HEALTH PHYSICS SOCIETY

Specialists in Radiation Safety

Background Information on
“Update on Perspectives and Recommendations on Indoor Radon”
Position Statement of the Health Physics Society*
Adopted: October 1990, Revised October 2009

This background document has been prepared by the Health Physics Society (HPS) Ad Hoc Committee on the Indoor Radon Position Statement (the Committee) to provide supplemental information to the Scientific and Public Issues Committee (S&PIC) of the HPS and to other interested parties.

Introduction

The purpose of the HPS indoor radon position statement “Update on Perspectives and Recommendations on Indoor Radon” is to provide basic information and recommendations with regard to indoor radon for members of the public, educators, public officials, and the media. The position statement has been written for a lay audience and is, by design, limited in its scope. This background document is intended to provide additional technical information to support the recommendations in the position statement.

In the fall of 2007, the president of the HPS appointed an ad hoc committee to revise the 1990 position statement “Perspectives and Recommendations on Indoor Radon.” The committee and its membership were approved by the HPS Board of Directors at the Society’s midyear meeting in January 2008. The committee consists of Society members and nonmembers with expertise in indoor radon epidemiology and measurement. The Committee met by telephone conference call, five times, during the summer and fall of 2008. Initial drafts of the position statement were circulated to the Committee in August and September 2008. The draft was revised in October 2008 and finalized in November and December 2008. While Committee members had differing viewpoints on certain aspects of the recommendations, the Committee achieved consensus on all aspects of the position statement. A final draft position statement was submitted to the S&PIC of the HPS in January 2009. The S&PIC approved the position statement, with a few minor wording changes, at its 1 February 2009 meeting.

This background document is divided into several sections:

- Radiological characteristics of radon and its decay products
- Radon risk
  - Miner epidemiologic data
  - Indoor radon epidemiologic data
- Radon dose estimates
- National and international radon guidelines
- Radon mitigation
- Conclusions
- References
- Glossary

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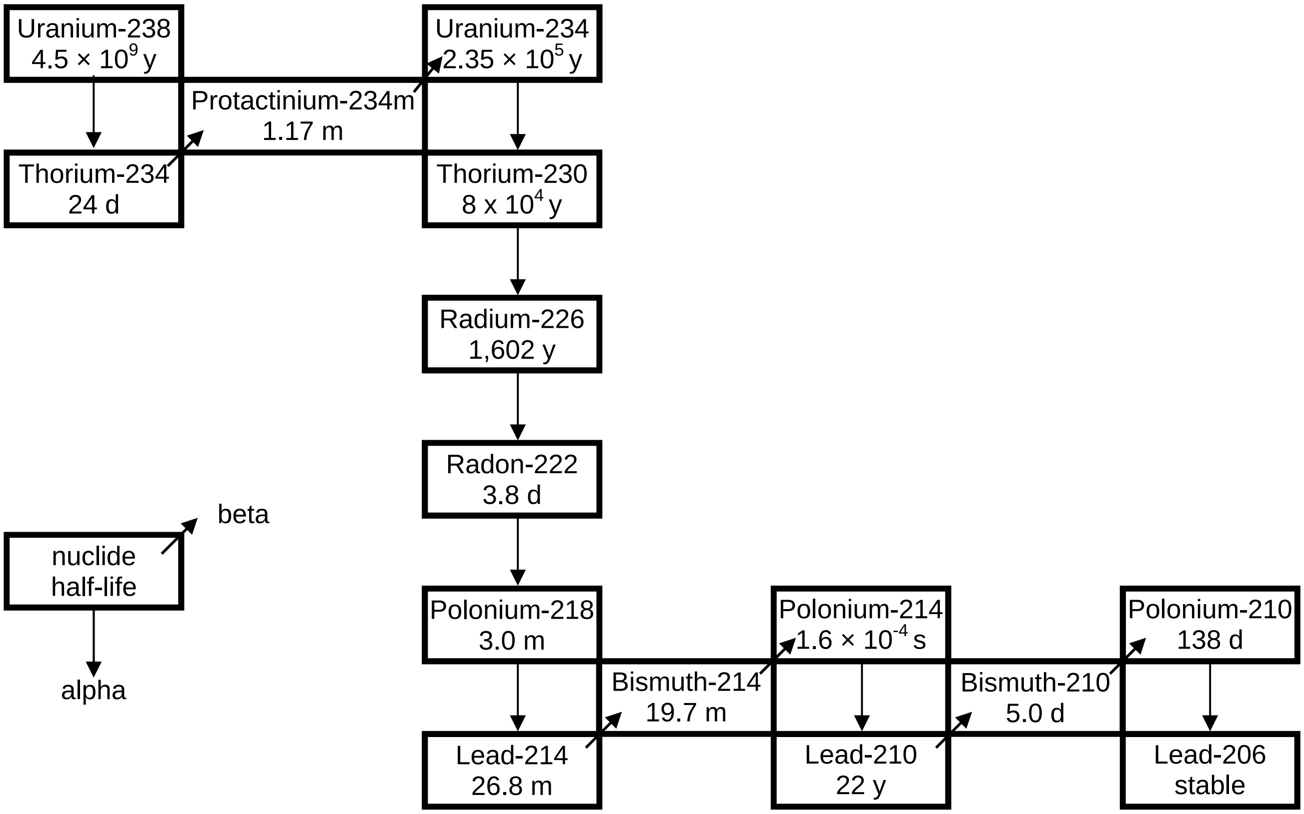
Radiological Characteristics of Radon and Its Decay Products

Radon is a naturally occurring radioactive gas derived from the decay of uranium and thorium. Radon has three naturally occurring isotopes. Radon-222 is the decay product of radium-226, a member of the uranium-238 decay series. Radon-220 is a decay product of radium-224, a member of the thorium-232 decay series. Radon-219 is a decay product of radium-223, a part of the uranium-235 decay series. Radon-222 is generally considered the most important radon isotope from the perspective of radiation dose from residential exposure, although, there is some information to indicate that radon-220 and its decay products that are also frequently present in residential structures may pose some additional risk. Nevertheless, this background document applies only to radon-222.

Natural uranium is present in the Earth's crust at a worldwide average concentration of about 1.8 parts per million or approximately 46 Bq kg^{-1} (1.3 pCi g^{-1}). The uranium-238 decay series is shown in Figure 1.

Figure 1: Uranium-238 Decay Series



Radon is a noble gas produced in soil and rock. It can enter a structure by diffusion through the building foundation or flow through penetrations or cracks in the foundation. It may also enter the structure through release from domestic water supplies with high radon concentrations.

Radon gas is inhaled and exhaled with no long-term absorption in the body. A small fraction of the radon can be absorbed into body fluids to produce a radiation dose. Radon is lipophilic, so absorption is enhanced in fat-containing tissues, with biological half-lives of several hours. However, it is inhalation of the solid short-lived radon decay products that produces the major portion of the dose, that is, dose to the lung. The radiological characteristics of radon-222 and its short-lived decay products are given in Table 1.

In a completely closed system, radon decay products reach equilibrium with the parent radon-222, that is, the same activity concentration, in approximately four hours. In typical residential structures, partial equilibrium is achieved in much shorter times. The typical fraction of equilibrium in homes is approximately 0.4.

While it is the radon decay product concentration that is of importance in determining the dose and risk to the lung, radon gas is commonly measured in homes. Radon-222 concentration is a reasonable surrogate for radon decay product concentration.

Table 1: Characteristics of Radon-222 and Its Short-Lived Decay Products

Nuclide	Half-Life	Alpha Energy (MeV)	Maximum Beta Energy (MeV)	Principal Gamma Energies (MeV)
Radon-222	3.8 days	5.49		
Polonium-218	3.0 minutes	6.0		
Lead-214	26.8 minutes		0.65, 0.71, 0.98	0.29, 0.35
Bismuth-214	19.7 minutes		1.0, 1.51, 3.26	0.609, 1.12, 1.764
Polonium-214	1.64×10^{-4} seconds	7.69		

Radon Risk

Miner epidemiologic data

The epidemiologic data regarding radiation risk to miners is described in detail in the BEIR VI Report (NRC/NAS 1999) and numerous articles in the scientific literature. Eastern European silver miners were reported to suffer from lung disease in the late fifteenth century. Georgius Agricola, in his publication *De Re Metallica*, described the condition as “this terrible consumption” (Agricola 1912). In 1879 malignant tumors were found to be the actual cause of death in miners with this condition, and in the 1920s and 1930s exposure to airborne radioactivity was determined to be the cause of the tumors.

Epidemiologic studies of lung cancer in miners are confounded by exposure to other airborne contaminants such as silica dust and diesel fumes. In studies where such data were available, a strong synergistic effect between tobacco use and radon decay product exposure was observed. Because of the very high prevalence of smoking in most populations of uranium miners, the early epidemiologic studies concluded that only smokers were likely to get lung cancer from radon decay product exposure. However, as more data became available, the increased incidence of lung cancer due to inhalation of radon decay products even among nonsmoking miners was established.

In order to apply the findings from the occupational exposure studies to indoor radon exposure, the data for miners with cumulative radon decay product exposures less than 100 working level months (WLM)[1] from 11 pooled studies were analyzed (Lubin et al. 1997). The results of the analysis are summarized in Table 2. A total

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[1] Working level month (WLM) is the common unit used to express exposure to radon decay products. It is defined in the Glossary at the end of this document.

of 115 lung cancer cases had no known occupational radon decay product exposure. The 562 lung cancer cases with cumulative occupational exposures from 0.1 to 99.9 WLM were divided into deciles. The range of exposures and the mean exposure for each decile were determined. The relative risk was calculated for each decile. The relative risks for all deciles exceeded 1.0. The 95 percent lower confidence limit for cumulative exposures exceeding 43.4 WLM, the four highest deciles, exceeded 1.0.

Dr. Jay Lubin of the National Cancer Institute estimated the excess relative per WLM as 0.008 for exposures less than 100 WLM (Lubin et al. 1997). While the exposure variable for the miner risk analysis is different from the indoor radon analyses, that is, cumulative WLM versus average radon concentration, the relative risks show a consistent trend even at low exposures.

Table 2: Summary of Miner Epidemiological Data at Low Cumulative Exposures (adapted from Lubin et al. 1997)

Cumulative Exposure Range (WLM)	Number of Cases	Mean Exposure (WLM)	Relative risk	95% Confidence Interval
0	115	0	1.00	NA
0.1–3.5	56	2.4	1.37	1.0–2.0
3.6–6.9	56	5.3	1.14	0.8–1.7
7.0–15.1	56	12.4	1.16	0.8–1.7
15.2–21.2	57	17.3	1.45	1.0–2.2
21.3–35.4	56	33.1	1.50	1.0–2.2
35.5–43.5	57	38.6	1.53	1.0–2.2
43.6–59.4	56	53.2	1.69	1.1–2.5
59.5–70.3	56	63.3	1.78	1.2–2.6
70.4–86.5	56	81.1	1.68	1.1–2.5
86.6–99.9	56	91.4	1.86	1.2–2.8

Indoor radon epidemiologic data

Epidemiologic studies of lung cancer incidence or mortality rates related to residential radon exposure have been conducted in many different countries and by a range of methods. Because of power limitations with relatively small numbers of cases, researchers have pooled the data from residential case-control epidemiologic studies. Case-control methodology involves comparing the exposure history of individuals with lung cancer (cases) to the exposure history of individuals without lung cancer (controls). Controls may be selected randomly or matched to individual cases in characteristics other than the disease of concern, lung cancer. Case-control methodology is considered a scientifically credible approach to evaluating whether a particular exposure causes a specific outcome.

Pooling and meta-analysis are methods of combining the results of several studies to obtain a more robust statistical analysis. The pooling studies of the residential radon case-control studies are very different from meta-analyses. In a meta-analysis, the results of each study are averaged. Sometimes the study results are weighted before averaging based on the investigators' sense of the robustness of data, quality of estimates, technical competence of the individual studies, etc. This weighting can be subjective instead of objective. Pooling, by contrast, goes back to each original study and pools the individual data for each of the study subjects. While both pooling and meta-analysis provide a summary analysis of the data, Lubin believes that the pooling approach provides “finer control of confounding and assessment of effect modification” (Lubin et al. 1997).

Planning for the pooling studies was completed long before the pooling studies were undertaken and before many of the individual residential radon epidemiologic studies were completed. The principal investigators of global residential radon case-control studies met for a series of three International Workshops on Residential Radon, sponsored by the U.S. Department of Energy (U.S. DOE) and the Commission of European Communities, from 1989 to 1995 to discuss the best way to combine the data from the numerous completed and ongoing residential radon studies (U.S. DOE 1989; U.S. DOE 1991).

The first meeting determined that pooling the results of the different studies was essential and that coordination of study designs and facilitation of mechanisms for pooling individual data should be pursued. New studies were discouraged until the results from existing studies could be evaluated. Further meetings recommended two separate study centers for the pooling of the North American and European studies that appeared to be on different timelines, with procedures and funding in place for maintaining communication between the two centers, particularly with regard to design issues. This ensured that the separate pooling efforts could eventually result in a worldwide pooled analysis.

At a planning meeting for the combined analysis of the North America Residential Radon Studies held in October 1995, a project working plan was developed and a data format for the submission of data for pooling the North America studies was developed. Since the data analyzed in the pooling study needed to be consistent from study to study, the data were necessarily constricted by the least sophisticated study included. Therefore, it is possible that the resultant risk is underestimated (Field et al. 2002). Based largely on the results of the North America and European pooling studies, on 13 January 2005 the U.S. Surgeon General issued a National Health Advisory for Residential Radon encouraging the public to test for indoor radon and to take action if the radon level in the home is 4 pCi L^{-1} or greater (U.S. Surgeon General 2005). The results of the pooling of the residential radon studies are presented in Table 3.

Based on the rate of increase in risk per concentration increment, all of the pooled studies showed an increased risk of lung cancer at a concentration of 100 Bq m^{-3} (2.7 pCi L^{-1}) at a 95 percent confidence level. The pooled analyses provide strong evidence that long-term exposure to radon decay products at radon concentrations less than the U.S. Environmental Protection Agency (U.S. EPA) guideline (4.0 pCi L^{-1}) present a statistically significant increase in lung cancer risk.

While the absolute risk of lung cancer due to indoor radon is much higher for smokers because their baseline risk is higher, the European pooled analysis found no evidence that excess relative risk of lung cancer (that is the relative proportion of the risk due to indoor radon exposure) varied with age, sex, or smoking history (Darby et al. 2006). The ratios of the estimated risks of lung cancer for various average radon concentration and smoking status to the risk for lifelong nonsmokers with no radon exposure are given in Table 4. The relative risks for smokers versus nonsmokers were estimated for two radon concentrations. The lung cancer risk for a smoker at minimal radon concentration (<25 Bq m^{-3}) was found to be approximately 26 times greater than the risk for a nonsmoker. The ratio of the risk for a smoker compared to a risk for a nonsmoker remained approximately the same at radon concentrations of 100 Bq m^{-3} and 400 Bq m^{-3}.

Table 3: Results of Pooled Residential Radon Studies

Residential Epidemiologic Study	Number of studies pooled	Number of cases	Number of controls	Increased risk at 100 Bq m^{-3}	Increased risk at 100 Bq m^{-3} (adjusted for temporal radon variation)	Increased risk at 100 Bq m^{-3} Analyses based on improved radon concentration data[1]
North American Pooled Analysis[2,3]	7	3,662	4,966	11% (95% CI: 0%–28%)	Pending[4]	18% (95% CI: 2%–43%)
European Pooled Analysis[5,6]	13	7,148	14,208	8% (95% CI: 3%–16%)	16% (95 CI: 5%–31%)	
Chinese Pooled Analysis[7]	2	1,050	1,995	13% (95% CI: 1%–36%)		

[1] Analysis restricted to individuals who resided in either one or two homes for the period 5 to 30 years prior to recruitment with at least 20 years covered by a year-long radon measurement

[2] Krewski et al. 2006

[3] Krewski et al. 2005

[4] Smith et al. in preparation

[5] Darby et al. 2005

[6] Darby et al. 2006

[7] Lubin et al. 2004

Table 4: Relative Risk of Lung Cancer by Smoking Status and Average Radon Concentration (Darby 2006)

Smoking Status	Average Radon Concentration (Bq m^{-3})		
	<25 Bq m^{-3} (0.7 pCi L^{-1})	100 Bq m^{-3} (2.7 pCi L^{-1})	400 Bq m^{-3} (10.8 pCi L^{-1})
Lifelong Nonsmoker	1.0	1.2	1.6
Continuing Smoker (15–24 cigarettes per day)	25.8	29.9	42.3

The European pooled study showed statistically significant increased relative risks in all concentration categories greater than 99 Bq m^{-3}. The mean observed radon concentration in the 100 Bq m^{-3} to 200 Bq m^{-3} category was 136 Bq m^{-3}. The increased relative risks at concentration categories between 25 Bq m^{-3} and 99 Bq m^{-3} were greater than 1.0 but not statistically significant at the 95 percent confidence level (Darby et al. 2006). The relative risk at concentrations less than 25 Bq m^{-3} (mean 17 Bq m^{-3}) was 1.0.

As with the European pooled study, the North American study concluded that there was no evidence of a difference in relative risk between smokers and nonsmokers or between genders (Krewski et al. 2005). However, the study did find evidence of a decreasing radon-associated lung cancer risk with age. The North American study compared lung cancer risks at various radon concentrations ranging from 25 Bq m^{-3} to greater than 200 Bq m^{-3} to risks at concentrations less than 25 Bq m^{-3}.

At an average indoor radon-222 concentration of 100 Bq m^{-3} (2.7 pCi L^{-1}), the 30-year exposure would be approximately 13 WLM assuming an average equilibrium factor of 0.4 and 80 percent indoor occupancy: *Exposure = (0.4 x 2.7 pCi* L^{-1} *x 30 y x 8760 h* y^{-1} *x 0.8)/(100 pCi* L^{-1} WL^{-1} *x 170 h* M^{-1}*) = 13 WLM.*

The range of excess relative risks for the indoor radon pooled analyses (8 percent to 18 percent) at 100 Bq m^{-3} is consistent with the estimated excess relative risk of 0.008/WLM for the low-exposure cohort miner analysis: *Risk = 13 WLM x 0.008* WLM^{-1} *= 0.11 or 11 percent.*

Radon Dose Estimates

In its 2003 position statement “Ionizing Radiation Safety Standards for the General Public,” the Society adopted effective dose, rather than risk, as a basis for establishing radiation protection standards and then reaffirmed this in 2009 (HPS 2009). For a controllable source, the recommended effective dose limit is 1 mSv per year. The use of effective dose to compare different types of radiation exposures allows protective standards to be established for an exposure where the risk is poorly known but the dose can be estimated. Recent epidemiologic studies have improved the lung cancer risk estimates for radon-related exposures. However, using the effective dose for radon exposures allows for consistency in setting protective standards. Effective dose estimates combine a measurable quantity, energy deposited per unit volume, with factors that adjust for the type of radiation and the sensitivity of the exposed tissue. Effective dose is an imperfect attempt to equate the risk of detriment from different types of radiation exposure because of the uncertainty in the radiation effectiveness and sensitivity factors as well as the possibility that nonradiation risk factors might modify the radiation risk. For radon-related exposures, these factors include lifestyle (smoking) and genetic disposition. In a 1995 position statement on risk assessment, the HPS anticipated these kinds of problems by recommending that the radiation protection practices take uncertainties into account (HPS 1995). Radon-related dose is usually calculated from a surrogate measurement such as radon or radon progeny concentration because it is virtually impossible to measure the absorbed dose directly. The use of these surrogates to estimate effective dose through a dose conversion factor introduces substantial uncertainty in the dose estimate. These uncertainties should be taken into account when comparing the 1 mSv y^{-1} effective dose limit for members of the public with the range of likely effective doses calculated in a particular radon environment.

Two approaches have been used to estimate the dose conversion factors. There are many complicated and subtle differences between the details of each approach. Therefore, this document provides only a summary of these approaches. A more complete description can be found in Chen (2005), Stather (2004), and Vanmarke (2008). Dose conversion factors based on direct dosimetric modeling calculate the absorbed dose from the airborne radon progeny activity that is deposited in the lung. Variations in atmospheric conditions, activity size distributions, and deposition parameters create effective dose estimates that range from 0.7 to 3 mSv y^{-1} when 80 percent of the time is spent in a 1 pCi L^{-1} radon concentration (James et al. 2004; Porstendörfer 2001). The risk equivalent dose conversion factor approach is based on the risk of detriment from A-bomb survivor data and radon-related risk modeled from human epidemiologic studies. The most recent dose conversion coefficient using this approach is 0.8 mSv y^{-1} per pCi L^{-1} for an atmosphere where the equilibrium ratio is 0.4 (ICRP

2008). The United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 2000 report takes a compromise approach and recommends a dose conversion coefficient of 0.9 mSv y^{-1} per pCi L^{-1} (UNSCEAR 2000). The National Council on Radiation Protection and Measurements (NCRP) recommends a dose conversion coefficient of 1.7 mSv y^{-1} per pCi L^{-1} based on dosimetric modeling (NCRP 2009). The estimated dose coefficients, calculated assuming an equilibrium ratio of 0.4 and an 80 percent occupancy rate, are summarized in Table 5.

In summary, the best current estimate for the range of effective doses at a 4 pCi L^{-1} exposure level is 3 to 7 mSv y^{-1}. Radon mitigation systems that can reduce radon concentrations below 2 pCi L^{-1} have the potential to reduce the lower end of the range of estimated doses to the 1 mSv y^{-1} recommendation for controllable sources.

Table 5: Estimated Dose Conversion Factors for Indoor Radon Exposure

Source	Estimated Annual Effective Dose per 1.0 pCi L^{-1}	Estimated Effective Dose per WLM	Estimated Annual Effective Dose per 100 Bq m^{-3} (2.7 pCi L^{-1})
James Porstendörfer	0.7–3.0 mSv	4.2–18 mSv	1.9–8.1 mSv
ICRP	0.8 mSv	4.8 mSv	2.2 mSv
UNSCEAR	0.9 mSv	5.5 mSv	2.4 mSv
NCRP	1.7 mSv	10 mSv	4.6 mSv

National and International Radon Guidelines

Indoor radon guidelines have been issued by international organizations as well as governmental agencies. The U.S. EPA guideline of 4 pCi L^{-1} has been discussed in previous sections of this document. International advisory bodies such as the World Health Organization (WHO) and the International Commission on Radiological Protection (ICRP) have also issued recommendations in regard to indoor radon. Action levels established by specific countries are given in Table 6.

Table 6: International Action Levels

Country	Action Levels Bq m^{-3} (pCi L^{-1})	
	Existing Homes	New Construction
Australia	200 (5.4)	200 (5.4)
Canada	200 (5.4)	200 (5.4)
China	400 (10.8)	200 (5.4)
European Community (11 countries)	400 (10.8)	400 (10.8)
Finland	400 (10.8) mandatory	400 (10.8) mandatory
Sweden	400 (10.8) mandatory	200 (5.4) mandatory
Norway	400 (10.8) mandatory	200 (5.4) mandatory
Ireland	200 (5.4)	200 (5.4)
Luxembourg	150 (4.1) mandatory	150 (4.1) mandatory
Russia	400 (10.8) mandatory	200 (5.4) mandatory for Moscow
United Kingdom	200 (5.4)	

Radon Mitigation

Radon mitigation techniques have been demonstrated to be effective in reducing concentrations in existing structures and the potential for elevated radon concentrations in new construction. The U.S. EPA has published several documents describing radon mitigation techniques and provides guidance to homeowners, builders, and architects on radon reduction (U.S. EPA 1994; U.S. EPA 1995; U.S. EPA 1998; U.S. EPA 2001). The American Society for Testing and Materials (ASTM) has published standards for new and existing residential construction (ASTM E-2121, ASTM E1465-071). The U.S. EPA recommends these standards. The American Association of Radon Scientists and Technologists (AARST) Consortium on Radon Standards has also published a mitigation standard for existing residences (ASD-RMS 2007). There is an ongoing effort to harmonize ASD-RMS 2007 and ASTM E-2121.

Since the vast majority of radon moves from its source in the soil into homes and other buildings due to air pressure differences, radon prevention and remediation focuses on reversing this pressure-driven transport. Commonly, in low-rise residential buildings, the technique that has been used in North America and Europe since the late 1970s has been active soil depressurization (ASD). This technique uses a small fan that is placed in a vent pipe connecting to the permeable soil below the building and discharging to the outdoors, ideally above the highest roof. This system lowers the air pressure in the soil compared to that inside the building.

In larger, mechanically ventilated buildings such as schools, the mechanical heating, ventilation, and air conditioning system may be adjusted to slightly pressurize spaces in contact with the soil. In some cases, ventilation and ASD systems are used in combination.

Both approaches are capable of reducing indoor radon concentrations by more than 90 percent, and virtually all buildings have post-mitigation radon concentrations well below 150 Bq m^{-3} (4 pCi L^{-1}). Installation costs of ASD in single-family detached houses usually range between $1,200 and $1,800 (2009 USD).

In a small minority of cases, prevention or remediation may involve reducing radon concentrations in potable water from private drilled wells.

A recent study in Great Britain examined the cost-effectiveness of remediation of existing homes and new construction (Gray et al. 2009). The study used the cost per "quality adjusted life year" (QALY) as a measure of cost-effectiveness. The costs per QALY for different policies for control of radon were compared to the costs for other health-related policies. The study concluded that remediation strategies in new construction are cost-effective but the cost-effectiveness for existing homes in Great Britain is doubtful.

It is not clear that the conclusions from the British study are applicable to the United States. The study considered only societal economic costs and did not consider individual risks. The average radon concentration reported for Great Britain in that study (0.5 pCi L^{-1}) is less than half the average radon concentration in the United States (1.3 pCi L^{-1}), the costs of health care are greater in the United States than in Great Britain, and smoking rates differ between the two countries. These three factors would significantly influence the relative cost-effectiveness of radon mitigation strategies between the two countries.

The cost-effectiveness of remediating existing homes in the United States is addressed in the Technical Support Document for the U.S. EPA's 2009 "A Citizen's Guide to Radon" (U.S. EPA 2009).

Conclusions

Radon is ubiquitous in the environment and is present in both indoor and outdoor air as well as groundwater sources. Epidemiologic studies have demonstrated that inhalation of radon decay products at concentrations found in residential structures can cause lung cancer. Based on recent epidemiologic evidence, an action level of 4 pCi L^{-1} is reasonable. However, an increased risk of cancer has been demonstrated at indoor radon concentrations below that level, so decreasing radon concentrations even below that concentration is advisable from an ALARA (as low as reasonably achievable) perspective. Current mitigation techniques are effective in reducing radon concentrations to levels below the U.S. EPA guideline.

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Glossary

Becquerel (Bq)
A unit in the International System of Units (SI) of measurement of radioactivity equal to one transformation per second.

Curie (Ci)
The basic unit of activity. A quantity of any radionuclide that undergoes an average transformation rate of 37 billion transformations per second.
millicurie (mCi): one thousandth of a curie
microcurie (μCi): one millionth of a curie
picocurie (pCi): one trillionth of a curie

Relative Risk
An expression of excess risk relative to the underlying (baseline) risk (NRC/NAS 1999).

Excess Relative Risk
An expression of the risk imposed by exposures as a multiplicative increment to the excess disease risk above the background rate of disease (NRC/NAS 1999).

Rem
The special unit of dose equivalent.

Sievert (Sv)
The International System of Units (SI) of equivalent dose or effective dose. One Sv is equal to 100 rem.
millisievert (mSv): one thousandth of a Sv

Working Level (WL)
Any combination of the short-lived radon decay products in 1.0 liter of air, under ambient temperature and pressure, that results in the ultimate emission of 130,000 MeV of alpha particle energy (approximately equal to 100 pCi L^{-1} of radon-222 in equilibrium with its short-lived decay products).

Working Level Month (WLM)
A cumulative exposure to radon decay products equivalent to exposure to 1.0 WL for a working month (170 hours). One WLM is equivalent to 0.0035 J h m^{-3}.

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