	α
Rn-222	3.8 d	α
Po-218	3 min	α
Pb-214	27 min	β
Bi-214	20 min	β
Po-214	160 μs	α
Pb-210	22 yr	β
Bi-210	5 d	β
Po-210	138 d	α
Pb-206	Stable	

The uranium series starts with U-238 and ends with Pb-206. Each radioactive element has its own decay rate. The radioisotopes, decay modes, and half-lives of each decay product of the U-238 series are shown in Table 1.

In a decay series, radioisotopes have different modes of decay and different half-lives that may change many orders of magnitude from one isotope to the next. For example, the parent radioisotope U-238 in a uranium series decays to its daughter Th-234 by α-particle emission with a half-life of 4.47×10^9 yr, but another radioisotope in the same series, Ra-226, decays to Rn-222 by α-particle emission with a half-life of only 1600 yr.

In a decay series, if the daughter has a much shorter half-life than the parent and when radioisotopes of a decay series are kept together long enough (about five half-lives of the daughter), they reach the "secular equilibrium" and the parent and daughter radioisotope activitites become equal. For example, Ra-226 isolated from all of its decay products by selective precipitation would reach equilibrium after 8000 yr (five times the half-life of Ra-226) with its parent isotope U-238, and then they both will have the same activity. Similarly, Rn-222 ($t_{1/2}=3.8$ d) and its decay products Po-218 ($t_{1/2}=3$ min), Pb-214 ($t_{1/2}=27$ min), Bi-214 ($t_{1/2}=20$ min), Po-214 ($t_{1/2}=160$ μs) will reach the same activity after about 210 min. The change in the activity of radon and its shorter-lived decay products are illustrated in Fig. 2 in a time scale of 300 min, where initially only radon gas is permitted in a chamber passing through a filter. The activity of Rn-222 with $t_{1/2}=3.8$ d remains nearly constant in this time interval. However, the activities of shorter-lived decay products are initially zero, but the activity of Po-218 ($t_{1/2}=3$ min) will reach the same activity as Rn-222 in a time period less than 30 min and Po-214 ($t_{1/2}=19.7$ min) will attain the activity of Rn-222 in a time period of about 200 min.

The thorium decay series starts with Th-232 and ends with Pb-208, and the actinium series starts with U-235 and ends with Pb-207. Different isotopes of radon, Rn-222,

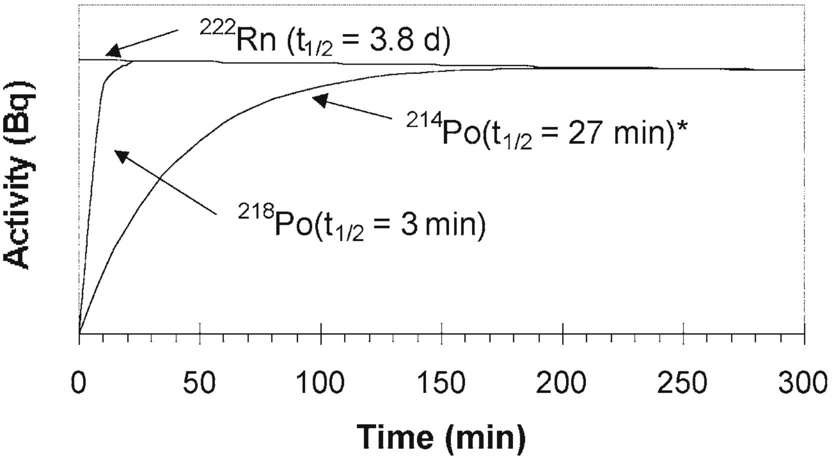

Fig. 2. The change in activity of Rn-222 ($t_{1/2}$=3.8 d) and its decay products Po-218 ($t_{1/2}$=3.1 min) and Po-214 ($t_{1/2}$=164 µs). Note: In a time scale of 300 min. Initially, radon is isolated from all its decay products (1).

Rn-220, and Rn-219, are produced in a decay series of uranium, thorium, and actinium, respectively. The half-lives of these Rn isotopes, Rn-219, Rn-220, and Rn-222, are 3.92 s, 54 s, and 3.82 d, respectively. As radon undergoes further radioactive decay, it produces a series of short-lived radioisotopes, known as radon "daughters" or "progeny." Because radon is a gas and a chemically inert element, it evolves from soil and underground water and decays to other radioactive elements in the series and finally transmutes to a stable lead isotope. The shorter half-lives of Rn-219 (3.92 s) and Rn-220 (54 s), compared to that of Rn-222 (3.82 d), make diffusion of the former into the above-ground air less probable (2). Consequently, Rn-222 is of most concern, and much of this gas can escape directly into outdoor air and contribute to the annual effective dose of ionizing radiation to humans (3). Steck et al. (4) found unusually high annual average outdoor Rn concentrations in parts of central North America and concluded that local soils may contribute to elevated outdoor Rn-222 concentrations, so such exposure should be included in epidemiological studies. Radon is potentially mobile and can diffuse through rock and soil to escape into the aboveground atmosphere. Radon formed in rocks and soils is released into the surrounding air. The amount of escaping radon varies enormously (5–7), depending on the geology (e.g., U content and its chemical form, degree of faulting), soil characteristics (e.g., permeability, moisture content), and climatic variables (e.g., temperature, humidity). Typical rates of radon release from soils throughout the world range from about 0.0002 to 0.07 Bq/(m^3s). Radon production rates from any soil are extremely dependent on the geological characteristics of the soil and its underlying geological strata (8). Porous soils overlaying uranium-rich alum shales, granite, and pegmatite rocks are a particularly high risk for radon, whereas gas-impermeable soils consisting of fine sand, silt, and moist clay present a low risk (9).

Outdoors, radon emanating from the ground is quickly dispersed, and concentrations never reach levels that can be a threat to health. Whereas radon gas can disperse quickly in open air, it can enter and accumulate in dwellings as a component of soil gas drawn from the soil by mass flow driven by the pressure difference between a house and soil beneath (10). According to Baird (11), most radon that seeps into homes comes from the top meter of the soil below and around the foundations. Inside confined areas, low rates of air exchange can result in a buildup of radon and its daughters to concentrations tens of thousands of times higher than those observed outside (12). Radon concentrations within a building depend very much on both the concentration of radon in the soil surrounding the structure and the presence of entry points that allow the gas to infiltrate from outside (13). Some of the common entry points of radon into buildings include foundation joints, cracks in floors and walls, drains and piping, electrical penetrations, and cellars with earth floors (14).

2. INSTRUMENTAL METHODS OF RADON MEASUREMENT

In the mid-1980s, widespread recognition of the health threat from radon exposure created the need for a standard of competency for radon service providers. In February 1986, the US Environmental Protection Agency (EPA or Agency) established the Radon Measurement Proficiency (RMP) Program (15) to assist consumers in identifying organizations capable of providing reliable radon measurement analysis services. The Radon Contractor Proficiency Program was established in 1989 to evaluate the proficiency of radon mitigators in residences and provide information on proficient mitigators to the public. In 1991, the EPA expanded the RMP Program, adding a component to evaluate the proficiency of individuals who provide radon measurement services in the home. In 1995, these programs were consolidated to form the Radon Proficiency Program (RPP). Presently, the RPP assesses the proficiency of these individuals and organizations and grants them a listing according to their measurement or mitigation service capabilities. RPP proficiency is determined for services involved with residential settings only and does not determine proficiency for services involving schools and other large buildings, radon in water, or radon in soil. The detectors used in measurements of radon gas and its progeny are summarized in Table 2 (15).

2.1. Radon Gas Measurement Methods

2.1.1. AC: Activated Charcoal Adsorption

For this method, an airtight container with activated charcoal is opened in the area to be sampled and radon in the air adsorbs onto the charcoal granule (16,17). At the end of the sampling period, the container is sealed and may be sent to a laboratory for analysis. The gamma decay from the radon adsorbed to the charcoal is counted on 1 scintillation detector and a calculation based on calibration information is used to calculate the radon concentration at the sample site. Charcoal adsorption detectors, depending on design, are deployed from 2 to 7 d. Because charcoal allows continual adsorption and desorption of radon, the method does not give a true integrated measurement over the exposure time. Use of a diffusion barrier over the charcoal reduces the effects of drafts and high humidity.

2.1.2. CR: Continuous Radon Monitoring

This method category includes those devices that record real-time continuous measurements of radon gas. Air is either pumped or diffuses into a counting chamber. The

Table 2
Radon Gas Measurement Methods in the Checklist of the EPA

	Radon gas measurement method
1. AC	Activated charcoal adsorption
2. CR	Continuous radon monitoring
3. AT	Alpha track detection (filtered)
4. UT	Unfiltered track detection
5. LS	Charcoal liquid scintillation
6. EL	Electret–ion chamber: long term
7. ES	Electret–ion chamber: short term
8. GC	Grab radon/activated charcoal
9. GB	Grab radon/pump-collapsible bag
10. GS	Grab radon/scintillation cell
11. SC	Evacuated scintillation cell (3-d integrating)
12. PB	Pump-collapsible bag
	Radon decay product measurement
13. CW	Continuous working level monitoring
14. GW	Grab working level
15. RP	Radon progeny integrating sampling unit

Source: ref. 15.

counting chamber is typically a scintillation cell or ionization chamber (18). Scintillation counts are processed by electronics, and radon concentrations for predetermined intervals are stored in the instrument's memory or transmitted directly to a printer.

2.1.3. AT: Alpha Track Detection (Filtered)

For this method, the detector is a small piece of special plastic or film inside a small container. Air being tested diffuses through a filter covering a hole in the container. When α particles from radon and its decay products strike the detector, they cause damage tracks (19–22). At the end of the test, the container is sealed and returned to a laboratory for reading. The plastic or film detector is treated to enhance the damage tracks and then the tracks over a predetermined area are counted using a microscope or optical reader. The number of tracks per area counted is used to calculate the radon concentration of the site tested. Exposure of alpha track detectors is usually 3–12 mo, but because they are true integrating devices, alpha track detectors may be exposed for shorter lengths of time when they are measuring higher radon concentrations.

2.1.4. UT: Unfiltered Track Detection

The unfiltered alpha track detector operates on the same principle as the alpha track detector, except that there is no filter present to remove radon decay products and other α- particle emitters. Without a filter, the concentration of radon decay products decaying within the "striking range" of the detector depends on the equilibrium ratio of radon decay products to radon present in the area being tested, not simply the concentration of radon. Unfiltered detectors that use cellulose nitrate film exhibit an energy dependency that causes radon decay products that plate out on the detector not to be recorded. This phenomenon lessens but does not totally compensate for the dependency of the calibration factor on equilibrium ratio. For this reason, the EPA currently recommends that these devices not be used when the equilibrium fraction is less than 0.35 or greater than 0.60 without adjusting the calibration factor. The EPA is currently evaluating this device further to determine more precisely the effects of equilibrium fraction and other factors on performance. These evaluations will lead to a determination as to whether to finalize the current protocol or remove the method from the list of program method categories.

2.1.5. *LS: Charcoal Liquid Scintillation*

This method employs a small vial containing activated charcoal for sampling the radon. After an exposure period of 2–7 d (depending on design), the vial is sealed and returned to a laboratory for analysis. Although the adsorption of radon onto the charcoal is the same as for the AC method, analysis is accomplished by treating the charcoal with a scintillation fluid, then analyzing the fluid using a scintillation counter.

2.1.6. *EL: Electret–Ion Chamber: Long Term*

For this method, an electrostatically charged disk detector (electret) is situated within a small container (ion chamber). During the measurement period, radon diffuses through a filter-covered opening in the chamber, where the ionization resulting from the decay of radon and its progeny reduces the voltage on the electret. A calibration factor relates the measured drop in voltage to the radon concentration. Variations in electret design determine whether detectors are appropriate for making long-term or short-term measurements. EL detectors may be deployed for 1–12 mo. Because the electret–ion chambers are true integrating detectors, the EL type can be exposed at shorter intervals if radon levels are sufficiently high.

2.1.7. *ES: Electret–Ion Chamber: Short Term*

This method is similar to Electret-Ion Chamber for long term measurement (EL) described in Section 2.1.6, but ES detectors may be deployed for 2–7 d. Because electret–ion chambers are true integrating detectors, the ES type can be exposed at longer intervals if radon levels are sufficiently low.

2.1.8. *GC: Grab Radon/Activated Charcoal*

This method requires a skilled technician to sample radon by using a pump or a fan to draw air through a cartridge filled with activated charcoal. Depending on the cartridge design and airflow, sampling takes from 15 min to 1 h. After sampling, the cartridge is placed in a sealed container and taken to a laboratory where analysis is approximately the same as for the AC or LS methods.

2.1.9. *GB: Grab Radon/Pump-Collapsible Bag*

This method uses a sample bag composed of material impervious to radon. At the sample site, a skilled technician fills the bag with air using a portable pump and then transports it to the laboratory for analysis. Usually, the analysis method is to transfer air from the bag to a scintillation cell and perform analysis in the manner described for the grab radon/scintillation cell (GS) method in Section 2.1.10.

2.1.10. GS: Grab Radon/Scintillation Cell

For this method, a skilled operator draws air through a filter to remove radon decay products into a scintillation cell either by opening a valve on a scintillation cell that has previously been evacuated using a vacuum pump or by drawing air through the cell until air inside the cell is in equilibrium with the air being sampled; it is then sealed. To analyze the air sample, the window end of the cell is placed on a photomultiplier tube to count the scintillations (light pulses) produced when α particles from radon decay strike the zinc sulfide coating on the inside of the cell. A calculation is made to convert the counts to radon concentrations.

2.1.11. SC: Three-Day Integrating Evacuated Scintillation Cell

For this method, a scintillation cell is fitted with a restrictor valve and a negative pressure gage. Prior to deployment, the scintillation cell is evacuated. At the sample site, a skilled technician notes the negative pressure reading and opens the valve. The flow through the valve is slow enough that it takes more than the 3-d sample period to fill the cell. At the end of the sample period, the technician closes the valve, notes the negative pressure gage reading, and returns with the cell to the laboratory. Analysis procedures are approximately the same as for the GS method described above. A variation of this method involves use of the above valve on a rigid container requiring that the sampled air be transferred to a scintillation cell for analysis.

2.1.12. PB: Pump-Collapsible Bag

For this method, a sample bag impervious to radon is filled over a 24-h period. This is usually accomplished by a pump programmed to pump small amounts of air at predetermined intervals during the sampling period. After sampling, analysis procedures are similar to those for the GB method.

2.2. Radon Decay Product Measurement Methods

2.2.1. CW: Continuous Working Level Monitoring

This method encompasses those devices that record real-time continuous measurement of radon decay products. Radon decay products are sampled by continuously pumping air through a filter. A detector such as a diffused-junction or surface-barrier detector counts the α particles produced by radon decay products (23) as they decay on this filter. The monitor typically contains a microprocessor that stores the number of counts for predetermined time intervals for later recall. Measurement time for the program measurement test is approximately 24 h.

2.2.2. GW: Grab Working Level

For this method, a known volume of air is pulled through a filter, collecting the radon decay products onto the filter. Sampling time usually is 5 min. The decay products are counted using an alpha detector. Counting must be done with precise timing after the filter sample is taken.

2.2.3. RP: Radon Progeny (Decay Product) Integrating Sampling Unit

For this method, a low-flow air pump pulls air continuously through a filter. Depending on the detector used, the radiation emitted by the decay products trapped on the filter is registered on two thermoluminescent dosimeters (TLDs), an alpha track detector, or an electret. The devices presently available require access to a household electrical supply, but do not require a skilled operator. Deployment simply requires turning the device on at the start of the sampling period and off at the end. The sampling period should be at least 72 h. After sampling, the detector assembly is shipped to a laboratory where analysis of the alpha track and electret types is performed. The TLD detectors are analyzed by an instrument that heats the TLD detector and measures the light emitted. A calculation converts the light measurement to radon concentrations.

In the open environment, radon concentration varies considerably, but an average is taken as 7.4 Bq/m^3 (24). The average radon concentration is about 20 Bq/m^3 in UK homes and 50 Bq/m^3 in US homes. The ranges of all instrumental techniques are sensitive enough to measure the indoor and outdoor radon concentration. Usually, passive methods are used for monitoring average radon concentrations in dwellings, but active methods are preferred for studying the mechanisms of radon dynamics.

3. HEALTH EFFECTS OF RADON

The above-ground atmosphere is a significant source of radon exposure, although the gas is derived through the radioactive decay of U-238 and Th-232 in rock and soil minerals (25). Baird (11) states that Rn-222 by itself does not pose much danger to people because it is inert and because most of it is exhaled after inhalation. By comparison, the daughter isotopes (the progeny), Po-214 and Po-218 in particular, are electrically charged, adhere to dust particles, and are inhaled either directly or through their attachment to airborne particles (26) to cause radiation damage to the bronchial cells. Once inhaled, they tend to remain in the lungs, where they may eventually cause cancer (27,28).

It was not until the early 1970s that this potential hazard from the inhalation of radon gas and the daughter progeny in the domestic environment was first identified. In the past, contamination of air by radon and subsequent exposure to radon daughters were believed to be a problem only for uranium and phosphate miners. However, it has recently been recognized that homes and buildings far away from uranium or phosphate mines can also exhibit high concentrations of radon. Subsequently, radon and radon progeny are now recognized as important indoor pollutants (8).

Radon exposure has been linked to lung carcinogenesis in both human and animal studies. It has also been associated with the development of acute myeloid and acute lymphoblastic leukemia and other cancers (29). However, the estimation of health risks from residential radon is extremely complex and encompasses many uncertainties. Studies on smoking and nonsmoking uranium miners indicate that radon at high concentrations is a substantial risk factor for lung cancer. Based on data regarding dose–response relationships among miners, it is estimated that between 5% and 15% of lung cancer deaths might be associated with exposure to residential radon (30). The relevance of data from mines to the lower-exposure home environment is often questioned (31). Nevertheless, a meta-analysis of eight epidemiological studies undertaken (32) found that the dose–response curve associated with domestic radon exposures was remarkably similar to that observed among miners.

Ecological (geographical) study designs have been adopted by a number of recent epidemiological investigations into the health risks associated with nonindustrial radon exposures. Lucie (33) reported positive county-level correlations between radon exposure and mortality from acute myeloid leukemia in the United Kingdom, and Henshaw et al. (29) found that mean radon levels in 15 counties were significantly associated with the incidence of childhood cancers and, specifically, all leukemias. However, these reports have been met with considerable criticism because ecological designs can suffer from serious limitations (34). In particular, the effects of migration are often difficult to account for, information on potential confounding variables can be unavailable, and estimates of exposure for populations of large areas may differ greatly from actual individual doses. More refined ecological analyses, such as that undertaken by Etherington et al. (35), have reported no association between indoor radon exposure and the occurrence of cancer.

An alternative to ecological analyses is the case-control study design, in which radon exposures among individuals with cancer are compared to those of control subjects free from the disease. Most case-control studies have reported a small but significant association between radon exposure and lung cancer mortality. For example, in a recent examination of more than 4000 individuals in Sweden, Lagarde et al. (36) estimated that there is an excess relative risk of contracting lung cancer of between 0.15 and 0.20 per 100 Bq/m^3 increase in radon exposure.

The radon (progeny) concentration in indoor air is responsible for the largest contribution to the natural radiation exposure to people. This fact and the knowledge of the enhanced lung cancer rate in cohorts exposed to high radon concentrations have raised the question about the lung cancer risk for the population caused by radon in the domestic environment. The National Research Council published in its 1988 report (4th Committee on Biological Effects of Ionizing Radiation, BEIR IV) on a lung cancer risk model mainly based on epidemiological studies of lung cancer rates among underground miners (37). The cancer risk of radon among miners is greater than other population groups. In a study regarding Czech Republic miners, 1323 cytogenetic assays and 225 subjects were examined. Chromatid breaks were the most frequently observed type of aberration and the frequency of aberrant cells was correlated with radon exposure. A 1% increase in the frequency of aberrant cells was paralleled by a 62% increase in the risk of cancer. An increase in the frequency of chromatid breaks by 1 per 100 cells was followed by a 99% increase in the risk of cancer (38).

A new report (BEIR VI) entitled “Health Effects of Exposure to Radon” is a re-examination and a reassessment of all relevant data. Compared with the 1988 report, much more information was available (39). Again, the BEIR VI committee based their lung cancer risk model primarily on miner studies (empirical approach) because of principal difficulties in the dosimetric approach (lung model, atomic bomb survivors) and the biologically motivated approach (tissue growth, cell kinetic). Epidemiological studies on lung cancer and radon exposure in homes give limited information because of the overwhelming cancer risk from smoking (responsible for 90–95% of all lung cancer cases). In the development of an empirical risk model to describe rates of radon-induced lung cancer, several assumptions are needed. It is not only the shape of the exposure–response function but also the factors that influence risk that must be modeled to extrapolate the risk from the radon exposure of miners to the radon situation in homes. Usually, the radon concentrations in mines are one magnitude higher than in common houses; however, the highest concentrations in homes often reach values as high as those in mines.

The committee adopts a linear, no-threshold, relative-risk model with different weighting factors for exposures 5–14, 15–24, and more than 24 yr ago and two effect-modification factors (attained age and exposure rate indexed either in duration of exposure or in exposure rate). From the individual ERR (excess relative risk), a lifetime relative risk (LRR) and a population attributable risk (AR) are deduced. The latter indicates how much of the lung cancer burden could, in theory, be prevented if all exposures to radon were reduced to the background level of radon in the outdoor air.

During the development of the risk model, combined effects of smoking and radon were also extensively discussed. Finally, the committee preferred to use a submultiplicative relationship to describe the synergistic effects between these carcinogens. The committee could not identify strong evidence indicative of differing susceptibility to lung carcinogens by sex. No clear indication of the effect of age on exposure could be identified and only for infants (age 1 yr) was a slightly higher risk (+8%) adopted. Despite sophisticated analyses of existing data, the committee states that, for the extreme low-exposure region mainly, the mechanistic basis of cancer induction supports the linear, no-threshold model. However, there is also the possibility of a nonlinear relation, or even a threshold below which no additional lung cancer risk exists.

Compared with the BEIR IV report, the improved risk model gives slightly higher risks for lung cancer from radon exposure. Thus, in the United States, the estimated attributable risk (AR) for lung-cancer death from domestic exposure to radon raised from approx 8% to 10% in the exposure age–duration model and even to 15% in the exposure age–concentration model. This means that a total of 15,000–20,000 lung cancer deaths per year were attributable to indoor residential radon progeny exposure in the United States. Although the models used are the most plausible to date, it must be emphasized that these numbers are derived by extrapolation from generally substantially higher exposures. Presently, there is no way to validate these estimates (39,40).

The extent of the radon problem will vary globally, and in equatorial areas where domestic conditions are usually different, the indoor level of Rn-222 and its daughters is likely to be considerably lower than in the northern regions. In the latter areas, the radon problem can be evaluated by making reference to the United Kingdom. Here, surveys have shown that 100,000 houses built on certain types of ground mostly in Cornwall and Devon and in some parts of Derbyshire, Northamptonshire, Somerset, Grampian, and the Highlands of Scotland are more likely to have high indoor radon levels. Southwest England (i.e., Cornwall and Devon) is particularly affected; 53% of UK homes were estimated to contain a concentration of Rn-222 above the action level of 200 Bq/m^3. The granites found in this region have relatively high uranium content and are suitably jointed and fractured to generate a high radon emanation rate. Varley and Flowers (41) showed that soil gas concentrations over the granites were twice that found in soils above other rocks and, as expected, homes located in granite regions had the highest indoor radon levels. It was estimated that residential radon is responsible for approx 1 in 20 cases of lung cancer deaths in the United Kingdom (approx 2000 per year). The first direct evidence for the link between residential radon and lung cancer has been published relatively recently (although not without some controversy [*see* Miles et al. (42)] and agrees with these figures (43). Working in southwest England, these authors found that the relative risk of lung cancer increased by 8% per 100 Bq/m^3 increase in the residential radon concentration.

In the United States, results of 19 studies of indoor radon concentrations are summarized (44), covering 552 single-family homes. They determined that the mean indoor concentration as 56 Bq/m^3. As part of the more recent US National Residential Radon Survey, Marcinowski et al. (45) estimated an annual average radon concentration of 46.3 Bq/m^3 in US homes. They also calculated that approximately 6% of homes had radon levels greater than the US Environmental Protection Agency (EPA) action level for mitigation of 148 Bq/m^3. Exposure to high concentrations of radon progeny produces lung cancer in both underground miners and experimentally exposed laboratory animals. The goal of the study was to determine whether or not residential radon exposure exhibits a statistically significant association with lung cancer in a state with high residential radon concentrations. A population-based, case-controlled epidemiological study was conducted examining the relationship between residential radon gas exposure and lung cancer in Iowa females (46) who occupied their current home for at least 20 yr. The study included 413 incident lung cancer cases and 614 age–frequency-matched controls. Participant information was obtained by a mailed-out questionnaire with face-to-face follow-up. Radon dosimetry assessment consisted of five components: (1) on-site residential assessment survey; (2) on-site radon measurements; (3) regional outdoor radon measurements; (4) assessment of subjects' exposure when in another building; and (5) linkage of historic subject mobility with residential, outdoor, and other building radon concentrations. Histologic review was performed for 96% of the cases. Approximately 60% of the basement radon concentrations and 30% of the first-floor radon concentrations of study participants' homes exceeded the US EPA Action Level of 150 Bq/m^3 (4 pCi/L). Large areas of western Iowa had outdoor radon concentrations comparable to the national average indoor value of 55 Bq/m^3 (1.5 pCi/L). A positive association between cumulative radon gas exposure and lung cancer was demonstrated using both categorical and continuous analysis. The risk estimates obtained in this study indicate that the cumulative radon exposure presents an important environmental health hazard.

Outside of the United States Albering et al. (47) found a much higher average concentration of 116 Bq/m^3 in 116 homes in the township of Visé in a radon-prone area in Belgium. In Italy, Bochicchio et al. (48) reported an average concentration of 75 Bq/m^3 in a sample of 4866 dwellings and observed concentrations exceeding 600 Bq/m^3 in 0.2% of homes. Yu et al. (49) recently undertook one of the relatively few studies of radon concentrations in the office environment. In 94 Hong Kong office buildings, they recorded radon concentrations similar to those that have been observed in domestic situations, with a mean of 51 Bq/m^3.

As activities such as the smoking of cigarets can lead to considerably elevated levels of airborne particles, smokers are at particular risk from the inhalation of radon progeny (50). Indeed, the US EPA has estimated that the cancer risk from radon for smokers is as much as 20 times the risk for individuals who have never smoked (*see* Table 3) (51).

4. RADON MITIGATION IN DOMESTIC PROPERTIES

The most enhanced research on the radon problem has been carried out in the United States. The US EPA and the US Geological Survey have evaluated the radon potential in the United States and have developed a map to assist national, state, and local organizations to target their resources and to assist building-code officials in deciding whether radon-resistant features are applicable in new construction. The map was

Table 3
Radon Risks for Dying as a Result of Lung Cancer for Smokers and NonSmokers Exposed to Different Radon Levels During Lifetime and Remedies

Radon level (Bq/m^3)	Ratio of smokers/nonsmokers out of 1000 exposed to this level over a lifetime who could die from lung cancer	What to do: Stop smoking and . . .
750	135/8	Fix your home.
375	71/4	Fix your home.
300	57/3	Fix your home.
150	29/2	Fix your home.
75	15/1	Consider fixing between 75 and 150 Bq/m^3.
50	9/less than 1	Reducing radon levels below 75 Bq/m^3 is difficult.
15	3/less than 1	

Source: ref. 57.

developed using five factors to determine radon potential: indoor radon measurements, geology, aerial radioactivity, soil permeability, and foundation type. Radon potential assessment is based on geologic provinces. The Radon Index Matrix is the quantitative assessment of radon potential. The Confidence Index Matrix shows the quantity and quality of the data used to assess radon potential. Geologic Provinces were adapted to county boundaries for the Map of Radon Zones. The map can be accessed from the EPA website (www.epa.gov/iaq/radon/zonemap). EPA's Map of Radon Zones assigns each of the 3141 counties in the United States to one of three zones based on radon potential:

- Zone 1 counties have a predicted average indoor radon screening level greater than 148 Bq/m^3 (4 pCi/L).
- Zone 2 counties have a predicted average indoor radon screening level between 74 and 148 Bq/m^3 (2–4 pCi/L).
- Zone 3 counties have a predicted average indoor radon screening level less than 74 Bq/m^3 (2 pCi/L).

Since the mid-1980s, the United States has made significant progress in reducing the risk from exposure to radon. This progress is the result of a long-term effort among the EPA, the public, nonprofit organizations, state and local governments, the business community, and other federal agencies working together. More Americans are knowledgeable about radon than at any time since the mid-1980s, when radon became a national health concern. Approximately two-thirds (66%) of Americans are generally aware of radon, and of those, three-quarters (75%, on average) understand that radon is a health hazard. Since the mid-1980s, about 18 million homes have been tested for radon and about 500,000 of them have been mitigated. Approximately 1.8 million new homes have been built with radon-resistant features since 1990. The EPA will continue to focus its efforts and those of its partners on achieving actual risk reduction through the mitigation of existing homes and the building of new homes to be radon resistant. The EPA's estimates of risk reduction are predicated upon mitigation systems being properly installed, operated, and maintained. As a result of these actions to reduce radon levels in homes through 1999, the EPA estimates that approx 350 lung cancer deaths will be prevented each year. This annual rate is expected to rise as radon levels are lowered in more new and existing homes.

The 1988 Indoor Radon Abatement Act (IRAA) required the EPA to develop a voluntary program to evaluate and provide information on contractors that offer radon control services to homeowners. The Radon Contractor Proficiency (RCP) Program was established to fulfill this portion of the IRAA. In December 1991, the EPA published "Interim Radon Mitigation Standards" as initial guidelines for evaluating the performance of radon mitigation contractors under the RCP Program. The effectiveness of the basic radon mitigation techniques set forth in the "Interim Standards" has been validated in field applications throughout the United States. This experience now serves as the basis for the more detailed and final Radon Mitigation Standards (RMS) presented in that document. A detailed document on RMS can be found on the EPA's website (www.epa.gov/iaq/radon/pubs/graphics/mitstds). The RMS provides radon mitigation contractors with uniform standards to ensure quality and effectiveness in the design, installation, and evaluation of radon mitigation systems in detached and attached residential buildings three stories or fewer in height. The RMS is intended to serve as a model set of requirements that can be adopted or modified by state and local jurisdictions to fulfill objectives of their specific radon contractor certification or licensure programs.

The American Society of Home Inspectors (ASHI) recommends that homeowners and home buyers test their current or prospective home for the presence of radon gas in indoor air. The EPA strongly recommends that steps be taken to reduce indoor radon levels when test results are 148 Bq/m^3 (4 pCi/L) or more of radon in the air. A radon mitigation system inspection checklist can be obtained from the website (www.epa.gov/radon/risk_assessment_factsheet.html).

Radon moves up through the ground to the air above and into homes through cracks and other holes in the foundation. Homes may trap radon inside, where it can build up. Any home may have a radon problem. This means new and old homes, well-sealed and drafty homes, and homes with or without basements (51). Radon from soil gas is the main cause of radon problems. Sometimes, radon enters the home through well water. In a small number of homes, the building materials can give off radon, too. However, building materials rarely cause radon problems by themselves.

Radon problem in homes can be attributed to the following sources:

1. Soil around the house
2. Cracks in solid floors
3. Construction joints
4. Cracks in walls
5. Gaps in suspended floors
6. Gaps around service pipes
7. Cavities inside walls
8. The water supply

Nearly 1 out of every 15 homes in the United States is estimated to have elevated radon levels. Although radon problems may be more common in some areas, any home may have a problem. The only way to know about the radon level in a home is to test. There are two general ways to test for radon in homes:

> *Short-term testing*: The quickest way to test is with short-term tests. Short-term tests remain in a home for 2–90 d, depending on the device. "Charcoal canisters," "alpha track," "electret–ion chamber," "continuous monitors," and "charcoal liquid scintillation" detectors (15) are most commonly used for short-term testing. Because radon levels tend to vary from day to day and season to season, a short-term test is less likely than a long-term test to give a year-round average radon level. If one needs results quickly, however, a short-term test followed by a second short-term test may be used to decide whether to fix a home.
>
> *Long-term testing*: Long-term tests remain in a home for more than 90 d. "Alpha track" and "electret" detectors are commonly used for this type of testing. A long-term test will give a reading that is more likely to indicate a home's year-round average radon level than a short-term test

The EPA recommends the following testing steps:

1. Take a short-term test. If the result is 148 Bq/m^3 (4pCi/L) or higher (0.02 working levels [WL] or higher) take a follow-up test (Step 2) to be sure.
2. Follow up with either a long-term test or a second short-term test:

   - For a better understanding of year-round average radon level, take a long-term test.
   - If the results are needed quickly, take a second short-term test.

   The higher the initial short-term test result, the more certain one can be that a short-term rather than a long-term follow-up test should be taken. If the first short-term test result is several times the action level (e.g., about 370 Bq/m^3 [10 pCi/L] or higher), one should take a second short-term test immediately.

3. If followed up with a long-term test, fix the home if the long-term test result is 148 Bq/m^3 (4 pCi/L) or more (0.02 WL or higher).

   If followed up with a second short-term test, the higher the short-term results, the more certain one can be that the home should be fixed. Consider fixing the home if the average of first and second test is 148 Bq/m^3 (4 pCi/L) or higher (0.02 WL or higher).

High radon concentrations in dwellings can be reduced to acceptable levels by using various techniques. A homeowner may wonder whether his house has a high potential of radon concentration as a result of the mineral composition of the location, building material used in construction, or the condition of house. The radon concentration can be measured to determine the seriousness of the condition. If high radon levels are found, some remedial measures can be implemented. Radon problems may be handled most efficiently during construction through some low-cost modifications to common practices. As air space is improved in new houses for better thermal insulation, radon buildup in the house may become a serious problem.

This section discusses a number of radon concentration control methods. Control measures may be classified as the following: removal of a source containing high uranium concentration around the house, modification of source material that gives off radon isolated from the indoor air, ventilation of indoor air, and air cleaning by some physical or chemical methods. Several methods are available to contractors for lowering radon levels in homes. Methods preventing radon from entering homes are preferred to methods that reduce radon levels after it has entered homes. For example, soil suction can be used to prevent radon from entering homes by drawing the radon from below the house and venting it through a pipe or pipes to the air above the house for dilution (52).

4.1. Source Removal

The soil around the outside of a house is the most common source of radon. Removal of sources is the first logical option, but it is frequently expensive, especially for existing houses. The following discussion describes source removal for both new and existing houses.

The removal of high-radium-content soil around a house requires replacement with new soil and should have low diffusion for soil gas flow. Fractional reduction of radon flux for a 10-ft cover thickness of a nonuraniferous fill material is 80% (53). The main disadvantage of this method lies in the initial capital for excavation of the site and extra earth-moving costs for replacement with the chosen fill material. If a building was constructed inadvertently from high-uranium-content material, the slabs could be replaced by a new one containing nonuraniferous material. If the fill material is not a strong source of radon, sealants may be used to close cracks and openings in the slab, or acceptable radon levels may be reached by increasing ventilation moderately. In these cases, the costs of removal must be balanced against increased ventilation costs or the costs of a sealing program.

4.2. Contaminated Well Water

Radon concentration in water is typically of the order of 100 Bq/L (several thousand picocuries per liter). Thus, use of such water could be an important radon source. Surveys of US drinking water sources indicate that 74% had radon concentrations below 100 Bq/L and only 5% had values above 400 Bq/L. The problem may be the result of deep-drilled wells and a concentration of 400 Bq/L will increase the indoor radon concentration by about 0.04 Bq/L.

Contaminated well water can be a major source of radon in both planned and existing structures. The safety limit of Ra-226 and Ra-228 (total) in drinking water is 0.18 Bq/L (5 pCi/L). The EPA published the safety limits of drinking water on its website (www.epa.gov/safewater/mcl.html). Municipal and surface water can be substituted for the contaminated well water. If the replacement of well water with a cleaner source is not possible, various water-treatment methods should be considered. Decay products of radon can be removed if water is kept in a storage tank long enough so that all short-lived products die out (54). A holding time of 19 or 31 d is required for 96.9–99.6% removal. The tank may be compartmentalized to prevent back mixing. Spray aeration of contaminated well water increases the rate of desorption of radon by increasing the surface area for mass transport across the water–air interface. The disadvantage of this method is use of exhaust ventilation for the process, as well as higher capital and operating costs.

Granulated activated carbon may be used to process radon-contaminated water. Although the carbon filter requires regeneration, the decay of radon may enhance the lifetime of the filter. Because of the low capital cost of a carbon filter, it is recommended for single-home applications. The spray aeration method is more economical for multiple dwellings (55).

4.3. *Building Materials*

In the past, it was thought that building materials were the principal sources of indoor radon (56). However, most recent studies have shown that with the exception of some unusual materials such as Swedish alum shale concrete, the effect of building materials on indoor radon is small. However, significant amounts of radon are emitted from materials with an elevated radium level have been found in phosphogypsum wallboards and concrete containing alum shale. Although not quite as high, elevated radium concentrations have also been found in concrete containing fly ash and some bricks (57).

4.4. *Types of House and Radon Reduction*

Different types of house will affect which radon-reduction system is selected. Houses are normally categorized according to the foundation design. These may include basement, slab-on-grade, which has concrete poured at ground level, or crawl space, which has a shallow unfinished space under the first floor. Different house foundation types are illustrated in Fig. 3. Some houses may have more than one foundation design feature and may require a combination of radon-reduction techniques in order to reduce radon levels below 4 pCi/L (0.15 Bq/L).

> *Basement and slab-on-grade houses*: Four types of soil suction methods can be used to reduce radon concentration for houses that have a basement or a slab-on-grade foundation. These include subslab suction, drain tile suction, sump hole suction, or block wall suction.
>
> Active subslab suction (also called subslab depressurization) is usually the most reliable radon reduction method. Suction pipes are inserted through the floor slab into the crushed rock or soil underneath. A fan that is connected to the pipes draws the radon gas from below the house and releases it to the outdoor air. Passive subslab suction is similar to the active subslab suction except it depends on air currents instead of a fan to draw radon gas up from below the house. Passive subslab suction is usually not as effective in reducing high radon levels compared to the active subslab suction method. For houses that have drain tiles to direct water away and form a complete loop around the foundation, suction on these drain tiles can be used to reduce radon levels. If a house with a basement has a sump pump to remove unwanted water, the sump can be capped so that it can continue to drain water and serve as the location for a radon suction pipe. Block wall suction can be used in houses with basements and hollow block foundation walls. This method can remove radon from the hollow spaces within the basement's concrete block wall and is often used together with subslab suction.
>
> *Crawl-space houses*: In houses with crawl spaces, radon levels can sometimes be lowered by ventilating the crawl space passively or actively. Crawl-space ventilation reduces indoor radon levels by reducing the home's suction on the soil and by diluting the radon beneath the house. Passive, or natural, ventilation in a crawl space is achieved by opening vents or by installing additional vents. Active ventilation uses a fan to blow air through the crawl space. In colder climates, the water pipes in the crawl space need to be insulated against the cold.
>
> A second method of crawl-space ventilation involves covering the earth floor with a heavy plastic sheet. A vent pipe and fan can be used to draw the radon from under the sheet and vent it to the outdoor air. This type of soil suction is called submembrane depressurization.

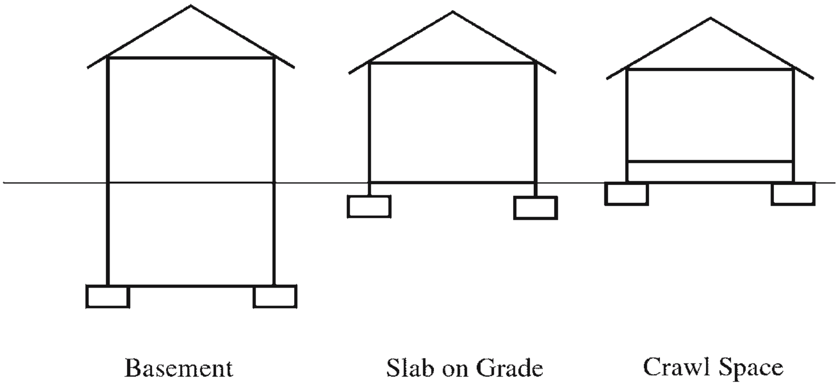

Fig. 3. House Foundation Types: basement, slab-on-grade, and crawl space.

An example for crawl-space ventilation is the village of Varnhem, Sweden, where the soil is permeable gravel containing alum shale with an elevated activity of uranium (58). The crawl space was ventilated separately from the ventilation of the dwelling. The concentration of radon was measured between 122,000 and 340,000 Bq/m^3 in the capillary breaking layer. However, the radon activity dropped down to 70–240 Bq/m^3 after ventilation. The modification in design added approx 4% to the building cost. Moreover, there was no conflict between energy conservation and radon protective or safe design. Radon-safe construction can be made as energy efficient as conventional design. Energy conservation by increased tightness of the building and very low air-exchange rates must be discouraged because of its effect on indoor air quality and humidity even without regard to radon. In order to avoid strong negative pressure indoors, heat exchangers with balanced ventilation are preferred to exhaust ventilation with a heat exchanger.

Other types of radon-reduction methods: Other radon reduction methods applicable to houses consist of sealing, house pressurization, natural ventilation, and heat recovery ventilation. Most of these methods are either temporary measures or only partial solutions to be used in combination with other methods.

Sealing cracks and other openings in the foundation is a common element of most approaches to radon reduction. It limits the flow of radon into the home and it also reduces the loss of conditioned air, thereby making other radon-reduction techniques more effective and cost-efficient. However, it might be difficult to identify and permanently seal the places where radon is entering to the house. Normal settling of a house may open new entry routes and reopen old ones.

House pressurization uses a fan to blow air into the basement or living area from either upstairs or outdoors. Enough pressure is created at the lowest level indoors to prevent radon from entering into the house. The effectiveness of this method is limited by house construction, climate, other appliances in the house, and the occupant's lifestyle. In order to maintain enough pressure to keep radon out, doors and windows at the lowest level must be closed except for normal entry and exit.

Natural ventilation occurs in all houses to some degree. By opening doors, windows, and vents on the lower floors, one can increase the ventilation in the house. This increase in ventilation will mix radon with outdoor air and can reduce radon concentration. It can also lower indoor radon levels by reducing the vacuum effect. Natural ventilation in any type of

Table 4
Installation and Operating Cost of Radon Reduction in Homes

Technique	Typical radon reduction	Typical range of insulation costs (contractor)	Typical operating cost range (annual)*	Comments
Subslab suction (subslab depressurization)	80–99%	$800–2500	$75–175	Works best if air can move easily in material under slab.
Passive subslab suction	30–70%	$550–2250	There may be some energy penalties	May be more effective in cold climates; not as effective as active subslab suction.
Draintile suction	90–99%	$800–1700	$75–175	Works best if draintiles form complete loop around house.
Blockwall suction	50–99%	$1500–3000	$150–300	Only in houses with hollow blockwalls; requires sealing of major openings.
Sump hole suction	90–99%	$800–2500	$100–225	Works best if air moves easily to sump under slab, or if draintiles form complete loop.
Submembrane depressurization in a crawl space	80–99%	$1000–2500	$70–175	Less heat loss than natural ventilation in cold winter climates.
Natural ventilation in a crawl space	0–50%	None ($200–500 if additional vents installed)	There may be some energy penalties.	Costs variable
Sealing of radon entry routes	0–50%	$100–2000	None	Normally used with other techniques; proper materials and installation required.
House (basement) pressurization	50–99%	$500–1500	$150–500	Works best with tight basement isolated from outdoors and upper floors.
Natural ventilation	Variable	None ($200–500 if additional vents installed)	$100–700	Significant heated/cooled air loss; operating costs depend on utility rates and amount of ventilation.

(continued)

Table 4 *(Continued)*

Technique	Typical radon reduction	Typical range of insulation costs (contractor)	Typical operating cost range (annual)*	Comments
Heat recovery ventilation	25–50% if used for full house; 25–75% if used for basement	$1200–2500	$75–500 for continuous operation	Limited use; best in tight house; for full house, use with levels no higher than 8 pCi/L; no higher than 16 pCi/L for use in basement;less conditioned air loss than natural ventilation.
Water systems				
Aeration	95–99%	$3000–4500	$40–90	More efficient than GAC; requires annual cleaning to maintain effectiveness and to prevent contamination; carefully vent system.
Activated carbon (GAC)	85–99%	$1000–2000	None	Less efficient for higher levels than aeration; use for moderate levels (around 5000 pCi/L or less); radon byproducts can build on carbon may need radiation shield around tank and care in disposal.

**Note*: The fan electricity and house heating/cooling loss cost range is based on certain assumptions regarding climate, house size, and the cost of electricity and fuel. Costs may vary. Numbers based on 1991 data. http://www.epa.gov/iaq/radon/pubs/consguid.html.

house except the ventilation of a crawl space should usually be considered as a temporary radon-reduction approach because of the loss of conditioned air and related discomfort, greatly increased costs of conditioning additional outside air, and security concerns.

A heat recovery ventilator (HRV), also called an air-to-air heat exchanger, can be used to increase ventilation. It operates by using the heated or cooled air being exhausted to warm or cool the incoming air. HRVs can be used to ventilate all or parts of the house, although they are more effective in reducing radon concentrations if confined to the basement. If properly balanced and maintained, HRVs ensure a constant degree of ventilation throughout the year. They also can improve air quality in houses that have other indoor pollutants. However, there might be a significant increase in the heating and cooling costs with an HRV.

Comparison of radon-reduction installation and operating costs are compared in Table 4 (59). This table was prepared by the EPA using 1991 data. Although the costs may vary, it gives an idea about typical radon reduction for the investment made.

REFERENCES

1. G. Friedlander, J. W. Kennedy, E. S. Macias, et al., *Nuclear and Radiochemistry*, Wiley, New York, 1981.
2. E. Steinnes, in *Geomedicine* (J. Lag, ed.), CRC, Boca Raton, FL, 1990, pp. 163–169.
3. R. H. Clarke and T. R. E. Southwood, *Nature* **338**, 197–198 (1989).
4. D. J. Steck, R. W. Field, and C. F. Lynch, *Environ. Health Perspect.* **107**, 123–127 (1999).
5. C. Bowie and S. H. U. Bowie, *Lancet* **337**, 409–413 (1991).
6. N. R. Varley and A. G. Flowers, *Environ. Geochem. Health* **15**, 145–151 (1993).
7. R. L. Jones, *Environ. Geochem. Health* **7**, 21–24 (1995).
8. B. LeHvesque, D. Gauvin, R. McGregor, et al., *Health Phys.* **72**(6), 907–914 (1997).
9. IARC (International Agency for Research on Cancer), *Man-made Mineral Fibres and Radon*, IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans, Vol. 43, International Agency for Research on Cancer, Lyon, 1988.
10. G. Sharman, *Environ. Geochem. Health* **14**, 113–120 (1992).
11. C. Baird, *Environmental Chemistry*, Freeman, New York, 1998.
12. H. U. Wanner, *IARC Sci. Publ.* **109**, 19–30 (1993).
13. W. Jedrychowski, E. Flak, J. Wesolowski, et al., *Central Eur. J. Public Health* **3**(3), 150–160 (1995).
14. K. K. Nielson, V. C. Rogers, R. B. Holt, et al., *Health Phys.* **73**(4), 668–678 (1997).
15. *EPA Radon Proficiency Program (RPP) Handbook*, US Environmental Protection Agency, Washington, DC, 1996; available from www.epa.gov/iaq/radon/handbook.
16. M. Kawano and S. Nakatani, in *The Natural Radiation Environment* (J. A. S. Adams and W. M. Lowder, eds.), 1964, pp. 291–312, University of Chicago Press.
17. K. Megumi and T. Mamuro, *J. Geophys. Res.* **77**, 3051–3056 (1972).
18. D. K. Talbot, J. D. Appleton, T. K. Ball, et al. A comparison of field and laboratory analytical methods for radon site investigation, *J. Geochem. Explor.* **65**(1), pp. 79–90. (1998).
19. S. A. Durrani and R. Ilic, (eds.), *Solid State Nuclear Track Detection*, Pergamon, Oxford, 1997, p. 304.
20. S. A. Durrani, *Radiati. Measure.* **34**, 5–13 (2001).
21. A. Canabo, F. O. Lopez, A. A. Arnaud, et al., *Radiati. Measure.* **34**, 483–486 (2001).
22. V. S. Y. Koo, C. W. Y. Yip, J. P. Y. Ho, et al., *Appl. Radiati. Isotopes* **56**, 953–956 (2002).
23. K. Jamil, F. Rehman, S. Ali, et al., *Nucl. Instrum. Methods Phys. Res. A* **388**, 267–272 (1997).
24. J. I. Fabrikant, *Health Phys.* **59**(1), 89 (1990).
25. P. W. Abrahams, *Sci. Total Environ.* **291**, 1–32 (2001).
26. B. S. Cohen, *Health Phys.* **74**(5), 554–560 (1998).
27. P. Polpong and S. Bovornkitti, *J. Med. Assoc. Thailand* **81**(1), 47–57 (1998).
28. A. P. Jones, *Atmos. Environ.* **33**, 4535–4564 (1999).
29. D. L. Henshaw, J. P. Eatough, and R. B. Richardson, *Lancet* **335**, 1008–1012 (1990).
30. K. Steindorf, J. Lubin, H. E. Wichmann, et al., *Int. J. Epidemiol.* **24**(3), 485–492 (1995).
31. J. H. Lubin, L. TomaHsek, C. Edling, et al., Estimating lung cancer mortality from residential radon using data for low exposures of miners, *Radiati. Res.* **147**(2), 126–134 (1997).
32. J. H. Lubin and J. D. Boice, *J. Natl. Cancer Inst.* **89**(1), 49–57 (1997).
33. N. P. Lucie, *Lancet* **2**(8654), 99–100 (1989).
34. S. P. Wolff, *Nature* **352**(6333), 288 (1991).
35. D. J. Etherington, D. F. Pheby, and F. I. Bray, *Eur. J. Cancer* **32**(7), 1189–1197 (1996).
36. F. Lagarde, G. Pershagen, G. Akerblom, et al., *Health Phys.* **72**(2), 269–276 (1997).
37. The National Research Council, 4th Committee on Biological Effects of Ionizing Radiation, *BEIR IV Report*, National, Washington, DC, 1988.
38. Z. Smerhovsky, K. Landa, P. Rössner, et al., *Mutat. Res.* **514**, 165–176 (2002).

39. BEIR VI Report (2000) National Research Council, 6th Committee on Biological Effects of Ionizing Radiation, *BEIR VI Report* National Academic Press, Washington, DC, 2000.
40. H. Friedmann, *Eur. J. Radiol.* **35**, 221–222 (2000).
41. N. R. Varley and A. G. Flowers, *Radiat. Prot. Dosim.* **77**, 171–176 (1998).
42. D. Miles, J. O. O'Brien, and M. Owen, *Br. J. Cancer* **79**, 1621–1622 (1999).
43. S. Darby, E. Whitley, P. Silcocks, et al., *Br. J. Cancer* **78**, 394–408 (1988).
44. A. V. Nero, M. B. Schwehr, W. W. Nazaro, et al., *Science* **234**(4779), 992–997 (1986).
45. F. Marcinowski, R. M. Lucas, and W. M. Yeager, *Health Phys.* **66**(6), 699–706 (1994).
46. R. W. Field, D. J. Steck, B. J. Smith, et al., *Sci. Total Environ.* **272**, 67–72 (2001).
47. H. J. Albering, J. A. Hoogewer, and J. C. Kleinjans, *Health Phys.* **70**(1), 64–69 (1996).
48. F. Bochicchio, G. Campos-Venuti, C. Nuccetelli, et al., *Health Phys.* **71**(5), 741–748 (1996).
49. K. N. Yu, E. C. M. Yung, M. J. Stokes, et al., *Health Phys.* **75**(2), 159–164 (1998).
50. S. E. Hampson, J. A. Andrews, M. E. Lee, et al., *Risk Anal.* **18**(3), 343–350 (1998).
51. US Environmental Protection Agency, *Consumer's Guide to Radon Reduction*; US EPA Office of Air and Radiation, Washington, DC, 1992; available from www.epa.gov/iaq/radon/pubs/consguid.
52. US EPA, *How to Reduce Radon Levels in Your Home*, Office of Radiation and Indoor Air Report No. 402-K92-003, US EPA Office of Air and Radiation, Washington, DC, 1985.
53. J. E. Fitzgerald, et al., *A Preliminary Evaluation of the Control of Indoor Radon Daughter Levels in New Structures*, EPA Office of Radiation Programs, Report No. EPA-520/4-76-018.
54. A. P. Becker, *Evaluation of Waterborne Radon Impact on Indoor Air Quality and Assessment of Control Options*, PB84246404 (1984).
55. G. W. Reid, S. Hataway, and P. Lassovszwy, *Health Phys.* **48**(5) (1985).
56. United Nations Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation*, Annex B: Natural sources of radiation UNIPUB, New York, 1977.
57. R. A. Wadden and P. A. Scheff, *Indoor Air Pollution* Wiley, New York, 1983.
58. S. Ericson and H. Schmied, in *Modified Design in New Construction Prevents Infiltration of Soil Gas That Carries Radon* (in Radon and its Decay Products: Occurrence, Properties and Health Effects, ACS Symp. Series No 331. P. H. Hopke, ed.), American Chemical Society, Washington, DC, 1987, p. 526.