RADON

Prevalence, Measurements, Health Risks and Control

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ASTM

Radon: Prevalence, Measurements, Health Risks and Control

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Foreword

This publication, *Radon: Prevalence, Measurements, Health Risks and Control,* was sponsored by ASTM Committee D22 on Sampling and Analysis of Atmospheres. The editor was Niren L. Nagda of ENERGEN Consulting, Inc., Germantown, MD. This is Manual 15 in ASTM's manual series.

Acknowledgments

The solid efforts by the authors of the chapters are clearly seen as one peruses this book. The authors responded to the many requests from ASTM and from me to complete their contributions for this book initiated in 1989.

The behind-the-scene efforts by the reviewers and by the ASTM staff may not be as easy to recognize at first glance. I wish to thank Michael Brambley, Edward Maher, Gordon Nifong, and Harry Rector, who reviewed the chapter manuscripts. Their recommendations helped the authors and me to improve the content and presentation.

The patience and hard work by the ASTM staff to publish this book is acknowledged. Without the persistent efforts of Kathy Dernoga, Manager of Acquisition and Review, and her staff including Monica Siperko, and David Jones, who served as the ASTM editor, this book would not have been possible.

Finally, I am grateful to my family, who gracefully accepted the serious encroachment the preparation of this book had on our family and leisure time.

Niren L. Nagda
Editor

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Radon—A Multifaceted Environmental Problem: An Overview

by Niren L. Nagda[1]

IMPORTANCE OF RADON

DURING THE LAST TWO DECADES, it has been well publicized that exposure to radon causes lung cancer. Radon, a naturally occurring radioactive gas, seeps into and accumulates inside buildings. Elevated indoor radon concentrations have been observed in all parts of the United States [*1*]. A consensus of opinion on human carcinogenicity of radon has been well established from studies of uranium miners by national and international health organizations such as the World Health Organization's International Agency for Research on Cancer (IARC) [*2*], the Biological Effects of Ionizing Radiation (BEIR IV) Committee of the National Academy of Sciences [*3*], the International Commission on Radiological Protection (ICRP) [*4*], and the National Council on Radiation Protection and Measurement (NCRP) [*5*]. Still, the magnitude of exposure to and risks due to radon are not fully recognized by the general public.

Among sources of ionizing radiation, natural radiation contributes the largest percentage to the total average annual effective dose equivalent to members of the U.S. population [*6*]. Fifty-five percent of that total is caused by radon (Fig. 1). Radiation from medical procedures, cosmic radiation, terrestrial radiation, radionuclides deposited inside the human body, and consumer products contribute the bulk of the remainder. Often-feared sources of radiation such nuclear power production and nuclear weapons testing contribute well below 1%. Further, Nero [*7*] estimates that exposure to radon exceeds the lifetime dose from radiation exposure to the average resident of Europe and Asia from the nuclear accident at Chernobyl (Fig. 2).

Indoor radon is the second leading cause of lung cancer, next to smoking, which is estimated to cause 146 000 lung cancer deaths annually in the United States [*8*]. The U.S. Environmental Protection Agency (EPA) estimates that the number of lung cancer deaths per year in the United States due to residential radon exposure is approximately 13 600, with an uncertainty range of 7000 to 30 000 [*9*]. The estimates of radon risk are based on the BEIR IV committee's risk projection model as modified by the EPA and the most recent exposure information [*10,11*]. Some of the major uncertainties in the estimates of radon risks are related to the effect of smoking. Presuming multiplicative interaction between radon and smoking, it is estimated that smokers and former smokers face the greatest radon risk: 70% of radon risk is borne by smokers who comprise approximately 30% of the U.S. population; 24% of the risk is borne by former smokers or 23% of the population; and the remaining 6% is shared by 47% of the population—those who have never smoked [*11*]. The EPA has also compared the number of deaths attributed to radon-induced lung cancer with other causes of deaths: drunk driving—23 400 annual deaths; drowning—4600 deaths; fire and burns—4400 deaths; air transport accidents—1000 deaths [*1,9*]. Thus, no matter how one looks at the radon issue or which estimate is chosen for radon-induced lung cancer deaths, radon is an extremely important environmental health issue.

Radon was recognized as a potential public health threat in the United States more than 30 years ago. Table 1 provides a brief historical (1955–1985) overview of important developments relative to radon exposure indoors. To understand and effectively deal with radon, one needs to understand the physics of radon, its health effects, measurement techniques and protocols, the extent of its occurrence in the United States, mitigation principles and practices, and legislative and regulatory actions. These areas are touched upon in the discussion below and are further expanded in subsequent chapters of this book.

RADON AND THE NATURAL ENVIRONMENT [*24*]

Chemically, radon is the heaviest noble gas and occurs as three isotopes of atomic weight 219, 220, and 222. Radon 222, the isotope of main concern, is produced by radioactive decay of radium which, in turn, is a radioactive product of uranium. Radon has a half-life of 3.8 days and disintegrates into a series of solid, short-lived radioisotopes or radionuclides collectively referred to as radon progeny, radon daughters, or radon decay products. A basic unit of measurement of radioactivity of radon is the becquerel (Bq), which is one disintegration per second; the unit of picocurie (pCi) is a commonly used unit in the United States and is equal to 3.7×10^{-2} disintegrations per second. The concentration of radon is expressed as becquerels per cubic meter (Bq m^{-3}) or picocuries per liter (pCi/L). Units of radon decay product concentrations, exposure, and dose are defined elsewhere [*24,25*].

Because radium—the parent of radon—is found in all crustal materials, radon is ubiquitous in both indoor and outdoor air. Sources of radon include soil, water, outdoor air, and building materials, but transport of radon-bearing gas from soil is generally the most predominant source of indoor

[1]ENERGEN Consulting, Inc., 19900 Wild Cherry Lane, Germantown, MD 20874-1016.

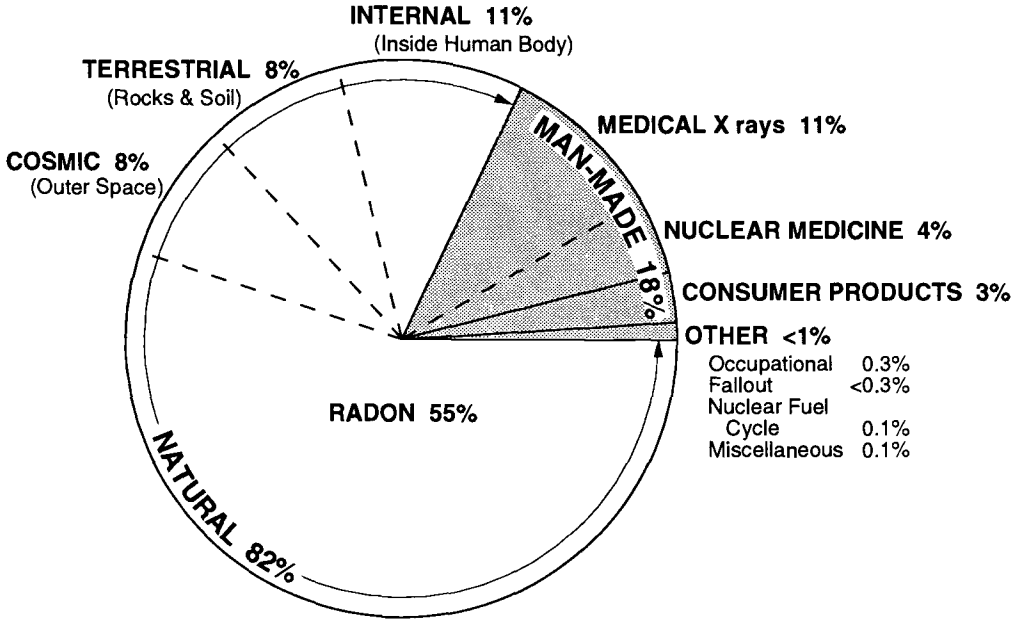

FIG. 1–Sources of radiation exposure to the U.S. population [*6*].

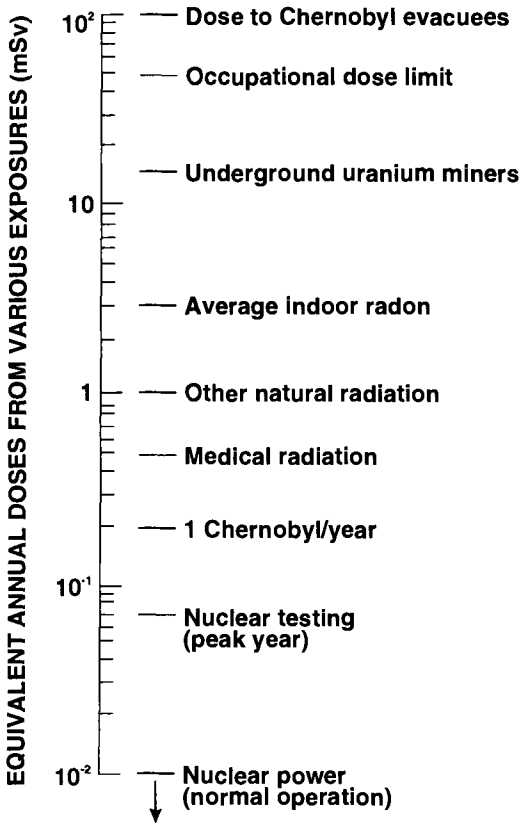

FIG. 2–Comparison of radiation doses from different sources [*7*].

radon, particularly in buildings with elevated concentrations. The indoor-outdoor air exchange rate of a building is another factor that influences the ultimate indoor concentration, but the soil-gas entry rate has a much stronger influence. Both the soil-gas entry rate and the air exchange rate are affected by outdoor conditions such as wind speed and indoor-outdoor temperature differences. In addition, factors such as geology, precipitation, and the type of foundation of a structure influence radon availability. Because the driving forces for radon entry can vary daily or seasonally, the dynamic interaction of all these factors in determining indoor radon concentrations in a specific building is complex.

HEALTH EFFECTS [*25*]

Lung cancer due to radon occurs as a result of the dose of alpha energy emitted by radon decay products, which is delivered to target cells in the lungs. Because alpha energy deposition in the lungs cannot be directly measured, modeling is used to simulate the sequence of events from inhalation of radon decay products to cellular injury. Such efforts in dosimetry, combined with animal studies, provide valuable insights and enable research into various aspects of the cause-and-effect relationship such as the effect of long-term exposures to low levels of radon.

Epidemiologic studies or health studies of human populations, whether specific segments of the population or the population in general, offer another avenue for assessing health effects of radon. Epidemiologic investigations, by their nature, have some constraints in yielding fully definitive conclusions because multiple causes of the same health effect, such as cigarette smoking and radon in the case of lung cancer, have to be carefully considered. Studies of lung cancer in uranium miners have consistently shown increased lung cancer occurrence from exposure to radon decay products. Studies of the general population are underway but are complicated by the fact that the history of exposure to radon is difficult to reconstruct, particularly for people who have changed residences, given the general mobility of the American population.

TABLE 1—An historical overview of indoor radon-related developments 1955–1985.

Year	Event/Action
1955	The term "working level" (WL) was originally proposed at the Seven States Conference held in Salt Lake City, Utah, in February 1955. It was considered that insufficient data were available to justify adoption of a maximum permissible concentration for radon decay products, but an interim guide was needed. In 1957, the WL unit was adopted by the U.S. Public Health Service, but its definition was still evolving. In 1973, the American National Standards Institute defined one WL as any combination of radon decay products in 1 L of air that will ultimately release 1.3×10^5 MeV of alpha energy [3].
1963	The First International Symposium on the Natural Radiation Environment was held at William Marsh Rice University, Houston, Texas, 10–13 April 1963. Papers on radon included a review of radon migration in the ground by Tanner [*12*] and a survey technique for measurement of radon by Lucas [*13*].
1970	The Surgeon General of the United States specified concentration guidelines for indoor radon decay products in dwellings constructed on or with uranium mill tailings (uranium- and radium-bearing waste materials). The recommendations were to take remedial action at levels above 0.05 WL, consider remediation for 0.01 to 0.05 WL, and exclude remediation below 0.01 WL [*14*].
1971	Congressional hearings were held on the use of uranium mill tailings in construction in Colorado [*15*].
1972	The Grand Junction Remedial Action Program (GJRAP) was authorized to survey and remediate structures in which uranium mill tailings from the Grand Junction uranium mill were used. Over 600 residential, commercial, or institutional structures have been remediated under GJRAP [*16*].
1975	Based on preliminary findings of a study involving homes built on reclaimed land and unreclaimed land in Polk County, Florida, an EPA report [*17*] concluded that "consideration should be immediately given to providing the State of Florida with the recommendation that continued use of reclaimed land for construction of new structures be discouraged."
1978	The Uranium Mill Tailings Radiation Control Act was enacted (Public Law 95-604). Title I of the act authorized the Uranium Mill Tailings Remedial Action Program (UMTRAP) to be conducted by the U.S. Department of Energy. Standards promulgated by EPA for conducting this remedial program specified that radon levels should not exceed 0.02 WL for existing structures. UMTRAP in Colorado has involved over 8000 contaminated properties of which 4000 require remedial action. In some cases remedial actions have been unsuccessful because of radioactivity from natural uranium deposits [*16*].
1979	In May 1979, the EPA Administrator recommended to the Governor of Florida that remedial action be taken in some existing homes and that future homes built in the region should incorporate construction techniques to resist the entry of radon [*18*].
1980–1984	Various studies identified elevated radon levels in residences surveyed in the states of Maryland [*19*], Pennsylvania and New Jersey [*20,21*], and Maine [*22*].
1984	In December 1984, Stanley Watras, an engineer at the Limerick Nuclear Generating Station in Pottstown, Pennsylvania, set off portal alarms that sense radioactive contamination on workers' clothing. Subsequent investigations determined that the radioactive materials were the decay products of radon and that the source of the radon was not at the nuclear power plant but in the indoor air of the Watras home. Radon levels of 13.5 WL were found in his home, greater than any indoor level ever reported in the literature [*23*].
1985	The EPA Administrator established the Radon Action Program in September 1985 [*1*]. The EPA's Radon Action Program was designed to create a federally coordinated nonregulatory program for reducing risks due to radon through assessment of the magnitude and distribution of radon problems, development of technologies for radon mitigation and prevention in new and existing buildings, transfer of technologies to state and local governments and the private sector, and communication of radon information to the public.

Risk-projection models, expressed in terms of occurrence of lung cancer per unit of exposure and derived from the above types of studies, are used to develop estimates of excess cancer risk due to radon. The estimates of lung cancer deaths attributable to radon mentioned earlier are derived from such models.

MEASUREMENT METHODS AND INSTRUMENTATION [*26*]

Various factors need to be considered in selecting methods and instruments for measurement of radon or radon decay products. Examples of such factors include measurement objectives, type of desired output, and sampling duration. For example, if the measurement objective is to assess exposure to radon in a large number of dwellings, a method providing an annual average concentration of radon would be a practical choice. Such a method would meet the objective and would be easier and less costly to use than that which provides a continuous readout of radon concentration every hour.

Methods for measuring radon and its decay products are based on the detection of radioactive emissions. Such methods can include detection of alpha particles, gamma rays, or less commonly, beta rays. A variety of methods and instruments based on such principles is commercially available. Measurements of radon are useful in conducting surveys of

radon concentrations in a building, whereas measurements of radon decay products are useful in dosimetric studies. Devices such as alpha track detectors, activated carbon monitors, and passive electret ion chambers are widely used to provide time-integrated measurements of radon over a period of days (activated carbon, electrets) or months (alpha track detectors, electrets). Scintillation cells are commonly used for continuous monitoring or for instantaneous or grab sampling of radon. Measurements of radon decay products are generally more difficult and more costly and, thus, radon decay product concentrations are often inferred from radon concentrations and theoretical considerations.

Radon-flux and soil-gas measurements are useful for characterizing the potential for radon prior to construction, as well as for aiding a diagnostic assessment for mitigation. The basic measurement techniques for radon and radon decay products are generally well established, and applications of these measurements to help improve the understanding of radon potential in soil and radon-resistant methods of construction are gaining increased attention in research.

As the number of measurements of radon and radon decay products have increased, so has the need for standardization of such measurements. Such need has become quite important as the use of measurements has gone beyond research studies. Recognizing this need, the ASTM D22.05 Subcommittee on Indoor Air has been developing standard methods, practices, and guides for the measurement of radon and radon decay products.

MEASUREMENT PROTOCOLS [*27*]

Radon concentrations in a building vary, depending on where and when a measurement is made. Within the same building, if the floor on which the measurement is made is in contact with the ground, then the radon concentration for this floor would generally be higher than for an upper-level floor, since the predominant source of elevated radon is soil gas. Within one floor, especially in large buildings with complex ventilation systems, concentrations can vary by location. Season or even time of day can make a difference in concentration at a given location. Further, open windows or doors and outdoor conditions such as wind speed or soil moisture can make a difference in indoor radon levels. Given all the factors that can influence concentrations, development of a well-defined, predetermined series of procedures, i.e., measurement protocol, prior to conducting any measurements is necessary.

The purpose of the measurements, choice of measurement methods, sampling and analytical techniques, selection of locations and frequency of measurements, and quality control and quality assurance procedures are some of the factors that need to be carefully defined in protocols. Some elements of quality control procedures include calibration of instruments and performance checks, use of replicate and blank samples, and analysis of samples of known radon content. A quality assurance program includes specifications for comprehensive documentation of procedures, preventive maintenance, corrective actions, and delineation of responsibilities.

Several measurement protocols for a variety of purposes have been developed by different organizations. For example, since the early 1970s, the U.S. Department of Energy (DOE) has developed and used protocols for measurement of radon and radon decay products in residences affected by uranium mill tailings. EPA has developed protocols for radon measurements in houses, schools, and workplaces. Such protocols undergo refinements in these organizations and through the consensus development processes of ASTM.

GEOLOGY AND OCCURRENCE [*28*]

The geology of an area determines the concentrations of radium and radon in the rock and soil as well as the ease with which radon can move through them. Some rock types having high radon emanation potential include carbonaceous shales, glauconite sandstones, phosphorites, uranium-bearing granites, metamorphic rocks, and sheared or faulted rocks. The radon emanation potential of such rock types, combined with soil characteristics such as porosity, permeability to gas movement, and moisture content, are important in determining radon potential, i.e., radon production and mobility.

Radon potential for a geologic province (geologically similar area) can be determined by analyzing available geologic, aerial radiometric, soil radon, and indoor radon data. Very generalized geologic provinces are depicted in Fig. 3. The Coastal Plain of the southern and eastern United States has the lowest potential, but localized concentrations of uranium and radium have produced high indoor radon concentration in certain areas of Florida, New Jersey, and Texas, for example. The Pacific Coastal Range and Sierra Nevada are expected to have low to moderate radon potential, but limited data are available to confirm such an inference. The Appalachian region and Rocky Mountains have low to moderate radon, but each of these areas has localized areas of high radon potential (Pennsylvania, New Jersey, Maryland, and Virginia in the Appalachian region and Colorado and Idaho in the Rocky Mountain region). In the Appalachians, the highest radon values occur in association with faults and fractures in the rock. Uranium-bearing clays in the Great Plains region are the probable cause of high indoor radon levels in South Dakota, Kansas, and eastern Colorado. Elevated indoor radon concentrations in areas of North Dakota and Minnesota are the result of high radon production potential and high permeability associated with clay-rich tills originating from glacial deposits which, in turn, are derived from uranium-bearing shales.

CONCENTRATION PATTERNS [*29*][2]

Since 1986, more than 40 states in the United States have conducted systematic statewide screening surveys of indoor radon concentrations using activated carbon monitors, primarily charcoal canisters. The canisters, which are typically used for sampling radon concentrations over two- to seven-day periods under closed-house conditions during the winter,

[2]The results of EPA's National Residential Radon Survey [*30*] were not available when the chapter on concentration patterns was prepared.

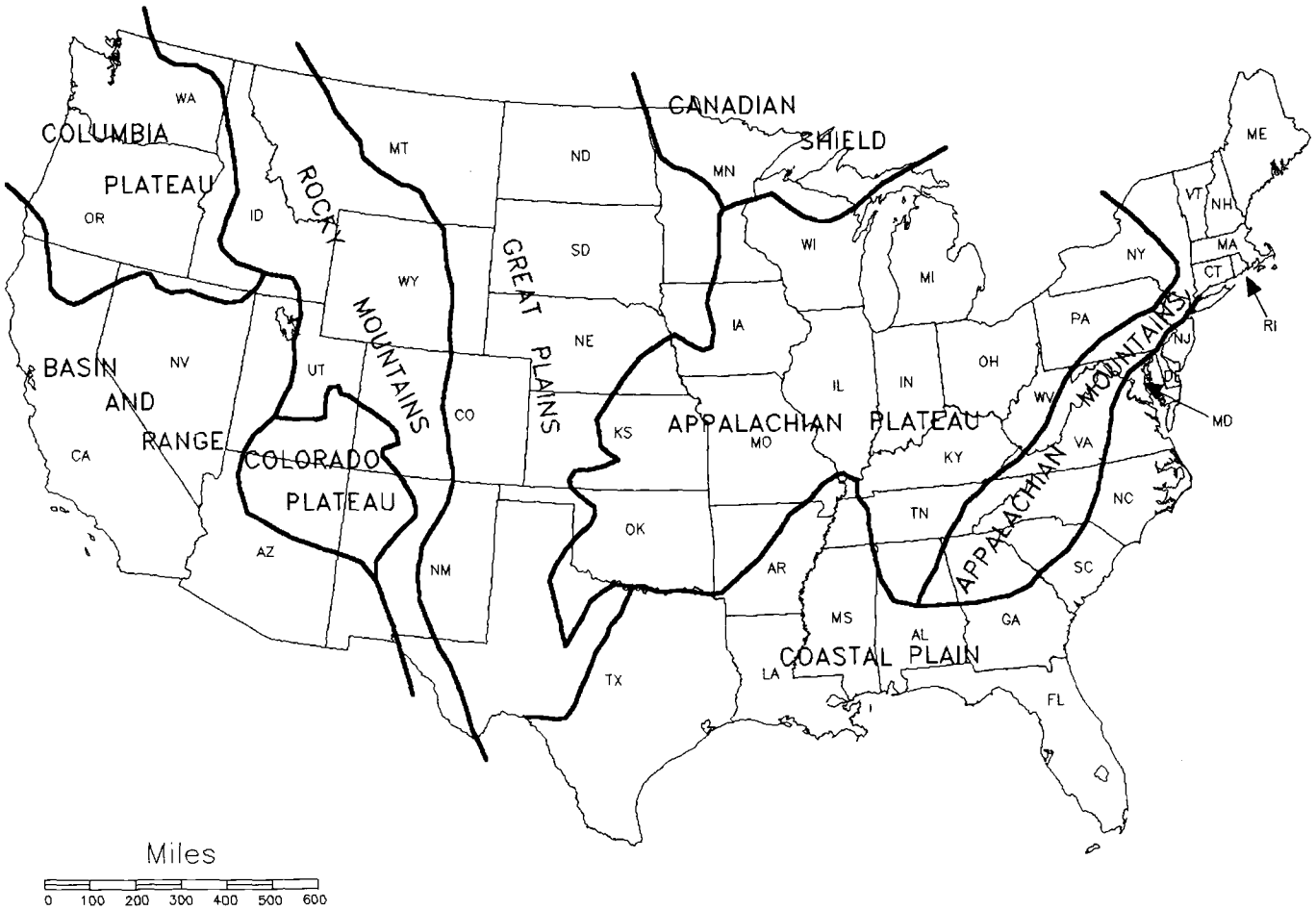

FIG. 3–Generalized geologic provinces [*28*].

tend to overestimate radon concentrations, relative to longer-term samplers used to measure radon concentrations under normal living conditions. Despite this bias, the results of statewide surveys using activated carbon monitors provide useful information on radon concentration patterns in the United States.

The statewide surveys indicate that indoor screening measurements are considerably lower in southern and western census regions of the country than in north-central and northeast regions (Fig. 4). Iowa and North Dakota in the north-central and Pennsylvania in the northeast have the highest average screening measurements among those states that have been surveyed. Maine, Minnesota, Nebraska, New Hampshire, New Jersey, and Ohio are other states with high averages. Consistent with geologic indicators, the states with the lowest screening measurements tend to lie along the western, southern, and southeastern coasts. However, even among states with relatively low average screening results, it is possible to find individual counties in which some fraction of homes have elevated radon measurements. Spatial patterns of indoor radon concentrations within the states generally have been consistent with expectations from geology and radioaerometric surveys. It should be recognized that, although geographic areas with higher radon potential can be delineated with a reasonable degree of certainty, radon levels in individual buildings cannot be safely deduced without conducting indoor radon measurements.

CONTROL STRATEGIES [*31*]

The most common way for radon to enter a building is through pressure-driven transport of soil gas. Other, but less prevalent, reasons for elevated indoor radon concentrations include emanation of radon from well water containing radium and use of uranium-contaminated construction materials. Thus, much of the emphasis of radon reduction or control is on prevention of radon entry from the soil gas into the building.

For radon control to be effective, a proper diagnosis of radon problems, such as radon measurements to determine entry routes, evaluation of construction integrity, and assessment of the HVAC system, is essential. Among the methods to reduce radon entry into a building, active subslab depressurization (ASD) is the most widely used control method. For ASD, a fan is used to create a negative pressure field in the soil under the building (Fig. 5). This negative pressure field reverses the flow of radon—instead of entering the building, the radon is exhausted by the fan to the outdoors. Depending on the prevalent entry route and building construction features,

FIG. 4–Average indoor radon screening measurement results by state and region [*29*].

ASD techniques include subslab depressurization, crawlspace depressurization, and block-wall depressurization.

Other approaches for reducing risk from radon exposure are by dilution with outdoor air or by treatment to remove radon or radon decay products. These techniques remove radon only after it enters the building, but do not prevent radon entry. Ventilation reduces the radon concentration through dilution, but its application is limited because of the impracticality of increasing the ventilation rate by severalfold in order to achieve a sufficient reduction in radon concentration. Further, energy penalties associated with even moderate increases in ventilation often make this approach unattractive. Removal by plating out of radon decay products, i.e., attachment of particles to surfaces, is advocated by some as a method for reducing risk due to radon, but that approach is fraught with uncertainties associated with its actual benefit in reducing health risks.

New construction offers a variety of avenues for reducing potential risk of elevated radon, typically at a much lower cost than a retrofit. These techniques focus on prevention of radon entry into the building and include changes in design and construction of foundations, slabs, and block walls, use of membranes to retard the flow of soil gas, as well as provisions for roughing in the piping and electrical components of an ASD system. Research on new construction techniques is continuing under the sponsorship of the EPA and some state agencies such as the Florida Department of Community Affairs.

The ASTM Subcommittee E6.41 on Building Infiltration is developing consensus documents on standardized approaches for controlling radon in buildings. For example, a standard guide for radon control options for the design and construction of new low-rise residential buildings was approved by ASTM in 1992 [ASTM Guide for Radon Control Options for the Design and Construction of New Low Rise Residential Buildings (E 1465-92)].

LEGISLATION AND EPA'S RADON ACTION PROGRAM [*32*]

In 1985, in response to the very high levels of radon discovered in the Reading Prong area, EPA established the Radon Action Program. The program was designed to address key needs such as an assessment of the extent of the radon problem, standardized measurement methods, cost-effective techniques for reducing radon levels, guidelines on radon levels at which reduction should be undertaken, and tools for communicating health concerns and solutions to the public. Subsequently, the U.S. Congress expanded EPA's program by

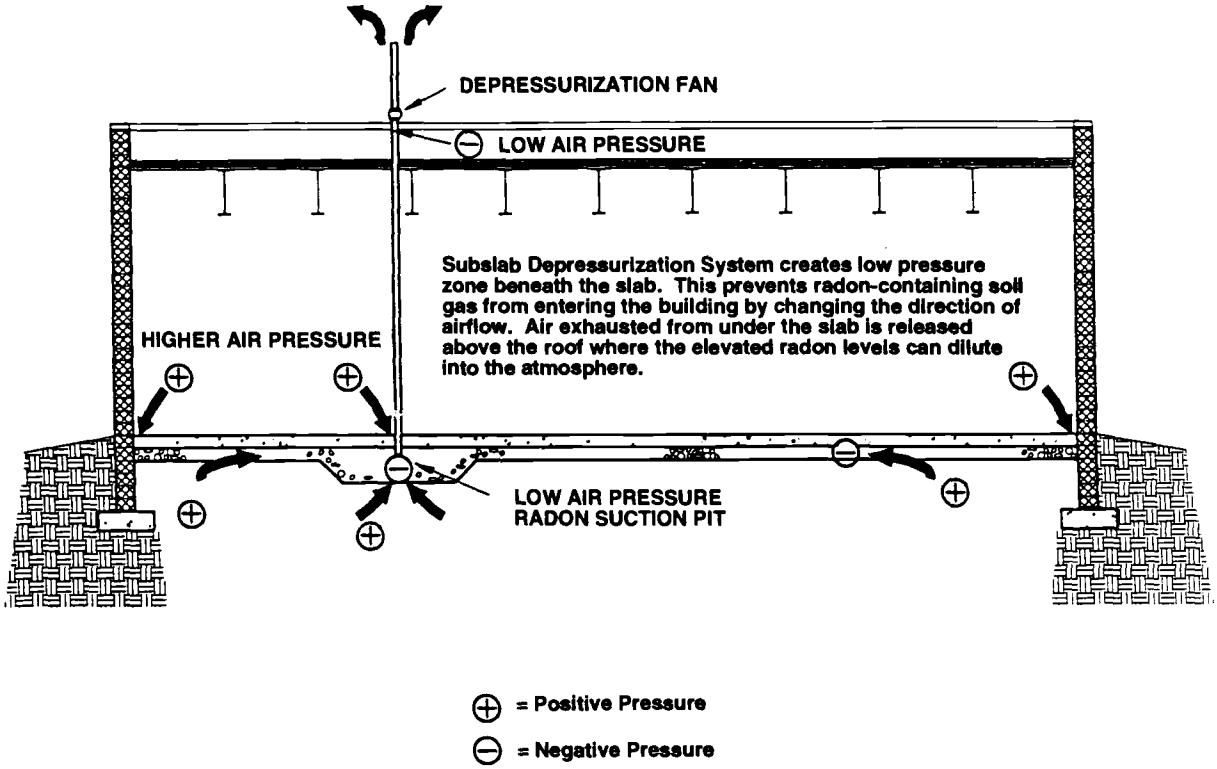

FIG. 5–Active soil depressurization method to prevent radon entry into buildings [*31*].

enacting two pieces of legislation: (1) Superfund Amendments and Reauthorization Act of 1986, and (2) the Indoor Radon Abatement Act of 1988. Important aspects of EPA's continuing research on radon include: further refining estimates of the magnitude of the health risk posed by residential radon exposure, assessing the interactive effects of smoking and radon, identifying geographic areas with the highest potential for radon problems, and studies to determine the cost and reliability of approaches for measuring, mitigating and preventing elevated radon levels in a variety of building types. A major area of emphasis for EPA is the use of a decentralized system for informing the public through state and local government agencies, non-profit public health and consumer protection organizations and professional and business associations. These cooperative partners can use their established communication channels to deliver radon information to individual members of public. Efforts to inform the public and encourage action are important and will be continued by EPA but they will be combined with incentive programs and initiatives to build institutional support for building codes and policies to require radon testing and mitigation when existing homes are sold, especially in high risk areas.

CURRENT AND FUTURE PERSPECTIVES [*33*]

Subjects such as the origin of radon, health effects, methods and protocols for measurements, geologic patterns affecting radon concentrations, radon concentration patterns across the United States, strategies for controlling radon, and EPA's Radon Action Program collectively provide a well-rounded look at the radon issue. For a complete and comprehensive understanding, though, perspectives on other federal agency programs, state programs, industry viewpoints, and public perceptions of risks need to be examined.

The DOE Office of Health and Environmental research has allocated a substantial funding (approximately $10 million per year over the 1987-to-1992 period) to conduct a basic radon research program [*34*]. The DOE's program has made significant contributions to the understanding of the indoor radon problem in the areas of radon measurements, availability, entry dynamics, and dosimetry. The DOE research formed the basis for an input to EPA's risk estimate of 13 600 annual deaths. A further DOE contribution is the focus on using new techniques in cellular and molecular biology to answer the important questions on whether there is a threshold for carcinogenic effect from radiation and repair of alpha radiation damage.

Some states such as Florida, Minnesota, and New Jersey have undertaken their own radon programs that, in certain aspects, go beyond the federal radon program because of specific state needs. For example, the state of Florida became involved in the radon issue because of the phosphate mining areas in the state. Concerns for elevated indoor radon in homes built on reclaimed phosphate lands have been raised since the mid-1970s. A radon statute passed in 1988 by the Florida state legislature provides Florida with a radon program to identify and eliminate radon problems through changes in building codes. To finance the research effort to accomplish these tasks, the statute has established a radon trust fund which levies a surcharge on new construction and renovation of buildings. The state has co-funded research with EPA, and such state-federal partnerships allow research

dollars to go further in developing long-term, more widely applicable initiatives.

Radon policies have been established quite promptly following the discovery of Watra's house. Yet, uncertainties remain in many aspects of the radon issue including identification of geographical areas with elevated radon potential and quantification of health risks to nonsmokers. Similarly, influencing peoples' perceptions about radon risks is more complex than ever thought before. Understanding and conveying the risks to people will require continued emphasis on research and education.

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2

Radon and the Natural Environment

by Richard G. Sextro[1]

RADON HAS COME TO BE RECOGNIZED as one of the most important environmental pollutants to which humans are exposed, in part due to the fact that it is widespread—indeed, radon is present in all houses—and due to the health risks associated with even average concentrations. Although the existence of radon has been known since the beginning of this century and the health effects associated with exposure to mine atmospheres (both uranium and nonuranium mines) have been studied for several decades, our understanding of it as an indoor air contaminant in ordinary houses has developed substantially only within the past decade. Some of the earliest indications of elevated concentrations in U.S. homes were associated with the use of uranium mill tailings as backfill in house construction [*1*] or in other areas where radium concentrations were elevated, such as parts of central Florida, where buildings were built on lands reclaimed from phosphate mining [*2*]. However, by the late 1970s, researchers had found homes in other parts of the U.S. with elevated radon concentrations for which there were no radon sources that could be associated with technological activities [*3–5*]. The discovery of high-to-very-high indoor concentrations in eastern Pennsylvania in the mid 1980s [*6,7*] did not offer a new scientific perspective on the radon question; rather, it focused the attention of the public and local and federal governmental agencies on the issue. This chapter provides a broad overview of radon and its radioactive decay products. A number of topics are introduced in this discussion that are covered in greater detail in later chapters.

BACKGROUND

Origin of Radon

Radon is a colorless and odorless monatomic gas. It is, under all conditions of interest here, chemically inert and is the heaviest of the six noble gases constituting Group 0 of the Periodic Table of Elements. Unlike other gases in this group, it has no stable isotopic form; instead, all of its isotopes are radioactive. There are three naturally occurring isotopes of radon, each associated with a different radioactive decay series that begin with the radionuclides ^{238}U, ^{232}Th, or ^{235}U, respectively. Radon-222, which has a 3.8 day half-life, is part of the uranium (^{238}U) decay chain. This nuclide is the most important of the three radon isotopes because of its concentrations in indoor air and due to the health effects associated with exposures to its radioactive decay products. Radon-220, alternatively referred to as thoron, is part of the thorium (^{232}Th) decay series and has a half-life of 56 s. Under certain circumstances, it can contribute to the radiation exposure in homes in the United States, though its short half-life typically limits the indoor concentrations of thoron and its decay products. The third radon isotope in this list, ^{219}Rn (archaically named actinon in reference to its presence in the "actinium," or ^{235}U, decay series), does not contribute significantly to human radiation exposures due both to the low natural abundance of the ^{235}U precursor (approximately 20 times smaller activity concentration than ^{238}U) and the very short (4 s) ^{219}Rn half-life. In this book, use of the word radon is generally synonymous with ^{222}Rn. In those cases where the discussion refers directly to the ^{220}Rn isotope (thoron), this will be noted.

The ^{238}U and ^{232}Th decay series are illustrated in Figs. 1 and 2, respectively. As can be seen, each decay chain proceeds through a series of radioactive transformations and ultimately terminates in a stable isotope of lead. These radioactive decays proceed either by alpha decay, in which the unstable nucleus emits an alpha particle, equivalent to the nucleus of a helium atom, or by beta decay, where the unstable nucleus releases an electron. In some cases, these alpha or beta decays may also lead to the production of gamma radiation, which is an important source of external radiation exposure, as discussed below.

Uranium-238, ^{235}U, and ^{232}Th are primordial radionuclides, that is, they were present at the origin of the earth and have half-lives that are of the same order of magnitude as the age of the earth (ca. 4.5×10^9 years). Although the natural abundance of ^{238}U and ^{232}Th varies by geological setting, they are widely distributed in the earth's crust. The highest average concentrations of these radioelements are found in relatively rare alkaline intermediate rocks, with both having concentrations on the order of 500 Bq kg^{-1} (13.5 pCi g^{-1}). Somewhat lower values are found in other igneous rocks, ~80 to 100 Bq kg^{-1} (2 to 3 pCi g^{-1}) for both these nuclides. Among the sedimentary rocks, shales tend to have higher concentrations, ~40 and 50 Bq kg^{-1} (1 and 1.5 pCi g^{-1}) for ^{238}U and ^{232}Th, respectively. The mean of the upper continental crust, weighted by the abundance of the various rock types, is about 50 Bq kg^{-1} (1.4 pCi g^{-1}) for each of these radionuclides [*8*].

The radiochemical composition of soil, which is a mixture of soild materials, air, and often water and organic matter, typically reflects the geological formations from which the soil has been derived, although weathering and other transport processes can affect the soil composition as well. On

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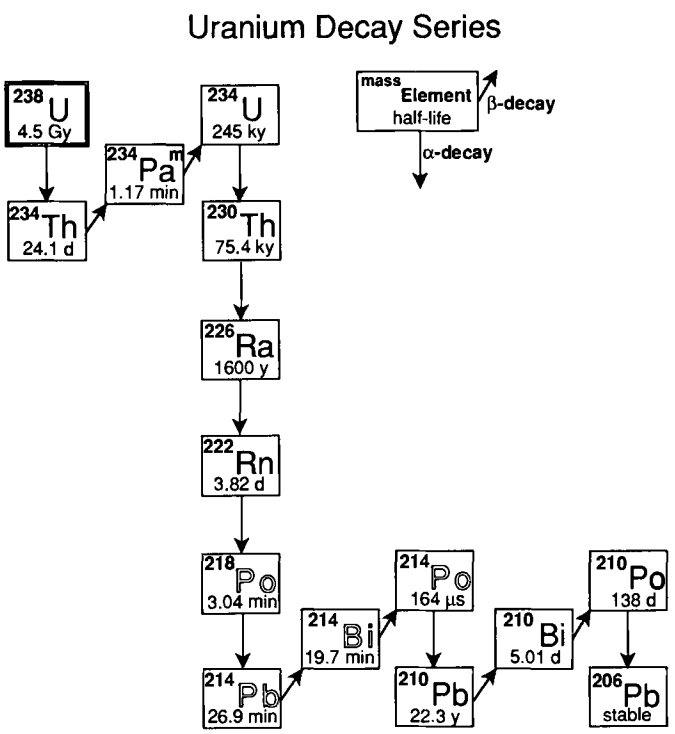

FIG. 1–^{238}U decay series, including ^{222}Rn and its decay products. Only the major decay branches are shown. The nuclides designated by the outline typeface are those whose inhalation and/or subsequent decay give rise to the health effects associated with exposure to ^{222}Rn. All half-lives except for those nuclides noted in Table 1, are from Ref *94*.

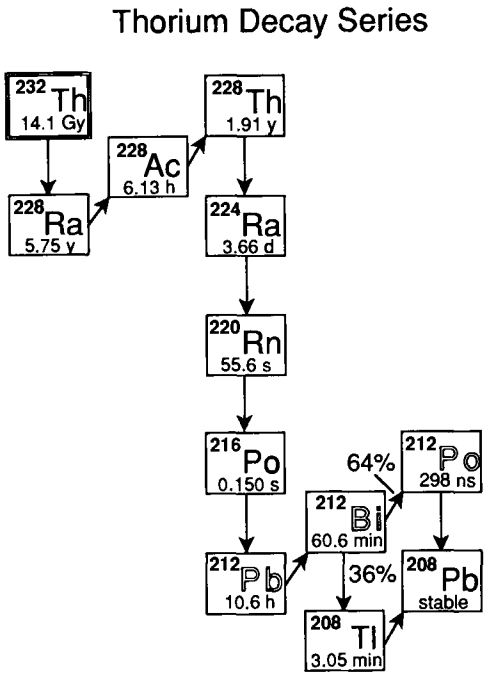

FIG. 2–The decay series for ^{232}Th, which includes ^{220}Rn and its decay products. The nomenclature for each nuclide and radioactive decay is the same as given in Fig. 1. Those nuclides responsible for the health effects associated with ^{220}Rn exposures are indicated by the outline typeface. Only the major decay branches are shown, and the branching ratios and half-lives are taken from Ref *94*.

average, the concentrations of ^{238}U and ^{232}Th in soils are about 30% lower than the average crustal concentrations [*8*]. Radioactive equilibrium (in this case, each of the decay products of these primordial nuclides, down to the gaseous radon isotopes, have approximately equal activity concentrations) is often observed, though not in all cases. Radium isotopes, like their original uranium or thorium sources, are also widely distributed in the earth's crust, and the radium concentration in soils is typically 40 Bq kg^{-1} (1 pCi g^{-1}). In general the observed values range from ~10 to 200 Bq kg^{-1} (0.3 to 5.4 pCi g^{-1}) for soils outside of areas with uranium mining and milling activities [*9*].

Due to the widespread presence of radium, the resulting ^{222}Rn and ^{220}Rn isotopes are ubiquitous constituents of the fluids present in soil pore spaces. Radium in crustal materials also accounts for the appearance of radon in groundwater, where the radon typically arises from the radium in the solid materials in which the aquifer is found, rather than coming from radium dissolved in the water. More details on radon and geology are presented in Chapter 6.

Each of the radon isotopes is radioactive. As illustrated in Figs. 1 and 2, these radioactive decays produce other radionuclides, referred to as radon decay products (alternative references in the literature are to radon progeny or to the more archaic term, radon daughters). Additional details regarding the half-lives, decay modes, and the alpha and gamma decay energies and intensities for ^{222}Rn and ^{220}Rn and their respective decay products are presented in Tables 1 and 2, beginning with their radium precursors. The behavior of radon decay products in indoor environments is discussed in greater detail later in this chapter.

Radioactive Decay—A Brief Primer

Radionuclides are inherently unstable; this property can be characterized by the half-title ($t_{1/2}$), which is the period of time it takes for one half of the initial quantity of radioactive atoms to radioactively decay. Radioactive decay is unaffected by any chemical interactions the radioactive atoms may undergo. The decays illustrated in Figs. 1 and 2, particularly beta decay, are often accompanied by the emission of one or more gamma rays. Some of the gamma decay energies associated with radon or thoron decay products are listed in Tables 1 and 2.

While a rigorous mathematical treatment of the equations describing radioactive growth and decay of a series of decay products is beyond the scope of this chapter, the main elements as they apply to radon and its decay products are provided here. Greater detail may be found in Ref *10* or in most standard texts on nuclear physics or nuclear chemistry. The equation describing the loss of atoms of a particular radionuclide by radioactive decay is

$$\frac{dN}{dt} = -N\lambda \qquad (1)$$

TABLE 1—^{222}Rn decay series[a].

Nuclide	Half-Life	Decay Constant, λ (s^{-1})	Major Radiation Energies		Potential Alpha Energy Calculation		
			E_α, MeV	E_γ keV	N, atoms Bq^{-1}	ΣE_α, MeV $atom^{-1}$	Fraction[b]
^{226}Ra	1600 years	1.37×10^{-11}	4.60 (6)[c]	...	7.3×10^{10}	...	...
	...	...	4.78 (94)	...	...	...	...
^{222}Rn	3.82 days	2.10×10^{-6}	5.49 (100)	...	4.8×10^{5}	...	...
^{218}Po	3.04 min[d]	3.80×10^{-3}	6.00 (~100)	...	263	13.69	0.104
^{214}Pb	26.9 min[e]	4.29×10^{-4}	...	242 (20)[f]	2329	7.69	0.517
	...	...	...	295 (52)	...	...	...
	...	...	...	352 (100)	...	...	...
^{214}Bi	19.7 min[e]	5.86×10^{-4}	...	609 (100)	1705	7.69	0.379
	...	...	...	1120 (33)	...	...	...
	...	...	...	1764 (35)	...	...	...
^{214}Po	164 μs	4.23×10^{3}	7.69 (100)	...	2×10^{-4}	7.69	0
^{210}Pb	22.3 years	9.86×10^{-10}	...	47 (100)	...	...	...
^{210}Bi	5.01 days	1.60×10^{-6}	...	...[g]	...	...	...
^{210}Po	138 days	5.81×10^{-8}	5.30 (100)	...	...	...	...
^{206}Pb	stable	...	...	...	...	...	...

[a]Except as noted, all data on half-lives, alpha- and gamma-decay energies, and decay intensities are from Ref *94*.
[b]Fraction of total alpha energy released, computed as $N_i \times (\Sigma E_\alpha)_i / \Sigma(N_i \times (\Sigma E_\alpha)_i)$.
[c]Fraction of total alpha decay.
[d]Half-life from Ref *95*.
[e]Half-life from Ref *96*.
[f]Fraction of decays proceeding by this mode (in percent), relative to the most intense gamma decay (= 100).
[g]No gamma emissions accompany this beta decay.

where N is the number of radioactive atoms, λ is the radioactive decay constant for that species, and t is the time. The solution to this differential equation is given by

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

where the decay constant, λ, is related to the half-life by

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

and N_0 is the number of radioactive atoms present initially (at time $t = 0$). The quantity $N\lambda$ is often referred to as the activity, designated by I (where $I_0 = N_0\lambda$). The equations relating the radioactive growth and decay equilibrium between two or more radioactive species (as in the case of the equilibrium established between radon and its decay products) are based on the same principles, although they are functionally more complicated. For the general case of $A \rightarrow B$, where both A and B are radioactive, the differential equation

TABLE 2—^{220}Rn decay series[a].

Nuclide	Half-Life	Decay Constant, λ (s^{-1})	Major Radiation Energies		Potential Alpha Energy Calculation		
			E_α, MeV	E_γ keV	N, atoms Bq^{-1}	ΣE_α, (MeV $atom^{-1}$)[b]	Fraction[c]
^{224}Ra	3.66 days	2.19×10^{-6}	5.45 (5)[d]	...	4.6×10^{5}	...	...
	...	...	5.69 (95)	241 (100)[e]	...	...	...
^{220}Rn	55.6 s	1.25×10^{-2}	6.29 (100)	...	80	...	...
^{216}Po	0.150 s	4.62	6.78 (100)	...	0.22	14.58	0
^{212}Pb	10.6 h	1.82×10^{-5}	...	239 (100)	5.5×10^{4}	7.80	0.913
	...	...	...	300 (8)	...	...	...
^{212}Bi	60.6 min	1.91×10^{-4}	...	...	5246	7.80	0.087
^{212}Bi α decay (36)[f]	...	...	6.05 (25)	...	...	...	...
	...	...	6.09 (10)	...	...	...	...
^{208}Tl	3.05 min	3.79×10^{-3}	...	511 (22)	...	...	...
	...	...	...	583 (86)	...	...	...
	...	...	...	860 (12)	...	...	...
	...	...	...	2615 (100)	...	...	...
^{208}Pb	stable	...	...	...	...	...	...
^{212}Bi β decay (64)[f]	...	...	...	727 (100)	...	...	...
	...	...	...	786 (2)	...	...	...
	...	...	...	1621 (2)	...	...	...
^{212}Po	298 ns	2.33×10^{6}	8.78 (100)	...	4×10^{-7}	5.62	0
^{208}Pb	stable	...	...	...	...	...	...

[a]All data on half-lives, alpha- and gamma-decay energies, and decay intensities are from Ref *94*.
[b]Alpha decay energies, weighted by ^{212}Bi branching ratios.
[c]Fraction of total alpha energy released, computed as $N_i \times (\Sigma E_\alpha)_i / \Sigma(N_i \times (\Sigma E_\alpha)_i)$.
[d]Fraction of total alpha decay.
[e]Fraction of decays proceeding by this mode, relative to the most intense gamma decay (= 100).
[f]Fraction of total ^{212}Bi decay.

describing the production of B from the decay of A and the subsequent radioactive decay of B is

$$\frac{dN_B}{dt} = N_A\lambda_A - N_B\lambda_B \tag{4}$$

Similar equations can be derived for successive parent-progeny relationships. These equations, known as the Bateman equations [*11*], can be simplified for specific cases where, for example, the half-lives of the parent and progeny species are quite different and where initial conditions can be specified. For $N_{B_0} = 0$ and $N_A = N_{A_0}$ at $t = 0$, the solution for Eq 4 is

$$N_B = \frac{\lambda_A}{\lambda_B - \lambda_A} N_{A_0}(e^{-\lambda_A t} - e^{-\lambda_B t}), \tag{5}$$

or using $I = N\lambda$ and Eq 3

$$\frac{I_B}{I_{A_0}} = \frac{t_{1/2}(A)}{t_{1/2}(A) - t_{1/2}(B)}(e^{-\lambda_A t} - e^{-\lambda_B t}) \tag{6}$$

More general treatments of these equations, including the detailed equations for all of the radon decay product concentrations, are available [*10,12*], but are beyond the scope of this chapter.

Using the Bateman equations for the production and decay of each of the radon decay products, the time-dependent activity concentrations can be calculated. The results are shown in Figs. 3 and 4 for ^{222}Rn and ^{220}Rn, respectively, each for the case of an initially pure sample of radon or thoron. These two figures also illustrate two conditions of radioactive equilibrium. In the case of ^{222}Rn, radioactive equilibrium between radon and the radon decay products is achieved after approximately 3 h. After that time, the activity concentrations of the short-lived decay products are essentially equal to that of the radon parent. This situation is referred to as secular equilibrium. As can be seen in Fig. 3, the activity concentration of ^{218}Po increases rapidly in a pure ^{222}Rn sample (as is also the case in a building in response to radon entry) so that approximately 50% of the equilibrium concentration is achieved within 4 min and almost 90% equilibrium between the radon parent and this first decay product is obtained within 10 min. For the ^{220}Rn series, on the other hand, the initial concentration of ^{220}Rn decays away quite quickly, and no equilibrium between the radon parent and the subsequent decay products exists. Instead, the total alpha activity observed for a sample of ^{220}Rn for times greater than 10 min after collection is controlled by the decay of the 10.6 h ^{212}Pb isotope. As discussed in more detail below, the equilibrium conditions in actual indoor environments are different than illustrated here, since the airborne radon decay product concentrations are affected by indoor aerosol concentrations, ventilation rates, and radon entry rates.

By combining the equations describing the concentrations of the alpha-active radionuclides, the total alpha activity as a function of time can be calculated. Using the decay constants or half-lives for the radon isotopes and their respective decay products as summarized in Tables 1 and 2, the equations for the total alpha activities are

$$\begin{aligned}\frac{\text{Total alpha activity}}{I_{\text{Rn-222 (initial)}}} = {} & 3.010\exp(-\lambda_{\text{Rn-222}}t) \\ & - 1.024\exp(-\lambda_{\text{Po-218}}t) \\ & - 4.404\exp(-\lambda_{\text{Pb-214}}t) \\ & + 3.418\exp(-\lambda_{\text{Bi-214}}t)\end{aligned} \tag{7}$$

and

$$\begin{aligned}\frac{\text{Total alpha activity}}{I_{\text{Rn-220 (initial)}}} = {} & 2.003\exp(-\lambda_{\text{Rn-220}}t) \\ & + 1.6\times10^{-3}\exp(-\lambda_{\text{Pb-212}}t) \\ & - 1.63\times10^{-3}\exp(-\lambda_{\text{Bi-212}}t)\end{aligned} \tag{8}$$

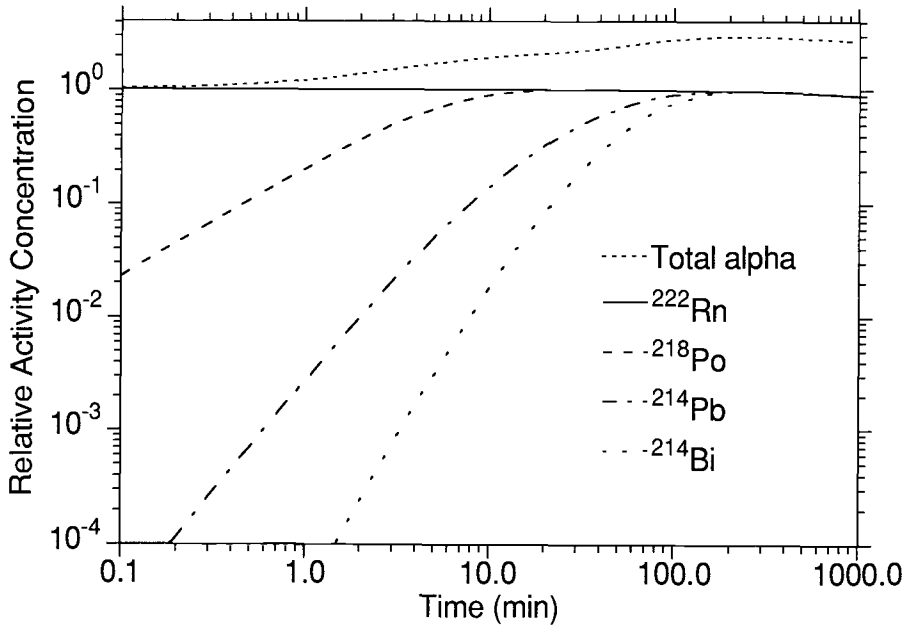

FIG. 3–Relative activity concentration of ^{222}Rn and its immediate radioactive decay products as a function of time. These concentrations assume that only ^{222}Rn is present initially. The total alpha activity concentration as computed from Eq 7 is also shown.

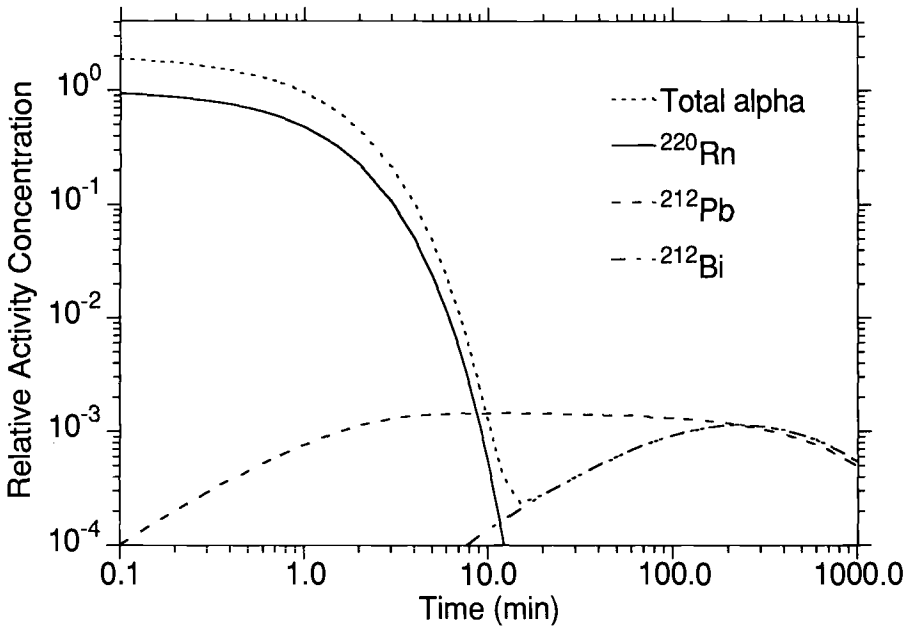

FIG. 4–Relative activity concentration of ^{220}Rn and its decay products as a function of time. Only ^{220}Rn is present initially, although due to the very short 150 ms half-life for ^{216}Po, the total alpha activity concentration as calculated from Eq 8 is already effectively twice the ^{220}Rn concentration after 6 s (the lower limit on the time axis in the figure).

As a practical matter, these equations are the basis for interpreting measurements of radon concentrations using grab samples taken with a scintillation cell. The total alpha activity concentrations are also shown in Figs. 3 and 4.

Measurement Units

Radionuclides are often measured in terms of their activity concentrations, that is, the amount of radioactive decay that occurs per unit of volume or mass. Until recently, the most common unit of radioactivity has been the curie and by modern definition is equal to 3.7×10^{10} disintegrations per second. More recently, the becquerel, defined as one disintegration per second by the International System of Units (SI), has been adopted for use in scientific publications. Thus, radionuclide concentrations formerly measured in units of picocuries per liter (pCi L^{-1}) or per gram (pCi g^{-1}) are now more properly denoted by Becquerels per cubic meter (Bq m^{-3}) or per kilogram (Bq kg^{-1}). This book has adopted the SI convention, although the equivalent concentration in pCi L^{-1} or pCi g^{-1} is often shown parenthetically. The units of measure and the conversions among them are shown in Table 3.

Most early measurements of radon decay product concentrations were done in mines and were part of efforts to characterize and eventually limit exposures of miners to radon decay products. The potential alpha energy concentration (PAEC) concept was devised such that the decay product concentrations are expressed in units of working levels (WL), where, by definition, 1 WL is equal to any combination of radon decay products in 1 L of air that ultimately releases 1.3×10^5 MeV of alpha decay energy [*13*]. By this definition, 100 pCi L^{-1} of radon, in complete equilibrium with its decay products (under the assumption that they all remain airborne), is equivalent to 1 WL. Each of the short-lived decay products of ^{222}Rn or ^{220}Rn leads to one or more alpha decays; the number of atoms of each radionuclide per unit activity and their ultimate alpha decay energies are shown in Tables 1 and 2. The conversion for PAEC in units of WL and the SI units of J m^{-3} is shown in Table 3.

An alternative method of expressing radon progeny concentrations is the equilibrium equivalent concentration (EEC), which is currently more widely used in Europe than in the United States. The EEC is expressed in units of activity concentration, either Bq m^{-3} or pCi L^{-1}, and is related to the individual decay product concentrations by

$$\text{EEC} = \sum_{i=1}^{n} a_i I_i \tag{9}$$

where a_i is the weighting factor for each decay product, as shown in the last column of Tables 1 and 2, I_i is the corresponding activity concentration, and $n = 3$ and 2 for decay products of ^{222}Rn and ^{220}Rn, respectively. The equilibrium equivalent concentration (EEC) and weighting factor for each of the radon decay subseries are shown in Table 3, along with the conversions between EEC and PAEC.

As can be seen from Table 1, the concentration of ^{214}Po in the air does not contribute to the overall PAEC since the very short half-life limits the actual number of atoms of this radionuclide in the air compared with the other decay products. However, its importance to the total PAEC is that the decay of any of the previous radon products will eventually lead to the 7.69 MeV alpha decay of ^{214}Po, as indicated in Table 1. Similarly, ^{212}Po does not directly contribute to the measured PAEC of the ^{220}Rn decay products due to its very short half-life, although in analogy to ^{214}Po, part of the ^{220}Rn decay chain eventually leads to the 8.78 MeV alpha decay of ^{212}Po.

TABLE 3—Conversion factors and units of measurement.

Activity	
SI units[a]: 1 becquerel (Bq)	= 1 disintegration per second (s^{-1})
1 curie (Ci)	= 3.7×10^{10} disintegrations s^{-1}
	= 3.7×10^{10} Bq
1 picocurie (pCi)	= 0.037 Bq
	= 2.22 disintegrations min^{-1}
Activity Concentration	
SI units: 1 Bq m^{-3}	= 0.027 pCi L^{-1}
1 pCi L^{-1}	= 37 Bq m^{-3}
SI units: 1 Bq kg^{-1}	= 0.027 pCi g^{-1}
Potential Alpha Energy Concentration (PAEC)	
PAEC	= 1.3×10^5 MeV L^{-1}
SI units:	= 2.08×10^{-5} J m^{-3}
	= 1 Working Level (WL)
1 mWL	= 20.8 nJ m^{-3}
Progeny	
Equilibrium Equivalent Concentration (EEC)	
EEC (^{222}Rn)	= 0.104 I [^{218}Po] + 0.517 I [^{214}Pb] + 0.379 I [^{214}Bi]
EEC (^{220}Rn)	= 0.913 I [^{212}Pb] + 0.087 I [^{212}Bi]
(where EEC and I[i] are in either Bq m^{-3} or pCi L^{-1})	
For ^{222}Rn: EEC (Bq m^{-3})	= 3700 × PAEC (WL)
PAEC (nJ m^{-3})	= 5.62 × EEC (Bq m^{-3})
For ^{220}Rn: EEC (Bq m^{-3})	= 276 × PAEC (WL)
PAEC (nJ m^{-3})	= 75.4 × EEC (Bq m^{-3})
Equilibrium factor (F)	= EEC/I [Rn]
1 Bq m^{-3} ^{222}Rn	= 2.81 nJ m^{-3} PAEC at F = 0.5
	= 1.35×10^{-4} WL
1 pCi L^{-1} ^{222}Rn	= 5.0×10^{-3} WL at F = 0.5
1 Bq m^{-3} ^{220}Rn	= 3.77 nJ m^{-3} PAEC at F = 0.05[b]
	= 1.81×10^{-4} WL
1 pCi L^{-1} ^{220}Rn	= 6.7×10^{-3} WL at F = 0.05[b]
Exposure	
1 working level month (WLM)	= 1 WL for 170 h
WLM	= WL × (exposure time in h/170 h)
SI units: 1 WLM	= 3.54×10^{-3} J h m^{-3}
working 170 h per month for 1 year at 1 WL	= 12 WLM
living for 1 year at WL (100% occupancy)	= 51.5 WLM
For 1 year exposure at 100% occupancy; F	= 0.5 for ^{222}Rn; F = 0.05[b] for ^{220}Rn
Exposure (1 Bq m^{-3} ^{222}Rn)	= 2.81 nJ y m^{-3} = 2.46×10^{-5} J h m^{-3}
	= 7.0×10^{-3} WLM
Exposure (1 pCi L^{-1} ^{222}Rn)	= 0.26 WLM
Exposure (1 Bq m^{-3} ^{220}Rn)	= 3.77 nJ y m^{-3} = 3.30×10^{-5} J h m^{-3}
	= 9.3×10^{-3} WLM
Exposure (1 pCi L^{-1} ^{220}Rn)	= 0.35 WLM
Dose	
SI units: 1 gray (Gy)	= 1 joule per kilogram (1 J kg^{-1})
1 Gy	= 100 rad
Dose Equivalent	
Si units: sievert (Sv)	= 100 rem

[a]Measurement units adopted by the International System of Units.
[b]Equilibrium factor for ^{220}Rn decay products based on estimates from Refs *15 and 16*.

The relationship between the radon concentration and the combined radon decay product concentrations, expressed as EEC, is given by the equilibrium factor, F, which is defined as

$$F = \frac{\text{EEC}}{I_0}, \tag{10}$$

where I_0 is the corresponding activity concentration of radon (in the same units as the EEC). If all of the radon decay products remained airborne, F would equal 1, reflecting complete airborne equilibrium between the activity concentrations of all of the nuclides in the decay subseries. However, as will be illustrated below, there are a number of factors that influence the behavior of radon decay products in indoor air, leading to a reduction in observed *airborne* concentrations. The average equilibrium factor for ^{222}Rn and its decay products in U.S. homes is usually taken to be 0.5, although a number of recent measurements have suggested that F may be closer to 0.4 or even lower in some homes [*14*]. The relation between PAEC and radon concentration at $F = 0.5$ is shown in Table 3. For the ^{220}Rn series, the few measurements in houses suggest that F is about ten times smaller, implying a greater disequilibrium between ^{220}Rn and its decay products [*15,16*]. Table 3 shows the relationship between PAEC and ^{220}Rn concentrations for $F = 0.05$.

Finally, a term often used in evaluating the dose arising from exposure to radon decay products is the unattached fraction, defined as the ratio of the EEC arising from the unattached decay products, denoted by the superscript u, to the total EEC

$$f_p = \frac{\text{EEC}^u}{\text{EEC (total)}}. \tag{11}$$

This term is important because the largest portion of the dose to the bronchial tissue per unit of inhaled activity is thought to arise due to inhalation and deposition of the unattached decay products. Dosimetric models have indicated that the ratio of the dose due to the unattached decay products to that arising from the attached decay products ranges from 13 to 30, depending upon the modeling details and assumptions [*17*].

Exposure is the product of concentration (or PAEC) and time. Because the original concerns regarding exposures to radon decay products were associated with uranium mining, the concept of a working level month (WLM) was devised to characterize exposures encountered working a daily 8-h shift for one month, or approximately 170 h. It is interesting to note that for the same concentrations (PAEC), living in a house for one year (at 100% occupancy) yields an exposure that is 4.3 times larger than working for one year in a mine at 170 h per month.

In order to make comparisons among the radiation doses attributed to various sources of radiation, it is necessary to account for the absorbed dose (particularly if it is organ specific, such as the radiation of the bronchial epithelium by alpha particles from inhaled radon decay products), the type of radiation, and a weighting factor accounting for the risk of incurring specific radiation-induced diseases in that organ [*18*]. The absorbed dose has units of gray (Gy) and is equivalent to the amount of energy absorbed by the organ of interest (in J kg^{-1}). The dose equivalent, which has the SI unit of sievert (Sv), is the multiple of the absorbed dose and the quality factor, which accounts for the radiation type. The generally accepted quality factors are 20 for alpha radiation, 1 for gamma, electron, and muon radiation [*19*], and a mean value of 6 for cosmic ray neutrons averaged over the neutron energy distribution [*20*]. Thus, 1 Gy of alpha radiation provides a dose equivalent equal to 20 Gy of gamma radiation.

Finally, the organ-specific weighting factors are used to convert dose equivalent to effective dose equivalent, which also has units of sieverts. This concept will be used in the next section in comparing human exposure to various sources of radiation, a practice that has been followed elsewhere [*19,21*]. However, as also noted in these references, there are uncertainties in converting specific doses to effective dose equivalents. One particular example is the conversion for radon decay product exposures, so that the calculated effective dose equivalent for radon decay products should be used for general comparisons to other sources of natural or man-made radiation and not as a means of estimating risk.

Average Radiation Background

There are several sources of natural and man-made radiation to which members of the general public are exposed. The estimated annual effective dose equivalent from each of these sources is summarized in Table 4. Natural radiation has two main sources, cosmic rays and terrestrial radioactivity. The composition of the cosmic radiation flux varies with altitude, although at mid-latitudes and for altitudes less than 3 km, the predominant radiation is charged particles. These particles are mainly muons, which are secondaries created by the decay of pions formed by the interaction of high-energy galactic protons with the nuclei of atoms comprising the atmosphere and, to a lesser extent, electrons. In addition, there is a neutron component, also formed from the incident proton bombardment of the upper atmosphere.

The effective dose equivalent from the ionizing component of cosmic radiation at sea level is 0.24 mSv y^{-1} (y = year), while the neutron contribution to the effective dose equivalent is small, approximately 0.02 mSv y^{-1}. However, the neutron component of the dose increases more rapidly with increasing elevation than the ionizing component, so that above 6 km the dose equivalent for neutrons exceeds that for the ionizing component. The combined effective dose equivalent approximately doubles with every 1.5-km increase in altitude for low altitudes [*20*]. Thus, a person living in Denver (~1.6 km above sea level) receives about 0.5 mSv y^{-1} due to cosmic radiation. At aircraft altitudes of ~11 km, the effective dose rate equivalent is approximately 5 μSv h^{-1} [*19*]. Thus, airplane flights averaged over the entire population (flying and nonflying) provide an additional exposure to cosmic radiation with an estimated effective dose equivalent of 0.01 mSv y^{-1}.

Cosmic radiation also produces radionuclides in the atmosphere which enter the food chain and ultimately contribute to the internal radiation dose. The most important of these cosmogenic radionuclides is ^{14}C, which has a small effective dose equivalent of 0.01 mSv y^{-1} [*19*].

Human exposure to radiation from terrestrial sources (exclusive of the alpha dose from inhaled radon decay products)

TABLE 4—Estimated annual average radiation exposures of the U.S. adult population. Values are effective dose equivalents in mSv y^{-1}.

Radiation Source	External	Internal	Inhaled	Total	Fraction, %
Cosmic	0.26[a]	...	...	0.28	8
Cosmic-air travel	0.01[a]	...	...	...	...
Cosmogenic radionuclides	...	0.01[a]	...	...	...
^{238}U series	0.05[a]	...	...	2.0	58
$^{238}U \rightarrow {}^{226}Ra$	...	0.01[a]	...	...	...
$^{222}Rn \rightarrow {}^{214}Po$	...	...	1.8[b]	...	...
$^{210}Pb \rightarrow {}^{210}Po$	...	0.17[a]	...	...	...
^{232}Th series	0.13[a]	...	...	0.3	9
$^{232}Th \rightarrow {}^{224}Ra$	...	0.01[a]	...	...	...
$^{220}Rn \rightarrow {}^{208}Tl$	...	...	0.2[c]	...	...
Other primordial (mainly ^{40}K)	0.10[a]	0.20[a]	...	0.30	9
Medical	0.40[d]	0.14[d]	...	0.54	16
Totals:	...	...	...	...	...
Natural sources	0.55	0.40	2.0	2.9	...
All sources, including medical	0.95	0.54	2.0	3.5	...
Fraction of all sources, %	27	16	57	...	100

[a]From Ref *19*.
[b]Calculated based on an annual average indoor ^{222}Rn concentration of 46 Bq m^{-3}, an occupancy factor of 0.75, and exposure to an outdoor ^{222}Rn concentration of 10 Bq m^{-3} for the remaining time; a dose conversion factor of 10 mSv/WLM (= 0.025 mSv nJ^{-1} y^{-1} m^3) and a mines-to-home correction factor of 0.7. See discussion in text.
[c]Calculated based on a PAEC (^{220}Rn) of ~50 nJ m^{-3}, a combined mines-to-home and ^{222}Rn-to-^{220}Rn correction factor of 0.2, an occupancy factor of 0.75, and negligible outdoor exposures to ^{220}Rn. See discussion in text.
[d]From Ref *22*.

is due principally to gamma radiation from the ^{238}U and ^{232}Th decay series and from the primordial ^{40}K. These contribute to the external radiation exposure, primarily from the soil or near-surface geologic features, and to a lesser extent to the small background radiation, exclusive of radon directly, found inside homes due to earth-based building materials. Terrestrially derived radionuclides also contribute to the radiation exposure due to internally deposited nuclides. In the latter case, ingestion of foodstuffs contributes almost all of the ^{40}K entering the body and the major portion of ^{210}Pb. The numbers listed in Table 4 are averages from which there may be considerable variation for individuals.

Man-made sources of external radiation exposures are mainly medical and dental X-rays, while nuclear medical techniques contribute to the average exposure from internal radionuclides [*22*]. Other sources, such as fallout from nuclear weapons testing or the nuclear fuel cycle, contribute very little to average exposures, although, as the Chernobyl reactor accident in the Ukraine demonstrates, accidental exposures from anthropogenic sources of radiation can have important consequences for local populations [*21*].

On average, exposure to ^{222}Rn decay products constitutes the largest single source of radiation for members of the general public. Although the health effects are associated with radioactive decay of the inhaled radon decay products, a number of studies have suggested that reasonable estimates of the dose rate can be made based on the radon concentration [*17,23*], for which time-averaged concentrations are easier to measure (see Chapters 4 and 5 for more complete discussions of measurement techniques and protocols). The estimates shown in Table 4 are based on an annual average ^{222}Rn concentration in residences of 46 Bq m^{-3} (1.2 pCi L^{-1}) [*24*], an average outdoor concentration of 10 Bq m^{-3} (0.3 pCi L^{-1}) [*25*], and an average occupancy factor of 0.75 [*26–28*]. Therefore, annual average ^{222}Rn decay product exposures are 97 nJ y m^{-3} (0.24 WLM) indoors and 7 nJ y m^{-3} (1.8×10^{-2} WLM) outdoors. For ^{220}Rn progeny, the annual average PAEC is estimated to be 50 nJ m^{-3}, based on a PAEC(Rn-220)/PAEC(Rn-222) ratio of 0.4 [*15,29–31*], which yields an indoor exposure estimate of ~40 nJ y m^{-3}.

A recent comparison indicates that doses from exposures to ^{222}Rn decay products in homes are about 30% less than comparable exposures in mines. For exposure to ^{220}Rn decay products in homes, the estimated dose is about 20% of that for ^{222}Rn decay products in mines [*14*]. Using an average dose conversion factor of 10 mSv/WLM (=0.025 mSv nJ^{-1} m^3 y^{-1}) for ^{222}Rn decay product exposures in mines [*17*], the annual average effective dose equivalent is 1.8 mSv y^{-1} and 0.2 mSv y^{-1} for ^{222}Rn and ^{220}Rn, respectively.

The total annual average radiation exposure for the general adult population is summarized in Table 4 and illustrated by the first bar in Fig. 5. As can be seen, the radiation dose due to inhaled radon decay products is the most important single source, comprising over half the total effective dose equivalent even at an average radon concentration of 46 Bq m^{-3}. Since the radiation dose associated with radon is proportional to the concentration, living in a house with radon concentrations at the EPA guideline of 150 Bq m^{-3} [*32*] increases the radon contribution to approximately 80% of the total average radiation exposure and increases the total radiation exposure by a factor of two, as illustrated by the second bar in Fig. 5. A more complete discussion of the health effects and risks associated with radon is given in Chapter 3.

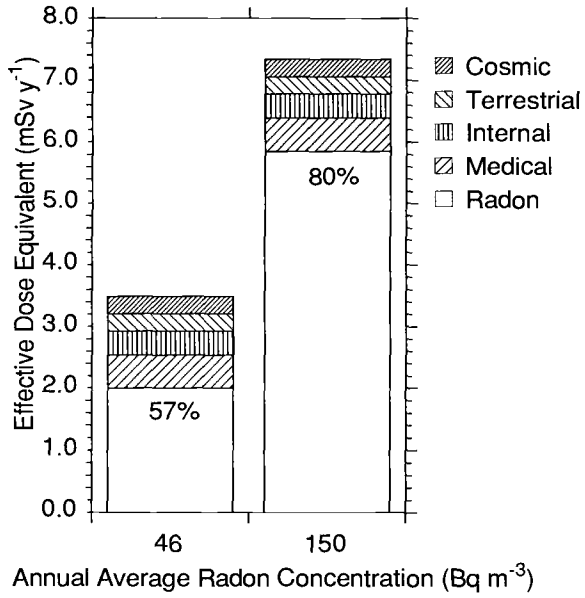

FIG. 5–Annual effective dose equivalent to the general adult population due to radiation from various sources, as compiled in Table 4. The bar on the left is based on the annual average radon concentration in U.S. housing [*24*], while the bar on the right is based on a radon concentration equal to the U.S. EPA recommended "action" guideline level [*32*]. The effective dose attributed to radon in this figure includes exposures to ^{222}Rn decay products both indoors and outdoors, and to ^{220}Rn decay products indoors, as discussed in the text. Only the indoor ^{222}Rn concentration changes for the two cases are illustrated here. The fraction of the total exposure arising from radon is shown for each year.

THE INDOOR ENVIRONMENT

Humans are exposed to a variety of airborne pollutants in various settings. While much of the focus of air pollution research during the past several decades has been on the sources, nature, and control of outdoor air pollutants, there has been a growing awareness that exposure to a number of pollutants is greatest indoors [*33*]. There are two primary reasons for higher indoor exposures; first, people typically spend 75% or more of their time indoors, either at home or in an office or other nonindustrial environment [*26–28*]. Second, concentrations of many pollutants are higher indoors than outdoors because the indoor volumes into which pollutants are emitted are small and have low air exchange rates with the outdoors. This section provides a general description of some of the factors affecting the indoor environment.

A Simplified Model for Pollutant Concentrations Indoors

There are two principal source locations for indoor air pollutants: emissions from sources within the building shell and pollutants whose origins are exterior to the building and are transported indoors, usually by the movement of air from the outside into the building. In certain cases where the origin of the pollutant is outdoors, such as radon or volatile organic compounds (VOCs) dissolved in water, the contaminant is still released indoors at point-of-use and thus can be thought of as an indoor source. Indoor concentrations can be described as a function of time, taking into account both sources and sinks of the specific pollutant. In its most general form, the time-dependent mass-balance equation is given by

$$\frac{dC_i}{dt} = \frac{S}{V} + P\lambda_v C_o - \lambda_v C_i - kC_i \qquad (12)$$

where

S = the indoor pollutant source strength or release rate, typically in units of mass or particle number per time unit, or as in the case of radon, activity per time unit,
V = the volume of the affected indoor space,
C_i = the indoor concentration, usually in units of mass, particle number, or radioactivity per unit of volume,
P = the fraction of the outdoor pollutant that penetrates the building shell or enters via a mechanical ventilation system. In this latter case, P will account for losses due to filtration efficiency,
λ_v = the ventilation rate, including both natural and mechanical ventilation terms, in units of inverse time,
C_o = the outdoor pollutant concentration, and
k = the removal rate due to other chemical or physical processes, such as deposition, or chemical or radioactive decay, in units of inverse time.

The first two terms represent indoor and outdoor sources, respectively, while the last two terms account, for removal by ventilation and by other physical or chemical processes, respectively. Each of these terms can be expanded to explicitly account for specific sources or sinks within these four broad categories. For ^{222}Rn the radioactive decay constant is small compared with the ventilation rate, so that for most practical cases, the radioactive decay can be neglected as a removal term. For ^{220}Rn the opposite situation exists; the airborne concentration is controlled by the 56-s half-life rather than the ventilation rate. Ventilation does affect the radon decay product concentrations; however, the dynamics of the growth and decay, plus the interaction with surfaces in the room, make this a more complicated problem. These effects will be discussed in more detail later in the chapter.

Assuming that the pollutants are well-mixed, and that S, λ_v, and C_o are time independent, then the solution to this equation is

$$C_i(t) = \frac{S/V + P\lambda_v C_o}{\lambda_v + k}(1 - \exp[-(\lambda_v + k)t]) + C_i(t = 0)\exp[-(\lambda_v + k)t] \qquad (13)$$

where C_i $(t = 0)$ is the initial indoor pollutant concentration. In the more general situation where S and/or λ_v vary as a function of time, as is often the case, Eq 13 no longer holds, and the exact solution will depend upon the functional forms for $S(t)$ and $\lambda_v(t)$.

In the idealized case where S and λ_v are constant and steady-state conditions are achieved, $\frac{dC_i}{dt} = 0$, and Eq 13 reduces to

$$C_i = \frac{S/V + P\lambda_v C_o}{\lambda_v + k} \tag{14}$$

For those pollutants for which k is small (or zero) compared with the ventilation rate, Eq 14 can be further simplified to

$$C_i = \frac{S}{V\lambda_v} + PC_o \tag{15}$$

This equation, though idealized, helps illustrate the relationships among the sources and removal terms. For example, for pollutants generated outdoors, the indoor concentrations will depend upon the fraction entering the building (for most gases, P is essentially 1), and, at steady state, the indoor concentrations will equal those outside. Thus, outdoor airborne radon, for example, will always make a contribution to the total indoor radon concentration. For pollutants generated indoors or that may enter from an essentially constant source, such as radon entry by means of molecular diffusion from or through the building materials, the concentrations are a result of the balance between the generation and removal terms. Often ventilation rates in existing buildings cannot be changed significantly (as in the case of weatherization of existing buildings), so that the most important and practical means of control of indoor concentrations is reduction or elimination of the pollutant source term.

Building Factors

Buildings themselves, their construction details, and how they are operated are important factors influencing indoor pollutant concentrations, particularly radon. There are a variety of different buildings, ranging from residential, single-family-detached housing to multistory residential and office buildings. Within these broad categories, there are considerable differences in the way the buildings are constructed or the types of equipment installed within them. As noted in the earlier discussion, ventilation is one part of the equation determining indoor pollutant concentrations.

Ventilation air enters a building in three ways: (1) infiltration, usually defined as uncontrolled air flow through unintended cracks, holes, or other openings in the building shell either above or below the soil grade; (2) natural ventilation, which is the flow of air through intended and usually controllable openings such as doors, windows, or vents; and (3) mechanical ventilation, which is the use of either unbalanced or balanced air flow driven by a blower or fan. In the case of unbalanced ventilation, air is usually exhausted from a room or house without specific provision for makeup air. An example might be a room or whole-house exhaust fan where makeup air enters through gaps below doors, around windows, or through openings for plumbing or electrical service. Balanced ventilation refers to situations where air supply vents furnish makeup air. One such example is the use of an air-to-air heat exchanger, where incoming air passes through a heat exchanger to recover heat from the outgoing air stream. Of these three, infiltration can be the largest contributor to the overall annual ventilation.

Buildings interact with their surrounding environment in two important ways, both of which provide the forces driving infiltration. When the indoor temperature is higher than that of the surrounding ambient air, different air density gradients are established in the two air columns, resulting in horizontal pressure differences across the building shell. The pressure difference between the pressure indoors (P_i) and that outdoors (P_o) at height z, is given by

$$\Delta P\,(=P_i - P_o) \approx 12.65\left(\frac{T_i - T_o}{T_i}\right)(z - z_n) \tag{16}$$

where the pressure difference has units of Pa (101 kPa = 1 atm), T_i is the indoor air temperature in K, T_o is the outdoor air temperature in K, z_n is defined as the height (in metres) at which the indoor-outdoor pressure difference is zero (the neutral pressure level), and z is in metres (see Ref *34* for a more complete treatment of stack and wind effects on buildings). In this convention, z and z_n are measured with respect to the lowest level in the house. A negative pressure means the pressure inside is lower than that outside. At the lowest level in the house, the basement floor, for example, where $z = 0$, the air pressure difference between the inside and outside is the most negative. Conversely, at the highest level of the conditioned space, the ceiling, for example, the pressure gradient is the most positive. As an illustration, when T_o is 273 K, T_i is 293 K, and the neutral pressure plane, z_n, is 3 m above the basement floor, the static pressure across a basement slab floor ($z = 0$) can be computed to be -2.6 Pa.

This gradient in the pressure differences due to the "stack effect" is illustrated in Fig. 6*a*. Air will flow out of the building through leaks above the neutral pressure level and inward through leaks below this level. If some fraction of this leakage is below grade, such as a gap at the floor-wall joint of a basement or gaps around utility penetrations through the floor slab or basement wall, then radon-bearing soil gas entry may be driven by this pressure difference.

The second important effect is that of the interaction of the wind with the building walls and roof. Flow across the roof can help depressurize the structure, especially in the case where appliances are vented through the roof (such as a space-heating furnace in the basement). At the same time, the wind alters pressure difference across the upstream and downstream walls, as shown in Figs. 6*b* and 6*c*. The overall effect of the wind is more complicated than that of the stack effect, since the angle of the wind hitting the structure and the location of any shielding structures or vegetation complicate the wind dynamics. In addition, wind speeds and directions may be highly variable within a span of minutes, whereas the temperatures giving rise to the stack effect are slower to change. The general form of the relation between wind speed and surface pressure is

$$\Delta P_j = \frac{C_p(j)v^2}{2} \tag{17}$$

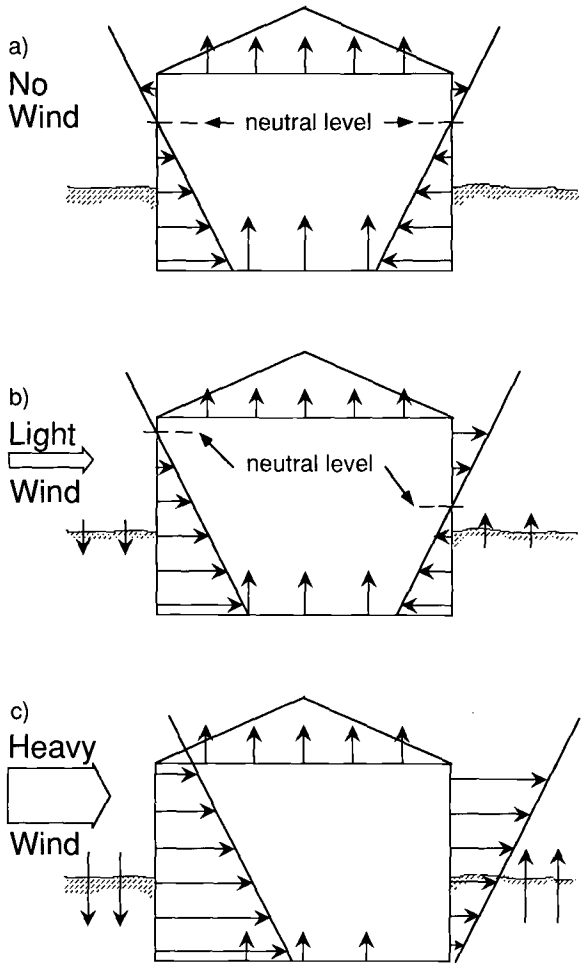

FIG. 6–Schematic illustration of pressures (flows) across the building shell, established by (a) the thermal stack effect, (b) the stack effect plus light wind conditions, and (c) the stack effect plus heavy wind conditions. The arrows indicate the direction of flow from a higher to lower pressure region. Note the pressures (flows) into or out of the soil adjacent to the house due to the pressure fields created by the wind striking the structure. Figure adapted from Ref *97*.

where ΔP_j is the pressure (in Pa) on face j of the building due to the wind minus the free stream pressure, C_p (j) is the pressure coefficient for face j, ρ is the air density (1.2 kg m^{-3} at 20°C and 1 atm pressure), and v is the wind velocity (in m s^{-1}). In general C_p (j), which is relatively independent of the wind velocity, can vary from +1 to −1 and depends greatly upon the orientation to the wind of the face in question. The interior pressure coefficient, C_p (in), arises due to the effects of the exterior pressure on the building envelope and will depend upon the building orientation with the wind and the distribution of the leaks between the interior and exterior. Pressure coefficients have been measured, usually in wind tunnels, for simple, idealized geometries and the results compiled as a function of wind angle (see, for example, Ref *35*). The pressure *across* the building surfaces, due to the wind, has the same form as Eq *17* above, except the net pressure coefficient is the algebraic difference between the interior and exterior pressure coefficients. A typical value for C_p (in) is ~0.2. Thus, at a wind velocity of 3 m s^{-1}, the resulting depressurization of the structure is ≈ −1 Pa. Since the pressure difference depends upon the square of the wind speed, small changes in wind velocity will have large effects on the pressure differential; in the above example, an increase in the wind speed from 3 to 4 m s^{-1} almost doubles the pressure difference (to ≈ −2 Pa).

The pressure coefficients discussed earlier are those that apply to the building surfaces and in the simplest cases are assumed to apply uniformly to the entire surface. Wind tunnel experiments have also shown that similar pressure coefficients are developed on the soil surface surrounding a house and extend away from the wall for distances approximating that of the wall height [*36*]. The wind can therefore increase the pressure difference between the soil surface and the interior of the substructure on the windward side and decrease it on the leeward side, thus affecting the total driving pressure for advective flow of soil gas. These effects are also illustrated schematically in Figs. 6*b* and 6*c*.

Overall infiltration rates vary among houses; reported average ventilation rates range from 0.3 h^{-1} for electrically heated houses in the Pacific Northwest [*37*], 0.6 h^{-1} for newer houses in several locations in the U.S. [*38*], and 1.2 h^{-1} for homes older than about 45 years [*39*]. These rates will change daily and seasonally as temperature and wind conditions change. An example of the variations in whole-house ventilation rates, as measured every 3 h with a tracer gas, is shown in Fig. 7 for two-week-long periods during different seasons [*40*]. As can be seen, there is a general correspondence between the diurnal variations in the temperature difference and the ventilation rate. The overall magnitude of the ventilation rate drops with decreasing temperature difference. During the first time period, the average indoor-outdoor temperature difference was 19.6°C and the average ventilation rate was 0.25 h^{-1}, while for the second time period, the average temperature difference was 3.9°C, and the average ventilation rate was 0.1 h^{-1}. Wind and fireplace operation were also found to have an effect on the ventilation rates for short time periods [*40*].

The operation of mechanical systems in houses, such as forced-air furnaces, can significantly increase the ventilation rates of the structure, in some cases by 40% [*29*] to 60% [*37*]. Much of this is due to duct leakage in either the supply or return systems [*41,42*]. These leaks can also have an important effect on the radon entry, due to the increased pressure difference across the building shell, and the radon concentration distribution within the house. Basements are often observed to have average radon concentrations several times higher than in the first-floor living space. In homes with a forced-air furnace located in the basement, radon concentrations on the nonbasement floors often approach those of the basement due to mixing induced by the forced-air system during those times when the furnace fan is operating [*43*]. In experiments comparing flows in a house where a forced-air furnace and electrical resistance heating were alternately employed, the flows between the basement and upstairs zones, averaged over typical winter-time forced-air furnace usage, were eight to ten times larger when the space was conditioned with the forced-air furnace [*44*].

Although temperature and wind effects also exist for larger, nonresidential buildings, mechanical systems are often the

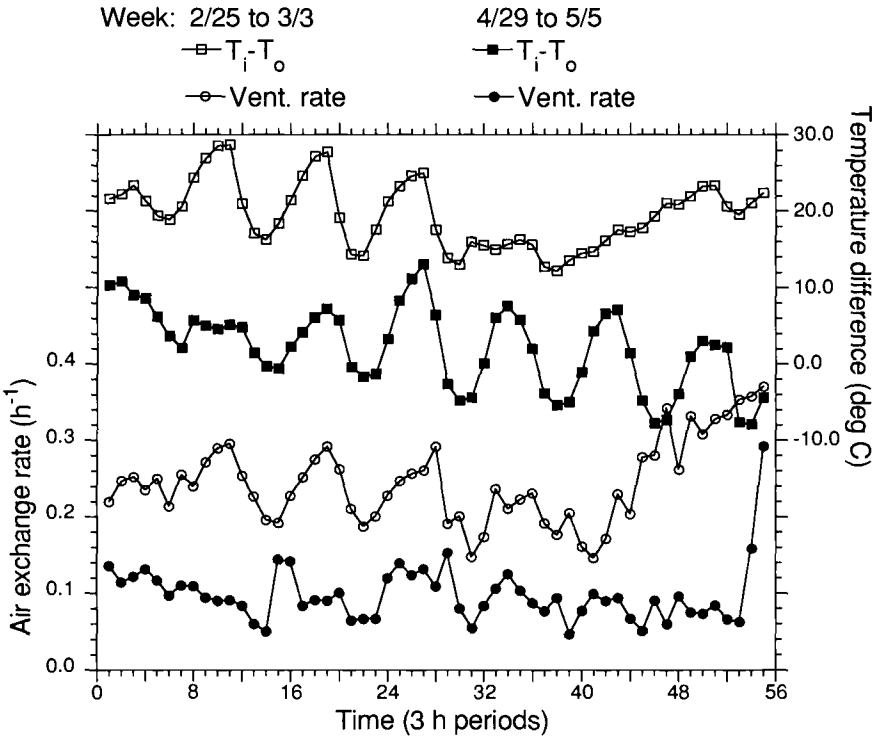

FIG. 7–Indoor-outdoor temperature differences and ventilation rates measured in a house near Chicago [*40*]. Data were recorded every 3 h. The open symbols indicate data obtained during 7 days, from February 25 to March 3. Data obtained during the second 7-day time period, extending from April 29 to May 5, are designated by the closed symbols.

most important source of building depressurization. Observations of elevated radon concentrations in some school rooms have focused attention on ventilation systems in school buildings [*45–47*]. In one such examination, three types of heating, ventilating, and air conditioning (HVAC) systems were found. In most buildings with air conditioning, central air-handling systems were used. These systems incorporate a number of elements, depending upon the size of the building and the system design. The air return systems are often a significant cause of depressurization in the buildings, either as a result of the design of the system or because the proper balance between the air supply and return flows has not been maintained. A second type of HVAC system found in some schools is the unit ventilator, which is installed in each room. In some cases, air is exhausted through a separate, central fan system, which may contribute to the depressurization of the room. The third type of system is radiant hot water, which in some cases has additional powered exhaust ventilation [*45*].

Other factors influencing radon entry into these school buildings were the substructure types and the presence of cracks or utility penetrations through the slab floors. Radon concentrations in many schools were found to vary from room to room. This was particularly the case in those schools that were mainly slab-on-grade construction. In some cases, radon concentrations were found to be reduced with the HVAC system on and elevated when the system was shut down at night or over the weekend. In almost all cases, however, radon concentrations were usually correlated with the relative pressure in the room; higher radon concentrations usually accompanied larger negative pressures [*45*].

RADON INDOORS

Measured indoor radon concentrations range over more than three orders of magnitude, from average concentrations of less than 20 to more than 1×10^5 Bq m^{-3} (<0.5 to >2500 pCi L^{-1}). Radon concentrations also vary from location to location and as a function of time. This section summarizes the various sources of radon, the important mechanisms responsible for transport of radon indoors, and the variability of radon and radon progeny concentrations indoors. These topics are covered in more detail in Chapters 5, 6, and 7.

Distribution of Indoor Radon Concentrations

With the increased perception of the importance of radon as an indoor air pollutant, a number of surveys have been conducted to assess radon concentrations at a variety of geographical levels. In addition, there have been several hundred thousand measurements conducted in individual homes in the United States, either on behalf of the individual homeowners (one collection of such data is described in Ref *48*) or as part of various state or local surveys (state survey examples are described in Refs *49–52*). Many of the surveys and most of the measurements in individual homes have utilized short-term radon measurement techniques [*48–50*], which may

provide an indication of whether an individual home has elevated indoor radon concentrations during the time of the measurement. However, in most cases, such measurements do not provide reliable information on long-term average concentrations for an individual house [*53–55*], which is necessary in determining the exposures and health risks and the need to take action to reduce the indoor radon concentration.

A nationwide survey of annual average radon concentrations has been conducted by the Environmental Protection Agency (EPA) [*24*]. Based on approximately 5700 measurements, a distribution of annual average radon concentrations has been developed that is representative of that expected for the U.S. housing stock. The radon concentration is the arithmetic mean of measurements made in all frequently occupied levels of the house. The resulting concentration distribution is shown in Fig. 8. This arithmetic mean concentration is 46 Bq m^{-3} (1.2 pCi L^{-1}), and the median concentration is 25 Bq m^{-3} (0.68 pCi L^{-1}). The median should approximate the geometric mean (GM) for a lognormal distribution. Based on these measurements, about 6% of the U.S. housing stock (approximately six million homes) is expected to have annual average indoor radon concentrations exceeding the EPA recommended guideline of 150 Bq m^{-3}. Approximately 0.7% of the measured radon concentrations were above 370 Bq m^{-3}.

The distribution of annual average concentrations shown in Fig. 8 illustrates the skewed nature of the concentration distribution. As can be seen, there is a significant number of measurements in the high concentration "tail" of the distribution; however, most of the measured concentrations are actually below the average. Although there are a number of different ways to mathematically describe such data sets, the lognormal distribution has been widely used to characterize the results of many types of environmental measurements [*56,57*]. This distribution has turned out to be a convenient, and in most cases, a reasonably robust descriptor of such data. The distributional form is characterized by two parameters, the geometric mean (GM) and geometric standard deviation (GSD). In addition, the average or arithmetic mean (AM) is often of interest, for example, in using the measurement results to estimate radon exposures or health risks.

Sources of Indoor Radon

Early investigations of radon in homes tended to focus on building materials as a major source of radon, along with radon release from domestic water in certain regions of the country. However, data on indoor radon concentrations combined with simultaneous measurements of ventilation rate showed no correlation between the two [*58,59*]. Such an inverse correlation would be expected if the major source of radon were located *inside* the building envelope or if the radon entered at a constant rate, independent of ventilation or other building factors, as described in Eq 15. In this section, various potential sources of radon are briefly de-

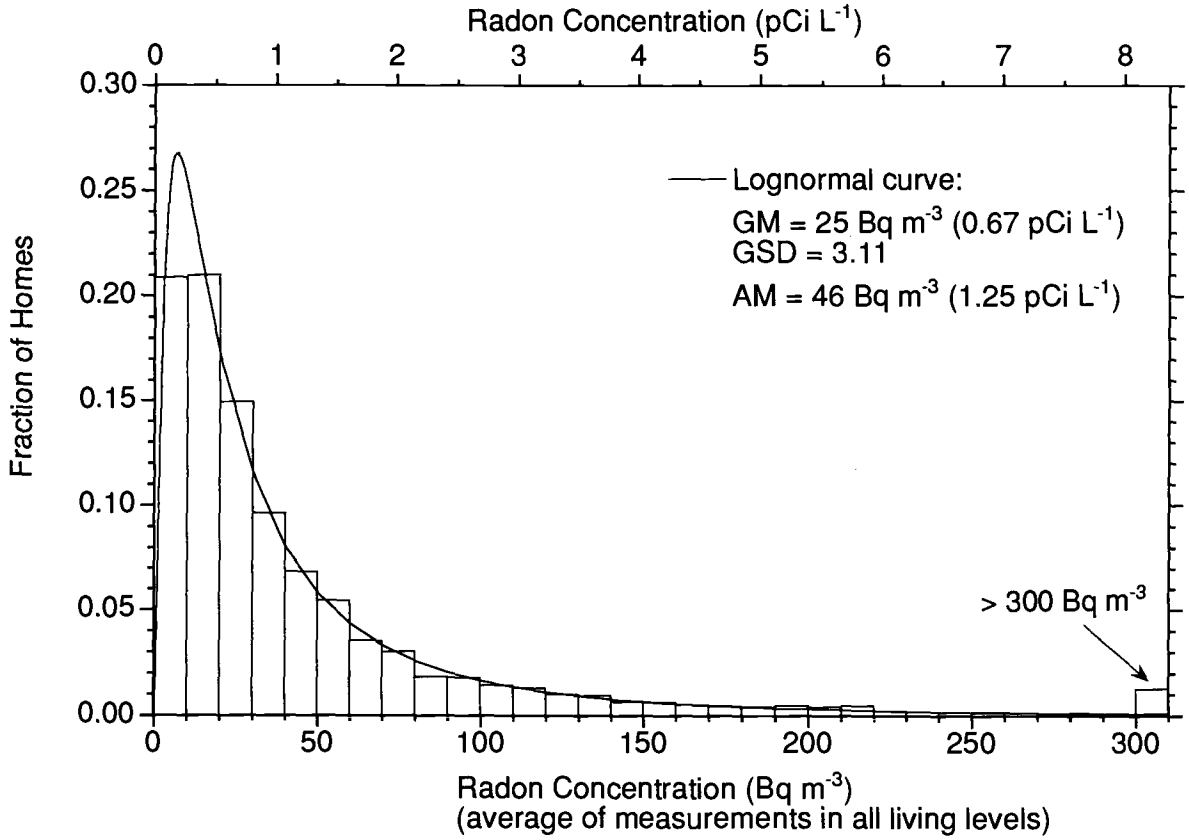

FIG. 8–Distribution of long-term average radon concentrations in the U.S. housing stock. The bars indicate the fraction of houses falling into each 10 Bq m^{-3} concentration bin. The curve shows the log normal distribution with a GM of 25 Bq m^{-3} and a GDS of 3.11. The data are from the EPA National Residential Radon Survey and are discussed further in Ref *24*.

scribed; the nominal indoor radon concentration due to each source is summarized in Table 5. Additional discussion of radon occurrence is provided in Chapter 6.

Soil

The principal source of radon in homes with elevated indoor radon concentrations is the soil adjacent to the building substructure. Several recent experimental studies and analyses have investigated soil gas migration through soils and into houses and have helped illuminate the role of advective flow as an important soil gas transport and entry process [*60–64*]. The importance of soil gas flow in radon entry has also been demonstrated by the results of mitigation efforts which have employed subslab depressurization or basement pressurization to reverse the pressure gradients responsible for soil gas entry into buildings. In those cases where the mitigation technique was successfully applied, the radon entry decreased sharply when the pressure gradient across the building substructure was reversed [*65,66*].

A number of analytical and numerical simulation models have been developed to investigate transport of soil gas or radon by advective flow alone [*67–69*] or to examine both advective and diffusive radon migration [*70–73*] through soils and into houses. In general, these models demonstrate that the building substructure interacts with the surrounding soil and that the gas flow through the soil depends upon characteristics of the soil medium. The building-soil interaction is illustrated schematically in Fig. 9 for a relatively simple substructure geometry and homogeneous soil conditions. The pressure field develops in the soil adjacent to a basement substructure as a result of the pressure difference between the openings in the basement floor and the soil surface. Soil gas flow lines established in response to the pressure field are also indicated. Most of the flow in such a system occurs through the soil located within 1 m of the basement wall. Similarly, because the 3.8-day radon half-life limits the distance radon may travel, the soil regions closest to the house will make the largest contribution to the radon entry rate.

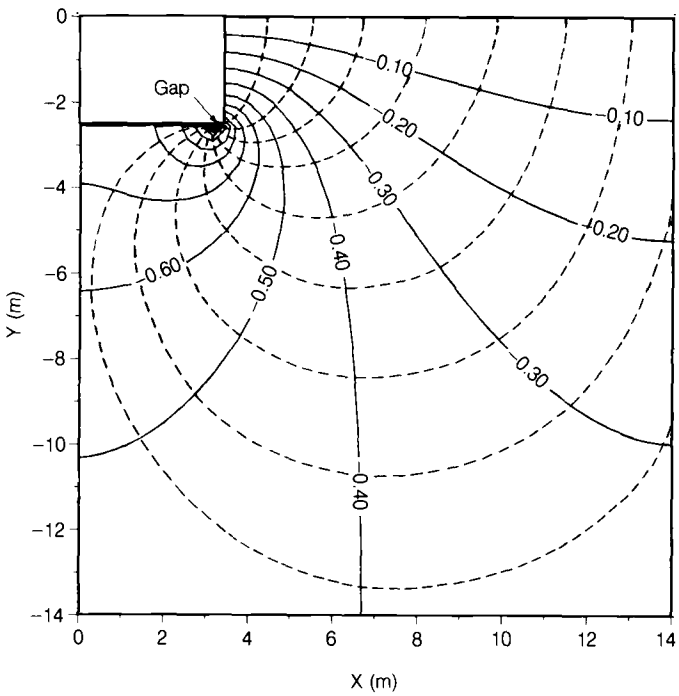

FIG. 9–Pressure and flow fields in the soil surrounding a basement substructure. The solid lines indicate lines of constant pressure difference and are labeled with the fraction of the applied pressure. The model geometry includes solid, no-flow walls and floor with a 1-mm-wide perimeter crack at the floor-wall interface. The pressure at the interior of the substructure is −3.5 Pa with respect to the pressure in the soil. Flow streamlines for soil gas movement in response to the pressure gradient are indicated by dashed lines. (Figure from Ref *98*).

TABLE 5—Nominal contributions from various sources to indoor radon concentrations for a single-story residence[a].

Source	Indoor Radon Concentration, Bq m^{-3}	Note or Reference
Outdoor air	10	[*25*]
Potable water	...	Table 6
Surface water	0.13	...
Public groundwater	1.3	...
Private wells	23	...
Natural gas	0.07	[*85*]
Building materials	...	...
Concrete floor	3	...[b]
Concrete walls	5	...[b]
Gypsum wallboard	3	...[c]
Soil	...	...
Diffusion through floor	7	...[b]
Diffusion through walls	2	...[b]
Uncovered soil	15	...[d]
Convective entry	~0.5 – 1100	...[e]
Compare with the average indoor radon concentration	46	[*24*]

[a]The "reference house" has a basement with a 10-cm-thick concrete floor and 15-cm-thick poured concrete walls. The single above-grade floor has interior walls and ceiling covered with gypsum-based wallboard. Total house volume is 500 m^3 and has an average ventilation rate of 0.9 h^{-1}.

[b]Based on Eq 23, assuming $D_e = 5 \times 10^{-8}$ m^2 s^{-1}; $f = 0.2$; $\epsilon = 0.2$; $L = 10$ cm for the floor slab, $L = 15$ cm for the walls, and a soil gas concentration of 40 kBq m^{-3}.

[c]Assumes an exhalation rate of 0.001 Bq m^{-2} s^{-1} for gypsum [*80,81*].

[d]Based on a soil exhalation rate of 0.017 Bq m^{-2} s^{-1} [*78*].

[e]Based on Eqs 18 and 19 and the assumptions discussed in the text.

It is of interest to know the relative contribution of diffusion and advective flow to radon transport through soil and entry into buildings. The bulk flux density for radon through the soil medium, which is a combination of the diffusive and advective flux densities, has been computed as a function of soil permeability, k [*70*]. For values of $k < 10^{-12}$ m^2, the flux density is dominated by the diffusive component, and the flux density is almost invariant with changes in k. On the other hand, for $k > 10^{-12}$ m^2, advective flow increasingly becomes the dominant term in the flux density. An analysis of the transport equations for radon migration through soil obtained a similar result: $k \approx 10^{-12}$ m^2 represented the boundary between transport dominated by diffusion and that dominated by advective flow [*64*]. Diffusive entry of radon is discussed further in the section on building materials, below.

An estimate of the contribution of advective radon entry to indoor concentrations, for comparison with other sources listed in Table 5, may be obtained from the analytical model developed in Ref *69* for a basement substructure. This model is based on a number of simplifying assumptions, primarily that the soil properties are uniform and isotropic and that soil gas entry into the basement occurs via a perimeter gap that

can be described by a buried cylinder of dimensions equal to the basement perimeter and the width of the opening. No other structural features are incorporated in the model; more detailed numerical modeling has indicated that some of these substructure features can have a significant influence on the radon entry rate. For example, the presence of a high-permeability soil layer immediately below the floor slab can increase the advective radon entry rate by as much as a factor of five over that calculated for the situation without such a soil layer [74]. For the simplified analytical model, the radon entry rate, F, is given by

$$F = \frac{3.5 \times 10^5 L}{\ln(2H/r)} \Delta P k I_{Rn} \qquad \text{for } \Delta Pk < \Phi \tag{18}$$

$$= 5.8 \times 10^3 L (\epsilon \lambda_{Rn})^{1/3} \left[\frac{H}{\ln(2H/r)}\right]^{2/3} \times (\Delta Pk)^{2/3} I_{Rn} \qquad \text{for } \Delta Pk > \Phi \tag{19}$$

where $\Phi = 9 \times 10^{-6} \epsilon \lambda_{Rn} H^2 \ln(2H/r)$; L is the length of the cylinder (taken to be the length of the basement perimeter); H is the depth of the cylinder (basement floor depth) below the soil surface; r is the radius of the cylinder (half-width of the perimeter gap in the basement floor); ϵ is the soil porosity; λ_{Rn} is the radioactive decay constant for radon; ΔP is the pressure difference (in Pa) between the soil surface and the cavity (basement opening); and I_{Rn} is the soil gas radon concentration at the opening.

The radon entry rate is the product of the airflow rate and the radon concentration in the entering soil gas. For low airflow rates, the radon entry rate is proportional to the product of the permeability and the driving pressure, as indicated in Eq 18. However, at high airflow rates, depletion of the soil-gas radon concentration occurs because the transit time of the air through the soil is small compared with the radon half-life. For conditions where $\Delta P \times k$ is greater than Φ, as defined above, the radon entry rate is no longer simply proportional to $\Delta P \times k$, as shown in Eq 19.

To illustrate the use of these equations, typical values for some of the parameters are: $L = 40$ m, $H = 2$ m, and $\epsilon = 0.5$. For a small perimeter gap of 0.001 m, Φ is 3.4×10^{-10} Pa m^2, while for a gap two orders of magnitude larger (0.1 m), Φ is 1.7×10^{-10} Pa m^2. Thus, for this larger gap radon depletion in the entering soil gas will begin to occur when the air permeability of the soil is greater than $\approx 4 \times 10^{-11}$ m^2 for a typical pressure difference of 4 Pa. Using these parameters and a soil gas radon concentration of 100 kBq m^{-3} (2700 pCi L^{-1}), Eq 18 now becomes: $F \sim 1.5 \times 10^{11} \Delta Pk$ for a gap of 0.001 m, and $F \sim 3.2 \times 10^{11} \Delta Pk$ for the larger 0.1 m gap. At the lower permeability limit for advective soil gas flow, $k \sim 10^{-12}$ m^2, and a small 0.5-Pa driving pressure, ΔPk is 5×10^{-13} Pa m^2, which yields radon entry rates of 0.075 and 0.16 Bq s^{-1} for the two gap sizes. At a ΔPk value of $\sim 1 \times 10^{-10}$ Pa m^2, which is near the onset of soil gas radon depletion in this case, the radon entry rate is estimated to be 15 and 30 Bq s^{-1} for the two gap widths. For a ΔPk value of 1×10^{-9} Pa m^2, which is greater than Φ and thus is in the depletion regime where Eq 19 applies, the radon entry rate is 90 and 140 Bq s^{-1} for the two gap sizes. Assuming a house volume of 500 m^3, the volumetric radon entry rates span a range from 0.5 Bq m^{-3} h^{-1} at the lowest flow rate and smaller gap, to 1000 Bq m^{-3} h^{-1} at the highest flow rates and larger gap. As can be seen in comparison with the contributions from other sources listed in Table 5, pressure-driven radon entry can predominate, even for the moderate soil-gas radon concentrations used in these examples.

An example of the variability of the indoor radon concentrations and the associated driving forces for advective flow is shown in Fig. 10. The top three curves show similar diurnal and day-to-day changes during this two-week continuous monitoring period. The correspondence between the indoor-outdoor temperature difference, the resulting pressure difference across the building shell, and the basement radon concentration confirms, at a general level, the contribution of advective flow to elevated indoor radon concentrations. Note also that the basement radon concentration varies by more than a factor of five during this time. Other environmental variables were monitored, including soil gas radon monitored below the basement slab, barometric pressure, and soil temperatures at two depths. No association between the variations in these parameters and the basement radon concentration was found [75].

Water

Since radium is widely distributed in the earth's crust, it is found in minerals that come in contact with groundwater. Radon, which is soluble in water, is found in groundwater, and in some cases, significant concentrations have been observed [76]. These concentrations appear to depend upon the structure of the aquifer and the distribution of the radium in the rock matrix. In many cases, these radon-in-water concentrations are "unsupported," meaning that there is relatively little radium dissolved in the water giving rise to the radon. Rather, the radon is transferred into the water directly from the radioactive decay of the radium in the solid materials in the aquifer, and the dissolved radon is then transported with the water.

Indoor water use, particularly in circumstances where the water is heated or aerated such as in a shower or a laundry, will release radon into the indoor air. The amount of radon released per unit of radon dissolved in the water depends upon the water-use rate for each type of use, W_i, and the efficiency (often referred to as the transfer coefficient) of the radon release for each of these water uses, e_i. Data on these parameters can be used to estimate the average contribution from water use to indoor airborne radon concentrations [77]. Referring to Eq 15, the source term for radon released from water is

$$\frac{S_w}{V} = C_w \frac{\Sigma W_i e_i}{V} \tag{20}$$

Dividing each side of the equation by the ventilation rate, λ_v, yields the steady-state air concentration, C_a. The overall ratio of air-to-water radon concentration can be estimated from

$$f = \frac{C_a}{C_w} = \frac{S_w}{V\lambda_v} \tag{21}$$

$$= \frac{We}{V\lambda_v} \tag{22}$$

where W is now the total per capita water-use rate and e the use-weighted transfer coefficient. On average, almost complete transfer of radon from water to air occurs when both

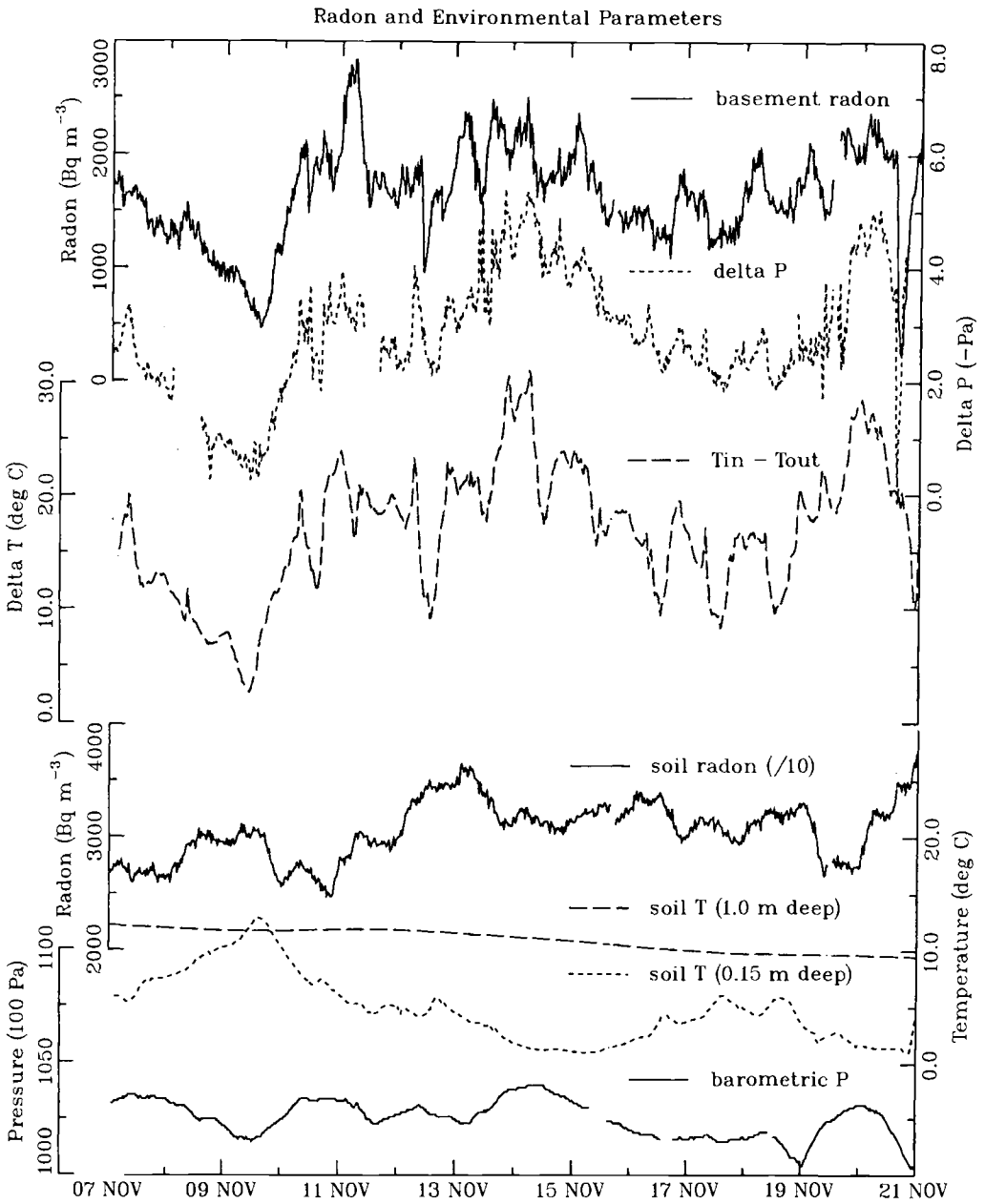

FIG. 10–Variations in radon and environmental parameters observed over a two-week period in a New Jersey residence. Data were acquired continuously and recorded every 30 min. Note that the scale for the basement-outdoor pressure difference (ΔP) is increasingly negative toward the top of the figure. (Figure is from Ref *75*.)

heat and aeration or agitation are involved, such as in a dishwasher or laundry, when the measured transfer coefficients average 0.92 to 95, while water use in a toilet has an average transfer coefficient of 0.3. Based on estimates of the distributions for each of the four parameters in Eq 22, the distribution for the overall transfer factor, f, can be estimated to have a GM of 0.65×10^{-4}, a GSD of 2.88, and an average of 1.14×10^{-4} [77]. These results indicate that, on average, a radon concentration of 10 000 Bq m^{-3} in water is needed in order to yield an indoor air radon concentration of 1 Bq m^{-3} due to use of that water indoors. The likely range in the value for f, derived from the GSD, provides an estimate of the range in expected indoor radon concentrations, in this case from ~0.3 to ~3 Bq m^{-3} for a radon-in-water concentration of 10 000 Bq m^{-3}.

There are three main categories of domestic water supply—surface water, public groundwater, and private groundwater. This last category is comprised mainly of private wells directly serving individual homes (or perhaps in some cases, a small cluster of homes). Radon concentrations have been examined fairly extensively for public groundwater and only sporadically in the case of private well water. This is partly a consequence of the fact that the drinking water standards—and thus regulations—apply only to public supplies. Relatively few measurements of radon in surface waters have been reported, though these can be expected to be quite low

TABLE 6—Distribution of radon concentrations in water and in air due to water use[a].

Type of Water Supply	Fraction of Population Served	C_w GM, kBq m^{-3}	C_w GSD	C_w AM,[b] kBq m^{-3}	(C_a)[c] GM, Bq m^{-3}	(C_a)[c] GSD	(C_a)[c] AM,[b] Bq m^{-3}	Fraction of C_a Exceeding 40 (150) Bq m^{-3}
Surface water	0.50	0.3	5.0	1.1	0.020	6.86	0.13	5×10^{-5} (–)
Public groundwater	0.32	5.2	3.53	12	0.34	5.19	1.3	0.002 (0.000 14)
Private well water	0.18	36	6.5	200	2.3	8.6	23	0.09 (0.03)

[a]Data and table adapted from Ref 77.
[b]For a lognormal distribution, the average or arithmetic mean (AM) can be found from: AM = GM exp[0.5 (ln(GSD))^2].
[c]Derived from: GM(C_a) = GM(C_w) GM(f), and GSD(C_a) = exp [[ln(GSD(C_w))]^2 + [ln(GSD(f))]^2]$^{1/2}$; where GM(f) and GSD(f) are the GM and GSD for the distribution of the air-to-water ratio.

in dissolved radon. Table 6 presents a summary of data on radon in domestic water supplies. As can be seen, surface water supplies serve almost half the U.S. population and have an average AM radon concentration of ~1100 Bq m^{-3} (~30 pCi L^{-1}). Public groundwater, which supplies water to about one third of the U.S. population, has an average radon concentration of ~12 kBq m^{-3} (~300 pCi L^{-1}). Based on the limited data available, the average radon concentration for private groundwater supplies is 200 kBq m^{-3} (~5000 pCi L^{-1}). Also shown in Table 6 are the inferred distributions for the airborne radon concentrations, C_a, due to water use from the different water supply sources. The last column shows the estimated fraction of airborne radon concentrations exceeding 40 and 150 Bq m^{-3} for each type of water supply. Based on the data and analysis presented in Table 6, the probability of having significant indoor air radon concentrations due to use of water from public water supplies (surface or ground) is quite small. On the other hand, private wells, for which there are few data, can be an important source in some circumstances [*76*].

Outdoor Air

As can be seen from the steady-state indoor concentration model described in Eq 15, the outdoor radon concentration constitutes the minimum indoor concentration, to which other sources will add. Soil is the principal source of outdoor radon, with only 2% of the atmospheric radon contributed by radon release from the oceans [*78*]. The soil contribution is mainly due to diffusion, driven by the large concentration gradient between the radon in the soil gas and that in the first few centimeters of outdoor air. The average flux density across the air-soil boundary (reviewed in Ref *78*) is 0.017 Bq m^{-2} s^{-1} for ^{222}Rn and about 100 times larger, 1.5 Bq m^{-2} s^{-1}, for ^{220}Rn.

Outdoor radon concentrations have been observed to vary diurnally, seasonally, and by geographical location and altitude. Near-ground concentrations are typically highest in the early morning hours, when the atmosphere is the most stable, and lowest in midafternoon. Daily variations of about a factor of three or four have been observed. Atmospheric ^{222}Rn concentrations show seasonal variations of about the same size, i.e., factors of three or four, although the maxima and minima show some geographic variation. This pattern appears to depend upon local soil moisture conditions and solar heating of the soil. In general, these variations and the observed atmospheric behavior are all consistent with diffusion of radon from the soil as the principal transport mode, with eddy diffusion then responsible for mixing in the lower atmosphere. The mean eddy diffusion distance has been estimated to be about 1 km for ^{222}Rn and about 20 m for ^{220}Rn [*15*]; thus, the airborne concentrations of these nuclides will be reasonably well mixed at elevations that are typical of building heights. Annual average ^{222}Rn concentrations at 1 to 2 m above the ground have been reported to vary between 0.6 Bq m^{-3} as measured in Kodiak, Alaska, to 28 Bq m^{-3} for Grand Junction, Colorado. Coastal regions are generally lower, in the range of 8 to 10 Bq m^{-3}. The estimated U.S. continental average concentration in outdoor air is ~10 Bq m^{-3} for both ^{222}Rn [*25*] and ^{220}Rn [*15*]. For houses with average radon concentrations, or for multistory buildings where the soil source term is not likely to be significant for above-grade floors, outdoor air may contribute a significant fraction of the total indoor radon concentration.

Building Materials

Since radium is widely distributed in the earth's crust, it is present in trace amounts in all earth-based building materials. Release of radon from a variety of building materials has been examined by a number of researchers in the U.S., Canada, and Europe [*79–81*] (see also reviews in Refs *21, 60*). With the exception of building materials derived from alum shales in Sweden [*79*], the average indoor radon concentration due to radon emanation from building materials is quite small. In the United States, the emanation rate from concrete averages 7.7 $\times$ 10^{-6} Bq kg^{-1} s^{-1} and for gypsum the average is 6.3 $\times$ 10^{-6} Bq kg^{-1} s^{-1} [*80*]. Even in the case where phosphate slag materials, which can have elevated Ra concentrations, were incorporated in the building materials, the radon release from the materials was small, apparently because the processing reduced the specific emanation rate from these materials [*82,83*].

For building components in contact with the soil, diffusive entry can arise from radon generated in the soil exterior to the building shell, and from the building material itself. This can be illustrated in the solution to the one-dimensional diffusion equation for the flux density for radon [*84*], as shown in Eq 23. This equation incorporates radon diffusion from the building material itself as well as diffusion through the material from an external source, as in the case of a concrete slab placed on the soil.

$$J_D = \frac{(\epsilon\lambda_{Rn}D_e)^{1/2}}{\sinh(L/l)}[(G/\lambda_{Rn})(\cosh(L/l) - 1) + C_s - C_l\cosh(L/l)] \quad (23)$$

where the radon production rate in the building materials is given by

$$G = \frac{\rho f_e I_{Ra} \lambda_{Rn} (1 - \epsilon)}{\epsilon} \quad (24)$$

and the diffusion length is

$$l = \left[\frac{D_e}{\lambda_{Rn}}\right]^{1/2} \quad (25)$$

where J_D is the flux density in Bq m^{-2} s^{-1}, ϵ is the concrete porosity ($\approx$0.2), D_e is the effective diffusion coefficient, L is the thickness of the building material, C_s is the radon concentration in the soil, ρ is the average grain density of the concrete materials (usually 2650 kg m^{-3}), f_e is the emanation coefficient for concrete ($\approx$0.2), I_{Ra} is the concrete radium concentration, and C_I is the indoor radon concentration. This equation treats the soil concentration as a constant; in those cases where the concrete diffusivity approaches or exceeds that of the soil, this assumption will begin to break down.

Based on this equation and assuming that the indoor radon concentration is effectively zero compared with the pore-space concentrations in either the soil or the concrete, the radon flux density as a function of the effective diffusion coefficient in concrete has been calculated and the results displayed in Fig. 11. These calculations assume a concrete-slab thickness of 10 cm, and the four cases illustrated represent different values for the radium concentration in the concrete and the soil-gas radon concentration adjacent to the outer surface of the concrete. Figure 11 illustrates that, except for very low diffusion coefficients, the flux density from radon in the adjacent soil dominates that generated internally from the radioactive decay of the radium in the concrete; this is particularly true as the soil radon concentration increases. At a nominal value for $D_e = 5 \times 10^{-8}$ m^2 s^{-1}, the total radon flux density is estimated to be $\sim 1.2 \times 10^{-2}$ Bq m^{-2} s^{-1}, for a concrete radium content of 40 Bq kg^{-1} and a soil gas radon concentration of 40 kBq m^{-3} (the solid curve in Fig. 11). The relative contribution of radon in the adjacent soil can be estimated to be about 70% of the total by examining the case where the concrete radium concentration is set to zero. These results are presented in Table 5 for radon diffusion from and through the floor slab. Results from a similar calculation for the radon entry through the basement walls are also given in the table. In combination, these sources may contribute about 15 to 20 Bq m^{-3} to indoor radon concentrations under the modeling assumptions described above.

Natural Gas

As with groundwater, natural gas can accumulate radon gas from radium in the rocks and materials surrounding the gas formation. Almost all natural gas is processed, stored, and shipped by pipeline. Some of the original radon will have decayed simply due to the time elapsed between initial production from the well and final delivery to the point of use. Radon concentrations in gas distribution lines have been surveyed at various locations in the United States; these concentrations have varied between ~40 and 4000 Bq m^{-3}, with an average of ~750 Bq m^{-3} [*85*]. The combined residential gas-use rates in appliances such as cooking ranges and unvented ovens and gas heaters is ~1 m^3 d^{-1}, or about 0.04 m^3 h^{-1}, averaged over the entire day. This yields a volumetric source term of $\approx$0.1 Bq m^{-3} h^{-1}, which makes a negligible contribution to indoor radon compared with other sources. Other

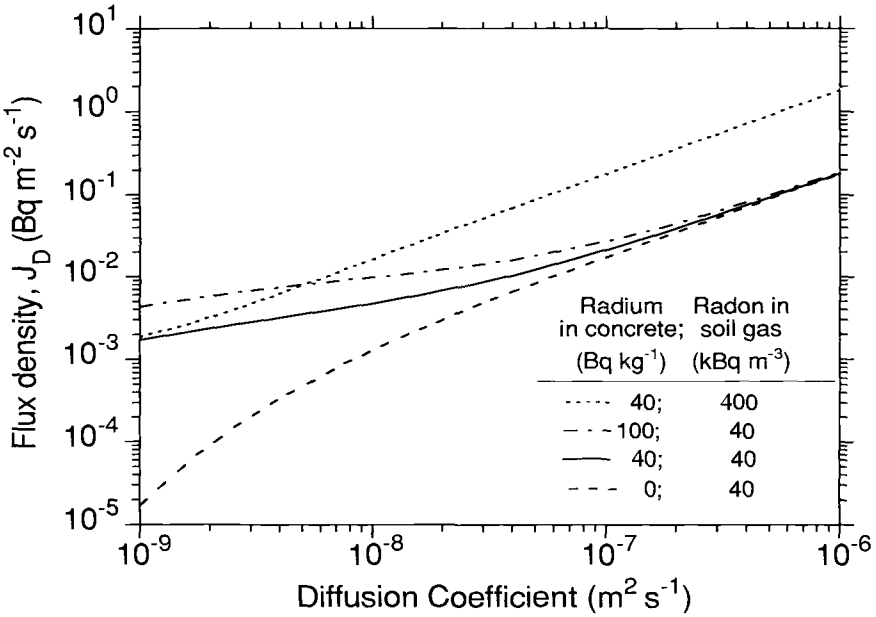

FIG. 11–Flux density for ^{222}Rn as a function of diffusion coefficient through a 10-cm-thick slab with a porosity of 0.2 and an emanation fraction of 0.2. This range of diffusion coefficients is typical of most U.S. concretes. The calculations have been done for three values of radium (^{226}Ra) concentration in the concrete (0, 40, and 100 Bq kg^{-1}) and for two different radon concentrations in the soil gas (40 and 400 kBq m^{-3}) immediately adjacent to the exterior side of the slab.

major appliances such as gas furnaces and water heaters are vented, and the radon released in these applications will be vented outdoors with the combustion gases.

Sources and Concentrations of ^{220}Rn

The discussion above has focused on ^{222}Rn; however, indoor exposures to ^{220}Rn decay products are estimated to contribute 10 to 15% of the effective dose equivalent attributed to radon, as discussed earlier. Based on the relatively few indoor measurements of ^{220}Rn [*16*] or its decay products [*15,29–31*], the estimated indoor ^{220}Rn concentration is ~10 to 15 Bq m^{-3}. There are two related questions of considerable interest. The first is the importance of various sources. Due to the short ^{220}Rn half-life, the diffusion length for this isotope is of the order of 1 cm, which effectively limits diffusive sources to the indoor surfaces of building materials. On the other hand, the mean exhalation rates for ^{220}Rn have been reported to be about two orders of magnitude higher than for ^{222}Rn, $\approx 4.5 \times 10^{-2}$ Bq m^{-2} s^{-1} for ^{220}Rn as compared with $\approx 4.9 \times 10^{-4}$ Bq m^{-2} s^{-1} for ^{222}Rn. These results are an average over several different building materials [*81*]. Using this value for the diffusive source term, an indoor surface area of 400 m^2 and an indoor volume of 500 m^3, the indoor ^{220}Rn concentration due to exhalation from building materials is estimated to be 3 Bq m^{-3} based on Eq 14, where removal of ^{220}Rn is almost entirely due to its radioactive decay.

The second question is whether houses with elevated ^{222}Rn concentrations also have significant ^{220}Rn decay product concentrations. While it would appear from the previous discussion that outdoor air plus exhalation from interior surfaces can account for typical indoor ^{220}Rn concentrations, some simultaneous measurements of the decay products from ^{222}Rn and ^{220}Rn suggest that there might be a positive correlation between the respective PAECs [*30,86*]. Simultaneous measurements of PAECs in a few homes also appear to show similar diurnal behavior [*30*]. However, other results show little, if any correlation [*29*]. One significant result, although tentative due to the small number of houses involved, is that the ratio of PAEC (^{220}Rn) to PAEC (^{222}Rn) for houses with ^{222}Rn concentrations greater that 140 Bq m^{-3} is about 0.1 or less, depending upon whether the measurements were conducted in the basement or on the ground floor. By comparison, for houses with ^{222}Rn concentrations less than 36 Bq m^{-3}, the ratio is closer to 0.4 [*31*]. At present, there are insufficient data to determine whether or under what circumstances pressure-driven flow from soil is an important source of ^{220}Rn.

Radon Decay Product Behavior Indoors

Because the radiation dose to the lungs is conferred by the radon decay products, the behavior of these species in indoor air is an important consideration. This behavior is strongly influenced by the fact that these species are chemically active, unlike the inert radon parent, and thus can become attached to various surfaces. The factors influencing radon decay-product concentrations in indoor air are shown schematically in Fig. 12 with the rate constant for each process shown in parentheses. Radon has two decay or removal mechanisms—removal by ventilation (λ_v) and radioactive decay to ^{218}Po (λ_0). Initially, these decay products are "unattached," that is, they are not associated with aerosols that may also be present in the indoor air, although in the thermalization process the alpha-decay recoil may form an ultrafine aerosol (with particle diameters ≈0.5 to 10 nm) with other gaseous molecules [*87*]. There are six possible interaction or removal modes for the subsequent progeny: (1) ventilation; (2) removal by a control device ($\lambda_F^{u,a}$); (3) deposition or plateout on a macrosurface, such as a wall ($\lambda_d^{u,a}$); (4) attachment to an airborne particle (λ_a); (5) detachment of ^{218}Po from the aerosol, denoted by the product of the recoil probability and the

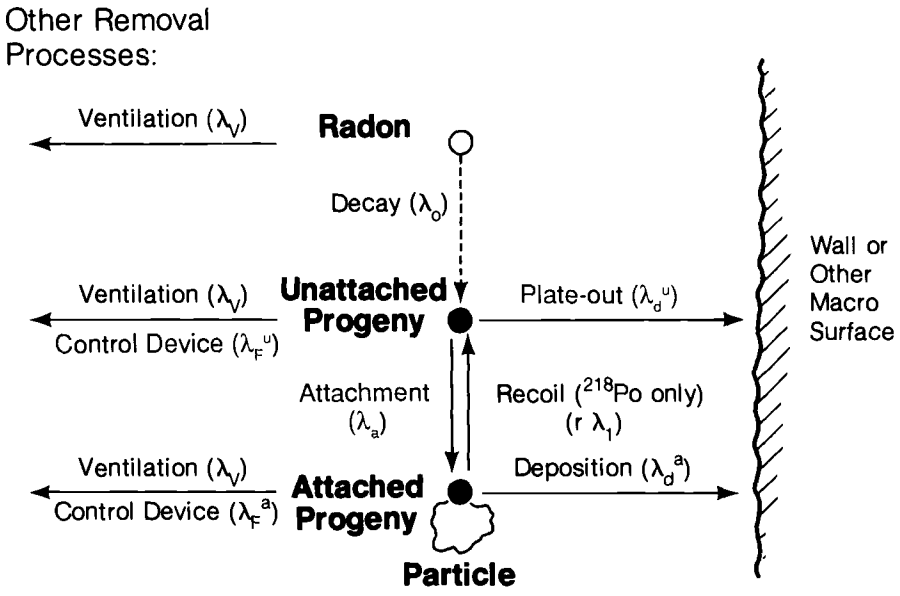

FIG. 12–Schematic illustration of the behavior of radon decay products indoors, showing deposition, attachment to indoor aerosols, and removal processes and their respective rate constants. The rate constants are described in the text. Radioactive decay of the radon progeny, an additional removal term, is not shown here.

^{218}Po decay constant; and (6) radioactive decay to subsequent radionuclides (not explicitly noted in Fig. 12). The superscripts u and a refer to unattached and attached radioactive decay products, respectively. With the exception of radioactive decay and recoil detachment, all interactions or removal processes are assumed to be the same for the three progeny species of interest here.

These factors comprise a set of source and sink terms that may be combined to provide a mathematical description of the radon decay-product behavior. These equations are collectively referred to as the room model [*88,89*] and were recently reviewed in Ref *90*. There are a number of assumptions and limitations to such a model; perhaps the most significant are the assumptions that indoor concentrations can be treated as well mixed and that dynamic terms or interactions are not important. Under steady-state conditions, equations that summarize the concentration of each of the unattached and attached decay products can be written as

$$I_i^u = \frac{\lambda_i I_{i-1}^u + r_{i-1}\lambda_i I_{i-1}^a}{\lambda_v + \lambda_i + \lambda_a + \lambda_d^u + \lambda_F^u} \tag{26}$$

and

$$I_i^a = \frac{(1 - r_{i-1})\lambda_i I_{i-1}^a + \lambda_a I_i^u}{\lambda_v + \lambda_i + \lambda_d^a + \lambda_F^a} \tag{27}$$

where $I_i^{u,a}$ is the concentration of the unattached (u) or attached (a) species and i = 1 to 3, which corresponds to the ^{222}Rn decay products, ^{218}Po, ^{214}Pb, and ^{214}Bi, respectively, or for the case of ^{220}Rn decay products, ^{216}Po, ^{212}Pb, and ^{212}Bi, respectively. I_0 (without any superscripts) is the concentration of the respective radon isotope and the recoil detachment probability, $r_1 = 0.83$ (and $r_2 = r_3 = 0$) [*90*]. The rate of attachment (λ_a) of the decay products to indoor aerosols depends not only upon the aerosol number concentration but also upon the size of the aerosols. However, for aerosols typically found in indoor air, $\lambda_a \approx 7.3 \times 10^{-3}$ cm^3 h^{-1} N, where N is the particle number concentration [*90*].

These equations can be used, along with equations for EEC and f_p defined earlier in Eqs 9 and 11, respectively, to estimate the effect of changes in the various removal parameters on the decay-product concentrations, the EEC, and the unattached fraction, f_p. Assuming no filtration and using values for the deposition rates of the unattached and attached progeny of 20 and 0.2 h^{-1}, respectively [*90*], the total unattached fraction has been computed as a function of particle concentration and for three different ventilation rates. The results are presented in Fig. 13.

As shown in this figure, changes in particle concentration have a more significant effect on the unattached fraction (and thus, the health effects associated with exposure to radon progeny) than do changes in ventilation rates that span the range of typical values for houses. These results are from a simplified model and do not take into account the complex air flow and circulation dynamics often found indoors. Detailed numerical modeling results suggest, for example, that airflow along room surfaces can increase the decay-product deposition rates [*91*].

The relative importance of the unattached fraction is also illustrated in Fig. 14, where a typical alpha-activity weighted size distribution can be compared with the corresponding estimated lung dose. The size distribution data were obtained in three residences in the eastern United States [*92*]. The smaller mode, ranging in size from ~2 to ~10 nm, is commonly referred to as the unattached ^{222}Rn decay product, while the larger mode, from ~50 to 300 nm, consists of decay products attached to indoor aerosols. The relative intensity of each mode depends upon the aerosol concentration; the size

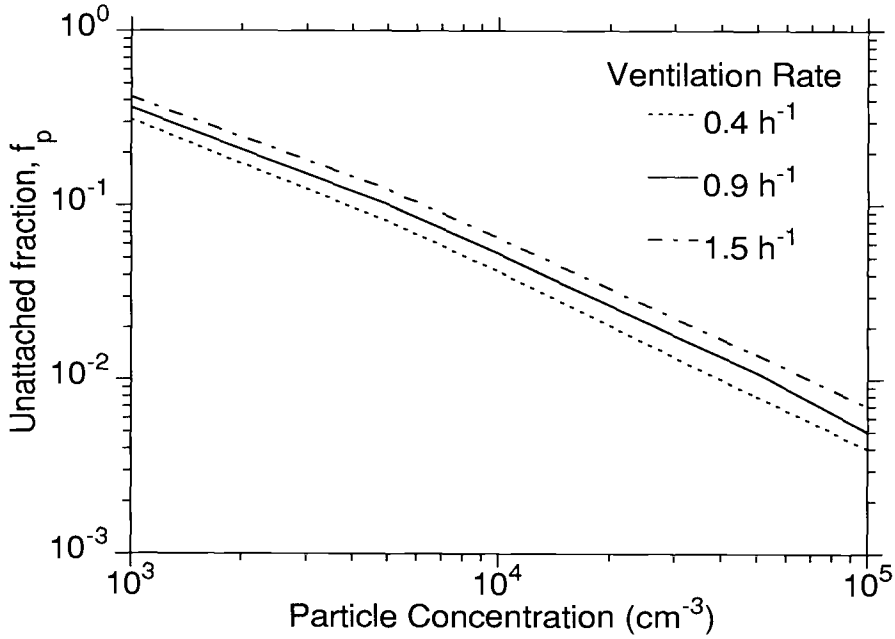

FIG. 13–Unattached fraction of PAEC (or EEC) as a function of particle concentration, calculated for three ventilation rates using the steady-state room model. Model parameters are described in the text.

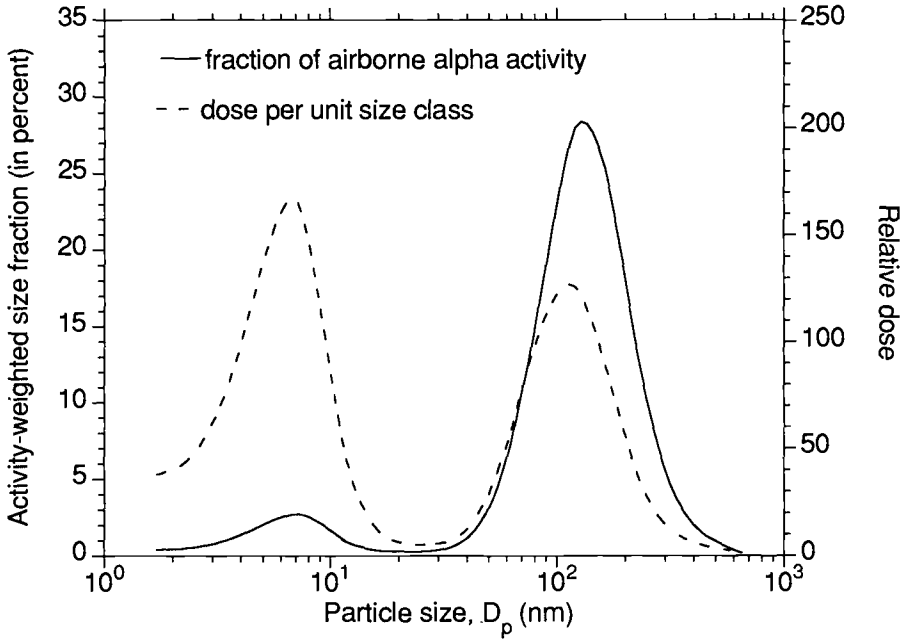

FIG. 14–Alpha-activity weighted size distributions and the associated relative lung dose. The solid line is a smoothed average of size distributions measured in three residences [*92*]. The corresponding dose, shown as the dashed line, is based on an average of the dose conversion coefficients for dose to secretory and basal cells as a function of particle size [*93*]. In this figure a relative dose of 100 ~ 100 mSv WLM^{-1} (~2.8 × 10^4 mSv m^3 J^{-1} h^{-1}).

of the lower mode is also a function of other contaminants that might be present in the indoor atmosphere [*87*]. No indoor aerosol concentrations were reported, although based on the reported f_p = 0.07, the indoor aerosol concentration can be estimated from Fig. 14 to be ≈10 000 cm^{-3}, which is a typical value for residential environments.

The estimated dose shown in the figure is based on dose conversion factors calculated as a function of particle size for both secretory and basal cells in the lung epithelium [*93*]. The two cell types were weighted equally in deriving an overall dose conversion and a volumetric breathing rate of ~1 m^3 h^{-1} was assumed. These results were then applied to the measured activity-weighted size distribution to yield the dose spectrum shown in Fig. 14. Based on the observed size spectrum, in this case the unattached decay products contribute more than half of the overall dose even though the unattached mode comprises ~7% of the total PAEC. These results also indicate that small changes in the unattached fraction, as might arise from changes in the aerosol concentration or from changes in the ventilation rate, can have a pronounced effect on the estimated dose.

SUMMARY

Radon is an ubiquitous contaminant in indoor air. It is also a significant source of radiation exposure for the general population, constituting more than half the annual effective dose equivalent, even at average indoor concentrations. These average concentrations, ≈50 Bq m^{-3}, may result from contributions from several sources, such as outdoor air, diffusion from or through building materials, or indoor water use from private groundwater sources. The contribution of pressure-driven flow of soil gas bearing radon to such concentrations is unclear, though the magnitude of the estimated contribution from this source covers a wide range of values, as indicated in Table 5, and could easily account for all or part of the observed average concentrations. For elevated indoor radon concentrations, advective flow of soil gas is the predominant source in almost all cases. This is suggested by the estimates presented in Table 5 and by the empirical observation that many of the successful radon mitigation systems reverse the natural pressure gradient across the building substructure so that entry of radon-bearing soil gas is reduced or prevented.

Radon-220 may account for 10% or more of the annual effective dose equivalent. Few measurements of ^{220}Rn or its decay products have been conducted, and the basis for estimating indoor concentrations and exposures is tentative. Outdoor air and emanation from building materials indoors may account for the indoor concentrations that have been observed; however, it is not known, in general, whether indoor ^{220}Rn concentrations may increase with increasing ^{222}Rn concentrations.

The indoor environment is very dynamic, with changes in ventilation rates and pollutant emissions occurring at several time scales, from hourly to seasonal effects. In part, these are a result of the interaction of the building with the external environment, where temperature differences or winds provide the driving forces for both ventilation and for advective radon entry. The operation of mechanical systems within the building shell can affect the ventilation rate of the structure, the radon entry rate, and mixing within the building. In actual buildings, these interactions are often complex. The

resulting indoor radon and radon decay-product concentrations can also be highly variable over similar time periods. These are important considerations in the measurement of indoor pollutants and in estimating exposures.

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3

Health Effects of Radon

by Jonathan M. Samet[1]

ALTHOUGH RADON IN INDOOR AIR has been widely recognized as a significant public health problem only since the 1970s, radon has been linked to excess lung cancer in underground miners since the early decades of this century. As long ago as the 1500s, Agricola described unusually high mortality from respiratory diseases among underground metal miners in the Erz Mountains of eastern Europe, a region presently encompassed by Germany and Czechoslovakia [*1*]. The disease, termed "bergkrankheit," probably represented lung cancer, silicosis, and tuberculosis, common diseases of underground miners. In 1879, Harting and Hesse [*2*] reported autopsy findings in miners of Schneeberg in Germany that documented an occupational hazard of lung cancer, although they did not identify the disease as primary cancer of the lung. Early in this century, further pathological studies showed that the miners developed primary carcinoma of the lung [*3,4*].

Measurement of radon in the mines of Schneeberg and Joachimsthal early in this century documented the presence of radon at concentrations that would be considered high by present occupational standards [*5–7*]. By the 1930s, excess lung cancer was demonstrated among miners in Joachimsthal on the Czechoslovakian side of the range, and radon was found in the air of the mines. Radon was considered a likely cause of lung cancer in these miners [*6*], but a causal role of radon was not uniformly accepted. For example, in a 1944 review of the subject, Lorenz [*8*] argued that radon alone could not be the cause of lung cancer and proposed that genetic susceptibility to develop lung cancer might be unusually high in the miners of Schneeberg and Joachimsthal. However, the association of exposure to radon with lung cancer became widely accepted as causal as the biologic basis of carcinogenesis by radon was better understood and excess lung cancer was documented in additional populations of underground miners [*9–11*]. Bale's 1951 memorandum showing that the decay products of radon, rather than radon itself, delivered the alpha energy dose to the respiratory tract was an important advance [*12*].

Evidence on radon and lung cancer, as well as other diseases, is now available from about 20 different groups of underground miners. These groups have been investigated using epidemiologic study designs; epidemiology is the biomedical research science used to describe the occurrence of diseases and to determine the causes of diseases in populations. In investigating the various mining groups, the cohort study design has been most widely applied. In this design, miners are followed longitudinally and the occurrence of lung cancer and other diseases monitored; the disease experience of the miners is often compared to the expected occurrence of disease based on the rates in the general population. Disease risks are also examined in relation to exposure to radon or other agents. The relative risk is used to describe the effect of exposure; it compares the risk in exposed persons to those in an unexposed or less exposed reference category. Another design, the case-control study, has also been used to investigate lung cancer in miners. In this design, the exposures of lung cancer cases are compared with those of controls who do not have lung cancer.

Epidemiologic studies have shown excess occurrences of lung cancer in uranium miners in the United States, Czechoslovakia, France, and Canada, and in other underground miners exposed to radon decay products, including Newfoundland fluorspar miners, Swedish and U.S. metal miners, British and French iron miners, and Chinese and British tin miners [*13*]. In the United States and elsewhere, regulations have been implemented to limit the exposure of underground miners to radon decay products, and exposure in the mining environment has progressively declined since the 1950s [*14,15*]. In recent years, the exposure of animals to radon and decay products has confirmed that radon decay products cause lung cancer [*13*].

As information on air quality in indoor environments accumulated, it became apparent that radon and its decay products are invariably present in indoor environments and that concentrations may reach levels as high as those in underground mines in some dwellings. The well-documented excess of lung cancer among underground miners raised concern that exposure to radon decay products might also be a cause of lung cancer in the general population. Thus, the lung cancer hazard associated with radon exposure is presently of concern not only for the relatively small number of exposed underground miners, but for the general population. The lung cancer risk associated with indoor radon has not yet been extensively investigated. The risk of indoor radon has been primarily assessed by using risk models that extend the findings of the studies of miners to the general population. However, numerous epidemiological investigations of the association between indoor radon and lung cancer are now in progress throughout the world.

This chapter reviews the evidence on lung cancer and exposure to radon decay products. It covers concepts of exposure and dose, the relevant epidemiological studies, and risk assessment. It also considers the more limited information on

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health effects other than lung cancer. Of necessity, it cannot cover these topics in depth. Other recent reviews and monographs provide more complete treatments of various aspects of the subject [*13,16–22*].

DOSIMETRY OF RADON

Concentration and Exposure

For historical reasons, the concentration of radon decay products in mines has been generally expressed as working levels (WL), where one WL is any combination of radon decay products in one liter of air that ultimately releases 1.3×10^5 MeV of alpha energy during decay [*23*]. Exposure to 1 WL for 170 h equals one working level month (WLM) of exposure. The WLM was developed to describe exposures sustained by miners during the average number of hours spent underground during a work month. Nevertheless, this unit of exposure has been applied in the United States to indoor exposures. Because most persons spend much more than 170 h at home each month, a concentration of 1 WL in a residence results in an exposure much greater than 1 WLM on a monthly basis. Thus, assuming that 70% of time is spent at home, a 1 WL concentration (7400 Bq m^3 or 200 pCi/L) would yield an exposure of 3.0 WLM monthly or 36 WLM annually. The approximate average concentration in U.S. homes (55 Bq m^3 or 1.5 pCi/L) [*24*], under the same home occupancy assumption, results in an exposure of about 0.02 WLM monthly, about 0.3 WLM annually, and about 20 WLM over a 70-year lifetime. Cumulative exposure in SI units is expressed in Joule hours per cubic meter (Jh m^3) and 1 WLM is a 3.5×10^{-3} Jh m^{-3}.

Respiratory Dosimetry of Radon Decay Products

The lung cancer risk associated with exposure to radon is considered to result from the alpha particles emitted by inhaled radon decay products which have been deposited on the lining of the airways of the lung. The genetic material of cells in this lining, referred to as the epithelium, may be damaged by the energy released by the alpha particles as they pass through the cells. Thus, the lung cancer risk associated with exposure to radon is presumed to vary with the dose of alpha energy delivered to target cells in the lung [*22*].

The relation between exposure to radon decay products, measured as WLM or Jh m^{-3}, and dose of alpha energy to target cells in the respiratory tract is extremely complex and is dependent on both biological and nonbiological factors, including the physical characteristics of the inhaled air, the amount of air inhaled, breathing patterns, and the biological characteristics of the lung (Table 1) [*25,26*]. These factors influencing the relation between exposure and dose could plausibly differ for the circumstances of exposure in homes and in mines; it cannot be assumed that the same exposures in a home and in a mine lead to the same doses of alpha radiation to target cells in the lung and hence to the same lung cancer risk. Thus, in using the epidemiological evidence from studies of miners to estimate the risk of indoor radon, the dosimetry of radon decay products in the mining and indoor environments needs to be compared.

TABLE 1—Physical and biological factors influencing the dose to target cells in the respiratory tract from radon exposure.

Physical Factors
Fraction of daughters unattached to particles
Aerosol size distribution
Equilibrium of radon with its progeny
Biological Factors
Tidal volume and respiratory frequency
Partitioning of breathing between the oral and nasal routes
Bronchial morphometry
Mucociliary clearance rate
Mucus thickness
Location of target cells

Certain aspects of lung structure and function are important determinants of the dosimetry of radon decay products [*25,27*]. Inhaled air flows through the nasal and oral airways to the trachea; at rest, the nasal route predominates, but flow through the oral route increases with exercise. The lung comprises the airways, a dichotomously branching system of tubes, and the alveoli, the saccular structures where gas exchange takes place. Gas flow is turbulent in the larger airways and laminar in the smaller airways; gases move by diffusion in the alveolar spaces. The respiratory system has multiple defense mechanisms for handling inhaled particles, such as radon decay products. The nose efficiently removes large particles and charged particles; the latter is the state of the unattached fraction of radon decay products. In the lung, particles in the size range of 2 to 10 μm tend to deposit in the airways and are cleared by the mucociliary apparatus, which moves mucus towards the larynx, where it is coughed or swallowed. Submicron particles also deposit in the airways with increasingly high deposition fractions as the particle diameter decreases.

Most human lung cancers arise at the level of about the third through the fifth airways generations, and relatively few originate peripherally [*28*]. These airways have a cartilaginous structure and are lined by a pseudostratified ciliated columnar epithelium; that is, the superficial layer includes cells with cilia, hair-like structures which beat in an organized fashion to propel mucus towards the trachea. The cells appear to be in multiple strata, although only one layer is present [*27*]. The cellular components of the airways epithelium include the ciliated epithelial cells, mucus-secreting cells, basal reserve cells, and other types. Although the cellular origins of human lung cancer are controversial, all of the principal cell types of the airways epithelium are considered to have the potential to undergo malignant transformation [*22,29,30*]. The relevant target for carcinogenesis by alpha particles is assumed to be the mucus-secreting cells and the basal cells of the bronchi, the airways where most human lung cancers occur [*22*].

The dose of alpha energy delivered to these target cells in the lungs cannot be directly measured; modeling approaches are used to simulate the complex sequence of events, from inhalation of radon decay products to cellular injury by alpha particles. The models incorporate not only the biological processes that follow inhalation, but the physical state of the inhaled radon decay products, also an important determinant of the exposure-dose relation for radon decay products.

Radon is an inert gas, but its decay products are solid, charged particles. While most of the decay products attach to aerosols immediately after formation, a variable proportion

of the atoms exist in an ultrafine mode, historically referred to as the unattached fraction [22,26,31]. The fraction of unattached radon decay products in inhaled air is an important determinant of the dose received by target cells at a particular concentration in inhaled air; as the unattached fraction increases, the dose also increases because of the efficient deposition of the unattached decay products in the larger airways (Fig. 1) [25]. The size distribution of particles in the inhaled air also influences the dose to the airways because particles of different sizes deposit preferentially in different generations of airways [25]. The specific mixture of radon decay products also affects the dose to target cells, although to a lesser extent.

The amount of inhaled radon decay products varies directly with the minute ventilation, the total volume of air inhaled each minute. The increased ventilation associated with physical activity increases the inhaled burden of radon decay products. The deposition of radon decay products within the lung, however, does not vary in a simple fashion with the minute ventilation but varies with the flow rates in each airway generation (Fig. 2) [25]. These flow rates depend on both tidal volume and breathing frequency. The dose changes approximately with the square root of breathing rate. The proportions of oral and of nasal breathing also influence the relationship between exposure and dose [25]. A substantial proportion of the unattached radon decay products deposits in the nose with nasal breathing, whereas the oral filtration efficiency is lower [22].

Characteristics of the lung also influence the relationship between exposure and dose (see Table 1). The sizes and

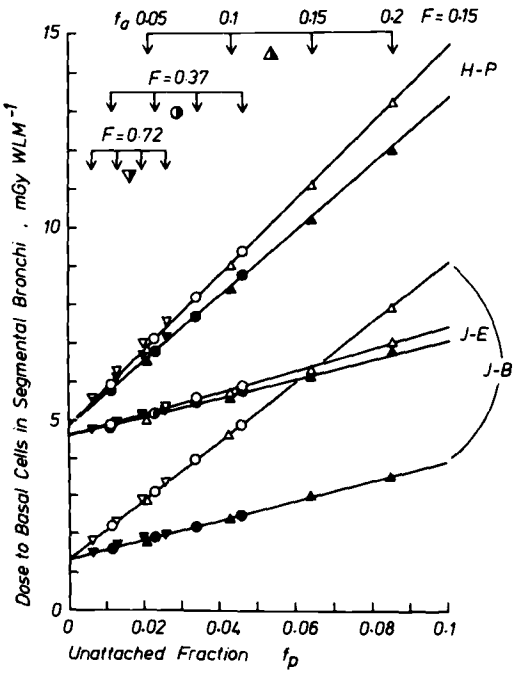

FIG. 1–Dose (mGy/WLM) in segmental bronchi calculated as a function of the unattached fraction (f_p) and equilibrium factor (F) using different dosimetric models: Harley-Posternack (H-P), Jacobi-Eisfeld (J-E), and James-Birchall (J-B). The open symbols represent unattached Po-218 particles of 1-nm diameter, and the solid symbols represent particles of 3-nm diameter. Used with permission from Ref *25*.

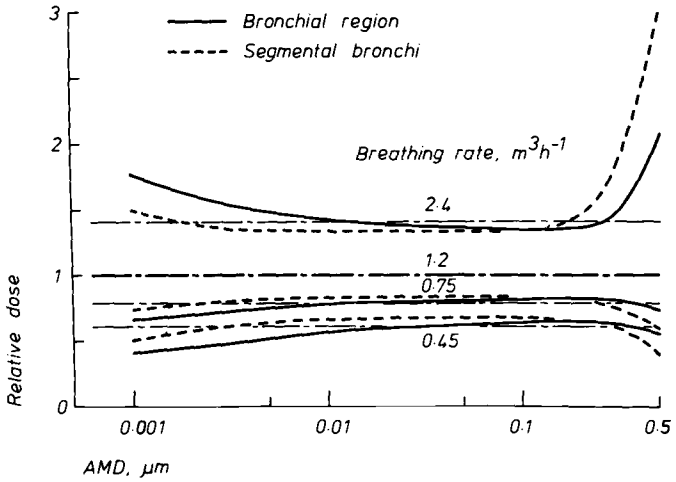

FIG. 2–Relative epithelial doses in the bronchial region and segmental bronchi in relation to aerosol size and breathing rate. Calculations are relative to values for occupational exposure at a breathing rate of 1.2 m³/h. Used with permission from Ref *25*.

branching patterns of the airways affect deposition, and these aspects of airways configuration may differ between children and adults, and between males and females. The exposure-dose relation is thus different for infants, children, and adults and for males and females [22,25,32]. Once deposited in the airways, radon decay products are cleared by the mucociliary apparatus. Thus, the rate of mucociliary clearance and the thickness of the mucous layer in the airways also enter into dose calculations. The dose increases as the mucociliary clearance slows and diminishes with increasing thickness of the mucous layer. Cigarette smoking tends to reduce the rate of clearance and to increase the thickness of the mucous layer.

The cells of the airways absorb alpha energy as alpha particles released in the decay of polonium-218 and polonium-214 on the epithelium's surface move through the epithelial layer. These particles have a short range in tissue but can penetrate to the basal layer. Cellular doses can be calculated [22,25].

Computer models have been developed to describe the relation between exposure to radon decay products and the dose of alpha radiation received by target cells. These models can be used to assess the effects of the physical and biological factors listed in Table 1 on the exposure-dose relation. These complex models generally incorporate biological factors, including airways geometry, mucociliary deposition, particle deposition, ventilation pattern, and location of the target cells, and physical factors, including the unattached fraction and the aerosol size distribution [22,25,26,33]. Using such models, factors for converting exposure to an absorbed radiation dose can be calculated, but the range of published dose conversion factors is wide [25]. As summarized by James [25], the values span from 0.8 rad/WLM (0.8 mGy/WLM) to about 10 rad/WLM (100 mGy/WLM). For the attached and unattached fractions specifically, the dose conversion factors cover a narrower range. Recent estimates for the attached fraction are about 0.2 to 1.3 rad/WLM (2 to 13 mGy/WLM) and for the unattached fraction about 10 to 20 rad/WLM (100 to 200 mGy/WLM). To convert absorbed dose to tissue dose equivalent in units of rem, or sieverts in the SI system, the

absorbed dose in rads or grays is multiplied by 20, the quality factor for alpha radiation.

Comparisons of Dosimetry in the Indoor and Mining Environments

Dosimetric models have proved useful for evaluating uncertainties in extrapolating from the mining to the general indoor environment. Using dosimetry models, the alpha dose to the respiratory tract has been compared under the circumstances of exposure in homes and in mines [*22,25*]. In comparison with mines, the unattached fraction is higher in homes, and the aerosol size distributions may differ in the two environments. The ventilation rates of working miners are higher on average than the general population during usual activities at home. The physical configuration of the airways of children differs from that of adults as well.

A number of comparisons of dosimetry in mines and in homes have been reported [*22,25,26*]. Comparative analyses reported during the 1980s indicated that exposures to radon decay products in homes and in mines yield essentially comparable doses of alpha energy to the respiratory tracts of adults [*25,26*]; for children, the estimated doses were estimated to be higher than for adult miners and nonminers because of the physical differences between the lungs of children and adults [*25,26*].

The Biological Effects of Ionizing Radiation (BEIR) IV Committee of the National Research Council [*13*] used a descriptive approach and also concluded that exposure-dose relationships were similar for exposure in homes and in mines. The Committee reviewed the likely range of dose conversion factors for particle size, unattached fraction, equilibrium factor, and minute ventilation in homes and in mines. The Committee's estimates for the ratios of these factors in homes to mines were 1.4, 1.2, 1, and 0.56, respectively. When considered together, the product of these ratios was near unity. The Committee's approach assumed that the remaining biological determinants of the exposure-dose relationship were comparable in miners and in the general population.

More recently, another National Research Council committee further compared the relations between exposure and dose in homes and in mines [*22*]. This committee used the most recent information on the parameters of a new dosimetric model. The findings were expressed as a ratio, termed *K*, which represents the quotient of the dose of alpha energy delivered per unit exposure to an individual in the home to the dose per unit exposure to a male miner in a mine. At nearly all ages, *K* was less than 1, indicating lesser doses in the home environment (Table 2).

TABLE 2—Summary of *K* factors for bronchial dose calculated for normal people in the general environment relative to healthy underground miners.[a]

Subject Category	*K* Factor for Target Cells	
	Secretory	Basal
Infant, age 1 month	0.74	0.64
Child, age 1 year	1.00	0.87
Child, age 5 to 10 years	0.83	0.72
Adult female	0.72	0.62
Adult male	0.76	0.66

[a]Taken from Table S-1 in Ref *22*.

EPIDEMIOLOGICAL STUDIES OF RADON AND LUNG CANCER

Introduction

The causal association of exposure to radon decay products with lung cancer has been amply documented through epidemiologic investigations of underground miners [*13,16,34*]. Studies of miners have shown rising lung cancer risk as cumulative exposure to radon decay products increases and have provided data on the combined effects of cigarette smoking and exposure to radon decay products. These studies have been less informative concerning the temporal expression of the excess risk across the full life span and the effect of exposure rate. Animal experiments have also provided data on exposure-response relations and on the modifying effects of exposure rate and the physical characteristics of the inhaled radon decay products [*13*].

The lung cancer risk associated with exposure to radon decay products must be considered in the context of the extensive literature on lung cancer in the general population. This malignancy, uncommon at the start of the century, has become the leading cause of cancer death in the United States [*35*]. Most lung cancers are caused by cigarette smoking, and only 5 to 10% of the total occur in lifelong nonsmokers [*35,36*]. In cigarette smokers, the risk of developing lung cancer increases with the number of cigarettes smoked daily and with the number of years smoked [*35,37*]. The risk of lung cancer for a smoker compared with a nonsmoker is increased approximately ten-fold on average but reaches twenty-fold or higher in heavier smokers. Lung cancer occurs in multiple histopathological patterns, as assessed by conventional light microscopy [*38*]. The most common types of lung cancer are squamous cell carcinoma, adenocarcinoma, small cell carcinoma, and large cell carcinoma, accounting for about 30, 25, 20, and 10 to 15% of lung cancers in the general population, respectively [*39*].

Because cigarette smoking predominates as the cause of lung cancer, the risk from exposure to radon decay products must be addressed separately for smokers and for nonsmokers. When one agent (cigarette smoke, for example) modifies the effect of another (radon decay products, for example) interaction is present. An interaction between two agents may be either synergistic or antagonistic; synergism refers to an increased effect of the independent exposures when both are present, whereas antagonism refers to a reduced effect. If the combined effect equals the product of the independent risks, then the interaction is considered to be multiplicative; the interaction is considered additive if the combined effect equals the sum of the independent risks less unity. A multiplicative interaction yields the same level of relative risk in smokers and nonsmokers for a particular exposure, but the higher background risk of the smokers is multiplied by that resulting from radon decay products. If two agents interact in a synergistic fashion, then some cases can be attributed to the two factors acting alone and some to their joint action. The cases having shared causation can in theory be prevented by removing either of the interacting agents. Estimates of the

numbers or proportions of preventable cases may thus exceed the total number of cases or 100%.

Cigarette smoking has well-described effects on both the airways and the lung parenchyma [*40*]; these effects may plausibly modify the relationship between exposure to radon and dose of alpha energy to cells. In comparison with the dose in nonsmokers, the dose in smokers might be increased by the greater central deposition, the increased airways permeability, and the slowed mucociliary transport that have been demonstrated to result from smoking. The dose in smokers might be reduced by mucosal edema and by the increased mucus thickness, on average, secondary to the heightened mucus production in the airways of smokers. Components of tobacco smoke might also interact with alpha particles in the process of carcinogenesis itself. At present, a conclusion cannot be reached through biologically based considerations alone concerning the net consequence of interaction between cigarette smoking and exposure to radon decay products. Thus, the determination of the form of interaction between exposure to radon decay products and cigarette smoking has been based primarily on the epidemiological studies of underground miners.

The hypothesis has been advanced that the interaction of radon decay products with environmental tobacco smoke may contribute to the development of lung cancer in active smokers and in passively exposed nonsmokers [*41,42*]. The introduction of cigarette smoke into an unventilated room increases the concentration of radon decay products, an increase that may reflect attachment of decay products to tobacco smoke aerosol [*43*]. Increased exposure to radon decay products would thus result from the tobacco smoke. However, the results of dosimetric modeling indicate that increasing concentrations of particles decrease the dose received by target cells in the lung's airways. Thus, the net effect of environmental tobacco smoke on the lung cancer risk represents the summation of the factors tending to increase and to decrease dose to target cells. A conclusion cannot yet be reached on the balance of these factors [*44*].

Studies of Miners

The risk of lung cancer associated with exposure to radon decay products has been investigated in about 20 different populations of underground miners (Table 3). Although the methodology of these studies is varied, the findings uniformly indicate increased lung cancer occurrence from exposure to radon decay products. Not all of the investigations, however, include the data for individual subjects that are needed to characterize the exposure-response relation of lung cancer risk with exposure to radon decay products, and only a few of the investigations have incorporated assessment of cigarette smoking. Moreover, none of the longitudinal investigations have yet completed follow-up of all subjects from first exposure to death; thus, uncertainty remains concerning the full temporal expression of the excess risk of lung cancer associated with exposure to radon decay products.

Quantitative exposure-response relationships have been described using data from several of the cohort studies (Table 4) [*13,64,65*]. The range of excess relative risk coefficients, from 1.4 to 8.6 per Jh m^{-3} (0.5 to 3.0 per 100 WLM), is remarkably narrow in view of the differing assessments of exposure and analytical methods among the investigations. The most detailed analyses have been reported for the study of uranium miners in the Colorado Plateau [*66,67*]. In this cohort, the exposure-response relation was nonlinear across the full range of exposure which extended to 35 Jh^{-3} (10 000 WLM); the excess risk per unit exposure decreased at higher exposures. The decrease in excess risk at the higher exposures may reflect cell killing by alpha particles, but a greater degree of error in higher exposure estimates is an alternative explanation [*13*]. Subjects first exposed at an older age were at increased risk of lung cancer. Risk was also increased by a lower rate of exposure, and the relative risk declined with time since leaving mining.

Insight into the interaction between exposure to radon decay products and cigarette smoking can be gained from those epidemiologic studies of miners that documented both of these exposures; unfortunately, such information is available for only a few of the study groups [*13*]. Small case numbers in some of the studies also limit the statistical precision with which the interaction can be described. Although

TABLE 3—Epidemiological studies of radon-exposed underground miners.[a]

Substance Mined (Reference)	Location
Uranium [*11*]	U.S. Colorado Plateau
Uranium [*45*]	New Mexico
Uranium [*46*]	Czechoslovakia
Uranium [*47*]	Ontario, Canada
Uranium [*48*]	Beaverlodge, Canada
Uranium [*49*]	Port Radium, Canada
Uranium [*50*]	France
Iron [*51*]	Kiruna, Sweden
Iron [*52*]	Grangesberg, Sweden
Iron [*53*]	Malmberget, Sweden
Iron [*54*]	Northern Sweden
Iron [*55*]	England
Iron [*56*]	France
Magnetite [*57*]	Norway
Fluorspar [*58*]	Newfoundland, Canada
Metal ores [*59*]	United States
Zinc-lead [*60*]	Hammar, Sweden
Tin [*61*]	Cornwall, England
Tin [*62*]	Yunnan, China
Niobium [*63*]	Norway

[a]From Ref *31*.

TABLE 4—Relative risk coefficients for lung cancer from longitudinal studies of underground miners.[a]

Study	Excess Relative Risk, Jh m^{-3}	
Colorado Plateau uranium miners	1.4	(0.5)[b]
New Mexico uranium miners	3.1	(1.1)
Ontario uranium miners	3.7	(1.3)
Beaverlodge, Canada, uranium miners	7.4	(2.6)
Port Radium, Canada, uranium miners	2.0	(0.7)
Czech uranium miners	5.4	(1.9)
Malmberget, Sweden, iron miners	4.6	(1.6)
Newfoundland fluorspar miners	8.6	(3.0)
Chinese tin miners	2.6	(0.9)

[a]With the exception of New Mexico uranium miners, the data were abstracted from Table 2 in Ref *64* and refer to exposure categories below 1.75 Jh m^{-3} (500 WLM). For New Mexico uranium miners, the data were obtained from Ref *65* and refer to exposures less than 3.51 Jh^{-3} (1000 WLM).

[b]Values in parentheses are excess relative risk per 100 WLM.

the smaller investigations have yielded inconsistent descriptions of the combined effect of smoking and exposure to radon decay products, the largest investigation, that of Colorado Plateau uranium miners, indicates a multiplicative or somewhat submultiplicative interaction, and the data are not compatible with simple additivity [*13,66,67*]. Analyses of data from the New Mexico uranium miners [*65*] and the Beaverlodge, Canada uranium miners [*68*] also indicate a multiplicative interaction.

The histopathology of lung cancer cases has been characterized by light microscopy in some groups of underground miners to determine if exposure to radon decay products is associated with particular histologic types [*13,69*]. Most case series have come from mining groups in which cigarette smoking was prevalent. The case series, largely cross-sectional, have shown a greater prevalence of small cell lung cancer than would be anticipated based on the pattern of lung cancer occurrence in the general population; in these series, about 50% of the cases have been small cell cancer, approximately double the proportion of this histological type in the general population. In the longitudinal observations of lung cancer in the Colorado Plateau, reported by Saccomanno et al. [*70*], the proportion of small cell cancer declined from 76% in 1964 to 22% in the late 1970s, while squamous cell cancers increased concomitantly. Saccomanno [*71*] recently reported that 6 of 25 cases in nonsmokers from the Colorado Plateau region were small cell carcinomas. Butler et al. [*72*] reviewed the histopathology of lung cancer cases in Navajo uranium miners who were either nonsmokers or light smokers. The distribution of histopathological types was comparable to that for the general population, but the proportion of small cell cases was far greater than would be anticipated for cases in nonsmokers.

Analyses of excess lung cancer occurrence by histological type have been reported for the Colorado Plateau uranium miners and for the Czech uranium miners. In the Colorado group, the ratio of observed to expected cases was greatest for small cell carcinoma, but squamous carcinoma and adenocarcinoma also occurred in excess [*73*]. A similar analysis for the Czech cohort showed excesses of small cell carcinoma, squamous carcinoma, and types other than adenocarcinoma, which was not increased [*74*]. The ratio of observed to expected cases was greatest for small cell carcinoma.

Studies of the General Population

To date, epidemiologic investigations of indoor exposure to radon decay products as a risk factor for lung cancer have been limited by the methodological difficulties of studying this exposure. Both descriptive and analytical approaches have been used to examine the association between exposure to radon decay products in the home and lung cancer. Techniques for estimating lifetime exposure of individuals to radon decay products in indoor air have not yet been validated, and surrogates for exposure based on residence type, geology, or limited measurements have of necessity been used in the case-control and cohort studies. The principal published reports are reviewed; Borak and Johnson [*75*] summarized the relevant literature including several unpublished investigations.

In the descriptive studies, incidence or mortality rates for lung cancer within geographic units were correlated with measures of exposure for inhabitants of these units (Table 5). In spite of crude exposure measures, most of these studies showed associations between exposure to radon decay products and the incidence of or mortality from lung cancer. Two studies of counties in the Reading Prong are of particular interest because of the number of homes in this region with high radon concentrations [*84,85*]. Both studies indicated increased mortality from lung cancer in residents of the counties with the highest exposures. However, these descriptive studies, which did not consider the exposures of individuals to radon decay products and other agents, can provide only suggestive evidence that exposure to radon in the home increases the risk of lung cancer.

The association of radon exposure and lung cancer has been more directly tested in case-control and cohort studies (Table 6). In the first of these investigations, Axelson, Edling, and Kling [*87*] conducted a case-control study in a rural area of Sweden. Those subjects who lived in stone houses were assumed to be most exposed and those who lived in wooden houses were assumed to be least exposed; other types of dwellings were considered to be a source of intermediate exposure. In spite of this crude exposure classification, the study showed that residence in stone houses was associated with a significantly increased relative risk compared to residence in wooden houses (age- and sex-adjusted RR = 5.4). The study did not consider data on cigarette smoking or lifetime residence history.

In several later case-control studies performed in Sweden (see Table 5), surrogate exposure indexes were validated against measurements of radon decay products with the finding that average levels, as determined by measurement, paralleled the presumed concentration [*88,92,93*]. The findings of these case-control studies were mixed; some showed significantly increased risk associated with exposure, whereas others did not. However, this may be due to the small number of cases in several of the studies and the general use of surrogate measures of exposure. Reliance on surrogate measures may introduce misclassification; that is, some subjects may be assigned higher or lower exposures than they actually received. If misclassification occurs randomly in cases and controls alike, the relative risk estimates will be biased toward unity and an effect of exposure may not be found.

The more recent studies in Sweden have included larger numbers of cases and controls than those initially reported, and some have incorporated measurement of radon for large numbers of dwellings [*91–93*]. Two investigations in Stockholm have shown approximately doubled lung cancer risk for more exposed compared with less exposed subjects [*92,94*]. A study in northern Sweden that assumed exposure from residence type found no increased risk overall [*91*]. In a study in southern Sweden, Axelson et al. [*93*] used measurement data and information on residence type and geology to estimate exposure; association was found in rural but not urban dwellers. This variation in the effect of exposure to radon with residence location could not be readily explained by the investigators.

In the United States, Simpson and Comstock [*95*] examined the relationship between the incidence of lung cancer and housing characteristics. During a 12-year period in

TABLE 5—Descriptive studies of exposure to radon and lung cancer.

Location [Reference]	Outcome Measure	Exposure Measure	Findings
U.S. [*76*]	Lung cancer mortality for U.S. counties, 1950–1969	Presence of a phosphate deposit, mine, or processing plant in the county	Significant excess of high lung cancer rates in counties with phosphate mills.
Iowa, U.S. [*77*]	Lung cancer incidence for municipalities of 1000–10 000 residents for years 1969–1979.	Mean level of radium-226 in the water supply	Significantly increasing cancer incidence for males with exposure; increase not significant for females.
Sweden [*78*]	Lung cancer mortality rates by county, 1969–1978	Estimated background gamma radiation, assumed to correlate with radon	Significant correlations for lung cancer rates in males and females with exposure.
Canada [*79*]	Lung cancer mortality rates for 18 cities for 1966–1979.	Geometric mean WL from a survey of 14 000 homes done 1978–1980	No association of lung cancer mortality rates with radon daughter levels.
Maine, U.S. [*80*]	Lung cancer mortality rates by county, 1950–1969	Estimated county average for radon concentration in water	Significant associations in males and females of lung cancer mortality with exposure.
Central Italy [*81*]	Lung cancer mortality rates for 31 towns, 1969–1978	Soil geological features	Nonsignificant increase for males and females in higher exposure area.
Guangdong Province, China [*82*]	Lung cancer mortality rates for two areas, 1970–1983	By area: "control" and "high background"	Similar lung cancer mortality rates in the two areas.
Limousin and Poitou-Charentes, France [*83*]	Lung cancer mortality rates for the two regions, 1968–1975	By area: from geology, indoor radon estimated 3–4 times higher in Limousin region.	Similar lung cancer mortality rates in the two regions.
Reading Prong, U.S. [*84*]	Lung cancer mortality rates by county, 1950–1969	By county, based on the proportion within the Reading Prong	For the three counties mostly within the Reading Prong, lung cancer mortality significantly elevated for all three for men and in two for women.
Reading Prong, U.S. [*85*]	Lung cancer mortality rates by county, 1950–1979	By county, based on geology; three levels of exposure	For both sexes combined, lung cancer mortality follows a gradient consistent with exposure.
U.S. [*86*]	Lung cancer mortality rates for all U.S. counties, 1950–1969	By county, geometric mean concentration measured in 10 or more homes.	For males and females, lung cancer mortality rates were inversely associated with county-average radon levels.

Washington County, Maryland, the incidence of lung cancer in the county's residents was not significantly affected by the type of basement construction or building materials. Without specific validation, the dwelling characteristics were assumed to be surrogates for exposure to radon.

In New Jersey, Klotz et al. [*96*] evaluated mortality of 752 persons who had resided in 45 homes contaminated by radon from radium processing waste. Overall, lung cancer mortality was not elevated. The standardized mortality ratio for white males was increased, but the excess was not statistically significant. In another recent study in New Jersey, radon exposures for the 10 to 30 years before diagnosis were estimated for 433 cases and 402 controls drawn from a previously completed study of 994 cases and 995 controls [*97*]. Overall, the risk of lung cancer tended to increase at higher exposures, but the association of radon with lung cancer was not statistically significant in most analyses. Inexplicably, the risk of radon exposure was less among heavier cigarette smokers.

A case-control study was conducted in Port Hope, Ontario, where some homes had been constructed with contaminated building materials [*98*]. Exposures were estimated for the period of residence in Port Hope on the basis of earlier measurement data. The analyses indicated an increased risk for subjects with higher exposure, which persisted when cigarette smoking was controlled. However, the number of subjects was small and the results were not statistically significant.

Blot et al. [*99*] performed a case-control study in Shenyan, People's Republic of China, an area with particularly high lung cancer rates in women. The study included 397 cases and 391 controls. Homes were monitored with alpha-track detectors for one year; the mean concentration of radon was 85.1 Bq m^{-3} (2.3 pCi/L) and 20% of the levels were above 148 Bq m^{-3} (4 pCi/L), the current "action guideline" of the Environmental Protection Agency (EPA).

Many new case-control studies are now in progress throughout the world but most will not be completed for several years [*100*]. Most incorporate measurements of radon concentrations in current and former residences. The sample sizes of most of the investigations are substantially greater

TABLE 6—Epidemiological studies of domestic exposure to radon and lung cancer.

Location [Reference]	Study Design	Subjects	Exposure Measure	Findings
Southern Sweden [*87*]	Case-control	37 cases and 178 controls	Residence type: wood, "mixed," or stone	RR = 1.8[a] ($p < 0.05$) for stone and mixed vs. wood.
Oeland, Sweden [*88*]	Case-control	23 cases and 202 controls	Residence type and 4 months' measurements	RR = 4.3 (90% CI[b] 1.7–10.6) for low vs. high home type. RR = 2.7 (90% CI 1.4–18.5) low vs. high by measurement.
Southern Sweden [*89*]	Case-control	23 cases and 202 controls	Measurement with alpha-sensitive film	RR increased for higher vs. lowest exposure categories. Multiplicative interaction with smoking.
Northern Sweden [*90*]	Case-control	15 nonsmoker and 15 smoker case/control pairs	Construction characteristics	Estimated mean exposure significantly higher for smoking cases than controls; exposure not different for nonsmokers.
Sweden [*90*]	Case-control	11 nonsmoker and 12 smoker case/control pairs	Construction characteristics	Estimated mean exposures comparable for cases and controls regardless of smoking.
Northern Sweden [*91*]	Case-control	589 male cases, 582 deceased controls, 453 living controls	Residence type: wood or nonwood	RR not increased, with or without smoking adjustment. RR increased for those never employed in occupations not associated with lung cancer.
Stockholm, Sweden [*92*]	Case-control	292 female cases and 584 controls	Geology and living near ground level	RR = 2.2 (95% CI 1.2–4.0) for exposed vs. nonexposed. Exposure-response relationship not found.
Southern Sweden [*93*]	Case-control	177 cases and 677 controls	Residence type and geology, all homes; two-month measurement, some homes	Exposure associated with increased risk for rural, but not urban dwellers.
Stockholm, Sweden [*94*]	Case-control	210 female cases, and 209 population and 191 hospital controls	Two-week measurement and assumed values	RR = 1.8 (95% CI 1.2–2.9) comparing "high" and "intermediate" to low. RR highest for small cell cancer.
Maryland, U.S. [*95*]	Cohort	298 cases over a 12-year period	Housing characteristics	No associations of incidence rates with housing characteristics.
New Jersey, U.S. [*96*]	Cohort	752 persons who had resided in 45 homes contaminated by radium waste	Residence for at least one year in one of the homes	SMR[c] = 1.7 (95% CI 0.8–3.2) for lung cancer in white males. No excess for females.
New Jersey, U.S. [*97*]	Case-control	433 female cases and 402 controls	Year-long alpha-track measurements, some estimates	RR = 1.9 (95% CI 1.0–3.4) comparing ≥74 Bq/m^3 (≥2 pCi/L) to lower values.
Ontario, Canada [*98*]	Case-control	27 cases and 49 controls	Reconstructed exposures based on measurements	RR = 2.4 (95% CI 0.8–7.1) with smoking adjustment for exposed vs. nonexposed.
Shen yang, Republic of China [99]	Case-control	397 cases and 391 controls	Year-long alpha-track measurements	No association of lung cancer with radon exposure.

[a]Relative risk.
[b]Confidence interval.
[c]Standardized mortality ratio.

than many of the original studies (see Table 5), but extremely large studies are needed to address current questions concerning the risks of indoor radon [*101*]. Consequently, plans have been made to pool the data from the individual studies to obtain the most informative picture possible of the risks of indoor radon [*100*].

ANIMAL STUDIES

Animal studies on the respiratory effects of radon were initiated early in this century [*102*]. While the human evidence on the carcinogenicity of radon has been compelling, the animal studies have provided confirming data and enabled assessment of aspects of exposure, such as exposure rate and the presence of other agents, which cannot be readily addressed with epidemiological methods. The animal studies have also provided quantitative risk coefficients. Of the modern studies, the most important experiments were conducted at the Pacific Northwest Laboratory (PNL) and at the laboratory of the Compagnie Generale des Matieres Nucleaires (COGEMA) in France. Experiments during the 1950s at the University of Rochester addressed the dosimetry of radon and decay products in the respiratory tract.

TABLE 7—Summary of COGEMA studies with rats.[a]

Group Mean Exposure Jh m^{-3}, WLM	Exposure Rate, m Jh m^{-3} (WLM/week)	% Animals with Tumors	Mean Lifetime Risk Coefficient, 10^{-4}/m Jh m^{-3} (10^{-4}/WLM)
0.07–0.09 (20–25)	7.0–14.0 (2–4)	1.7	2.1 (7.5)
0.18 (50)	7.0–28.1 (2–8)	2.9	1.7 (5.8)
1.02 (290)	31.6 (9)	10	0.9 (3.3)
3.02 (860)	1298.3 (370)	20	0.8 (2.8)
5.16 (1470)	1298.3 (370)	25	0.5 (1.7)
6.32 (1800)	701.8 (200)	34	0.5 (1.9)
6.67 (1900)	1087.7 (310)	35	0.5 (1.8)
7.37 (2100)	771.9 (220)	43	0.6 (2.0)
9.82 (2800)	1087.7 (310)	41	0.4 (1.5)
10.53 (3000)	1298.3 (370)	43	0.4 (1.4)
15.79 (4500)	1298.3 (370)	73	0.5 (1.6)

[a]Abstracted from Table III-1 in Ref *13*.

Beginning in the 1960s, the COGEMA group conducted a series of experiments involving exposure of rats to radon decay products. The experiments demonstrated that lung cancer occurrence increased with exposure to radon decay products, even at mean cumulative exposures as low as 70 to 87.5 m Jh m^{-3} (20 to 25 WLM) (Table 7). Lung cancer incidence increased as the exposure rate decreased. Exposure to cigarette smoke after exposure to radon decay products resulted in synergism between the two agents, whereas antecedent cigarette smoke exposure did not. A variety of nonmalignant changes were observed in the airways and alveoli; extremely high exposure caused diffuse interstitial pneumonia, inflammatory changes in the lung's interstitial framework. The COGEMA investigators have recently reported errors in the exposure calculations for many of these experiments; replications are in progress [*103*].

The PNL studies have involved both dogs and rodents. The studies have had diverse objectives including assessment of exposure-response relations, of the effects of mixed exposures to radon decay products along with ore dust or diesel exhaust, of the effects of exposure rate, attachment fraction and equilibrium, and of the combined effects of smoking and radon decay products. These studies are comprehensively summarized elsewhere [*13,102*].

The PNL studies have confirmed that exposure to radon decay products alone causes lung cancer. Exposure-response relations were similar in the COGEMA and PNL studies (Fig. 3). In PNL studies with dogs, concomitant exposure to cigarette smoke and radon decay products reduced the incidence of lung tumors. The concomitant exposures to other agents did not affect tumor incidence. In rat experiments, lung cancer risk increased as the unattached fraction increased. As in the COGEMA studies of rats, nonmalignant changes were found in the airways and alveoli of exposed animals.

The COGEMA and PNL studies complement the epidemiological data. Their findings confirm that radon decay products cause lung cancer, although the cancers produced in animal models are not fully analogous to human lung cancer in location or histopathology. Risk coefficients derived from animal and human data are remarkably close [*102*].

RISK ASSESSMENT FOR LUNG CANCER

Introduction

Because only scant epidemiologic data on domestic exposure are available, the hazard posed by exposure to radon in indoor air has been primarily addressed with risk assessment procedures (Table 8). Information on the population distribution of exposure in dwellings is used in a risk-projection equation or "model" that describes the increment in the occurrence of lung cancer per unit exposure. Several nationwide data bases, including a national survey conducted by the

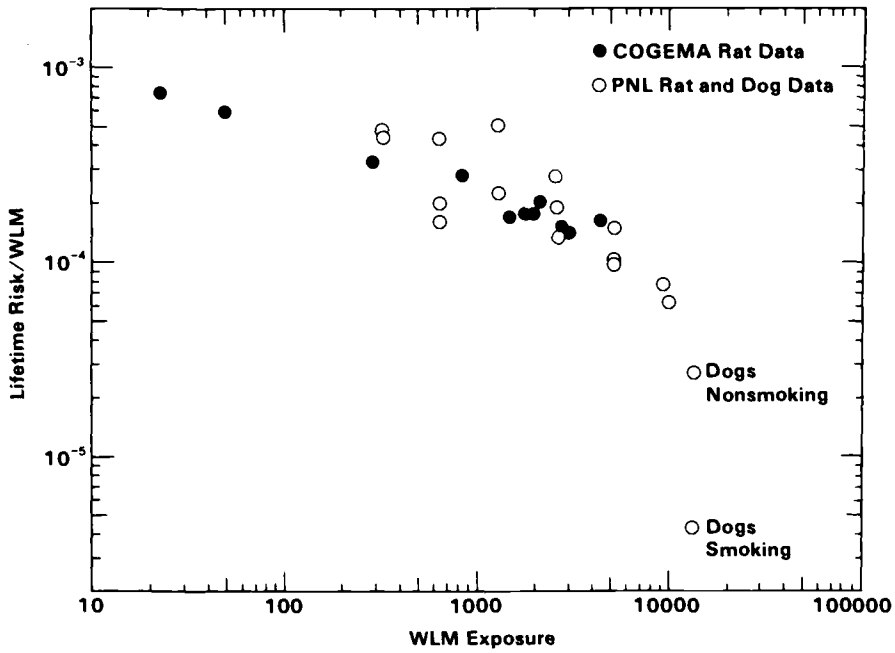

FIG. 3–Lifetime lung tumor risk coefficients for exposure to radon decay products in the COGEMA and PNL studies. Used with permission from Ref *102*.

TABLE 8—Recent risk projection models for radon and lung cancer.

Agency	Type of Model	Source of Risk Estimate
National Council on Radiation Protection and Measurements [*26*]	Attributable risk, time-dependent	Average risk coefficient from principal studies of miners
International Commission on Radiological Protection (ICRP) [*32*]	Constant relative risk	Adjusted risk coefficient from 3 studies of miners
Environmental Protection Agency [*104*]	Constant relative risk	Range of coefficients based on studies of miners
National Institute for Occupational Safety and Health [*105*]	Relative risk, time-dependent	Risk based on Colorado Plateau uranium miners
National Research Council, Biological Effects of Ionizing Radiation (BEIR) IV Committee [*13*]	Relative risk, time-dependent	Risk based on analysis of 4 studies of miners
Environmental Protection Agency [*106*]	Relative risk, time-dependent	Combines the ICRP and BEIR IV models

Environmental Protection Agency, provide an increasingly comprehensive picture of radon concentrations in U.S. homes.

The selection of risk coefficients to describe the excess lung cancer risk associated with exposure to radon decay products is problematic—the studies of miners included only males, much of the exposure of miners was at concentrations higher than generally occur in homes, and none of the miner populations have yet been followed throughout the full lifetime of the subjects. Furthermore, the various factors that affect the dosimetry of radon decay products may differ substantially in homes and in mines (see Table 1). As previously discussed, analyses based on dosimetric models of the respiratory tract suggest, however, that exposures to radon decay products in homes and in mines have approximately equivalent or even lower potency in causing lung cancer [*13,25*].

To accomplish the risk estimation, a mathematical model is used to project the occurrence of cases of lung cancer caused by exposure. These risk-projection models require assumptions concerning the temporal pattern of the occurrence of lung cancer after exposure and the effects of such potentially important cofactors as age at exposure, age at risk, and cigarette smoking. The two most widely applied are the relative risk and attributable risk models; the relative risk model assumes that the background risk is multiplied by the risk from radon decay products, whereas the attributable risk model assumes that the excess risk is additive to the background risk. Two models, those of the BEIR IV Committee [*13*] and the National Council on Radiation Protection and Measurements [*26*], describe the risk as varying with the time since exposure.

The manner in which exposure to radon decay products and cigarette smoking are assumed to interact strongly influences the results of risk estimation models for radon-associated lung cancer. If a multiplicative interaction is assumed, then the risk for smokers, already much greater than for nonsmokers, is multiplied by the risk from exposure to radon decay products. If an additive interaction is assumed, then the same excess risk is added to the background rates for smokers and for nonsmokers. The interaction between the two agents might plausibly take some form other than purely additive or purely multiplicative.

Principal Risk Assessment Models

Diverse risk projection models have been developed; Table 8 describes the most recent and widely used models (see Ref *13* for a review of earlier models). Each of these recent models estimates lung cancer risk on the basis of the epidemiological evidence from underground miners, but the biological assumptions underlying the models and their resulting risk projections differ substantially. Table 9 provides additional description of the most prominent risk models: those of the National Council for Radiation Protection and Measurements (NCRP) [*26*], the International Commission for Radiological Protection (ICRP) [*32*], and the BEIR IV Committee of the National Research Council [*13*].

The NCRP model generally projects the lowest excess risk because it is an additive model, and the radon-associated excess declines over time (Table 10). The ICRP model, a constant relative risk model, projects the highest risks. Exposures received by age 20 lead to a particularly large excess because of the three-fold higher risk assumed up to age 20 than at subsequent ages. In the BEIR IV model, the percent excess risk varies with both age and time since exposure.

When smokers and nonsmokers are considered separately, the substantial difference between assuming an additive or a multiplicative interaction between smoking and radon exposure is evident (Table 11). The additive NCRP model projects small increments for smokers in comparison with the multiplicative ICRP and BEIR IV models. Lifetime excess lung cancer risks for smokers estimated by the three models are markedly different. Land [*108*] has calculated the excess lung cancer risk per 100 000 smokers exposed to 3.5 m Jh m^{-3} (1 WLM) at age 15 as: NCRP—7.4, ICRP—278.7, BEIR IV—114.5; for exposure to 3.5 m Jh m^{-3} (1 WLM) at age 35, the corresponding projections are 15.5, 94.3, and 129.4.

These models have been used to project the lung cancer burden associated with exposure to indoor radon. For exposure at 0.7 m Jh m^{-3} (0.2 WLM/year) (approximately equivalent to residence in a home at 37 Bq m^{-3} (1 pCi/L)), the

TABLE 9—Features of selected risk projection models for radon and lung cancer.[a]

	NCRP	ICRP	BEIR IV
Form of model	Attributable risk	Relative risk	Relative risk
Time-dependent	Yes; risk declines exponentially after exposure	No	Yes; risk declines as time since exposure lengthens
Lag interval	5 years	10 years	5 years
Age at exposure		3-fold increased risk for exposures before age 20	No effect of age at exposure
Age at risk	Risk commences at age 40	Constant relative risk with age	Lower risks for ages 55 and older
Dosimetry adjustment	Increased risk for indoor exposure	Decreased risk for indoor exposure	No adjustment
Risk coefficient	2.9×10^{-6}/yr/m Jh m^{-3} (10×10^{-6}/year/WLM)	Excess relative risks: 0.5%/m Jh m^{-3} (1.9%/WLM) at ages 0–20 and 0.2%/m Jh m^{-3} (0.64%/WLM) for ages 21 and above	Excess relative risk of 0.7%/m Jh m^{-3} (2.5%/WLM) but modified by time since exposure

[a]From Ref *107*.

approximate average annual exposure, the NCRP model projects lifetime lung cancer risk as 0.18%; the NCRP report estimates that 9000 lung cancer deaths annually in the United States can be attributed to indoor radon. For an annual exposure of about 0.16 WLM, the ICRP model estimates lifetime risk of lung cancer as 0.42% for males and as 0.09% for females. The BEIR IV report describes risk for exposures received above background; for an exposure rate of 0.7 m Jh m^{-3} (0.20 WLM/year), the model projects attributable lifetime risks of 0.7% for males and 0.3% for females. Using the BEIR IV model, Lubin and Boice [*109*] have estimated that approximately 13 300 lung cancer deaths annually can be attributed to indoor radon exposure. Using EPA's current model, Puskin and Nelson of the EPA calculated that radon exposure in single-family homes may cause 20 000 lung cancer deaths annually in the United States [*106*]. The EPA's risk projections are undergoing revision.

Thus, in spite of the differing underlying assumptions and risk projections, each of the models indicates that radon must be considered as an important cause of lung cancer for the general population. Each model also demonstrates that unacceptable levels of risk are associated with higher levels of exposure. For example, in the BEIR IV model, exposure at 14.0 m Jh m^{-3} (4 WLM/year) above background leads to a tripling of the lifetime risk of lung cancer for males and females (Fig. 4) [*13*]; this level of exposure would be received from residing in a home with a concentration of about 925 Bq m^{-3} (25 pCi/L). As a basis for policy decisions, these risk projection models can be used to estimate the risks associated with levels of exposure that might be designated as guidelines or standards. The models can also be used to esti-

TABLE 10—Increments[a] in lung cancer risks for 3.5 m Jh m^{-3} (1 WLM)[b] projected by NCRP, ICRP, and BEIR IV models.

Increment at age	NCRP[a] Male	NCRP[a] Female	ICRP	BEIR IV
	EXPOSURE AT AGE 15 YEARS			
35 years	0 (%)	0 (%)	1.9(%)	1.5(%)
50 years	0.3	0.7	1.9	1.5
65 years	0.08	0.2	1.9	0.5
85 years	0.02	0.1	1.9	0.5
	EXPOSURE AT AGE 35 YEARS			
50 years	0.6	1.4	0.6	3.0
65 years	0.1	0.4	0.6	0.5
85 years	0.05	0.2	0.6	0.5

[a]The excess is additive for the NCRP model. The percent excess relative risk was calculated for illustration using sex-specific lung cancer mortality rates for the U.S., 1980–1984. The additive increments are 3.0×10^{-6}, 1.8×10^{-6}, and 0.9×10^{-6} for ages 50, 65, and 85 years, respectively, for exposure at age 15 years, and 6.0×10^{-6}, 3.5×10^{-6}, and 1.8×10^{-6}, respectively, for exposure at age 35 years. Based on Ref *107*.

[b]An annual exposure of 3.5 m Jh m^{-3} (1 WLM) would be received in a home with a concentration of 222 Bq/m^3 (6 pCi/L), assuming 70% occupancy.

TABLE 11—Lung cancer mortality rates per 100 000 projected for nonsmoking and smoking males at age 65 years by NCRP, ICRP, and BEIR IV models.[a]

	NCRP	ICRP	BEIR IV
Exposure to 35 m Jh m^{-3} (10 WLM) at age 15 years			
Nonsmoking	59.8	69.0	60.9
Smoking	698.3	828.8	731.3
Exposure to 35 m Jh m^{-3} (10 WLM) at age 35 years			
Nonsmoking	61.5	61.5	60.9
Smoking	700.0	738.3	731.3

[a]Background lung cancer mortality rates estimated as 58.0×10^{-5} for nonsmokers and 696.5×10^{-5} for smokers [*13*]. From Ref *107*.

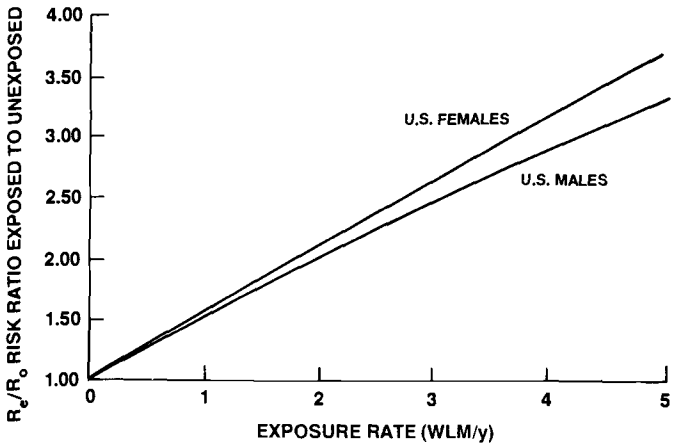

FIG. 4–Risk ratio of lung-cancer mortality for lifetime exposure to radon decay products at constant rates of annual exposure, as estimated by the BEIR IV model. Used with permission from Ref *13*.

mate the reduction in lung cancer occurrence that would follow reduction of exposure.

HEALTH EFFECTS OTHER THAN LUNG CANCER

The epidemiological studies of underground miners have provided information on health outcomes other than lung cancer including cancer at other sites, nonmalignant respiratory diseases, renal disease, and reproductive outcome. The plausibility of the findings on these disease endpoints must be judged in the context of the toxicology of radon and the relevant evidence from animal studies. Radon itself can be absorbed into the blood, but provides an insignificant dose to nonpulmonary tissues; radon decay products deliver their alpha energy to pulmonary tissues. Longer-lived decay products translocated from the lung could potentially cause adverse effects at distant sites.

With regard to cancer at sites other than the lung, several studies of underground miners have shown an excess of stomach cancer [*13*]. This finding is not consistent across all of the populations; furthermore, mining populations not exposed to radon also have excess stomach cancer. Two studies have indicated excess risk of skin cancer, but the numbers of cases were small, and the findings were not statistically significant [*110,111*]. Recently, Henshaw et al. [*112*] have proposed that the dose to the bone marrow cells from radon may be higher than projected by the usual dosimetric models. Descriptive data for the general population showed correlations between rates for several cancers, including childhood cancer, and indices of population exposure to radon.

Radon exposure is associated with alpha irradiation of the lung's airways and alveoli. Animals exposed to radon or decay products at high levels develop emphysema and interstitial fibrosis [*13*]. Thus, human radon exposure could plausibly be associated with chronic obstructive pulmonary disease, in which obstruction results from emphysema and airways changes, and with pulmonary fibrosis, an inflammatory disease of the lung's connective tissue. Underground miners, however, are also exposed to silica, diesel fumes, and other particles and gases that may also cause airflow obstruction or fibrosis. Consequently, epidemiological studies cannot readily separate the effects of radon exposure from the effects of other agents.

Early studies of Colorado Plateau uranium miners indicated pulmonary function abnormalities associated with estimates of exposure [*113,114*]. These studies were carried out with methods that would not be considered acceptable at present. In the longitudinal study of Colorado Plateau mines, mortality from nonmalignant respiratory diseases exclusive of tuberculosis, bronchitis, influenza, and pneumonia was increased five-fold across the interval 1950–1977 [*111*].

The most recent investigation of nonmalignant respiratory diseases was a survey conducted in the early 1980s of 192 long-term New Mexico uranium miners [*115*]. After controlling for cigarette smoking, the duration of underground uranium mining was associated with reduction of airflow. Review of chest X-rays showed abnormalities compatible with silicosis in 9% of the miners surveyed.

Excess mortality from nonmalignant renal disease was reported in one analysis of data from the Colorado Plateau study [*111*]. Mortality from chronic and unspecified nephritis was elevated over three-fold. This finding has not been replicated, and it cannot be readily interpreted as a direct consequence of exposure to radon decay products [*13*].

In a series of papers in the 1960s, Muller et al. described reproductive outcomes in children of Czechoslovakian uranium miners [*116–118*]. The secondary sex ratio (male to female births) was found to decline following underground employment. In the 1980s, descriptive data from New Mexico were considered to show adverse reproductive effects of the uranium mining industry, related to effects on the miners or to effects on those living near mines and mills [*119*]. Descriptive studies showed changes in the secondary sex ratio for counties in New Mexico with uranium mining, and high rates of congenital malformations and spontaneous abortions were reported for Shiprock Indian Health Service Hospital, which cares for Navajos in an area of uranium mining and milling [*13*]. A follow-up survey of reproductive outcome in the children of uranium miners did not show evidence of adverse effects [*120*].

CONCLUSIONS

Radon and its decay products are invariably present in indoor environments; most homes have concentrations of about 40 Bq m^{-3}, but concentrations in some homes are as high as those measured in uranium and other underground mines. Exposure to radon decay products has been shown to increase the mortality from lung cancer of underground miners working in mines with high concentrations. An increased risk of lung cancer must be presumed to result from indoor exposure as well, although the epidemiologic data on indoor radon exposure are still scant. Dosimetric analyses suggest that nearly comparable risks of lung cancer should be associated with radon exposure in mines and in homes. Risk assessments have been performed to evaluate the magnitude of the problem of lung cancer associated with indoor exposure to radon. Although the principal risk projection models

differ substantially, each shows that radon in indoor air poses a public health threat of substantial magnitude.

Determination of an acceptable concentration of radon with an acceptable associated level of lung cancer risk is problematic [*121*]. Substantial uncertainty remains concerning the risks of lower levels of exposure. Further follow-up of the cohorts of miners should provide additional information concerning the risks of lower levels of exposure. Numerous investigations of residential exposure to radon and lung cancer are in progress; difficult methodological problems may limit the precision with which these investigations characterize the risks of indoor radon.

With regard to cancers at sites other than the lung, the studies of miners do not provide consistent evidence of association with radon exposure. The provocative publication of Henshaw et al. [*112*] concerning leukemia and nonrespiratory cancers will undoubtedly spark additional research; however, the reported ecological associations cannot be regarded as causal. Underground uranium miners develop silicosis, as do other underground miners exposed to silica. In the study of New Mexico uranium miners [*115*], reduction of lung function level was associated with years of underground mining. It is uncertain, however, whether this effect represents a direct action of radon decay products or a consequence of exposure to other toxic agents in the air of a mine.

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4

Measurement Methods and Instrumentation

by Roy C. Fortmann[1]

THE RECOGNITION THAT INDOOR ENVIRONMENTS may be potentially important sites of exposure to elevated levels of the decay products of radon has resulted in an increased demand for measurements of radon and radon decay products indoors. Practical methods and instruments for the measurements of radon and radon decay products have been available since the 1950s as a result of the need to assess radiological exposures to radon-222 decay products in the uranium mining industry [*1–3*]. The methods developed for measurements in the uranium mining industry still form the basis for most methods used today in nonindustrial indoor environments. However, improvements have been made to the instrumentation, incorporating advanced technology to improve sensitivity and other performance parameters, ease of use, and size. There have been substantial advances in the development of passive sampling devices, which are relatively low cost and easy to use by homeowners and in large-scale screening surveys. Research in the area of radon decay product measurements has advanced significantly, resulting in improved understanding of their characteristics and development of improved measurement methods. Advances in radon and radon decay product measurement technology over the last 40 years have resulted in reliable, easy to use, portable, and relatively low-cost methods.

There are a number of methods available for measurement of radon that cover a wide range of cost and complexity. Probably the most widely used method at this time, in terms of the number of measurements performed, is the activated carbon monitor (also referred to as the charcoal canister). This device has been used extensively for screening measurements to determine if there are elevated radon levels in a building. The popularity of this device results from its low cost, ease of use, and short sampling period. A homeowner can easily use the device to perform a test over a two- to seven-day period. The cost to the homeowner is generally less than $20. These same features have also made it attractive for large-scale screening surveys. The monitor consists of a bed of activated carbon usually contained in a small metal canister. Sampling is initiated by removing the lid. Costs for the analytical instrumentation are also relatively low. As a result, a number of companies have begun providing analytical services for the monitor, making it widely available.

The next most popular monitor for radon measurements by homeowners and in large surveys is the alpha-track monitor. This monitor is also relatively low cost and easy to use. Its distinguishing feature is that it can be used for an integrated measurement of radon over periods as short as a couple weeks at high radon levels to periods as long as one year. This feature makes it attractive for follow-up measurements to obtain estimates of long-term radon concentrations in a building. Both the alpha-track and activated carbon monitors provide an integrated measurement result. A single average radon concentration is determined over the entire period during which the monitor was exposed.

More sophisticated monitoring instrumentation is available for measurement of radon by researchers and companies that provide radon measurement and mitigation services. Scintillation cells are used widely for measuring radon. They have been in use since the early 1950s. A scintillation cell consists of a container that has its interior surfaces lined with a phosphor. Alpha particles produced in the cell during the decay of radon strike the phosphor, generating light. A photomultiplier/scaler assembly is used for the measurement. The cells can be used to collect grab samples of air for analysis. Alternatively, the cells are used in a flow-through mode to make "continuous" measurements of radon. Continuous radon monitors are available from a number of manufacturers and are used extensively by the radon mitigation industry.

Another method available for measurement of radon is the pulse ion chamber. Pulse ion chambers had previously been used predominantly by researchers for measurements in the laboratory or in calibration programs because they are highly accurate. However, continuous monitors are now available that employ the pulse ion chamber technology.

A passive integrated radon measurement device based on electret technology is also commercially available. An electret is a piece of dielectric material exhibiting a quasi-permanent electrical charge. The reduction in charge is used for measurement of radon. Electrets can be used over exposure periods ranging from hours to months. The commercial device is marketed to radon measurement companies.

Radon decay products are not routinely measured for purposes of screening to assess health risks because the measurements are generally more costly and complex than measurements of radon. The technology for measuring radon decay products, however, is well established as a result of extensive development of instrumentation for use in the uranium industry. The simplest and most widely used method involves sampling on a filter and counting the gross alpha activity after a selected decay period. Extensive development work has been performed to optimize this method. Electrets have also been used for measurement of radon decay products.

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Radon progeny integrating sampling units (RPISUs) are commercially available. The units incorporate a sampling pump, filter, and detector. Newer units incorporate microcomputers and data acquistion systems to facilitate unattended sampling and data acquisition over selected time periods. Continuous working level (WL) meters are also available commercially. The units employ solid-state detectors and microcomputers. Integral algorithms are used to estimate working levels.

Measurement of unattached radon decay products has been the subject of extensive research during the last few years. The technology for these measurements includes diffusion batteries, electrostatic collectors, and screen samplers. Instrumentation development in this area is primarily being performed at the research level.

During recent years there has been renewed interest in soil-based measurements of radon levels. The objective of research in this area is to determine if a relationship between soil radon levels and transport into buildings can be established that would facilitate screening of building sites. A number of methods have been developed for measuring radon in soil gas and radon flux from the soil surface.

This chapter presents an overview of the methods currently in use for measurement of radon and radon decay products in nonindustrial indoor environments. The emphasis of the chapter is on measurement of airborne concentrations of radon-222. However, measurements of radon in water and measurements of radon flux are also briefly addressed.

The selection of methods and instruments for measurement of radon or radon decay products depends on many factors. Some of these factors are summarized in Table 1. The primary factor affecting selection of the measurement method is the study objective. Measurement of airborne concentrations of radon, for example, can be accomplished by a variety of methods, ranging from measurements with expensive continuous monitoring devices to collection with simple, low-cost passive samplers for subsequent laboratory analysis. Health effect measurements for lung dose calculations require use of substantially more sophisticated measurement devices. Similarly, selection of methods for measurement of source emanation rates requires consideration of different methods than for other measurement objectives. However, there may be substantial overlap in the use of various methods to meet different monitoring objectives.

Some factors, for example the media to be sampled, have an obvious impact on method selection. Other factors, such as operating specifications, may not impact selection so significantly as to preclude the use of a method, but must be addressed specifically with respect to sample analysis or data interpretation. For example, the effect of water vapor on the performance of charcoal canisters must be considered if the canisters are used for special tests under extreme conditions such as measuring radon in a sump or other moist environment. Factors such as instrument portability, ease of use, and cost per measurement are significant factors for screening large numbers of buildings.

Sampling duration and desired output may appear to be the same factors, since an instantaneous output is obtained by an instantaneous, or grab, sample. However, an integrated average can be obtained by (1) averaging the results of a series of grab samples, (2) integrating over a prescribed period during which continuous measurements were performed, or (3) by collecting a sample over a prescribed period and performing a single analysis of that sample. The latter category of measurement, for example, represents the output from measurements with charcoal canisters or alpha-track detectors. Therefore, various methods can be used to obtain a desired output, although not always in a cost-effective manner. A series of grab samples may be used to obtain an estimate of the annual indoor radon concentration, but this approach is more costly than exposure of a single alpha-track detector for a one-year period. Some methods can only be used for instantaneous measurements; a scintillation cell is filled over a short time period at a site and analyzed. Other methods, such as the charcoal canister monitor, have a minimum and maximum exposure duration and can only be used for an integrated measurement, generally over two to seven days. This measurement method, therefore, cannot provide instantaneous outputs, nor can the integration period be extended beyond approximately seven days, making it unsuitable for direct measurements of annual average radon concentrations.

Measurement methods for radon and radon decay products have historically been categorized on the basis of the sampling duration—instantaneous (grab sampling), continu-

TABLE 1—Factors affecting choice of measurement methods and instruments.

Factor	Example Variables
Measurement objectives	Measurement of concentrations
	Source identification
	Emanation rates
	Health effects measurements
Measurement parameter	Radon-220
	Attached radon decay products
	Unattached radon decay products
	Radon-222
Media	Air
	Water
	Soil
	Building materials
Scope of measurement program	Screening
	Followup
	Number of sites (buildings)
	Number of locations/sites
Desired output	Instantaneous
	Continuous
	Integrated average
Sampling method	Active
	Passive
Analysis method	On-site
	Laboratory
Operating specifications	Temperature
	Humidity
Performance specifications	Limit of detection
	Accuracy
	Precision
Sampling duration	Grab
	Short-term
	Long-term
Method/instrumentation requirements	Portability
	Power requirements
	Size
	Weight
	Ease of use
	Availability
	Cost

ous, or integrated. Instantaneous methods involve collection of a sample at a single point in time; the measurement result represents the concentration at the collection site at that "instant" in time. Continuous measurement methods involve repeated collection and analysis over a series of "instants" in time, allowing assessment of temporal variations of concentration. Integrated measurement methods involve collection of the sample over some prescribed duration of time. The single composite sample is analyzed to provide a single measurement value that represents the integrated average concentration during the duration of the measurement period. The use of instantaneous, continuous, and integrated methods to describe radon and radon decay product measurements is a convenient and logical categorization that is maintained in the following presentation.

PRINCIPLES OF RADIATION MEASUREMENTS

The occurrence of radon-219, radon-220, and radon-222 in nature as members of the primordial actinium, thorium, and uranium series was introduced previously. The discussion included physical considerations that affect the abundance of radon in the environment and the occurrence of radon decay products indoors. The following discussion highlights the properties of radon and radon decay products that impact their measurement. Emphasis in this discussion is on the properties of radon-222 and its decay products. The term "radon" as used in the following discussion represents radon-222 unless specifically stated otherwise.

Methods for measuring radon and its decay products are all based on detection of emissions from radioactive decay, either by measurement of alpha particles emitted, detection of gamma emissions, or less commonly, by measurement of beta emissions.

The alpha particle emitted by the decay of radon or its decay products can be detected when a current (pulse) is produced in an ionization chamber. The ionization chamber operates on the principle of ionizing gas inside the detector and measurement of the current flow induced by collection of air ions formed during radioactive decay.

Alpha particles can also be detected by the scintillations produced when striking a suitable phosphor, such as silver-activated zinc sulfide [ZnS(Ag)]. In this case, the striking of the phosphor by alpha particles produces light that can be converted to electric current and multiplied to measurable levels by a photomultiplier tube to produce electrical pulses that can be counted by a discriminator/scaler. Scintillation methods are in common and widespread use for radon measurements.

Radon decay product concentrations are determined by counting the alpha, beta, or gamma activities. Gross activities may be measured with simple scintillators, or activities attributable to individual decay products can be determined by spectroscopic methods that rely on differences in the energies and half-lives of the decay products.

Energy from gamma rays is utilized for measurements with scintillometers that operate on the principle of absorbing energy from the gamma rays in fluorescent material made from sodium iodide in a crystal form. Upon absorbing the energy, visible or ultraviolet light is emitted from the crystal and measured.

Instrumentation that utilizes these basic principles of measurements are further described in the following sections.

METHODS AND INSTRUMENTATION FOR MEASUREMENT OF AIRBORNE RADON

There are a number of methods available for measurement of radon in air. Many of these methods are established, well-documented methods with a proven history of field performance. The methods are based on measurement principles applied in the 1950s. Recent advances in these measurement methods consist of improved performance (e.g., sensitivity) and greater convenience in their use by application of improved electronics for signal processing and data acquisition. Currently available measurement methods, presented below in the categories of grab sampling, continuous monitors, and integrated sampling methods, are summarized in Table 2.

Grab Sampling

Scintillation Cells

One of the most widely used and accepted methods for measurement of radon both in the laboratory and the field is the scintillation cell. Scintillation cells, also referred to as Lucas cells in recognition of development work by H. F. Lucas [*4*], have been in use since the 1950s [*5,6*]. Scintillation cells (flasks) consist of a plastic, metal, or glass container that has the interior surfaces coated with a thin layer of silver-activated zinc sulfide phosphor. Either one or two sampling ports with valves are fitted to the flask to permit filling with the test atmosphere. Scintillation cells currently in use are predominantly right circular cylinders that range in volume from 0.09 to 2.0 L. Costs for commercial cells range from $50 for plastic cells to $400 for glass or metal. With proper care, the cells can be used for several years.

Some researchers use Tedlar or Mylar bags for sample collection and subsequent transfer to scintillation cells in the laboratory. This method provides acceptable results. However, plastic scintillation cells are low in cost. Their use for direct collection of the sample is more attractive since the potential for contamination during sample transfer is minimized.

For field use, the cells can be evacuated in the laboratory, then sent to the sampling site where they are filled by opening the valve. Alternatively, a small pump can be used. The inlet to the cell normally is fitted with a filter to remove radon decay products during filling. The sampling time is recorded, then the cell is sent back to the laboratory or analyzed on-site.

Measurement of radon with the scintillation cell is accomplished with a photomultiplier tube optically coupled to the transparent window of the cell. Alpha particles produced in the cell strike the phosphor, generating light that is converted to an electric current by the photomultiplier tube. For the analysis, a delay of at least 3 h allows for the in-growth to radioactive equilibrium of the radon decay products, Po-218 and Po-214. The scintillations from the radon/radon decay products are then counted with the photomultiplier tube/scaler assembly.

TABLE 2—Measurement methods for airborne radon.

Sampling Category	Method/Instrument	Measurement Principle	Notes	References
Grab	Scintillation cell	Alpha scintillation counting	Low cost field use	*4,5,6*
Grab/continuous	Ionization chamber	Current (pulse) counting	Suitable for field use	*9*
Grab	Liquid scintillator	Liquid scintillation counting	Samples collected in gas sampling bags are bubbled through scintillation solution	*11*
Continuous	Flow-through scintillation cell monitor	Alpha scintillation counting	Radon is passed through the cell continuously	*12,13,14*
Continuous	Passive diffusion electrostatic monitor	Po-218 collected electrostatically on scintillation detector	—	*18*
Continuous	Diffusion radon only monitor	Radon decay products removed by electret; alpha scintillation counting	—	*20*
Integrated	Alpha track detector	Alpha particles damage sensitive film on which "tracks" can be counted	Most commonly used for 1 to 12 month durations; passive sampler	*22,23,24, 25,26*
Integrated	Activated carbon monitor	Radon adsorption on activated carbon; analysis by gamma counting	Short-term (2 to 7-day) measurement device; passive sampler	*31,32,33*
Integrated	Electrets	Radon diffuses into a chamber where ionization occurs; ions are collected by a charged electret; change in electret charge measured	Both short-term and long-term electrets available	*48,49*

In work of Lucas [*4*] with a 0.1-L cell, the detection efficiency was 75 to 80%, the background count rate was 0.08 counts per minute (cpm), and detection efficiency was 143 cpm/Bq (5 cpm/pCi). The lower limit of detection (LLD) was 1 Bq/m^3 (0.03 pCi/L).

Measurement errors with scintillation cells are related to malfunction of the counting system, improper calibration, and leaks in the valves or joints during transport and storage of the cells. Measurement error (accuracy) and precision have been determined on a semiannual basis by the U.S. Department of Energy's Environmental Measurements Laboratory (DOE-EML) through their Radon Intercomparison Exercise. Results of the Radon Intercomparison Exercise conducted in April 1991 are depicted in Fig. 1. For the 34 participants, the ratio of the participant (facility) measured radon concentration to the EML reference mean concentration ranged from 0.66 ± 0.04 to 1.58 ± 0.05. For all but three facilities, the ratio was between 0.89 and 1.14. As shown in the figure, the precision of the measurement with four cells was better than ±10% for most facilities. DOE-EML has found that errors during this exercise are generally attributable to leakage of the cells or calculational errors [*7*].

Participants in the DOE-EML intercomparison exercises include government agency laboratories, university research groups, instrument manufacturers, and private research and testing companies. Many of the participants have been actively involved in radon research and measurements for many years, which may explain the high levels of accuracy and precision reported in this exercise. An analysis of the results of Round 5 of the U.S. Environmental Protection Agency (EPA) Radon Measurement Proficiency (RMP) program, presented in a report by the General Accounting Office (GAO), showed a large variation in the accuracy of measurements with grab sampling methods [*8*]. They reported that the average error for 66 tests was 18% and that the range of company error was 3 to 75%. The authors of the report suggested that the reason for the large variations observed in the RMP program may be related to inexperience with the instrumentation.

Ionization Chambers

Pulse-type ionization chambers [*9,10*] have been in use for many years for the measurement of radon in laboratory settings. An ionization chamber consists of a cylinder with an electric field established between two electrodes. When filled with radon-containing air, radiation from the decay of radon and radon decay products ionizes the air, causing a current to flow between the electrodes. The current is measured with a solid-state electrometer. Lower limits of detection (LLD) typically are approximately 4 Bq/m^3 (0.1 pCi/L), although lower LLDs have been reported [*10*].

Solvent Extraction Method

An alternative to the scintillation cell that employs a chilled liquid scintillator for measurement of radon in air has also been reported [*11*]. In this method, field samples of air, collected in collapsible gas sampling bags or other suitable containers, are passed through 20 mL of a hexane-based liquid scintillation solution to extract the radon, which is highly soluble in cold organic solvents. The extraction system, which consists of a dessicator section, an impinger with a fritted disk, and a vacuum pump, must be maintained at −78°C in a dry ice/acetone bath. After a 3-h period for radon decay product in-growth, the samples are counted with a standard liquid scintillation system. Liquid scintillators have a relatively high background compared to ZnS:Ag scintillation cells, but Prichard [*11*] addressed this problem by long background counts to determine a standard deviation

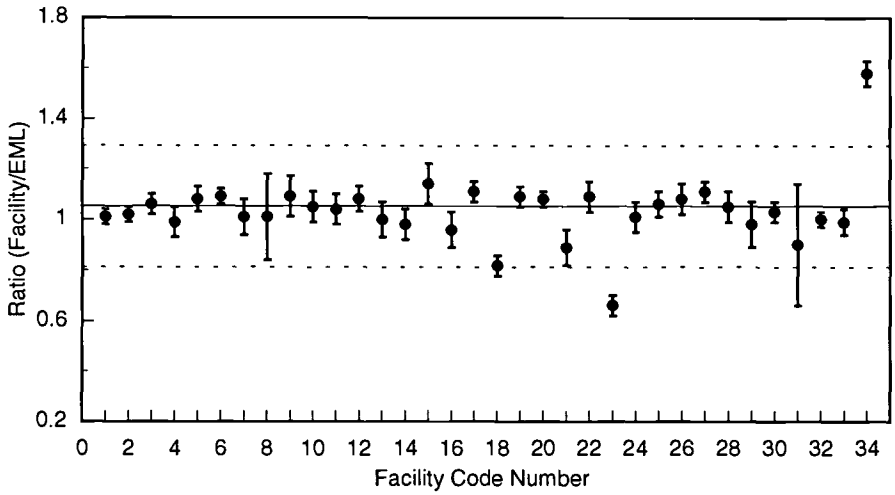

FIG. 1–Results of the April 1991, DOE-EML radon measurement intercomparison exercise (ratio of reported mean concentration to mean value obtained at EML by pulse ionization chamber measurements).

(S.D.) of the background that was considerably less than the S.D. of the samples. For a 10-L air sample and a 100-min count, the LLD was 1.5 Bq/m^3.

The liquid scintillation method has advantages similar to the scintillation cells with respect to collection of field samples for subsequent analysis in the laboratory. Samples can be collected and extracted in the field and sent back to the laboratory. The need for a dry ice/acetone bath is an obvious disadvantage of the method for field use. The liquid scintillation counting system is expensive relative to the counting system required for ZnS:Ag scintillation cells. This method may be an attractive alternative if the counting system is already available. The need to dispose of large quantities of liquid scintillation solutions is a limitation of the method that adds to the cost of the method in terms of both financial resources and its environmental impact.

Continuous Monitoring Methods

Continuous, or repeated short-term semi-continuous, measurements are useful in situations where radon concentrations change significantly or vary rapidly over time. Continuous measurements are most widely used for research applications. For example, continuous measurements are valuable in studies of the effects of various impact parameters, such as ventilation rate or pressure differentials, on indoor radon concentrations.

Continuous (Flow-Through) Scintillation Cells

Scintillation cells (ZnS:Ag) can be fitted with a filtered inlet and an air pump for use in a flow-through mode to make continuous measurements of radon [*12–14*]. The cell is coupled to a photomultiplier tube with associated electronics to count the scintillations from the cell on a continuous basis. The radon decay products (Po-218 and Po-214) deposit on the cell walls during flow-through. Since they have an effective half-life of approximately 30 min, a correction must be made to account for the activity of previously deposited radon decay products. A set of equations to calculate the average radon concentrations for time periods of 30 min or less has been developed by Thomas and Countess [*13*]. The equations account for the relative contribution of deposited radon decay products in the current interval and from previous measurement intervals. Cell volume, flowrate, and measurement interval are constants needed for the calculation. Calibration methods for the flow-through system have been described by Thomas and Countess [*13*] and Busigin et al. [*15*].

The lower limit of detection for flow-through systems using a 30-min counting period will range from 3.7 to 37 Bq/m^3 (0.1 to 1 pCi/L) [*16,17*]. Nazaroff et al. [*14*], using the standard propagation of errors formula, estimated a standard deviation of 0.74 Bq/m^3 for radon concentrations below 111 Bq/m^3 (3 pCi/L) using a 180-min counting period for a 0.17-L cell.

Performance of continuous radon monitors was reported to be highly variable in Round 5 of the RMP program. According to the analysis reported by the GAO [*8*], the average error for 99 tests was 25% and the company error ranged from 0 to 658%. The reason for this large range of error may be due to participation in the RMP by companies with relatively limited experience in the use and calibration of continuous radon monitors. Commercial monitors based on flow-through scintillation cells are available in a price range of $400 to $5000.

Pulse Ion Chamber Monitors

Pulse ion chamber technology has also been utilized for continuous measurement of radon. Until recently, ionization chambers were not widely used for field measurements. They have been most commonly used for laboratory applications and in calibration programs because they are highly accurate. However, continuous radon monitors that employ pulsed ion chamber alpha detectors are now commercially available. One manufacturer's monitor, for example, combines a phase-shifted, negative feed-back electrometer and an ultra-low capacitance open grid chamber design. Air is delivered to an internal detector by a pump or by passive diffusion. Radon decay products are electrostatically removed and prevented from entering the internal pulsed ion sensing volume. As a radon atom decays within the sensing volume of the chamber, a "burst" of ions is produced and is converted to

electrical pulses in the electrometer. These pulses are counted.

Commercial instruments are portable, have low power requirements, and are relatively low cost (approximately $2000). Instruments are available with a sensitivity of 0.008 cpm per Bq/m^3 and a dynamic range of 18 to 18 000 Bq/m^3. One manufacturer has reported accuracy of +3.5% and precision of ±4.1% at a concentration of 292 Bq/m^3 (7.9 pCi/L) in chamber tests.

Diffusion-Electrostatic Radon Monitor

Diffusion-electrostatic radon monitors [*18,19*] are diffusion-based devices for which detection of radon is based on the electrostatic collection of Po-218. Radon, but not thoron or radon decay products, diffuses through a foam membrane into a 1-L or larger hemisphere. Positive charged Po-218, formed from the decay of radon, is drawn electrostatically to a layer of aluminized Mylar covering a phosphor. Alpha particles from the decays of Po-218 and Po-214 are counted by a scintillation detection system.

The lower limit of detection for a commercially available model is 18 Bq/m^3 (0.5 pCi/L) for a 10-min counting period. The device is affected by humidity, possibly as a result of Po-218 neutralization. To overcome humidity problems, constant flow through the chamber with a pump and an in-line dessicant column on the inlet can be used. The humidity effect should be less than 10% in the 30 to 50% relative humidity range.

Diffusion Radon Only Monitor

This monitor uses electrostatic collection with an electret in a scintillation flask to prevent detection of radon decay products; only scintillations from the radioactive decay of radon are counted [*20*]. The LLD is approximately 3.7 Bq/m^3 for a 60-min counting interval. The reported measurement error is ±23% at 40 Bq/m^3. The instrument is not commercially available.

Integrated Measurement Methods

Measuring radon in thousands of structures to assess health risks due to radon exposure has resulted in widespread use of simple passive sampling devices for integrated measurements. These devices are low cost, small, and easy to use, making them ideal for use by homeowners. Because they can be deployed by building occupants, transferred by mail, and analyzed at central laboratories, such devices also facilitate performance of large-scale surveys at relatively low cost. When used properly, the passive samplers generally provide reliable results. Extensive research has documented the performance of these simple measurement methods. The limitations of these devices are now well-recognized and adequately documented. This section provides descriptions of the available methods, their advantages, and their limitations.

Alpha-Track Detectors

One of the most widely used integrating samplers for both screening and follow-up measurements is the alpha-track detector. The device is small, low cost, and easy to use. Alpha-track detectors (ATDs) are generally used as long-term integrating samplers for measurements over periods ranging from one to twelve months. But, ATDs can be used for measurements over even shorter periods if the radon concentration is high.

Geiger, in 1967, reported on a badge employing cellulose nitrate film for measuring radon [*21*]. The badge, termed a solid state nuclear track detector, allowed radon to diffuse into a central cavity where the film was contained. During decay, alpha particles from radon and its decay products impacted the film, causing "alpha tracks." The film was subsequently etched with an alkali solution to enlarge the tracks, which were then counted with optical microscopy. By use of standardized exposures to radon, the detectors could be calibrated; the number of tracks was shown to be directly proportional to the radon concentration.

The ATD method was further developed during the 1970s and 1980s by several investigators [*22–26*]. However, the basic measurement principle and detector geometry are still used in all commercial ATDs. Major developments to improve performance have been the use of allyl diglycol carbonate (CR-39) film, electrically conducting plastic containers, and improved etching methods.

ATDs consist of a small container, generally constructed of plastic, that contains a piece of film. Electrically conductive plastic is used by some manufacturers to minimize charge effects from predominantly positively charged radon daughter products. Detector design varies; for example, one manufacturer uses a hemispherical cup that purportedly provides more uniform distribution of tracks on the film. All ATDs include a filter that allows radon to diffuse into the detector but prevents entry of dust and radon decay products.

Performance of ATDs is strongly affected by the quality of the film. Cellulose nitrate and polycarbonate can be used, but CR-39 is currently the most widely used film. Dosimetry grade CR-39 material is used to minimize background tracks (due to imperfections in the material) and background variation. Etching methods may affect the precision and accuracy of the method. According to one manufacturer's literature, electrochemical etching improves precision because it produces larger tracks that are easier to distinguish from background tracks (imperfections) in the film.

To determine radon concentration, ATDs are calibrated by exposure for fixed time periods to known concentrations of radon in environmental chambers. Calibration factors are derived by dividing track density by the radon exposure (concentration × time) for each lot of film. In early studies, the sensitivity of one type of detector was reported by Alter and Fleischer [*25*] to be 0.0010 tracks per mm^2 per Bq/m^3. Background track densities of 0.3 to 0.8 tracks per mm^2 have been reported. For a measurement of 17.25 mm^2, the sensitivity was reported to be 7.4 Bq/m^3 for a one-month exposure [*25*].

The performance of ATDs has been examined by a number of researchers. The statistical accuracy has been reported [*26*] to range from 10% for a one-year exposure at 1110 Bq/m^3 to 42% for a three-month exposure to 18.5 Bq/m^3 (0.5 pCi/L), as shown in Table 3. Exposures of ATDs in controlled environment chambers have shown that they occasionally perform to theoretical expectations, but more frequently show much greater variability than predicted. Exposure results reported by Pearson [*27*], for example, showed that the ratio of the mean radon concentration (of six to eight detectors) re-

TABLE 3—Statistical accuracy of ATDs.

Radon Concentration		Accuracy	
Bq/m³	pCi/L	3 month	1 year
18.5	0.5	42%	21%
37	1.0	29%	17%
111	3.0	20%	17%
370	10.0	19%	10%
1110	30.0	11%	10%

ported versus the actual concentration ranged from 0.67 to 1.27 (Table 4). Precision, expressed as the coefficient of variation, ranged from 13 to 65% and was generally higher than expected based on counting statistics only. Oswald [*28*], at the same conference, reported biases of 0.95 and 0.91 for two types of ATDs and standard deviations of 14.2 and 15.6 tested in Round 4 of the RMP program. These results were based on sample sizes of approximately 70 and 200 for the two types of detectors. It should be noted that in tests reported by Pearson [*27*], the ratio of reported to actual concentrations ranged from less than 0.2 to approximately 3.5 for the newer type of detector (Fig. 2).

Recently a new alpha-track detector has been made available by a major foreign manufacturer. The detector uses LR115 film as a bare nuclear track detector. Reported sensitivity is 10 Bq/m³ for a 30-day exposure. Previous studies have shown that bare nuclear track detectors have poor precision and that calibration for radon measurements is impacted significantly by variations in equilibrium factors. However, the literature for the new detector suggests that it resists radioactive particles deposited on the surface. Performance studies of this new detector have not been reported in U.S. scientific literature.

Activated Carbon Monitors

Activated carbon monitors (ACMs) have gained widespread popularity as a low-cost, easy-to-use method for performing short-term screening measurements of radon indoors. The low cost of ACMs for the user is a result of the relatively simple sampling and analysis methods associated with the device. The sampler can be constructed at a cost of a few dollars for materials and labor. Sample collection is simple; the sampler is opened by removing the lid or a foil cover. Radon diffuses into the charcoal bed passively by molecular diffusion. Following sample collection, the device is returned to a laboratory where gamma rays emitted by the radon decay products are quantified by simple gamma detection methods.

Charcoal was shown to be useful in a method to adsorb radon by Rutherford [*29*] in 1900. He suggested that charcoal be used for passive adsorption to measure radon in air and emanation rates from soil. Pensko [*30*] in 1983 examined the factors that influence performance of charcoal for radon collection, which included the weight of the charcoal, exposure duration, water adsorption, and gamma spectrometry measurement accuracy. He suggested that a canister containing 150 g of charcoal could achieve a sensitivity of 1 Bq/m³ with an error of ±50%.

In 1984, George [*31*] reported test results on the performance of an ACM design that has been the basis for the open face ACMs now in widespread use. In his original work, George used an M11 gas mask canister that contained approximately 150 g of activated carbon. For this canister, George reported an LLD of 11 Bq/m³ (0.3 pCi/L) for a three-day exposure period. He suggested that measurement accuracy should be ±20% using empirically derived calibration factors with corrections for water adsorption and that differences between measurements with paired canisters should be less than 10%.

George [*31*] also reported that tests with a 5-cm-high cylindrical container with a cross-sectional area of 80 cm² had a higher adsorption capacity than the M11 canister. The canister is a cylindrical metal container 5 cm high and 10 cm (4 in.) in diameter. A charcoal bed 4.5 cm in depth is retained in the canister by a metal screen secured with a retaining ring. The lid on the canister is removed to initiate sample collection. The term "open face" is used for this ACM because the lid is removed to expose the entire top surface of the charcoal bed, allowing radon to diffuse into it at a rate dependent on differences in radon concentration between the charcoal bed and the atmosphere. Alternatively, diffusion can be restricted with a diffusion barrier as described in a following paragraph. Open face canisters have been used for exposure periods of 24 to 120 h, although EPA recommends a duration of 48 h to minimize water vapor effects.

TABLE 4—Results of chamber exposures of ATDs.

Monitor Type & Batch	No. of Detectors	Reported Radon Mean	Coefficient of Variation	
		Actual Radon	Observed	Expected[a]
A-1	59	0.75	51%	23%
A-2	42	1.32	59%	16%
A-3	55	0.96	25%	17%
A-4	18	0.67	47%	20%
B-1	50	0.81	31%	11%
B-2	33	0.96	36%	10%
B-3	50	0.91	52%	9%
C-1	51	0.95	65%	21%
C-2	32	1.27	40%	20%
C-3	29	1.07	18%	17%
C-4	10	0.92	17%	17%
C-5	24	0.98	13%	15%
All C	143	1.04	45%	19%
D-all batches	46	1.15	36%	24%

[a]"Expected" coefficient of variation based on the counting statistics of the net number of tracks from a 120 pCi-day/L exposure.

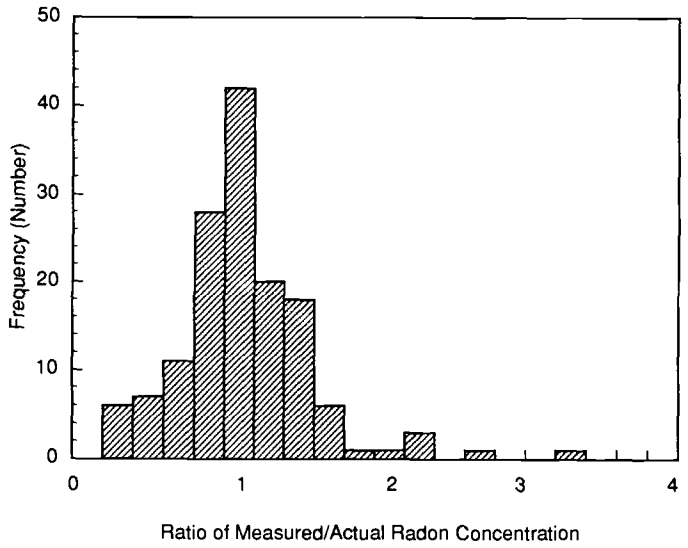

FIG. 2–Frequency distribution of measurement results for alpha-track detectors exposed in a chamber (adapted from Ref 27).

Variations on the 10-cm-diameter open face ACM exist. One variation uses a canister of smaller size, 7.5 cm (3-in.) diameter. Advantages of the smaller canister are slightly lower materials costs and lower costs for mailing. The primary limitation of the smaller canister is less adsorptive capacity and a resultant requirement for longer analysis (counting) periods. A second variation on the open face ACM is a sampler that consists of a paper container, often described as an oversized tea bag, that contains charcoal. The sampler is suspended for radon collection; diffusion occurs through both sides of the bag. The device has been in use for many years and has exhibited performance comparable to other ACMs. It has exhibited acceptable performance in all rounds of the RMP program.

As noted above, the rate of diffusion of radon into the canister can be controlled by use of a permeable membrane. A practical, low-cost passive activated carbon sampler that incorporates a diffusion barrier was developed by Cohen et al. [*32,33*]. Their sampler consists of a 2.5-cm-high, 7.6-cm-diameter metal can containing 25 g of charcoal. A diffusion barrier consisting of nylon screen is glued over a 1.9-cm hole in the lid of the can. A dessicant bag is taped to the screen to remove water. The diffusion barrier charcoal absorber (DBCA) has two major advantages. Because of the dessicant, water vapor adsorption effects and time integration problems are minimized. (Both problems are discussed below.) The major disadvantage is that the restricted sampling rate results in lower count rates. The combined low sampling rate and small size requires counting up to four times longer than for other ACMs.

Analysis of ACMs and DBCAs is accomplished by a gamma ray detector. Typically a NaI(Tl) detector with a 8 by 8 cm crystal is coupled with a multichannel pulse-height analyzer. The total radioactivity from the gamma rays of the radon-decay products is determined for selected energy ranges. George [*31*] measured adsorption peaks of Pb-214 (242, 294, and 352 keV) and of Bi-214 (609 keV). Cohen and Nason [*33*] measured activity in the 220 to 390 keV and 550 to 680 keV ranges. Rector et al. [*34*] used a single channel to determine total activity over the entire energy range encompassing the peaks for Pb-214 and Bi-214. Counting times are typically 10 to 30 min per sample.

Liquid scintillation methods have been proposed as an alternative for analysis of activated carbon samples. Prichard and Marien [*35*] described a method that involved extraction of 10-g samples of carbon with toluene, addition of fluor solution, and counting in an alpha scintillation cell. The accuracy and precision of the analysis method were good, but as the authors noted, the method involves considerable sampler manipulation. Schroeder et al. [*36*] recently reported a simpler liquid scintillation method. They used a commercial dessicant can (2 g) and activated carbon can (2 g) in a vial for sampling. In the laboratory, 15 mL of a toluene-fluor solution is added to the carbon. Once chemical and radiological equilibrium are reached, liquid scintillation counting is performed. The method gave reliable results with sensitivity of 675 cpm per Bq/L and has passed the RMP test program. Both methods can be used to obtain reliable radon measurements. The sample materials are low in cost, but analysis costs are substantially higher than the gamma-counting methods used for activated carbon monitors due to labor costs associated with sample handling, reagent costs, and the high cost of the liquid scintillation counters. Another major disadvantage of the method is that large quantities of radioactive fluor solutions are generated which must be disposed of.

Because ACMs and DBCAs are so widely used, it is appropriate to discuss the factors that affect their performance. An understanding of these factors and the limitations of this measurement method is essential to decisions regarding the utility and application of resultant measurement data to meet specific measurement objectives.

The concentration of radon measured with an ACM or DBCA is calculated as follows:

$$Rn = \frac{\text{Net cpm}}{(T_S)(E)(CF)(DF)} \quad (1)$$

where

Rn = radon concentration in pCi/L,
Net cpm = gross cpm minus background cpm (counts per minute),
T_S = canister exposure time (minutes),
E = detector efficiency (cpm/pCi),
CF = calibration factor (empirically derived), and
DF = delay factor (minutes) from the midpoint of exposure to the start of counting.

In practice, the calibration factor used is related to the exposure period and an adjustment factor for water vapor adsorption. Detector efficiency (E) and calibration factor (CF) may be combined in a single, empirically derived, calibration factor for some analytical systems.

Factors that affect canister performance include the following:

1. Temperature.
2. Relative humidity.
3. Time integration error.

4. Type of carbon and canister geometry.
5. Statistical counting error.
6. Calibration error.

The effect of temperature on canister performance has not been addressed extensively, although it is well established that temperature affects adsorption rates of gases onto carbon. George [*31*] reported no discernible differences in response of the M11 canister in tests over a temperature range from 18 to 27°C. But Ronca-Battista and Gray [*37*] observed a significant effect of temperature on canister performance. Measured concentrations differed from actual radon concentrations by +7% at 10°C, −4% at 16°C, and −21% at 27°C during exposures at 50% relative humidity (RH). At 80% RH, differences were +20, +1, and −23% for exposures at 10, 16, and 27°C, respectively. These results have practical implications for indoor measurements, particularly in basements where lower temperatures may be encountered and for surveys which compare seasonal differences in concentrations if the measurements are performed at temperatures outside the range used to determine calibration factors for the monitors.

The effect of relative humidity on canister performance has been studied extensively since it is recognized that water vapor competes with radon for adsorption sites in the carbon bed; as humidity increases, radon collection efficiency decreases. George [*31*] proposed that calibration curves be developed for open face ACMs over an RH range and that water weight gain be used to determine the appropriate *CF*. These procedures are used routinely. EPA uses an adjustment factor to correct the *CF* based on weight gain by the activated carbon during exposure [*38*]. For a 48 h duration sample, the adjustment factors would be approximately 0.105, 0.096, and 0.075 L/min for RHs of 20, 50, and 80%, respectively. Adjustment factors, however, will be specific to the activated carbon monitor used. Controlled tests must be performed to determine the factors appropriate for use with different types of monitors.

One advantage of the DBCA is that its design minimizes water vapor adsorption effects. Cohen found that the average humidity correction factor for the DBCA was 7.7% per gram of water weight gain [*39*]. Weight gain by the DBCA was reported to range from less than 0.4 to approximately 2.1 g and was related to the month of sampling. Cohen, therefore, used a humidity correction factor dependent on the month of sampling rather than on an actual measurement of water weight gain, which he believed gave results correct to a 3.3% standard deviation. This procedure is based on results from a fairly sizable data base, but it may be biased if most samples are from the Northeastern and Midwestern geographic regions. The error associated with this correction procedure may be larger for some geographic areas because of differences in relative humidity.

Adsorption of radon is a reversible process; desorption of radon from the activated carbon occurs continually at a rate dependent on differences in concentration between the carbon bed and the atmosphere. One of the advantages of the DBCA is that its time integration constant is three to five days [*39*] compared to 14 to 16 h for open face canisters [*40*]. As a result, the error associated with measurements under extreme variations in radon concentration should be lower for the DBCA than the ACM. This was confirmed both by mathematical models and measurements conducted by Lee and Sextro [*41*]. Canisters were exposed in their tests to time-varying concentrations in two rooms with initial concentrations of 7400 or 1110 Bq/m^3. Measurement errors as high as −90% were observed for open face canisters when they were exposed at high concentrations for 58 h followed by 58 h at the low concentration. Under the same protocol, the error with the DBCA was −12%, indicating that the DBCAs do integrate better than the open face canisters. Similar measurement errors with ACMs were reported by Ronca-Battista and Gray [*37*]. Average radon concentrations were underestimated by 75% over a four-day exposure to radon concentrations that were varied by a ratio of 10:1. With a two-day exposure there was a 54% underestimate.

The importance of deriving calibration factors specific to the canister and activated carbon being used has been demonstrated by George [*42*]. He measured radon adsorption for different types of carbon and canisters over a four-day exposure to 1295 Bq/m^3 (35 pCi/L) in a chamber. Results of these tests are depicted in Fig. 3. These tests showed that curves for radon adsorption were dramatically different for different types of ACMs. George also reported that collection efficiency was good for most detectors over a three- to four-day period, except for two types of detectors which had substantially reduced collection efficiency after two days.

Performance of activated carbon monitors has been evaluated in a number of studies. Most of these studies have involved a limited number of samplers or participants. By far the most comprehensive testing program is the U.S. EPA RMP program. In Round 5, 256 tests were performed. The average error was 19%, and the company error ranged from 1 to 133% [*8*]. White et al. [*43*] reported that their analysis of the RMP results from 1987 and 1988 showed that for most methods the median bias was between −10 and +10%. For charcoal canisters, 54% of the participating companies had an absolute relative bias of less than 10%. But 12% of the 224 companies for which the data were available had a bias greater than 30%. Sixty-eight percent of the 224 companies had a relative measurement error less than 10%. They also performed an analysis of 480 duplicate activated carbon monitors exposed in homes during the state indoor radon survey (15 states). The mean coefficient of variation for 278

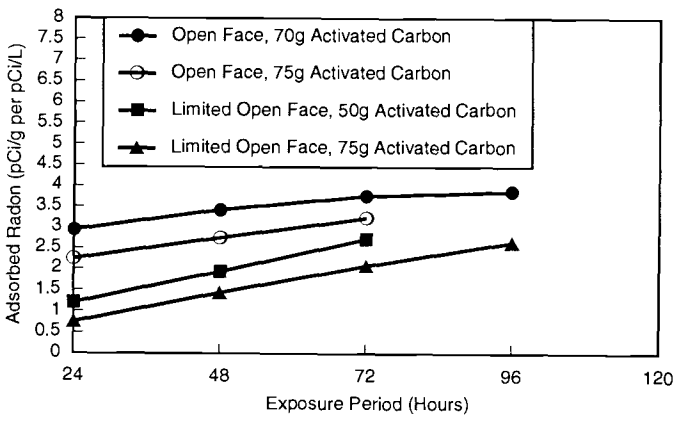

FIG. 3–Differences in radon adsorption by different types of activated carbon and canister configurations (adapted from Ref *42*).

pairs exposed at concentrations between 4.1 and 74 Bq/m^3 (0.11 to 2.0 pCi/L) was 14.7%. For the concentration range of 78 to 148 Bq/m^3 (2.1 to 4.0 pCi/L), the mean coefficient of variation was 7.8%, indicating good performance under natural conditions of exposure in a large survey.

Although the performance of activated carbon monitors is effected by a number of factors, their widespread use can be expected to continue. It is the responsibility of the user to recognize the limitations of the measurement method and attempt to minimize their effect on accuracy and precision. This can be accomplished by following standardized protocols such as those recommended by EPA [*44*].

Electrets

A passive integrated radon measurement method that has recently been developed commercially is an ionization chamber with an electret. An electret is a piece of dielectric material exhibiting a quasi-permanent electrical charge. For measurement of radon, the electret is enclosed in a chamber made of conductive plastic. Radon that diffuses into the chamber causes ionization in the chamber as the radon decays and the ions generated by radon decay products are collected by the charged electret. The reduction of charge in the electret is proportional to the integrated radon concentration over the exposure period.

As early as 1955, electrets were proposed for use as gamma dosimeters [*45*], but the suggestion was not practical because the reduction of charge was not stable for the available electret materials. Bauser and Range [*46*], in 1978, were able to develop a functional ionization chamber using Teflon™ electrets. Subsequently, electrets were used for measurement of X-ray and gamma radiation [*47*] and a personnel dosimeter was designed by Gupta et al. [*48*].

Development of a prototype electret for radon monitoring was completed in 1987 [*49,50*]. The commercial product has been tested extensively and has met the EPA RMP acceptance criteria. Electrets are available for short-term or long-term measurements. Both have a useful range of approximately 600 V. With the short-term electret, a one-day exposure to a concentration of 37 Bq/m^3 (1 pCi/L) discharges the electret by approximately 2 V. Electrets are also sensitive to background radiation. Kotrappa et al. [*50*] reported that the response for a one-day exposure at 0.1 μGy/h (10 urad/h) was approximately equivalent to a one-day radon exposure at 22.2 to 66.6 Bq/m^3 (0.6 to 1.8 pCi/L). The manufacturer of the commercially available electrets provides information and procedures for correcting measurement results to account for environmental gamma radiation levels, which may vary by geographic location.

The short-term electret container is approximately 10 cm in diameter and 12 cm high. The electret, which screws into the bottom of the container, is metal-coated Teflon™. The potential of the electret is read by the shutter method (capacitative probe method); a commercial reader is available for approximately $1000. The electrets cost approximately $15, and the container (shell) is approximately $35. An electret can be used repeatedly over its useful voltage range. For example, the electret could be used approximately 25 times for three-day periods at 3 pCi/L, making the electrets particularly cost-effective devices.

The electret radon monitor is possible because of the excellent stability of the electret. Tests have shown that surface potential is highly stable and not affected by either temperature or humidity [*50*]. The LLD of the electrets was reported to be 37 Bq/m^3-day (1 pCi/L-day) [*50*]. The performance has been evaluated in chamber exposure tests and in the RMP program. In a recent double blind test [*51*] of short-term passive monitors, electrets were exposed in a basement for two, five, or 7 days at mean concentrations of 340 or 395 Bq/m^3. Measurement results were compared to a pulse ionization chamber radon monitor. The average mean absolute relative errors (MAREs) for five electrets were 0.045, 0.091, and 0.052, and the coefficients of variation were 3.9, 11.8, and 5.1%.

METHODS AND INSTRUMENTATION FOR MEASUREMENT OF RADON DECAY PRODUCTS

Radon is measured much more frequently than radon decay products. The results of radon measurements are often used to estimate health risks using estimates of the equilibrium factor (usually assumed to be 0.5). The reason for this approach is that measurements of radon decay products are generally more difficult and costly than radon measurements. However, methods for the measurement of radon decay product concentrations have been available for many years. Methods developed for use in the uranium industry have now been optimized for use at levels that are found in nonindustrial indoor environments.

In the measurement of radon decay products, two categories of decay products, the attached fraction and the unattached fraction, are addressed. As Rn-222 decays, Po-218 appears as a singly charged positive ion. The ion undergoes chemical changes and the resulting molecules can attach to particulate matter present in the atmosphere. As a result, Po-218 and its decay products (Pb-214 and Bi-214) occur as both attached (to particles) and unattached. The unattached fraction may consist of positively charged, negatively charged, or neutral species. Terms used to describe this fraction have included "free ions," "uncombined," or "unattached"; the latter term is consistent with NCRP terminology [*3*] and is currently used by most researchers.

Radon decay product measurement methods involve sampling of a known volume of air through a filter on which the activity of the collected decay products is measured. To determine concentrations of the individual radon decay products, three independent gross alpha counts can be used. Alpha spectrometric methods (diffused junction or surface barrier detectors and multichannel analysis) can also be used. Currently available methods for measuring radon decay products are summarized in Table 5.

Grab Sampling Methods

The simplest approach to measurement of radon decay products is use of a single alpha count to determine the working level [1 working level (WL) is defined as any combination of radon decay products in 1 L of air that upon complete decay to Pb-210 results in the emission of 1.3×10^5 MeV

TABLE 5—Measurement methods for radon decay products.

Sampling Category	Method/Instrument	Measurement Principle	Notes	References
Grab	Kusnetz/Rolle	Alpha count of sample on filter	For WL	*52,53*
Grab	Tsivoglou	Alpha count of sample on filter	For individual decay products or WL	*54*
Grab	Electret	Collection of ions on electret	For total potential alpha energy	*71*
Semi-continuous	Tsivoglou modification	Alpha count of samples on filters	Optimized counting intervals; use of scaler	*55,56*
Integrating	Thermoluminescence RPISU	Sample on filter; detection with TLD	For 1 to 2 week sample WL monitor WL monitor	*75,76,77*
Integrating	Surface barrier alpha detector	Sample on filter silicon surface barrier detector	WL monitor; data acquisition system for recording sequential measurements	*89,80*

of alpha energy]. The method developed by Kusnetz [*52*] for measurements in uranium mines and modified by others [*53*] involves sampling on a filter for 2 to 10 min and counting of gross alpha activity after a decay period of 40 to 90 min.

Tsivoglou et al. [*54*] first described a measurement technique to measure individual radon decay products. An air sample was collected on a filter for five min. Alpha activity was measured with a ratemeter at 5, 15, and 30 min following sampling. The modified Tsivoglou method, developed by Thomas [*55,56*], used a scalar to record counts and optimized counting intervals of 2 to 5, 7 to 15, and 25 to 30 min after the end of air sampling.

Further development work on the gross alpha counting method has consisted of procedures to optimize the count intervals to increase the sensitivity and precision of measurements for environmental radon levels. Nazaroff [*57*] recommended extending the total measurement time from 36 to 60 min to improve measurement precision. The timing sequence proposed for a five-min sampling period and one-min delays was 1 to 4, 7 to 24, and 35 to 55 min after the end of sampling and 2 to 5, 8 to 25, and 37 to 55 min after the end of sampling for a two-min delay. Other counting intervals have been recommended to reduce the sensitivity of the measurement to variations in flow rate and concentration fluctuations [*58–60*]. Quindos et al. [*61*] and Khan et al. [*62*] have recommended use of five counting intervals to simultaneously measure Rn-222 and Rn-220 decay products. A simplified counting method that applies for any length of counting has been described by Marley and Geiger [*63*]. It is used for measurements with continuous working level monitors.

Alpha spectrometry methods are a useful alternative to gross alpha counting methods. With these methods, activities of Po-218 and Po-214 on a filter are determined over two counting intervals. Solid-state detectors are used to distinguish the 6.00 MeV (Po-218) and 7.69 MeV (Po-214) alpha energies. Bi-214 concentrations are assumed to equal Po-214 concentrations because they are in equilibrium.

Martz et al. [*64*] reported use of alpha spectrometry to measure count rates of Po-218 and Po-214 on a filter sample at 2 to 12 and 15 to 30 min periods after sampling. Variations of the method have included counting during sampling [*65*], use of a two-channel analyzer for measurements at one-min intervals for 20 min [*66*], and other modifications of either the delay period before counting or the length of the counting interval [*67–69*].

Electrets have also been used for the measurement of radon decay products [*70,71*]. Kotrappa et al. [*71*] described an alpha electret dosimeter for radon decay product measurements that consisted of a 5-cm diameter electret in a cylindrical chamber that contained a filter for collection of radon decay products. A known volume of air was drawn across the filter, then the electret was allowed to collect ions for at least 3 h after sampling. The charge difference (pre- and post-sampling) was then measured. The method provided a measure of total potential alpha energy since alpha radiation was measured during sampling as well as during the 3-h decay period. For an air sample of 68.4 L, the sensitivity was 0.1 WL. Further modifications to the electret, the surface potential reader, and the container have been performed by the manufacturer of the E-PERM™ to develop and market the device.

Continuous Monitors

Radon decay products can be measured with continuous working level meters which are commercially available. These instruments are based on technology originally developed for the uranium industry. The units operate by drawing an air sample through a filter onto which radon decay products are deposited. Alpha particles from the radon decay products are detected by a solid-state detector located at the filter. Commercially-available units are typically equipped with a microcomputer to record the number of alpha particles detected, store the data, and calculate estimated working levels using integral algorithms. The units are generally lightweight, can be operated on battery power, and are easy to use.

Lower limits of detection of 0.0001 WL have been reported for commercial monitors. Manufacturers report that accuracy is generally better than ±20%. In Round 5 of the RMP program, 75 tests were performed with continuous working level monitors. The average error was 22%, and the range of company error was 0 to 518%. White et al. [*43*] reported that 74% of the companies participating in the 1988 RMP had a relative bias below 20%. Ninety-four percent of the tests had relative measurement errors below 20%.

Other methods for the continuous or semi-continuous measurement of radon decay products have been reported. Nazaroff [*72*] described a radon daughter carousel for measuring Po-218, Pb-214, and Bi-214. Radon decay products were collected on seven filters that were rotated to place them under an alpha spectrometer for counting during two inter-

vals. The device had an LLD of 20 Bq/m^3 with a measurement uncertainty of approximately 20%. Other instruments for measurements of radon decay products that have been described [*73,74*] feature modifications or refinements in filter positioning, analysis, or data processing.

Integrated Sampling Methods

Integrating methods for radon decay products consist of three basic components: (1) an air sampling pump, (2) a filter to collect the decay products, and (3) a detector. There are no passive radon decay product methods; pumps and power (ac or dc) are required for the currently available methods. The detector may be of a type that is returned to a laboratory for analysis (e.g., TLD) or, in newer instruments, a solid-state alpha detector integrated with a data acquisition system.

A radon progeny integrating sampling unit (RPISU) consisting of a low-volume sampling pump, a membrane filter, and a thermoluminescent dosimeter (TLD) was developed for use in the uranium industry by Schiager [*75,76*] and Franz et al. [*77*]. A similar instrument was developed at EML [*78*] to measure environmental levels.

The sensitivity of the RPISU has been improved by replacing the TLD with a surface barrier alpha detector [*79,80*]. With this design, the lower limit of detection is 0.00004 WL for a one-week measurement at 0.2 L/min. Use of a data acquisition system allows the instrument to be used as a continuous WL monitor, with printout of data at fixed intervals. The instrument is more expensive ($2000 to $8000) than the TLD device, but is substantially easier to use and can provide information on temporal variation of radon decay product concentrations.

The performance of RPISUs has been evaluated in interlaboratory comparison programs by the U.S. DOE at the Technical Measurements Center (TMC) in Grand Junction, Colorado. Results of an exercise performed in 1985 [*81*] showed good agreement among RPSIU measurements. The means for each of the five groups that participated were within 0.021 WL (one standard deviation) of the mean for all instruments of 0.205 WL. The coefficient of variation for all measurements was 10.4%. In Round 5 of the RMP program, only four companies submitted RPISUs. The average error was 27% and ranged from 1 to 80% [*8*].

Measurements of Unattached Radon Decay Products

Measurement of unattached radon decay products is not commonly performed in field surveys to estimate human exposure and health risks. The complexity and costs of the measurement preclude its routine use. However, the unattached radon decay product fraction is very important in lung dosimetry models; its measurement in research programs is critical to understanding radon decay product dynamics and human exposure.

Measurement of the unattached fraction has been the subject of extensive research. Instrumentation used for the measurement have included devices using diffusion, impaction, and electrostatic deposition methods [*3,82*], as summarized in Table 6. Chamberlain and Dyson [*83*] used diffusion tubes 150 and 600 mm long by 18 mm in diameter to determine the unattached fraction by loss to the walls. They measured a diffusion coefficient of 0.054 cm^2/s for Po-218. Craft et al. [*84*] used the same type of tube (600 mm long by 37 mm diameter) in pairs, one with a reference filter on the inlet and the other with the filter on the outlet, to determine the unattached fraction by difference. The unattached fraction has also been measured with diffusion batteries [*85*] and impaction on parallel plates [*86*]. Electrostatic collectors have been used in studies of the unattached fraction [*87*], but they must be used in conjunction with a diffusion battery to determine the total unattached fraction since the neutral species are not collected.

Screen samplers have been used widely in recent years for measurement of the unattached fraction. Early work on the collection efficiency of wire screens was performed in 1972 by Thomas and Hinchcliffe [*88*], George [*89*], and others. Based on this work, equations were developed for the efficiency of screens. Cheng and Yeh [*90*] and Cheng et al. [*91*] also developed equations for collection efficiency for stacks of screens. Van der Vooren [*82*] noted that collection of the attached fraction of the aerosol results in large measurement errors. Calculated collection efficiencies of 0.05 to 4.3% for the attached fraction resulted in substantial errors since the unattached fraction is usually only a few percent of the total activity.

Recent studies [*92,93*] suggest that the unattached radon decay product fraction is an ultrafine particle mode, rather than free molecular polonium. Reineking et al. [*93*] determined that there was a Po-218 activity peak in the 1 to 3-nm diameter range. Hopke [*94*] pointed out that classical diffusion batteries have insufficient resolution for these ultrafine aerosols (0.5 to 3-nm diameter). He suggested use of single screens of different mesh numbers separately or in stack configuration for these measurements. Recognizing that the unattached fraction is an ultrafine aerosol, Ramanurthi and Hopke [*95*] used wire screen penetration theory to determine the wire screen collection efficiency for a number of screen-face velocity combinations reported in the literature. These calculations showed underestimation of the unattached fraction of 14 to 48% in the eight studies examined. Based on this work they suggest that appropriate screen-operating parameters must be chosen for efficient collection of the ultrafine aerosol or that, alternatively, wire screens be used in diffu-

TABLE 6—Measurement methods for unattached radon decay products.

Sampling Category	Method/Instrument	Measurement Principle	References
Grab	Diffusion batteries	Unattached fraction determined by loss to surfaces; may be parallel tubes, parallel plates, or screens	*82,83*
Grab	Electrostatic collectors	Collection of positive and negative ions	*84*
Grab	Screen samplers	Collection of unattached fraction on varying number or mesh size of screens	*87–91,94*

sion battery-type systems to determine activity size distribution over the 0.5 to 500-nm size range.

Measurement of the unattached fraction continues to be an area in which development of more refined methods is required and anticipated. The development, however, continues to be confined to only a few research groups. Commercial development is not anticipated.

METHODS FOR MEASUREMENT OF RADON FLUX AND SOIL GAS CONCENTRATION

Measurements of radon flux from materials have been performed extensively during the last 50 years. Early work in this area had geologic or physical/chemical applications for characterization of materials adsorption rates and surface properties. Much of this work was conducted in laboratory settings and has been reviewed by Colle et al. [*96*].

The emphasis of the following discussion is on field measurements of radon flux (also referred to as exhalation). Measurements of radon flux are routinely used in a diagnostic mode to identify radon sources, pathways of radon entry, and entry rates. Measurements of soil gas radon concentrations have gained increased attention in recent years as builders seek a technique to characterize building sites prior to construction. In some locales, radon mitigation systems are now being incorporated into the structure if there is a possibility of elevated levels of radon in the building. A method, therefore, that could correlate radon soil gas, soil permeability, and other physical factors with post-construction radon concentration would be particularly attractive because of cost savings associated with taking radon preventative actions during building construction. In the following discussion, methods for measurement of soil gas are described, but the utility of the results remains to be established since good correlation between soil gas concentrations and indoor radon concentrations has not been demonstrated.

A review of currently available soil-gas measurement technologies has recently been prepared by Rector [*97*]. He provided a description of technologies for measuring (1) radium content, (2) radon flux from the surface, and (3) radon in soil gas. Methods that he identified for each category of measurement are presented in Table 7. Radium content is typically measured by placing a soil sample in a container, allowing a sufficient period to establish radioactive equilibrium, then analyzing the sample by gamma spectroscopy [*98*].

Radon flux measurements have been performed by closed accumulation, flow-through accumulation, and adsorption methods. The closed accumulation method is a basic, easily implemented method that has been widely used. It consists of placing a vessel (accumulator) over the surface for periods of 1 to 10 h. The accumulator is sealed to the surface with appropriate resins or caulk; for soil measurements it may be embedded in the soil. Samples are collected for analysis into evacuated scintillation cells at the end of the period or at intervals. The length of the accumulation period, size of the can, and design of accumulator systems have been highly variable; no standard protocol exists for the method.

Requirements for the accumulator method described by Wilkening et al. [*99*] are: (1) the accumulation period should be short compared to the half-life of radon, (2) the concentration in the accumulator must be much lower than the soil gas concentration to prevent back diffusion, and (3) the presence of the accumulator should not affect the exhalation rate. The final requirement is the most difficult to meet and is the subject of continuing research.

TABLE 7—Soil gas measurement methods.

Method	Description	References
Radium content	Laboratory analysis of bulk sample in sealed container	*98*
Radon flux	Closed accumulator	*99*
	Flow-through accumulator	*100–102*
	Adsorption	*101,104*
Gas extraction probes	Packer probe	*110*
	Permeameter probe	*111*
	Reconnaissance probe	*112*

The flow-through method is a modification of the accumulation method that attempts to minimize the effect of the accumulator on the test surface and to make the measurement conditions more realistic. The system described by Pearson and Jones [*100*] involved passage of air through the accumulator vessel at a low rate and collection of the radon in a dry-ice cooled charcoal trap. Variations of the flow-through method utilize direct measurement of the radon in the air stream from the accumulator [*101,102*].

The adsorption method is widely used for measuring radon flux. This is also a simple, low-cost measurement method that uses charcoal to adsorb the exhaled radon. The technique was reported by Megumi and Manuro in 1972 [*103*]. They covered the soil surface to be tested with gauze, upon which a uniform bed of charcoal was placed and sealed with polyvinyl chloride film. After a 5-h collection period, gamma counting was used to calculate radon concentrations.

A much simpler method of sample collection is the use of charcoal canisters. Countess [*104,105*] originally used the M11 gas mask canister, but in current practice larger diameter canisters are used [*101*]. Countess embedded the canister in the soil and packed additional soil around it. Analysis was performed by gamma-counting methods.

The canister method has the advantage of being low cost and easy to use. However, the method has a number of limitations that should be recognized. As described in a previous section, performance of the canister is affected by both temperature and humidity, parameters that may vary substantially for the range of surfaces that are measured. Use of the canister on basement walls or floors or for measurements of flux from soils requires consideration of water vapor adsorption effects on collection efficiency. Countess [*105*] suggested that canisters exposed to wet soil for several days would not adsorb enough water to reduce collection efficiency by more than 10 to 15%. But like activated carbon monitors used for air sampling, the extent of water vapor effects may be related to the type of carbon [*42*]. Canisters used for flux measurements should be calibrated over a wide range of water vapor concentration and temperature as these parameters may vary more substantially for flux measurements than for indoor air measurements.

Results of flux measurements with canisters should be interpreted with caution. The sampling area with the canister method is small. As a result, spatial variation in flux rates is

not adequately addressed unless multiple samples are collected.

Soil gas measurements have been performed by in-situ measurements and by soil gas extraction methods. In-situ measurements of soil gas radon concentrations have been performed most commonly by burying passive detectors in the soil at various depths. Fleischer [*109*] used passive alpha-track detectors buried at different depths to determine soil radon gradients. Use of alpha track detectors for soil gas measurements has been reported for a number of studies [*107–109*]. An alternative to the alpha-track detectors are the passive electret monitors described previously [*49,50*]. Use of this technology is feasible, but their performance for measurement of radon in soil gas has not yet been well-documented.

Soil gas extraction methods for measurements of radon in the soil pore space have been used widely for uranium exploration. The basic technique involves driving a pipe into the soil to a prescribed depth. Typically a pump is used to draw a soil gas sample from the hole, and the sample is typically analyzed by scintillation methods.

The recent concern about the potential for elevated radon concentrations in newly constructed building has resulted in development of new soil gas extraction probes. Tanner [*110*] has described a "packer" probe for simultaneous measurement of radon and soil permeability. The unit is placed in an augered hole, and the packers that surround the probe are inflated to create a seal that prevents surface air from entering the space. Based on analysis of radon concentrations in air drawn from the soil, simultaneous measurement of soil permeability, and the estimate of the effective diffusion coefficient by means of soil content and moisture content, radon availability is estimated.

Nielsen et al. [*111*] described a "permeameter" probe for soil gas extraction. It is a small-diameter probe that is driven into the soil by hand. Radon concentration is measured by alpha scintillation. A controlled flow extraction system is used to estimate soil permeability.

A "reconnaissance" probe for soil gas measurements has been described recently by Reimer [*112*]. This probe is also a small diameter (6 to 9-cm) probe. It is driven into the ground to a nominal depth of 75 cm. The probe volume is only 3 cm^3, which facilitates collection of samples from the probe with a syringe for analysis using alpha scintillation.

METHODS FOR MEASUREMENT OF RADON IN WATER

Measurements of radon in water are relatively straightforward and easily accomplished. One method involves collection of water in modified Marinelli beakers made of polyethylene or lucite [*113*]. Analysis of the radon progeny in equilibrium with the water by gamma counting is used to determine the radon concentration. The lower limit of detection of the method is 185 to 445 Bq/m^3 (5 to 12 pCi/L) of water.

A second method, equally straightforward, is the liquid scintillation technique [*114*]. Water collected in the field is returned to the laboratory where a fluor is added and the sample is counted. This method requires availability of more expensive instrumentation then the gamma-counting method. For both of these methods, care should be taken in the collection of the sample to prevent outgassing of radon during the collection process and transport/storage. There are currently no published standard methods for sample collection, storage, handling, or analysis.

Measurement of radon in water can also be made in-situ using passive detectors. Alpha-track detectors have been marketed for many years for measurements of water concentrations. The device consists of an alpha-track monitor mounted in a plastic container placed into the water. The detector measures the radon in the air in the container. An empirically derived constant is used to relate the air concentration to the concentration in the water. The manufacturer reports that accuracy of the measurement is better than ± 10%. The manufacturers of the commercial electret monitors also market a detector for measurements of radon in water.

STANDARDIZATION ACTIVITIES FOR RADON AND RADON DECAY MEASUREMENTS

As requirements have increased for measurements of radon and radon decay products, the need to standardize the measurement methods has been recognized. Standardized methods are especially important for radon because measurements are now being performed by many commercial companies in addition to government agencies and research organizations. Recognizing this need, members of ASTM have been active in developing standard methods, practices, and guides for the measurement of radon and radon decay products. This activity has been ongoing in the Radionuclides section of Subcommittee D22.05 on Indoor Air. Many documents are currently under preparation, revision, or at various stages of balloting. Documents are currently under development for the following:

1. Sampling and analysis of radon content of the atmosphere (activated carbon methodology).
2. Use of alpha-track detectors for measurement of radon in indoor air.
3. Determination of radon in indoor air by use of electret chambers.
4. Determination of radon concentrations in indoor air by charcoal liquid scintillation analysis.
5. Determination of indoor radon progeny concentrations using radon progeny integrating sampling units.
6. Determination of radon decay product concentration and working level by active filter sampling.
7. Guide for radon measurement in indoor air.
8. Guide for radon monitoring in school buildings.

Development of additional methods is anticipated. These ASTM methods, practices, and guides, in conjunction with guidance from the EPA, will provide the information needed to use the measurement methods described in this chapter.

SUMMARY

As described in this chapter, there are a number of methods available for the measurement of radon and radon decay

products at the concentrations that occur in nonindustrial indoor environments. The measurement methods vary with respect to their performance characteristics, ease of use, and cost. Most of the methods currently being used are based on established measurement principles and their performance has been well-documented. Relatively simple methods are available that homeowners can use to perform screening measurements for radon. Researchers have a wide range of instrumentation available for measurement of radon and radon decay products. Because of the concern about the health effects of radon decay products and the potential for exposure to radon, there has been substantial development of instrumentation in recent years by the commercial sector. Additional instrumentation development is anticipated in the coming years.

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5

Radon Measurement Protocols

by Melinda Ronca-Battista[1] and Paul Magno[2]

INVESTIGATORS IN FEDERAL AND STATE government, universities, and private industry are making radon measurements using different measurement devices placed in different locations during various ventilation conditions and over different time periods. These public health officials, mitigators, researchers, and building engineers are measuring radon and decay products using a variety of practices, leading to sometimes vastly different results even in the same building. It is important for anyone measuring radon to recognize that different measurement practices lead to measurement results that may not be comparable. The specifications for the factors that can greatly influence the result of a measurement are defined as a protocol. It is the intent of this chapter to assist the reader in evaluating the type of protocol that is appropriate for his or her needs. The chapter discusses the different procedures and guidelines in use by different groups but does not necessarily recommend their use.

A clearly specified measurement protocol is a key element of any study because the purpose of the measurements dictates how the measurements should be made. Results of radon measurements can easily be misinterpreted if the researcher does not carefully consider how the measurement result can be interpreted and misinterpreted. Several common purposes include measurements made to determine the need for mitigation, measurements made to estimate the long-term exposure of the occupants, measurements for comparison with a standard radon concentration, diagnostic measurements made to investigate radon entry points, and post-mitigation measurements made to evaluate the effectiveness of remedial action.

A protocol needs to specify the duration of the measurement and, for most research projects, the season when the measurement should be made. These specifications are necessary because radon can vary greatly during the course of a year, a season, and even a day. For example, in 20 homes in Montana, monthly average radon levels varied from the annual averages by as much as a factor of three [*1*]. Similarly, high fluctuations have been recorded in other studies [*2–16,19,20,21,22,23,24*]. Although radon concentrations fluctuate, there is a general pattern seen in which radon levels tend to be higher during certain times of the day, such as in the predawn hours of the morning [*24–26*]. There has been considerable data gathered on the variation in radon concentration with season, and most studies show that levels are higher during winter months [*7,25,27,33*]; however, there are studies in which indoor levels were higher during the summer months [*9,29*]. An essential component of a protocol is, therefore, specifications for the duration of the measurements. When appropriate for the purposes of the measurements, the season(s) when the measurements should be performed may also need to be specified in the protocol.

Another essential element of a protocol are requirements for sampling conditions, including those factors that can affect ventilation rates. Radon levels are affected by the ventilation conditions in the structure during and prior to the measurement. Adherence to protocols will help ensure that conditions are as reproducible as possible. The specifications may be as loose as requiring that all windows and doors be closed or as rigorous as specifying the number of air changes per hour. Depending on the type of measurement and its duration, the protocol may also require that certain conditions exist for a time period prior to the beginning of the measurement.

The third component of a protocol is the location in a building, both in terms of floor and location, where the measurement is to be made. Protocols need to provide guidelines for measurement location because radon levels are usually different in different levels of a house, often being several times higher in basements or first floors than on upper floors [*5,8,19,25,27,30*]. For certain purposes, measurements may be made on several floors of a house. In addition to floor, the result of a measurement can be affected by its placement within a room, such as whether the measurement is made near a window or exterior wall, near the floor, or at face height.

Other important components of a measurement protocol are the type of measurement methods to be used, the quality assurance practices to be followed, and the intentions for the analysis and interpretations of the results. These elements depend on the type of equipment available, the measurement program being conducted, and the planned uses of the resulting data.

When developing a protocol, there are several important considerations. First, the measurement protocol is dependent on the objectives of the measurement program. If a large-scale survey or measurement effort is being planned, perhaps significant resources should be expended in obtaining measurements from many homes, and the protocols for measurements in individual homes may not call for multiple measurements. If a small number of homes are being investigated, the

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information obtained from each home is more critical and the number and type of measurements per home can be expanded.

Second, the types of measurements that are feasible for the study and that are available must be considered. Important considerations include whether the devices will be mailed, whether they are to measure radon or radon decay products, and the time period over which the measurements are to take place.

Finally, investigators should be aware of the protocols used by others, and how different specifications for important elements may affect results, so that results of different studies can be evaluated for possible comparison. It is critical to learn of the protocols used by others during the planning stages of a project, especially if it is important that the data gathered be comparable to data from other projects.

This chapter also reviews current practices for quality assurance in radon measurements, with information on calibrating radon measurement devices and intercalibration programs.

THE VARIABILITY OF RADON

Temporal and Spatial Variations in Houses

A primary reason measurement protocols are necessary is the great variability of radon and radon decay product concentrations. Radon levels in houses exhibit both temporal variability (variability over time) and spatial variability (variability between locations). In general the temporal variability is greater than the spatial variability. Temporal variations often range over several orders of magnitude, while spatial variations are usually a factor of two or three but can in some houses range up to one order of magnitude. These variations are an important consideration in designing, conducting, and interpreting radon measurement programs.

Temporal variations are influenced by a large number of complex and interrelated factors including radon infiltration rates, pressure differentials, ventilation rates, occupants' lifestyles, and meteorological and soil conditions. Spatial variations are less complex and are generally influenced by the routes of radon entry and the distribution of air within the building.

All buildings show hourly, daily, and seasonal variations in radon levels. Although many buildings exhibit similar patterns of temporal variation, the magnitude and type of these variations can differ greatly among buildings depending upon the radon levels and the factors which influence these variations.

Much of the information available on temporal variations of radon in buildings was obtained from northern climates with cold winters. Additional studies are needed to obtain information on temporal variations in other areas and climates. Also, all of the discussion below dealing with temporal variation relates to buildings where underlying soil is the principal source of radon in the building. When radon in water or building materials is the major source of radon, different patterns in both the temporal and spatial variations are likely.

Hourly and Daily Variations

All buildings exhibit diurnal variations in radon concentrations. Figure 1 shows the hourly radon concentrations in a house on the Reading Prong in Pennsylvania over a one-week period and is a typical example of the diurnal variation found in buildings. In general, the highest concentrations occur in the morning and the lowest concentrations in the afternoon. The magnitude and pattern of these temporal variations differ widely both between time periods in the same building and among buildings. Figures 2 and 3 illustrate these variabilities. These figures show the radon concentration in the same house in Butte, Montana during two different one-week periods during a study conducted to test different measurement protocols [*1*]. During one of the periods, the hourly radon concentration varied by a factor of less than two (Fig. 3), while during the other period it varied by a factor of almost ten (Fig. 2). The average daily concentration varied by much smaller factors. In studies in houses in Clinton, New Jersey, the radon concentration varied by a factor of 100 or more under various test conditions [*2*]. These test conditions involved the operation of fans, which produced changes in the differential pressure between the areas below the slab and lowest floor in the house.

The greatest variations in radon concentrations occur in buildings with very high radon levels. It is likely that the factors which control the radon entry rates in these buildings are responsible for the wide fluctuation in the radon concentration.

Monthly and Seasonal Variations

In addition to the short-term variations, radon concentrations in buildings also exhibit long-term or seasonal variations, with the highest concentrations occurring during the winter months and the lowest concentrations during the summer months in areas where winter temperatures drop significantly. A typical example of this variation is Fig. 4, which shows the weekly radon concentrations in Test House No. 3 in Butte, Montana over an 18-month period [*1*]. Figure 5 shows the average ratio of the monthly radon concentration to the yearly concentration in 20 test houses in Butte, Montana [*1*]. From October to May the monthly concentrations differ from the yearly concentrations by only small amounts (up to 30%). In the period June through September this difference can be as great as a factor of three. It is important to recognize that these differences are an average between a group of 20 houses. For individual houses the differences particulary between the summer months and the yearly average can be significantly greater. Similar data on seasonal variations have been observed in studies conducted in Colorado [*3*], South Dakota [*4*], Maine [*5*], Pennsylvania and Illinois [*6*], New York [*7*], and in other areas [*8–10,23,25,27,28*].

Seasonal variations are believed to be due primarily to two factors: (1) changes in individual living habits which affect the ventilation rates, i.e., more frequent and longer opening of doors and windows and (2) changes in the factors which influence the radon entry rates, i.e., changes in pressure differentials.

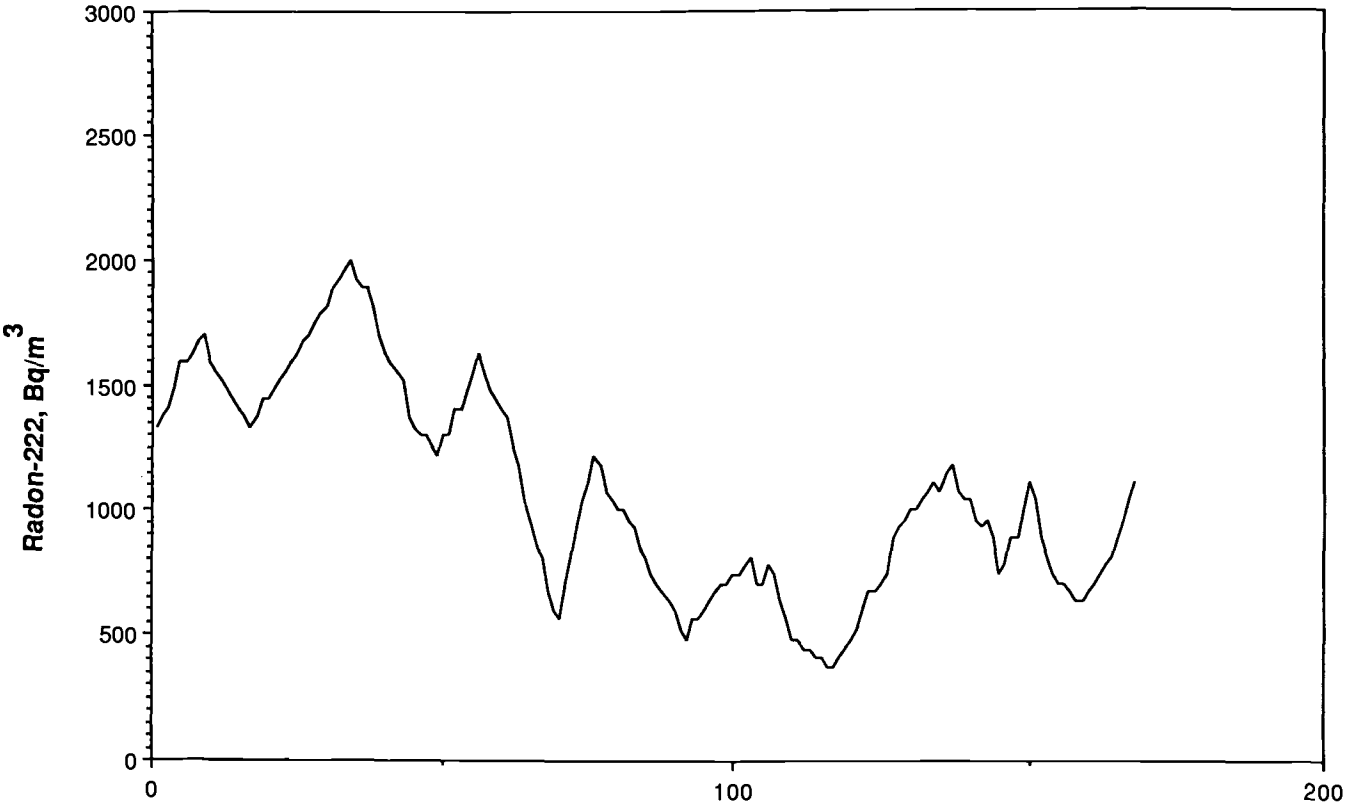

FIG. 1–Typical diurnal radon-222 variations in houses.

Spatial Variations

Radon concentrations in buildings vary depending upon the location in the building. Basement levels are on the average a factor of two to three times greater than the radon levels on the first floor [*1,3,6,8,9,11–18,25,27,30*]. However, for individual buildings, these differences have been observed to range up to a factor of ten. Table 1 shows the average basement to first floor ratios and the ranges of these values for a number of studies. Although basement levels are usually greater than the first floor level, in some buildings the radon levels in the basement and first floor are about the same. This may result from the type of heating/cooling system in use which produces rapid circulation of air between these levels. Also, a few unusual homes have first floor radon levels that can be significantly higher than the basement levels [*1*]. This has not been found in the majority of homes and may be due to some unusual aspect associated with the house construction.

Measured radon concentrations on the first and second floors of a house and between rooms on the same floor differ by only small amounts. Table 2 shows the average first floor to second floor radon concentration ratios and the range of these values for several studies [*1,7,16*]. These data were obtained mostly from houses with basements.

Table 3 shows the radon concentrations in several rooms on the first floors of a group of test houses in Butte, Montana. An analysis of these data showed no statistically significant difference in the radon concentration in different rooms on the same level when the analytical error in the measurement is taken into consideration [*1*].

Only small differences have been observed between radon concentrations in rooms on upper floors of houses. Basement radon concentrations may differ significantly between rooms because radon entry points can cause spatial differences in radon concentration.

Temporal and Spatial Variations in Schools

Temporal and spatial variations are different in schools than those observed in houses. Design and operation of the heating, ventilation, and air conditioning systems (HVAC) and the occupancy patterns can have a significant effect on the temporal variations. Also, unlike houses, schools may be built on several adjoining slabs. The joints between slabs may offer various entry points for radon, resulting in significantly different spatial variations than are observed in houses.

Although information on the temporal and spatial variations in schools is limited, an Environmental Protection

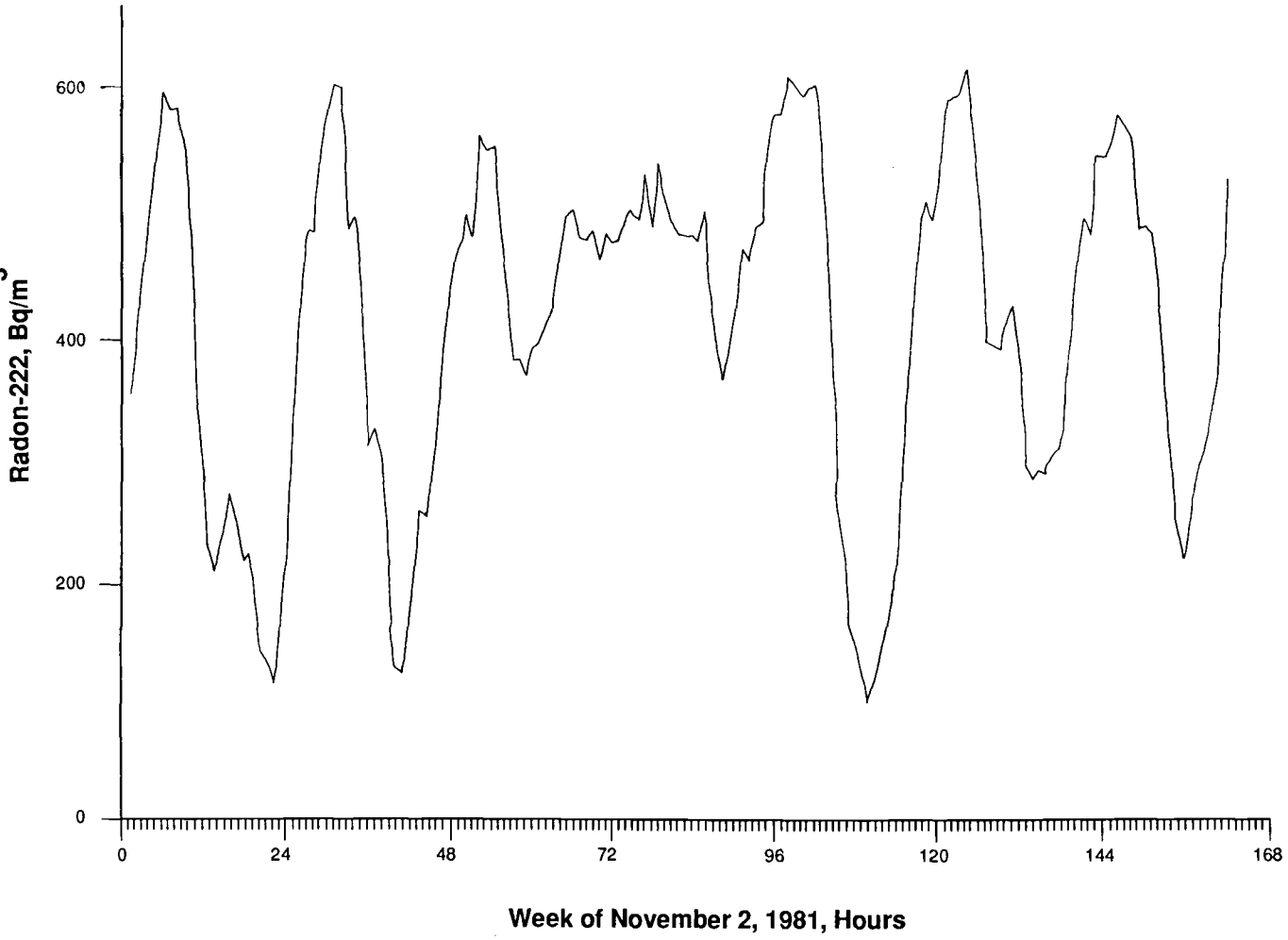

FIG. 2–Hourly radon-222 concentrations in test house No. 3 in Butte, Montana during the week of 2 Nov. 1981.

Agency study of schools [*31*] has led to the following preliminary observations and conclusions.

1. Radon concentrations in school rooms vary significantly over time. Changes in the ventilation, occupancy patterns, and weather conditions can cause short-term concentrations to vary with time by as much as a factor of ten. Figure 6 is an example of the temporal variability of radon concentrations in a school room over a several-week period. A diurnal variation is observed, with the radon concentration increasing during the night and abruptly decreasing in the morning when the ventilation and occupancy cycle begins. On weekends the diurnal cycle persists, but the abrupt changes in the morning are absent. The average radon concentrations on the weekends were higher than the average concentrations during the week. Because the temporal variations in a school are so highly dependent upon the HVAC system, the magnitude and pattern of these variations may differ greatly between schools. Additional studies are needed to better identify these variations and the factors which influence them.
2. Radon concentration in schools can vary significantly from room to room even on the same floor. Some classrooms may have elevated radon concentrations even if other rooms have relatively low radon concentrations.
3. Radon concentrations are higher in basement and first floor rooms than on upper-level floors.

MEASUREMENT AND SAMPLING ERRORS

When evaluating the result of a radon measurement, it is important to consider the uncertainty that should be attached to the result. As has been discussed, there is considerable variability in radon both in space and time. In addition to this variability, the measurement result is also uncertain due to instrument errors. It is the *combination* of the errors caused by spatial, temporal, and instrument variabilities that is important when considering a measurement protocol.

As an integral part of the development of their protocols, the U.S. Department of Energy (DOE) and the U.S. Environmental Protection Agency (EPA) conducted studies and evaluated data on the combination of all the uncertainties that exist in different types of radon and radon decay product measurements. The DOE conducted studies in homes in

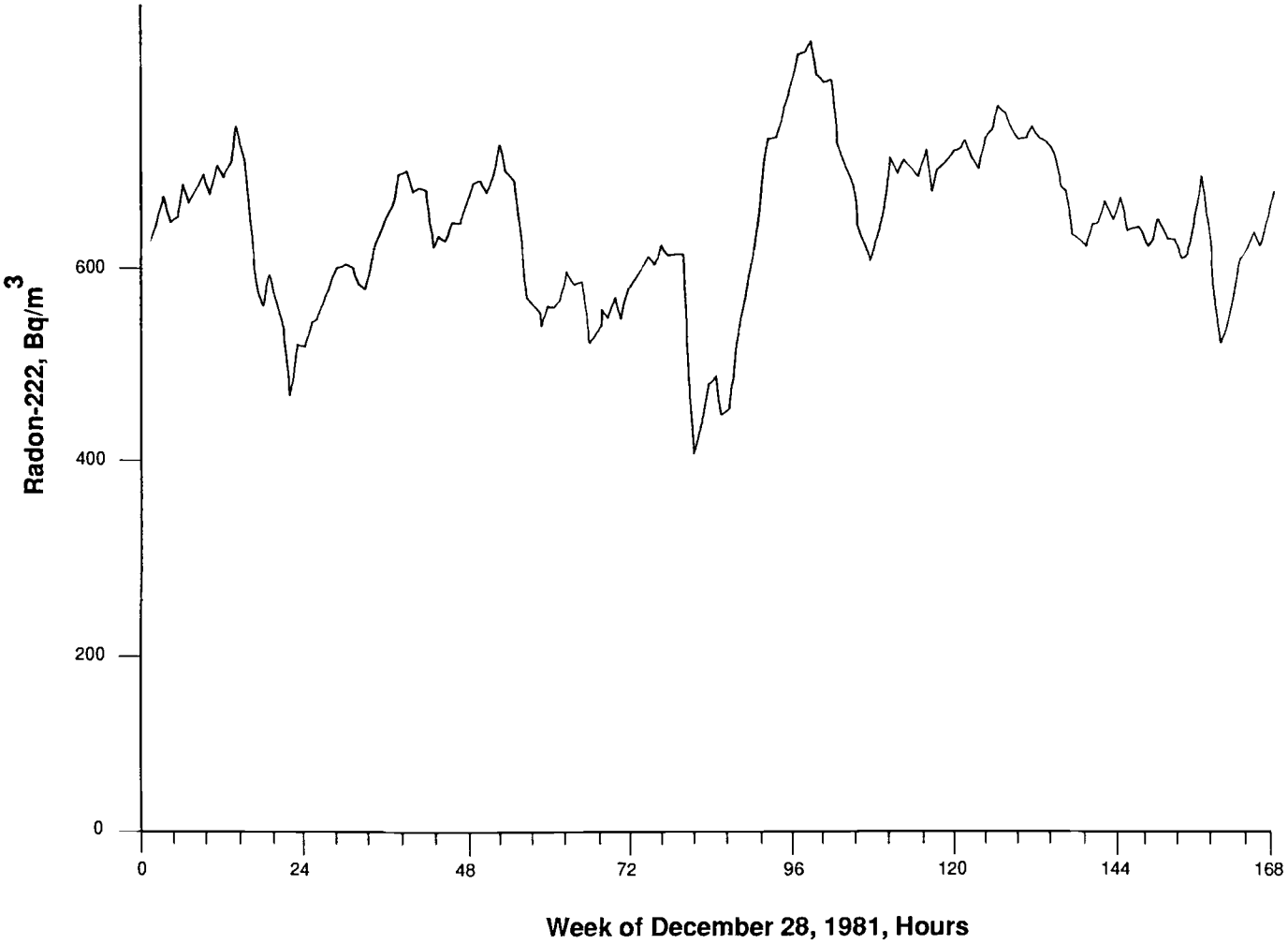

FIG. 3–Hourly radon-222 concentrations in test house No. 3 in Butte, Montana during week of 28 Dec. 1981.

Grand Junction, Colorado, using a variety of measurement techniques in both occupied and unoccupied homes, with the objective of determining the optimal protocol in terms of measurement device, sampling duration, number of repeated measurements, sampling conditions, and method of calculating results [*32*]. The protocol had to result in a value that represented the annual average radon decay product concentration in that house to within 50% with a 95% confidence.

The EPA has conducted studies and evaluated data during the development and evolution of its protocols. Data from homes in Butte, Montana were evaluated to determine the variability of different measurement techniques during different house conditions [*33*]. The EPA found from this study that the variability of measurements made during the winter months when homes are kept closed are smaller for all the methods studied than the variabilities of measurements made any other time during the year. They also found that the total measurement uncertainty decreases with increasing sampling time. Finally, they found that for similar sampling times, measurements of radon are less variable than measurements of radon decay products. These conclusions were used to develop the initial EPA protocols that have since been revised, as discussed in the following section.

Swedjemark [*34*] also conducted a study to evaluate the total error in radon measurement due to both sampling and instrument error. Her report reviews the results from a study in Sweden in which a variety of measurement techniques were used over a year. Individual results were compared with the annual average in the same home. Since the variability of radon measurements was found to be smaller during closed-house conditions, the results of this study were used to substantiate Sweden's protocol for measuring radon during the winter months only, when the overall ventilation is at a minimum as compared to milder seasons when windows and doors may be open.

One critical question for those evaluating data in the development of measurement protocols is how well the result of a particular protocol, whether it be a single long-term measurement or a series of shorter-term measurements, produces a result that represents an annual or longer-term average. The U.S. EPA found that the result of a one-day continuous radon monitor could be used to predict the annual average to within 39% in one set of houses studied [*33*]. The 39% represents the coefficient of variation (i.e., standard deviation expressed as a percentage of the mean) for one-day measurements made throughout the year. Assuming that the one-day results are

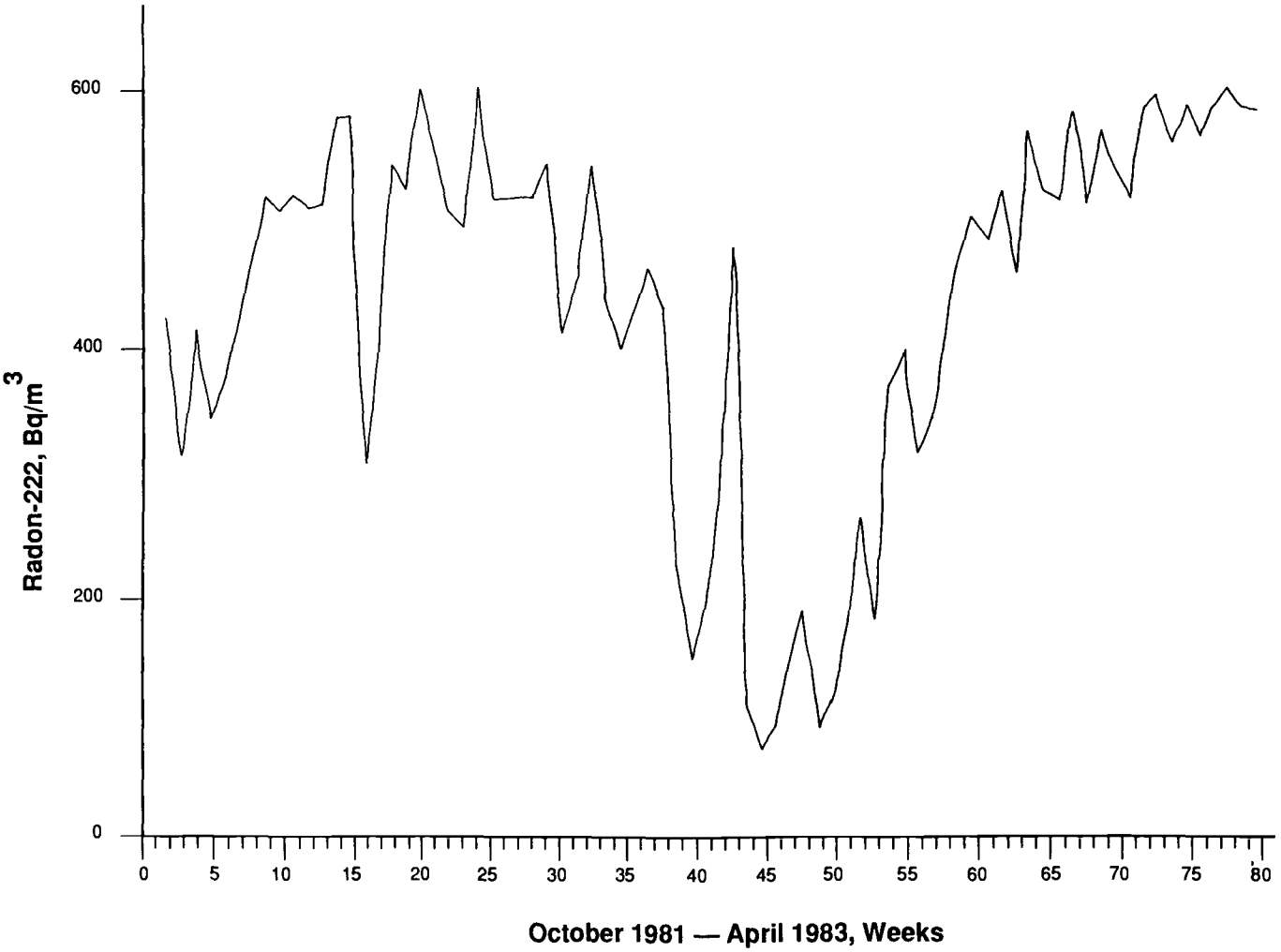

FIG. 4–Weekly radon-222 concentrations in test house No. 3 in Butte, Montana during period of October 1981 to April 1983.

normally distributed about the annual average, these data show that a one-day measurement provides a result within plus or minus 39% of the annual average in 68% of the cases in the study. Similarly, one-day results are within plus or minus 78% of the annual average in 95% of the cases in the study. This is a fairly large range, which is why it is very difficult to estimate an annual average from the results of a short-term measurement. Swedjemark found that the result of a one-day continuous radon monitor could be used to predict the annual average to within 25%. This smaller variability is due to the fact that she sampled exclusively during closed-house conditions, so that the radon levels were more stable.

MEASUREMENT STRATEGIES

This section discusses different strategies used for different purposes. Measurement protocols for residences are reviewed, as are protocols for measurements in schools and workplaces. A discussion of the different considerations that face a researcher when planning large-scale measurement programs for a variety of purposes is presented with examples of the protocols that different groups have used.

Strategies in Houses

The first consideration when planning any sort of measurement effort is the purpose of the measurement. It is very difficult to use the results of measurements made for one purpose for a different purpose after the measurements are completed. The different purposes for making measurements may vary greatly. For example, measurements may be made to estimate exposure. To do this, the investigator may measure the average radon or radon decay product concentrations to which occupants are exposed over a long time period and in several locations. Another purpose for a measurement is to determine the need for mitigation. Another purpose may be for diagnosing radon entry points. These different purposes dictate different measurement protocols. For example, it is difficult to use the results of a diagnostic measurement to determine the need for mitigation.

In addition to the different purposes for making measurements, the specific needs and resources of the investigators dictate the measurement protocol to be used. For example,

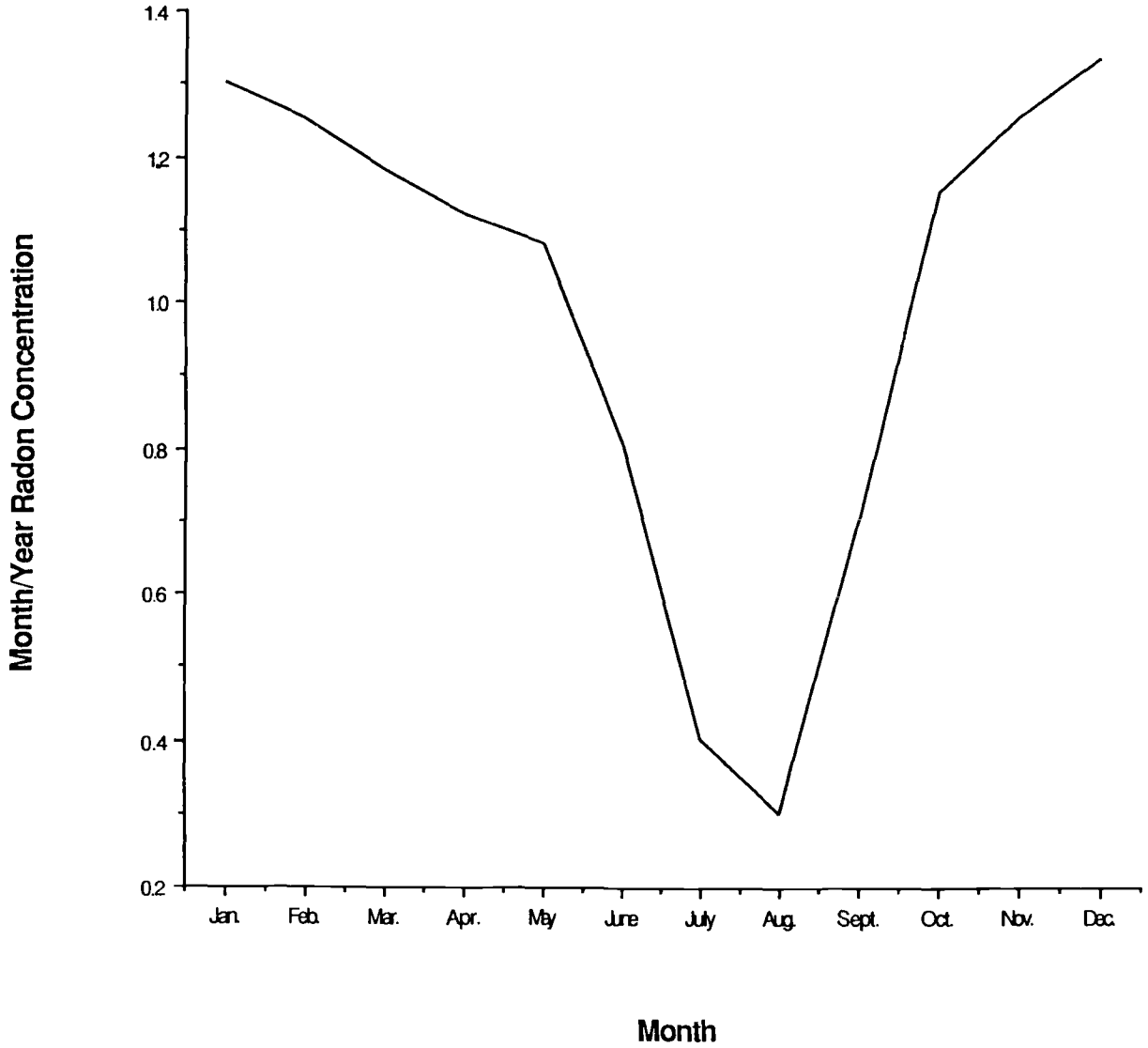

FIG. 5–Average ratio of monthly to yearly radon-222 concentrations in 20 test houses in Butte, Montana from October 1981 to April 1983.

measurements may be made by an individual homeowner to assess their potential exposure and whether radon mitigation is warranted, or exposure measurements may be made as part of an epidemiological study. Although both purposes are for exposure assessment, an individual homeowner may be able to expend more resources and make measurements on more than one floor in the home. The epidemiological study may have as a major goal the inclusion of as many cases as possible in the study, so only one measurement per home may be conducted.

This section will review three different protocols for making measurements in homes. There are two protocols that

TABLE 1—Ratio of basement to first floor radon concentrations in houses.

Location	No. of Houses	Basement/First Floor[a]	Range	Reference
Montana	19	2.2 ± 1.7	0.4–5.4	[*1*]
New York and New Jersey	17	1.9 ± 0.8	1.0–4.0	[*16*]
New York	22	2.7 ± 1.8	0.9–8.2	[7]
Colorado	15	2.2 ± 1.1	1.0–4.7	[*17*]
Maryland and Pennsylvania	80	2.4	NA	[*18*]
Maryland	53	2.4	NA	[*13*]

NA = Individual results not available.
[a]Errors represent one standard deviation.

TABLE 2—Ratio of first floor to second floor radon concentrations in houses.

Location	No. of Houses	First Floor/Second Floor[a]	Range	Reference
Butte, Montana	8	1.3 ± 0.3	0.9–1.7	[1]
New York and New Jersey	7	0.92 ± 0.19	0.6–1.2	[16]
New York	16	1.0 ± 0.2	0.6–1.3	[7]

[a]Errors represent one standard deviation.

TABLE 3—Radon concentrations in different rooms on first floors of houses in Butte, Montana [1].

Test House No.	Radon Concentration, Bq/m³		
	Living Room[a]	Bedroom	Kitchen
2	890	740	630
4	85	...	78
5	1300	1300	1100
6	700	670	700
7	370	370	...
8	410	330	410
9	370	300	410
10	430	370	...
12	410	...	630
13	780	740	...
14	440	...	700
15	330	...	410
16	90	...	85
17	220	300	...
18	190	110	...
19	1200	1100	1400
20	740	780	630

[a]Also includes family rooms and dining rooms.

have been recommended by the U.S. government, and both are designed for different purposes. The first is the protocol recommended by the U.S. DOE Office of Remedial Action and Waste Technology, and the second described here is the revised protocol recommended by the U.S. Environmental Protection Agency (EPA). As such protocols are being refined continuously, it is recommended that these federal agencies be contacted for the latest information before initiating any measurement efforts intended to be in conformance with these protocols.

U.S. DOE Protocols

The DOE protocols are written for use as DOE remedial action programs, including the Grand Junction Remedial Action Project, the Formerly Utilized Sites Remedial Action Program, and the Uranium Mill Tailings Remedial Action Project [35]. These are homes where the DOE has conducted mitigation to reduce indoor radon decay product concentrations. The protocols are written to provide procedures for providing "reasonable assurance that the average radon decay product concentration within a structure is either above, at, or below the standards (near 0.02 WL) currently established for remedial action programs."

The DOE wrote a central protocol and periodically, as different methods become available and are studied, issues additional documents for applying specific measurement methods. These additional documents are meant to be used in conjunction with the central document. Several supplementary methodology reports are also briefly reviewed.

The DOE considers that a method provides reasonable assurance if it estimates the annual average radon-decay product concentration to within 50% at least 95% of the time. This means that the coefficient of variation of the measurement should be less than or equal to 25%. Devices deployed for intermittent sampling are required to demonstrate a coefficient of variation of 18% or less. The DOE studied repeated measurements made in actual homes to develop a protocol that yields results that meet these criteria. The first such study was of 33 homes in Grand Junction, in which Radon Progeny Integrating Sampling Units (RPISUs) were used to make repeated measurements over a year. The researchers randomly chose six sets of measurements made at two-month intervals and compared the average of the six to the overall annual average. The DOE researchers determined that the coefficient of variation for the six-sample average was 20%, with 12% due to sampling error, 13% to precision, and 10% to bias [32].

This study led to the six-sample method for estimating annual averages. In this protocol, a RPISU is used to make one-week measurements (of at least 100 h in duration each) spaced evenly throughout the year (a minimum of four weeks apart), and the average is used as the annual average [36]. The DOE also evaluated the Eberline WLM-1 radon decay product monitor and found it acceptable for substitution as the RPISU according to these same protocols [32].

Similar studies were conducted with other types of measurement methods, including diffusion barrier charcoal canisters [37], alpha-track detectors, continuous working level and radon monitors, and grab sampling. The DOE Technical Measurements Center (TMC) evaluated these results and determined that these are acceptable methods, following the specific protocols reviewed below. A device that could not produce a reliable estimate of the annual average and was rejected was the Passive Environmental Radon Monitor [35].

The DOE protocols specify that the room in which the measurement is to be made is that room which is expected to contain the highest randon decay product concentration. Rooms not currently occupied, including storerooms and basements, should be included. The DOE provides locations that should be considered for the measurement location in relative order of importance. These are (1) the lowest room in the structure, (2) the room with the highest gamma radiation levels, (3) the room with the lowest ventilation rate, (4) the room with the smallest surface-to-volume ratio (surface includes furnishings). The DOE recommends that, if no one such room is found, measurements be made in two rooms and the result from the room with the highest radon concentration be used.

The DOE advises that the location in the room for the measurement be chosen so that it is away from moving air

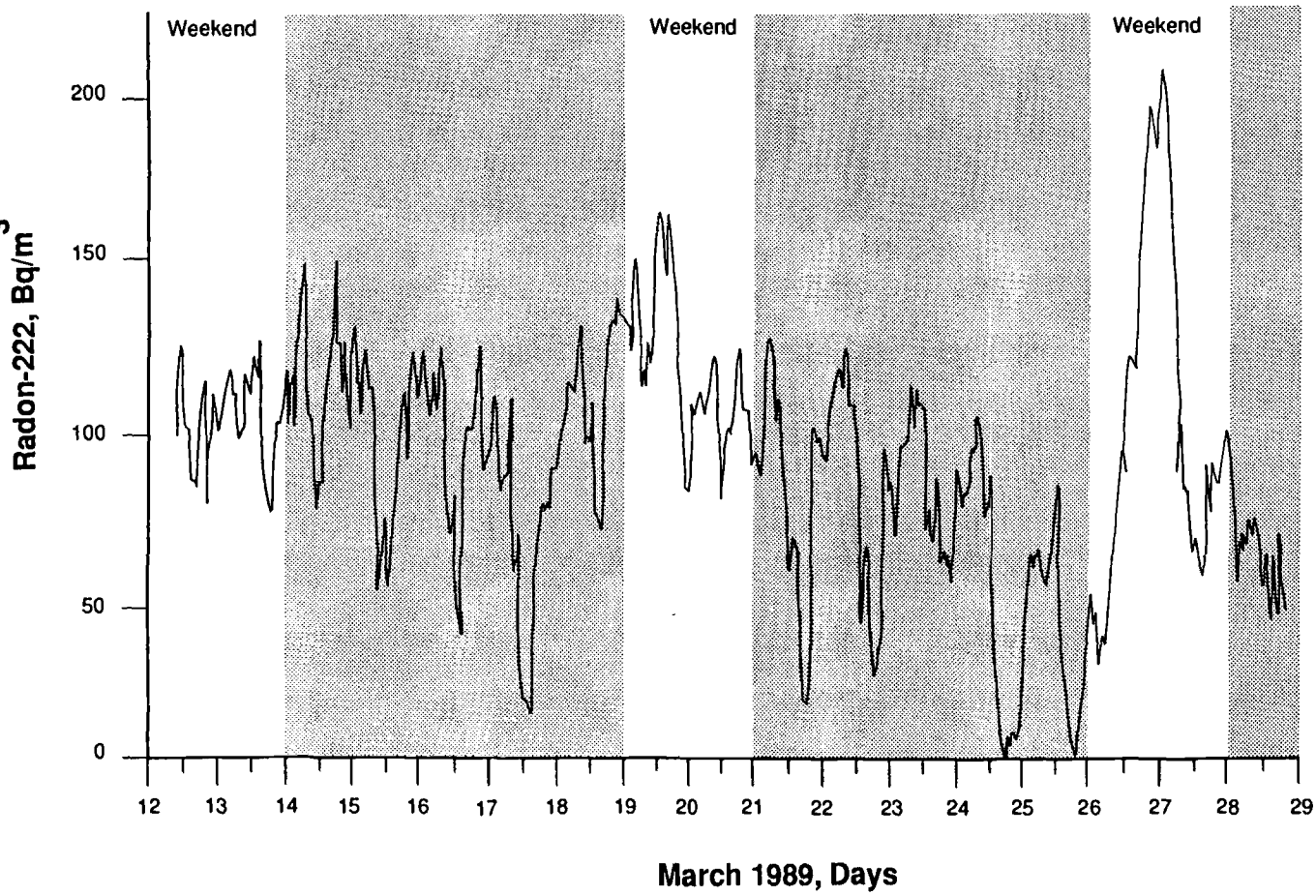

FIG. 6–Hourly radon-222 concentrations in test school during March 1989.

sources, about 45 cm from any surface, and closer to the inside than the outside walls.

The DOE issued two protocols for using alpha-track detectors to estimate annual radon decay product concentrations. The first is the Kodak-Pathe method, in which cellulose nitrate film is exposed without filters and the film is etched in sodium hydroxide according to the normal commercial process. The exposure period is one year. If the Kodak-Pathe technique is used, additional criteria for the location of the measurement are that sunlight never shines on the film, nothing is placed within 60 cm of the film, and the film is never touched or scratched during the exposure. The second DOE protocol for alpha-track detectors is the Filtered-Cup method, in which alpha-sensitive material is sealed in a container with a filtered opening that allows entry of radon gas [*39*]. These types of detectors are widely available. The exposure period is also one year. (See chapter 4 for additional details on alpha-track detectors.)

Two measurement methods that can be made over less than a year have been issued by DOE only for use in Mesa County, Colorado. These methods are based on extensive studies of test houses in Grand Junction in Mesa County. These are the Abbreviated RPISU and the Prompt Alpha-Track methods. The Abbreviated RPISU method allows the series of measurements to be terminated if one of the following two conditions occurs. If the levels are high enough so that the sum of the first few (at least two) results is greater than six times the standard, no further measurements need to be made. If the first few results are low enough so that the average of the measurements yet to be made would have to be at least twice the highest result so far for the full-year average to exceed the standard (and no more than one of these remaining measurements would be made during the winter months) the measurements may be terminated [*40*].

The Prompt Alpha-Track method allows for the estimation of the annual average radon concentration from the average of alpha-track measurements as short as two months, *if* the midpoint of the measurements are close to April 2 or October 2 [*41*].

The DOE also issued protocols for grab radon sampling under very specific circumstances [*42*]. This is when the building to be evaluated has a very high ventilation rate. The DOE reasons that there is a chance that the building, if used for a different purpose or by a different occupant, will have substantially decreased ventilation rates at some point in the future, and the radon decay product concentrations could increase. If the radon decay product concentrations are determined using one of the procedures described above, and if the ventilation rates are very high, then a radon grab method can be used. In this method, two radon grab measurements are made at different times. Only one measurement should be made during winter months. The following criteria are used to evaluate the results of the two grab measurements, and the results should be used as the annual average only if it is at

least twice the result found previously using another method. The criteria for evaluating the grab results are: (1) if the radon grab results differ by less than 30% of their mean, use the mean; (2) if the radon grab results differ by more than 30% of the mean, and both radon grab results are either higher or lower than the radon decay product standard, use their mean; (3) if the radon grab results differ by more than 30% of their mean and bracket the radon decay product standard, make a third radon grab measurement during the months when above-average concentrations are expected and use the mean of all three grab measurements as the annual average estimate.

There are also specific criteria for the conditions that must exist prior to and during a grab radon measurement made according to the DOE protocol. At least 12 h prior to and during sampling, all doors and windows must be closed, all ventilation systems must be turned off, the building should, if possible, be unoccupied, surface winds should be less than 10 miles per hour, and the atmospheric pressure must be stable.

The DOE protocols include requirements for quality assurance measurements. These include making 5% of the measurements in duplicate and several percent of the measurements as controlled exposures for calibrations. (Quality assurance measurements including duplicate measurements and calibration are discussed later in this chapter.) The number of background measurements are also specified for each technique in the DOE protocols.

U.S. EPA Protocols

The EPA has issued several reports on measurement protocols for residences, with initial protocols issued in 1987. Since then, the EPA has revised its philosophy and objectives for measuring radon in homes, as described in documents published in 1992 [*43*] and 1993 [*44*]. The EPA report issued in January of 1987 [*45*] describes the initial measurement strategy and is reviewed in published literature [*46*]. This section reviews the revised 1992 strategy recommended by the EPA.

The EPA has also issued technical reports describing different radon and radon decay product measurement methods, including technique-specific instructions and quality assurance guidance. EPA periodically issues revised versions as new methods are developed [*47,48*].

In the 1992 recommendations, EPA presents guidance for individual homeowners or for those undertaking large-scale measurement efforts for the purpose of determining the need for mitigation. The EPA prepared the recommendations to assist homeowners and others making measurements to obtain results that produce as few erroneous conclusions (e.g., to mitigate when it is not warranted or to decide not to mitigate when it is warranted) as possible.

The EPA investigated a variety of options for testing, including various "action levels," testing locations, durations, and ventilation conditions. The EPA used results from the National Residential Radon Survey [*49*] on the distribution of annual average radon levels and results from the State Radon Surveys [*50*] and other data on short-term measurements in conjunction with a statistical model [*43*]. This model was used to investigate each possible protocol in terms of how frequently it would result in homeowners making a correct decision on the need for mitigation.

The EPA also conducted research on how the public responds to information about radon [*43*] and found that the original recommendations presented in the 1987 protocols were not being implemented by the public, in part because the two-step process allowed homeowners to "drop out" of the testing process, and in part because most homeowners were not willing to perform a twelve-month measurement. Although EPA recognized the technical superiority of long-term versus short-term testing, EPA decided to accept that the public had proven its unwillingness to conduct long-term measurements. The statistical model applied by EPA evaluated the rates of false positive and false negative errors when the results of various testing options (in terms of measurement duration(s), location(s), and strategy) were compared to an "action level" triggering mitigation. The protocol that the EPA recommends in its 1992 guidance is based on the results of that analysis and is intended to maximize the total risk reduction the public may gain through future measurement and mitigation while minimizing error [*43*].

The protocol recommended by the EPA for use by homeowners to assess the need for mitigation is as follows. Initial measurements should be short-term tests placed in the lowest lived-in level of the home and performed under closed-building conditions. Short-term tests are conducted for 2 to 90 days. Closed-building conditions should be initiated at least 12 h prior to testing for measurements lasting less than four days and are recommended prior to tests lasting up to a week. If the short-term measurement result is equal to or greater than 150 Bq m^{-3} (4 pCi/L) or 0.02 WL, a follow-up measurement is recommended. Follow-up measurements are conducted to confirm that radon levels are high enough to warrant mitigation. If the result of the initial measurement is below 150 Bq m^{-3} (4 pCi/L) or 0.02 WL, a follow-up test is not necessary; however, the homeowner may want to test again sometime in the future, especially if a lower level of the house becomes more frequently used.

The duration of the follow-up test depends upon the results of the initial measurement. An initial result of 370 Bq m^{-3} (10 pCi/L) or 0.05 WL or greater should be followed by a second short-term test under closed-building conditions. If the result of the initial measurement is between 150 and 370 Bq m^{-3} (4 and 10 pCi/L) or 0.02 and 0.05 WL, the follow-up test may be made either with a short-term or a long-term (longer than 90 days) test.

The EPA recommends mitigation to reduce radon levels if the average of the initial and follow-up radon measurements is greater than 150 Bq m^{-3} (4 pCi/L) or 0.02 WL. If the follow-up test was a long-term test and the result is greater than 150 Bq m^{-3} (4 pCi/L) or 0.02 WL, the EPA recommends mitigation.

The EPA protocols specify that measurements made for the purpose of determining the need for mitigation be made in (1) the lowest lived-in area in the house, and (2) for short-term measurements only, during closed-house conditions. Potential locations for measurements include family rooms, living rooms, dens, playrooms, and bedrooms. The EPA recommends that measurements not be conducted in kitchens, laundry rooms, or bathrooms because of the likelihood that a fan may temporarily alter radon or WL concentrations, and that humidity and small airborne particles may affect the response of some detectors. The EPA's guidance for the loca-

tion of the measurement within the room includes that the measurement be further than 90 cm from exterior doors and windows, further than 30 cm from the exterior wall of the building, at least 50 cm from the floor, and at least 10 cm from other objects.

The EPA defines closed-building conditions as those existing when windows on all levels and external doors are closed (except during normal entry and exit). Internal-external air exchange systems (other than a furnace) such as high-volume, whole-house, and window fans should not be operating. However, attic fans intended to control attic and not whole-building temperature or humidity should continue to operate. Combustion or make-up air supplies should not be closed. Normal operation of permanently installed heat recovery ventilators and radon reduction systems may also continue to operate. Short-term tests lasting just two to three days should not be conducted during unusually severe storms or periods of unusually high winds.

The EPA recommends that closed-house conditions be maintained for at least 12 h before starting a measurement that is to last less than four days. Closed-house conditions are not necessary during measurements lasting longer than 90 days.

The EPA also presents recommendations for quality assurance in measurements. These are presented in several EPA documents [*44,48,51*]. In brief, they consist of making duplicate measurements in 10% of the measurement locations, or 50 per month, whichever is smaller; performing background measurements as a few percent of the total number of measurements; conducting spiked or known exposure measurements at a rate of three per 100 measurements, with a minimum of three per year and a maximum required of six per month; and conducting routine instrument performance checks. The EPA also presents recommended practices for furnishing results and information to consumers [*44*].

The EPA has also issued guidance for performing radon measurements specifically for real estate transactions [*44*]. These guidelines present three strategies for measurements made in the lowest level of the home suitable for occupancy. This is defined as the lowest level that is currently lived in, or a lower level, such as a basement, which a buyer could use for living space without renovations. The strategies for real estate testing are specific in terms of making the measurements tamper-resistant and allowing the detection of tampering. The options are too detailed to discuss here and are presented in EPA publications [*44,48*].

Strategies in Schools and Workplaces

Strategies in Schools

The EPA has assisted schools in testing for radon in a number of states and will continue assisting school districts to conduct surveys of schools throughout the country. Elevated radon levels have been found in schools in Virginia, Maryland, Pennsylvania, New Jersey, Florida, Tennessee, and other states. EPA has issued a report on radon in schools [*31*] that discusses the results of these studies and presents protocols for radon measurements in schools. The guidelines for selecting the rooms to be measured are summarized below:

1. Radon should be measured in all school rooms that are on or below ground level and that are frequently used, including classrooms, offices, cafeterias, libraries, and gymnasiums.
2. If a school does not have individual classrooms, measurements should be made at least every 200 ft^2 (18.58 m^2).
3. If all ground-floor rooms cannot be tested, then the rooms most likely to contain elevated radon concentrations should be selected, including rooms isolated from the central ventilation system, rooms on or near structural joints, rooms with a large floor/wall joint, and rooms that have significant cracks in the floor slab.

The EPA recommends that screening measurements in schools should be made during the cooler months of October through March. In warmer climates, measurements should still be made during the cooler months when windows and doors are more likely to be kept closed.

The EPA protocols for radon measurements in schools are similar to those for radon measurements in homes: both include a screening measurement as an initial test, followed by a confirmatory measurement before any permanent remedial action is taken. The EPA report discusses two options for screening measurements, the two-day (charcoal canister or short-term electret ion chamber) option and the three-month (alpha track detector or long-term electret ion chamber) option.

If using a two-day screening measurement, the recommended protocols are as follows:

1. A two-day measurement should be made during the weekend, with the ventilation system operating normally as it does during the week. Windows and doors should be kept shut.
2. If the result of a two-day screening measurement is greater than about 740 Bq m^{-3} (20 pCi/L), then confirmatory measurements should be made during conditions as similar as possible to those that existed during the screening measurement. Confirmatory tests should be conducted over a two-day to four-week period. The EPA report recommends that the shorter time period for confirmatory tests should be used when the result of the screening measurement was high, for example, greater than about 3700 Bq m^{-3} (100 pCi/L).
3. If the results of a two-day screening measurement are between about 150 Bq m^{-3} (4 pCi/L) and 740 Bq m^{-3} (20 pCi/L), then confirmatory tests should be made over a nine to twelve-month period.
4. If the results of a two-day screening measurement are less than about 150 Bq m^{-3} (4 pCi/L), then school officials need to consider on a case-by-case basis whether further measurements are necessary. The EPA cautions that long-term health risks for continuous exposure to levels near 150 Bq m^{-3} (4 pCi/L) are still significant.

A screening measurement made over a three-month period should also be made during the winter. There is one significant difference between the EPA-recommended action based on the result of a three-month measurement and that based on the result of a two-day measurement. If the results of a three-month screening measurement are greater than about

740 Bq m^{-3} (20 pCi/L), EPA recommends that school officials immediately begin investigating possible radon entry points by conducting diagnostic measurements.

The EPA report also gives school officials recommendations for remedial action, as well as guidelines for how quickly radon concentrations should be reduced.

Strategies in Workplaces

There is an increase in the number of office buildings being tested for radon. The most notable program for radon measurements in workplaces is mandated by Section 309 of the 1988 U.S. Indoor Radon Abatement Act. In this law, Congress called on each federal government department or agency that owns federal buildings to conduct a study to determine "the extent of radon contamination in their buildings." The studies are to be based on design criteria specified by the EPA Administrator and shall include testing of a representative sample of buildings in each high-risk area identified by the EPA.

The EPA has issued preliminary guidance to federal agencies for radon measurements in nonresidential buildings. These are as follows:

1. Measurements should be made in all occupiable (at least 520 h per year) rooms that are in ground contact, with a minimum of one detector per 2000 ft^2 (185.8 m^2).
2. Measurements should also be made in the unoccupied rooms in ground contact, with at least one detector per 2000 to 5000 ft^2 (185.8 to 464.5 m^2).
3. If the lowest occupied area is not in ground contact, a minimum of one detector per 2000 to 5000 ft^2 (185.8 to 464.5 m^2) should be used for each occupied floor.
4. Detectors should not be placed near elevators, stairs, and utility chases.
5. There should be at least one detector per floor.
6. Measurements should be made during the winter heating season.
7. Measurements conducted for longer than one month should be made under normal building conditions.
8. Short-term tests (less than one month) should be made with windows closed and ventilation systems operating normally but with minimum outside air intake.
9. Written quality assurance plans should be established by each agency, including the use of duplicates and blanks, and spikes if possible.

The EPA is assisting federal agencies in the development and review of their testing plans. It is anticipated that testing in commercial workplaces will use measurement protocols that are similar to the protocols established for federal agencies.

Strategies for Large-Scale Measurement Programs

There are many reasons for a large-scale survey involving measurements in many buildings. For example, the purpose of such a study could be to characterize a particular population of homes, often those in a specific area. The study may also have as a goal the characterization of a subset of homes, for example, all those in a smaller geographic area or all those of a certain construction type. These studies are usually called surveys, and this section will review factors that must be considered when planning a survey, as well as the protocols used by several different groups.

There are other purposes for making measurements in many buildings, including assessing the effects of different variables such as climate or geology on radon levels or epidemiological studies. However, those can dictate very specific measurement protocols, and examples are not discussed here.

Important Factors for Surveys of Geographic Areas

An exhaustive discussion of the factors that should be considered when planning a survey is outside the scope of this book. However, there are several issues that anyone planning a radon survey designed to characterize the radon levels in a geographic area should be aware of. The most important issue that is often overlooked is the nature of the process by which buildings are selected. An expert on survey design should be consulted to assist in the planning of a survey because it is impossible to obtain statistically meaningful results from a survey that is not constructed from a sample of homes based on some radom or systematic sampling scheme. Conversely, it is often surprising how useful such a sample can be in generating estimates of average radon levels for a particular population of homes or even a small subgroup of homes. These estimates can include confidence intervals.

The first factor to be defined is the target population. This is those homes that the survey is meant to represent. This may be all the homes in a particular area. This definition may have to be revised, however, when the logistics of obtaining a representative sample of homes from all the homes in an area is considered. For example, if the sample of homes to be chosen is based on a sample of telephone numbers, the target population can be only those homes in a particular area that have listed telephone numbers.

The next mechanism to be decided upon is the method of selecting the sample of homes to be measured. This can be done using telephone numbers, either by purchasing a list of telephone numbers from a marketing firm [*50*] or using the random-digit-dial technique [*52*]. Other methods include obtaining a random or systematic sample of homes from lists of registered motor vehicles or from other lists of households.

The protocol for measurement and the measurement technique to be used is dependent on the purposes of the survey and the constraints in time or budget of the investigators. Some surveys are limited to methods that use devices that can be mailed; others are limited to a short time period.

QUALITY ASSURANCE PROTOCOLS

In any measurement process, it is essential that the quality of the measurement results is validated by appropriate procedures. Procedures used to determine the quality of data in terms of precision, bias, and sensitivity are termed quality control procedures. Quality control programs for radon measurements in structures consist of five major components: (1) calibration of the instrument or detector system, (2) routine instrument performance and background checks, (3) analysis of known samples, (4) analysis of replicate or duplicate sam-

ples, and (5) analysis of blank samples. These quality control procedures are only part of an overall quality assurance program designed to ensure the validity of the measurement results. A quality assurance program includes:

1. *Quality assurance objectives*—The objectives of the measurements should be defined for bias, precision, sensitivity (lower limit of detection), and, where applicable, data completeness (the proportion of valid results to attempted measurements).
2. *Custody procedures*—There should be procedures that reduce lost data. Strict chain-of-custody procedures also ensure the admissability of data as legal evidence.
3. *Internal quality control checks*—The five components mentioned previously should be described in the standard operating procedures.
4. *Performance and systems audits*—Audits are used to determine the accuracy of the total measurement system and its components and to assess the ability of the system to meet the objectives of the measurements as they were defined in Item 1.
5. *Plans for corrective action*—Written plans for corrective actions in the advent of equipment malfunction or unsatisfactory results of internal quality control checks should be prepared prior to beginning the measurements.

Each individual laboratory is responsible for developing a quality assurance program. The program should contain written procedures to establish QA objectives and procedures for meeting those objectives. A system for documenting quality assurance measurements must also be developed. There are a number of reports that contain information on QA procedures, including those published by the EPA [*51,53,54*], in a book on quality assurance by Taylor [*55*], and in an article by Goldin [*56*].

The following sections review each of the five components of internal quality control measures.

Calibration

Calibration measurements are needed to determine the conversion factor to be used to convert the measured units to a radon concentration. Direct reading instruments and detector systems should be calibrated by exposure to known concentrations in a standardized radon calibration chamber. The chamber used should be one that has participated in intercomparison tests with other radon calibration chambers. These calibration factors should be determined over a range of radon concentrations.

The U.S. DOE provides calibration facilities for both research and commercial users. The Environmental Measurements Laboratory (EML) has for years been involved in the development and testing of methods and instrumentation for measuring radon and its decay products. The EML chamber is used routinely to evaluate measurement devices. EML hosts a semiannual radon intercomparison exercise [*57*] in which participants submit scintillation flasks to be filled with radon for analysis by the participant. Participants in this voluntary program include government, academic, and commercial investigators.

The DOE Technical Measurements Center (TMC) also runs extensive programs in radon instrumentation and method evaluation and calibration. TMC provides interlaboratory radon decay product comparisons [*58*] as well as commercial services for exposing radon and decay product measurement devices.

The Argonne National Laboratory provides QA support and research, but not to commercial clients on a routine basis. The U.S. Bureau of Mines has long been involved in the development and testing of radon and decay product measurement methods. They do not, however, provide routine exposures to the private sector.

There are a number of private facilities in the United States that offer radon exposure services. At several of these facilities, service contracts are offered to provide routine exposures on a monthly or quarterly basis for laboratory QA programs, generally for passive detectors. Radon concentrations are traceable to DOE-EML via the EML intercomparison program and to the EPA chambers through intercomparison and the EPA National Radon Measurement Proficiency Program.

Radon sources are also available commercially for laboratories who operate their own chambers. A Canadian company provides radon and decay product standardization products based on a dry powder radium source. This company provides sources that can be transferred to a scintillation cell, sealed sources, flow-through sources, and a passive source for chamber releases. Also available from this firm is a sealed source configured in a 10-cm-diameter cylindrical container of similar geometry to the 10-cm, open-face charcoal canister, which can be used as a check source for gamma counting of charcoal canister systems.

There are several organizations in the United States that currently provide calibration support to groups measuring radon and its decay products. The National Institute of Standards and Technology (NIST) provides standard reference materials (SRM) solutions of Rn-226 for calibration of instruments measuring Rn-222. The solutions of Rn-226, in a weak acid, with a carrier, readily release radon when nitrogen or other gases are bubbled through the solution. The standardized solutions, available in several concentrations, can be used to calibrate scintillation cells or ionization chambers.

NIST does not provide SRMs for radon decay products. Calibrations of instrumentation for measurements of radon decay products are generally accomplished by exposing the instruments in chambers with known concentrations of radon decay products. Similarly, continuous radon monitors and passive detectors are calibrated by exposure in chambers where radon concentrations are verified by methods traceable to SRMs.

The major organization involved in the quality control aspects of radon measurements by the commercial sector is the EPA. The Office of Radiation Programs in Washington, DC administers the National Radon Measurement Proficiency Program [*59*], which is a voluntary program designed to demonstrate the participant's competence to measure radon or decay products. The EPA does not accredit, certify, or endorse specific companies or methods, but provides a list of organizations that have met the requirements of the program.

Direct Reading Instruments and Scintillation Cell Detector Systems

Each individual direct reading instrument or scintillation cell should be calibrated in a calibration chamber and an instrument- or cell-specific calibration factor established. If resources do not allow each instrument or cell to be calibrated in a chamber, they should be carefully intercompared at least once every six months with a set of instruments or cells that have been calibrated by exposure in a chamber. The calibration factor for individual instruments and cells should be checked at least once every 12 months in a calibration chamber and adjusted as necessary. In addition, the calibration should be checked after instrument repair or modification.

Passive Radon Measurement Detector Systems

The calibration factor for a passive radon measurement detector system should be determined by exposure of a representative sample of detectors in a radon calibration chamber and measurement of the exposed detectors on the appropriate detection system. A minimum of 30 detectors should be exposed in determining the calibration factor. Preferably groups of ten detectors should be exposed to at least three different radon concentrations. Passive detection systems include alpha track detectors, activated carbon detectors, and electret ion chambers. Some charcoal detectors require calibration under various exposure times and conditions [*60*]. Calibration of the detector systems should be conducted once a year. Each new lot of detector material for alpha track detectors and charcoal canisters should be calibrated.

Instrument Performance and Background Checks

Proper operation of radiation counting instruments requires that their response to a reference source and a background sample be constant to within established acceptable limits. Therefore, counting equipment used in the measurement of radon should be subject to routine daily checks to ensure proper operation. This is achieved by counting an instrument check source and a background sample at least once per day. The characteristics of the check source (i.e., geometry, type of radiation, etc.) should whenever possible be similar to the samples to be analyzed. Similarly, the background sample should have a geometry and sample mixture as close as possible to the samples to be analyzed. The count rate of the check source should be high enough to give good counting statistics in a short period of time. A count rate of 1000 to 10 000 counts per minute is usually adequate.

The check source counts and background counts for each instrument are plotted on separate control charts following the procedures described by Goldin [*56*], Taylor [*55*], and the EPA [*51*]. These control charts have established warning action levels and control action levels. Most of the data should fall within the warning action level. The frequency with which data falls outside these action levels will determine the need for corrective action. The criteria and methods described by Goldin [*56*], Taylor [*55*], and the EPA [*51*] can be used in evaluating the need for corrective action based on the results of these performance and background checks.

Known Samples

The degree of systematic error, or bias, inherent in a measurement system should be evaluated on an ongoing basis through the measurement of known (spiked) samples. These samples are submitted for measurement without the analyst or analytical laboratory's knowledge that they are quality control samples. The EPA recommends in its guidance documents [*44,48*] that spikes should be conducted at a rate of three per 100 measurements, with a minimum of three per month and a maximum required of six per year.

The results of the analysis of known samples shall be evaluated to determine any bias in sample analysis and to identify the need to make adjustments in the calibration factors.

Replicate Measurements

The precision of a measurement method should be evaluated on an ongoing basis through the measurement of blind replicate measurements. These detectors are submitted for analysis without the laboratory's knowledge that they are replicates. Approximately 10% of the measurements should be replicate measurements.

Control charts are the usual way of evaluating quality control data for replicates. A range chart can be used to evaluate variations of replicate measurements among themselves. In constructing these control charts it is necessary to know the standard deviation of the method or to assign an acceptable standard deviation [*44,51,55,56*].

Although replicate measurements are more difficult to carry out using direct reading instruments, some replicate measurements using direct reading instruments are desirable during periods between calibrations.

Blank Measurements

The background signal that accumulates during the storage, shipping, and handling of detectors should be evaluated on an ongoing basis through the measurement of blank field measurements. These blank measurements should be stored, shipped, handled, and measured in the same manner as actual samples. The results of blank measurements should be evaluated to determine if additional corrections in the background signal are needed. If the average measurement for the field blank measurements is significantly greater than the laboratory background, the results of the field blanks should be used to correct for background. Several percent of the measurements made should be blank field measurements.

SUMMARY

Factors that can greatly influence the result of indoor radon measurements include the location of the measurement, the conditions under which the measurement is made, the time of day and year when the measurement is begun, and its duration. It is important for anyone measuring radon to understand the impact of these factors on the measurement result and to adopt or design measurement protocols that achieve the goals of the measurement program. The purpose of the measurements as well as the equipment, time, and

resources available will dictate the protocol that is developed for a particular program.

The DOE has issued protocols for measuring radon, including guidelines on the ventilation conditions in the house to be measured, the types of equipment used, the evaluation of the results, and the duration and times of year when the measurements should be made. The EPA has issued protocols for radon measurements in both residences and schools for purposes of determining whether mitigation is warranted and for pre- and post-mitigation measurements. In addition, the EPA has issued guidance that can be used as the basis for protocols for measuring radon in workplaces. Both the DOE and the EPA developed their protocols after studying the impact of various factors on the measurement results.

One of the most important factors that necessitate the use of a protocol is the variability of radon with time: radon concentrations vary significantly during the course of a year, a season, and a day. Protocols also need to provide guidelines for measurement location because radon levels are usually different in different levels of a house, often being several times higher in basements or first floors than on upper floors. Other important components of a measurement protocol are the quality assurance practices to be followed, including the objectives of the measurements and methods for determining their quality. The DOE has several longstanding programs for evaluating and intercomparing measurement methods, and the EPA has established a national program for assessing the proficiency of different organizations measuring radon.

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6

Geology and Occurrence of Radon

by R. Randall Schumann[1], Linda C. S. Gundersen[1], and Allan B. Tanner[2]

THE ACCUMULATION OF RADON INDOORS is commonly due to movement of radon from adjacent soil and rock into a building foundation through joints, utility openings, cracks, or porous block walls. When air pressure inside the building is lower than that in the soil, pressure-driven flow of radon-bearing soil gas can occur (see Chapter 2). Whether or not an indoor radon problem results depends on: (1) the radium concentration in the soil and underlying rock, (2) the ability of radon to escape from the solid material holding the parent radium, and (3) the ability of radon to move through the rock and soil fractures and pores.

The radium concentration in rock and soil is controlled by the uranium and radium concentration of the parent rock and on subsequent geochemical processes acting over time. The ability of radon atoms to escape from soil or mineral grains, quantitatively expressed as "emanating power" or "emanation coefficient," depends on the locations of the long-lived precursors of radon, ^{238}U, ^{234}U, ^{230}Th, and ^{226}Ra, at the times of their respective disintegrations, and the presence of water near the radium parent at the time of its disintegration. The mobility of radon is mostly dependent on the sizes and interconnection of pores and fractures and on how much water is present to impede soil-gas movement. Short-term variations in soil-gas radon concentrations may be caused by weather factors including precipitation, barometric pressure, and temperature.

On a broader scale, the soil properties that affect radon generation and transport are controlled by the geology of the parent rock and the physical and chemical weathering of the rock to produce soil. The rate and extent of these soil weathering processes are strongly influenced by climate. With an understanding of the physical and geochemical properties of rocks and soils, generalized estimates of radon potential can be determined for geologic provinces in the United States. A discussion of rock and soil properties that control the emanation and migration of radon, followed by a general description of the geology and radon potential of each major geologic province in the United States, are presented in this chapter.

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RADON EMANATION IN SOILS

When a radium atom disintegrates, it yields a helium atom, a radon atom, and kinetic energy that is shared by the two atoms. A small but important fraction of the excess energy causes the radon atom to recoil from the decay site and burrow through solid material. If its path carries it into a soil grain fissue or pore containing water, it may lose all its remaining kinetic energy in the water and remain in the pore; otherwise it may bury itself in more solid material and be unavailable to the pores. Because radium in soils tends to be concentrated on or very near the pore boundaries, and because most soils contain water in the finer fissures and capillaries, a significant fraction, usually 10 to 50%, of all the radon atoms produced come to rest in the pores. This fraction, the "emanating power" or "emanation coefficient," is lower in soils that are less than a few percent water saturated and probably in soils that are young relative to the half lives of ^{226}Ra (1600 years) and ^{230}Th (77 000 years). Conversely, in some old soils, equilibrium may have been established between the deposition and decay of ^{230}Th and radium, maximizing the radon source at the surfaces of soil pores.

RADON MOBILITY IN SOILS

Radon atoms in soil pores can move through the ground by diffusion, not necessarily involving any movement of the fluid in the pores (soil gas or ground water), or by convective or advective flow of the fluid, carrying radon along with it.

Diffusion

Diffusion is the mechanism by which radon atoms move along a concentration gradient from sites where the radon concentration is higher toward places where the radon concentration is lower. Diffusion is not very sensitive to pore or grain size, but it is very sensitive to the pore water content. The average distance of travel (the "diffusion length") of radon in dry soils was experimentally determined to be from 1.6 to 1.9 m, whereas in saturated soils it is only about 0.01 m [*1*]. Diffusion is the dominant transport mechanism in silty or clayey soils with permeabilities generally less than 10^{-11} m^2 [*2*].

Convection and Advection

Convective (vertical) and advective (lateral) flow occurs in response to pressure gradients within the fluids in soil pores and fissures. In the case of soil gas, the pressure gradients can occur within the soil air, between the soil air and atmospheric air, or a combination of both. Convection and advection are governed by the intrinsic permeability of the soil, the viscosity of the fluid moving through the soil pores, and the pressure gradient moving the fluid. At the small pressure gradients generated by underpressures in buildings, convection and advection become important in well-sorted fine sand and are dominant in coarse sands and gravels. As with diffusion, convection and advection are markedly reduced in wetter soils. A soil's permeability to water movement is a fair qualitative indicator of its permeability to gas movement, but a soil having an appreciable amount of water that is free to move through its pores would have a low permeability to gas flow. If the same soil is fairly dry, its gas permeability is much higher and its water permeability is much lower [*2*]. Soil structure can exert a strong influence on soil permeability and will be discussed in a following section.

Applications of Mobility Principles to Radon Potential

The mobility of radon is very strongly influenced by soil moisture content, and drainage plays a critical role in determining the soil's radon potential. If the presence of a house on a site causes a drying out of the soil beneath the house slab and subslab aggregate, the ability of radon to move upward to the subslab aggregate should increase.

In layered soils and those containing platy minerals such as clays, lateral movement of soil gas is favored and vertical movement of soil gas is inhibited. Where a low-permeability layer of soil is present above layers of higher permeability, a "permeability inversion" exists. A building foundation can then offer a path of less resistance to atmospheric pressure changes than the natural soil, forcing radon-bearing soil gas into the backfill, subslab aggregate, and foundation. The subslab aggregate and the backfill, if it is permeable, allow underpressure in a house to draw radon-bearing soil gas into the house, if entry routes are present.

Hillsides and ridges tend to have greater indoor radon potential because the soils are usually better drained and are composed of coarser and more permeable material. The soil cover is also usually thinner on hillsides, so that the bedrock, especially if fractured, can contribute significant amounts of radon.

SOIL CHARACTERISTICS

Although bedrock geology exerts an overriding control on radon distribution, soil characteristics are important in determining radon production and mobility. The importance of soil characteristics increases with the soil's age, thickness, and degree of development, as the soil's characteristics become increasingly different from those of its parent material. The most important factors are the soil's radium content and distribution, porosity, permeability to gas movement, and moisture content. These characteristics are, in turn, determined by the soil's parent-material composition, climate, and the soil's age or maturity. In theory, if parent-material composition, climate, vegetation, age of the soil, and topography are known, the physical and chemical properties of a soil in a given area can be predicted. An understanding of soil formation and weathering processes, and of their spatial and temporal variability, is an important part of a basic conceptual model for radon generation and transport in soils.

When rocks formed at great depths, commonly under high temperatures and pressures, are exposed at the surface by erosion and/or uplift, they are rarely in chemical equilibrium with the conditions that exist at the surface. Tectonic forces and unloading tend to weaken the rocks, making them susceptible to physical and chemical weathering. Physical weathering is the breakdown of rocks by erosional forces, expansion in cracks or along grain boundaries by freezing water or crystallizing salts such as gypsum or halite, or by thermal expansion and contraction. Physical weathering processes cause the parent rocks to be broken down into smaller fragments without significantly changing their mineralogy or chemical properties. In contrast, chemical weathering causes the chemical and/or mineralogical properties of the rocks to change through processes such as ion exchange, dissolution, chelation, hydration, and dehydration. Physical and chemical weathering occur together, often using different properties of the same agents; water is a notable example, as it can act as an agent in nearly all of the above-mentioned physical and chemical processes. In fact, movement of water through the soil is one of the most important processes in development of soil profiles because it carries dissolved and suspended substances downward into or through the soil, removes them completely from the soil, or forms completely new substances through chemical processes [*3*].

Structure, Texture, and Permeability

Soil texture and structure are especially important in determining radon transport characteristics because they directly influence permeability. Soil texture refers to the distribution and sorting of grain sizes within a soil unit. Most soil classification schemes use a ternary plot of the relative abundances of sand, silt, and clay in soil samples to assign the soil to a textural class, resulting in designations such as sandy clay or silt loam (Fig. 1). Soil permeability is determined by the number, size, and degree of interconnection of pore spaces, which are controlled by the size, shape, and arrangement of the soil grains or aggregates. Permeability is highest in coarse-grained, well-sorted, spherical materials (Fig. 2*a*) and lowest in poorly sorted and finer-grained materials where smaller grains and/or cements fill the void spaces between larger grains (Fig. 2*b*). Cracks and fissures in the soil also increase the soil's permeability.

Soil structure is the manner in which individual soil particles combine to form aggregates; these aggregates of soil particles are called peds. The shape and orientation of the peds control permeability and affect water and gas movement in the soil. Basic soil structure elements are illustrated in Fig. 3. Soils with blocky or granular structure have roughly equivalent permeabilities in the horizontal and vertical directions. In soils with platy structure, horizontal permeability is

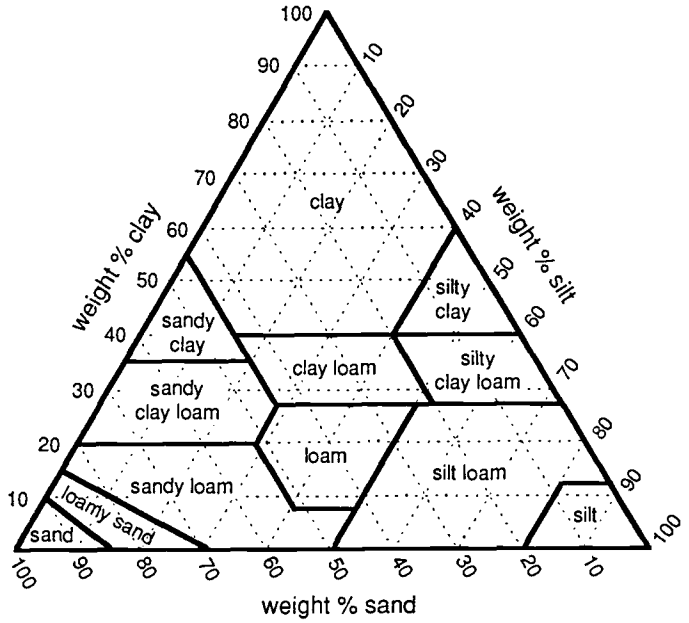

FIG. 1–Ternary soil classification system based on grain size [4].

much greater than that in the vertical direction, and moisture infiltration is generally slow. In soils with dominantly horizontal permeability, radon would be more likely to flow laterally into a building foundation (if a pressure gradient exists between the building and the soil) and less likely to escape to the atmosphere or be diluted by atmospheric air. Soils with prismatic or columnar structure have vertically dominated permeability, allowing soil gas to more easily escape to the atmosphere or atmospheric air to more easily enter the soil and dilute the soil gas. Platy, prismatic, and columnar structures form in soils with high clay contents. In soils with shrink-swell clays, moisture infiltration rates and depth of wetting may be limited when the surface soil layers swell shut upon addition of a relatively small amount of water. However, shrinkage of the clays can act to open or widen cracks upon drying, increasing the soil's permeability to gas flow during drier periods. Clay-rich B horizons, particularly those with massive or platy structure, can form a subsurface capping layer that impedes escape of soil gas to the surface [5].

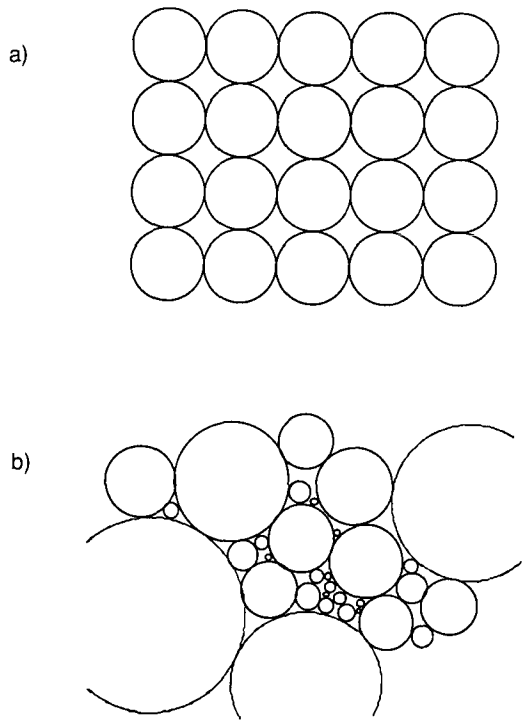

FIG. 2–(a) Uniform-sized grains with open packing (high permeability); (b) poorly-sorted material in which smaller grains fill interstices between larger grains (lower permeability).

Weathering Processes and Products

The process of soil formation involves physical and chemical interactions with the air and water that pass through the soil, often resulting in the formation of different chemical compounds (minerals, grain coatings, cements) than those that existed in the parent material. Biological processes also contribute heavily to the weathering process. Clays, iron and manganese oxides, and carbonates tend to preferentially sorb or complex with uranium and radium, so they can play a major role in determining the distribution of radionuclides in the soil. The redistribution of these materials may also change the grain-size distributions and control the presence and extent of grain cements, thus affecting permeability. The position and extent of these zones are controlled primarily by the soil's parent material mineralogy and chemistry, climate, and time. Parent material composition determines not only the initial amount and distribution of radionuclides in the soil, but also how the rock will interact with climate to form the soil, thus determining the soil's radon emanating power and transport characteristics.

Leaching and illuviation are the chemical and physical processes, respectively, by which mineral matter and dissolved solutes are moved downward through the soil profile and concentrated in discrete zones. Uranium can be removed from or concentrated in particular soil horizons by these processes, depending on the pH, dissolved-oxygen content, and presence and availability of humic and fulvic acids and other ions in solution. In general, solutes and mineral matter are removed from the A or E horizon and concentrated in the underlying B horizon. Radionuclides generally tend to follow this pattern as well. In a study by Rosholt et al. [6], the highest uranium concentrations in Minnesota till soils were found in the upper part of the B horizon. Hansen and Stout [7] noted that uranium and thorium concentrations are highest in the clay fractions of soils, but that the uranyl ion (UO_2^{+2}) also complexes readily with carbonates, migrating with calcium into the crystalline structure of calcium carbonate ($CaCO_3$) in calcic horizons. Uranium is commonly associated with iron oxides and hydroxides [8], including hematite and goethite, common weathering products in soils. Several researchers have noted a trend toward increased iron oxide content with depth and a general downward movement of the zone of highest iron oxide accumulation in well-drained soils with time [9]. However, the proportion of translocated iron is probably small compared to the amount of in-place formation of iron oxides by weathering processes.

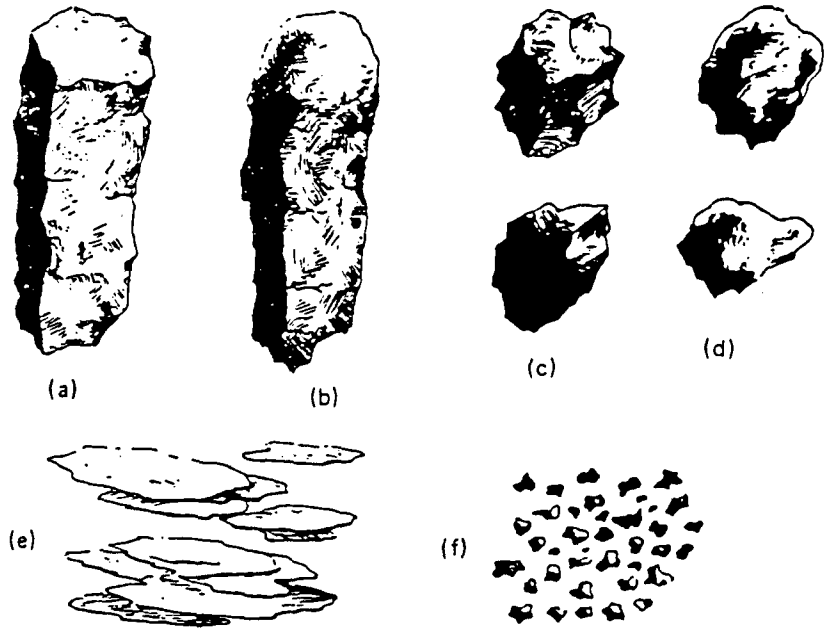

FIG. 3–Soil structure elements: (a) prismatic, (b) columnar, (c) blocky (angular), (d) blocky (subangular), (e) platy, (f) granular [4].

The radioactive decay of a uranium atom liberates enough energy to disrupt the crystal structure in the vicinity of the atom, making the host mineral more susceptible to leaching [*10,11*]. As rock and soil minerals are exposed to breakdown by various means, ^{234}U is leached from the exposed surfaces of the mineral grains and moves freely in the upper layers of most soils [*12*]. It decays to ^{230}Th, which is sorbed or precipitated on soil grain surfaces and organic matter. The oxide of thorium is extremely stable and insoluble [*13*], so that sorbed ^{230}Th and $^{230}ThO_2$ are likely to remain on the surfaces of soil grains or in solid coatings and cements wherever disintegration of the parent ^{234}U takes place.

Radium (^{226}Ra) is produced from ^{230}Th decay. Radium is an alkaline-earth element, like magnesium, calcium, strontium, and barium. Radium is practically never present in sufficient concentration to precipitate by itself with those anions, especially sulfate, that have a strong affinity for alkaline-earth cations, but it is preferentially coprecipitated with those elements. Radium is also efficiently scavenged by iron and manganese hydroxides and by organic matter. As a result, most radium atoms exposed to soil pore spaces stay attached to the grain surfaces or contained within cements or grain coatings. The process of weathering moves radium atoms from sites within mineral grains, where their liberated radon atoms will remain trapped within the grains, to sites on the periphery of grains, where liberated radon atoms will be available to pore spaces, thus significantly increasing the radon emanation coefficient of the soil over that of the parent rock.

CLIMATE AND WEATHER EFFECTS

Meteorologic conditions have a marked effect on radon transport in soils. The most important factors appear to be precipitation (as it affects soil moisture conditions) and barometric pressure. Temperature and wind appear to have less discernible effects, and there are conflicting observations in the literature concerning these factors.

Precipitation and Soil Moisture

If the discussion of meteorologic effects on soils is restricted to the unsaturated (or seasonally saturated) zone, an approximately direct correlation between wet- and dry-weather periods and soil-moisture conditions may be assumed. This is an oversimplification for individual precipitation events because it disregards the importance of antecedent soil-moisture conditions, but in a seasonal context, this relationship is valid. Radon exhalation into soil pores is enhanced at low to moderate soil-moisture levels (up to about 15 to 17 wt%) and inhibited at higher levels [*14,15*]. Radon transport is also generally inhibited by high soil moisture because water tends to block soil pores, reducing the gas permeability of the soil. In finer-grained soils, especially those with high clay contents, less moisture is necessary to inhibit transport because: (1) the pore spaces are smaller, (2) interlayer water molecules are electrostatically bound to the clay particles, causing clay-rich soils to dry out more slowly, and (3) expandable clays swell with the addition of moisture, closing pore spaces and cracks in the soil more readily than in a coarser-grained soil.

Capping is a moisture-related effect that increases measured soil-gas radon concentrations. Capping effects occur when the uppermost soil layers become saturated or the moisture in them is frozen, inhibiting the release of radon to the atmosphere and allowing radon to concentrate beneath the capping layer. The capping layer isolates the soil air from the atmosphere, suppressing barometric, thermal, and wind effects. Beneath the capping layer, the soil may be relatively dry and soil pores open, allowing, and sometimes enhancing, lateral movement of soil gas toward building foundations. Heavy rainfall can produce an effective moisture cap

[5,16,17], and freezing of the moisture in the uppermost soil layers appears to be a relatively common and efficient capping mechanism [15,18,19]. Capping may be enhanced during spring and fall, when the diurnal freeze-thaw cycle allows water to infiltrate the near-surface soil layers during the day and subsequently freeze at night. Capping occurs more readily in soils with expandable clays because the surface layers swell shut, blocking both radon exhalation and further infiltration of moisture. With moisture infiltration inhibited, soil horizons beneath the capping layer may remain permeable to gas transport for a considerable time after the surface becomes saturated. This effect may be quite significant in soils with clayey B horizons that act as the capping layer [17].

Soil structure, soil-moisture variations, and capping effects cause an order-of-magnitude variation in soil-gas radon concentrations in a clay-rich soil on the Denver Federal Center (DFC) in Colorado [5]. An extensive desiccation-crack system imparts a prismatic structure to the soil and allows deep infiltration of atmospheric air during dry periods. A good correlation exists between wetter and drier seasons and soil-gas radon highs and lows (Fig. 4). Moisture capping occurs when precipitation infiltrates the uppermost soil layers, causing the clays to swell and cracks at the surface to close. Percolation through the clayey soil is slow, so pores and cracks deeper in the soil may remain open for a considerable time after the surface has swelled shut, and radon accumulates beneath the capping layer. A moisture cap is more common during cool months because evaporation rates are lower, so the soil dries more slowly. At the DFC, the wetter season occurs during late winter, spring, and early summer and provides favorable conditions for the formation and maintenance of moisture caps (frozen or unfrozen).

A similar magnitude of seasonal variation in soil-gas radon concentrations was noted in soils formed on limestones in central Pennsylvania, except that the high values were recorded during the summer [20]. The lower winter values may

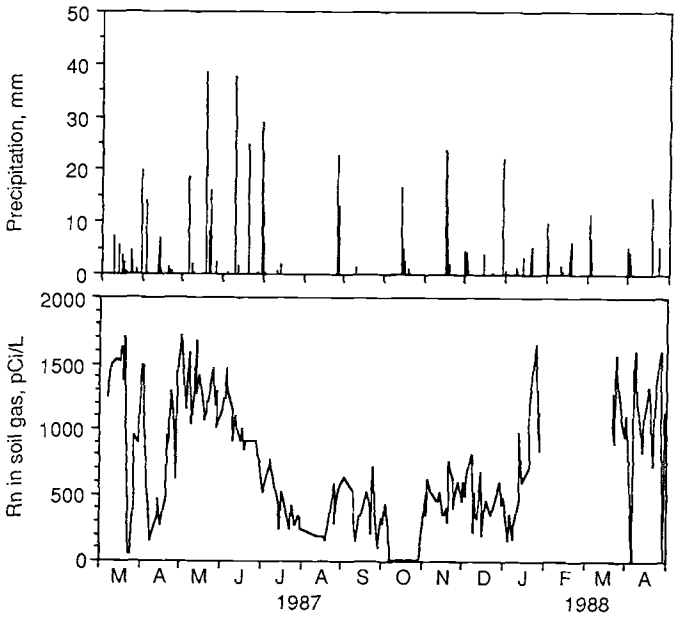

FIG. 4–Plots of soil-gas radon concentrations at 100-cm depth and precipitation at the Denver Federal Center for the period March 1987 to April 1988 [5].

be due to saturated soil conditions, which reduces gas permeability and the amount of radon available to the gas phase in the pore spaces.

Barometric Pressure and Wind

Changes in barometric pressure can cause significant changes in measured soil-gas radon concentrations. Falling pressure tends to draw soil gas out of the ground, increasing the radon concentration in the near-surface layers. Conversely, high or increasing barometric pressure forces atmospheric air into the soil, diluting the near-surface soil gas and driving radon deeper into the soil [15,16,18,19]. Bakulin [21] found that a decrease in pressure causes an increase in radon exhalation "proportional to the square of the pressure drop rate, [and to the] square of the gas permeable soil layer depth, and [radon exhalation] increases linearly with time, during which the radon concentration in the upper layer [of soil] increases." Clements and Wilkening [22] noted that pressure changes of 1 to 2% associated with the passage of weather fronts could produce changes of 20 to 60% in the radon flux, depending on the rate of change of pressure and its duration. Wind turbulence and the Bernoulli effect imparted by wind blowing across an irregular soil surface can draw soil gas upward from depth in a manner similar to that of decreasing barometric pressure [18,19,23].

Temperature

Some authors suggest that temperature has little or no effect on soil-gas radon content [15,19]. However, Ball et al. [24] found that changes in soil-gas radon concentrations correlate with changes in soil temperature and, to a lesser extent, with changes in air temperature. Kovach [19] reported higher radon emanation during temperature lows. Klusman and Jaacks [25] observed negative correlations between both soil and air temperature and radon concentrations and suggested that temperature gradients within the soil, or between the soil and air, can induce convective soil-gas transport. Temperature effects on radon exhalation have also been noted. In one experiment, radon exhalation rates in soil and shale samples increased by 50 to 200% in response to increasing the temperature of the samples from 5 to 22°C [26], whereas in another experiment, radon emanation increased approximately 10% when granite samples were heated from −20 to 22°C [27].

GEOLOGIC FACTORS

Uranium Mineralogy and Occurrence

Uranium is present to some extent in all rocks (Table 1). It forms its own family of uranium minerals, including uraninite, coffinite, tyuyamunite, carnotite, uranophane, autunite, and brannerite, or occurs in other minerals, the most common of which are heavy minerals such as titanite, zircon, allanite, and monazite. These minerals are found in predictable abundance in most rocks.

Rock types with uranium concentrations greater than 5 ppm that are most likely to cause indoor radon problems include carbonaceous black shales, glauconite-bearing

TABLE 1—Average uranium concentration in some common rock types (after Refs *8* and *28*).

Earth's crust	2.8 ppm
Basalt	0.5 ppm
Andesite	2.0 ppm
Granite and syenite	4.0 ppm
Metamorphic rocks	2.0 ppm
Black shale	10 ppm
Other shale	3.0 ppm
Sandstone	2.2 ppm
Limestone	1.3 ppm

sandstones, some fluvial sandstones, phosphorites, chalk, some carbonates, some glacial deposits, bauxite, lignite, some coals, uranium-bearing granites and pegmatites, metamorphic rocks of granitic composition, felsic and alkalic volcanoclastic and pyroclastic volcanic rocks, syenites and carbonatites, and many sheared or faulted rocks. The most common modes of occurrence of uranium and radium within these rocks are summarized in Table 2. Rock types least likely to cause radon problems include marine quartz sands, noncarbonaceous shales and siltstones, some clays and fluvial sediments, metamorphic and igneous rocks of mafic composition, and mafic volcanic rocks. Exceptions exist within these general lithologic groups because of the occurrence of localized uranium deposits, commonly of the hydrothermal type in crystalline rocks or the "roll-front" type in sedimentary rocks. Roll-front deposits are formed by oxidation-reduction reactions caused by the movement of oxidizing fluids through sedimentary rock. Uranium is mobilized by the oxidizing fluid and reprecipitated in a reduced zone along the margins of the solution front. The most common sources of uranium and radium are the heavy minerals and iron-oxide coatings on rock and soil grains and in organic materials in soils and sediments. Less common are phosphate and carbonate complexes and uranium minerals (Table 2).

TABLE 2—Rocks most likely to cause radon problems and the uranium and radium sources they host (compiled from Refs *8,28,29,30–34*].

Rock Types	Uranium/Radium Sources
Black shales, lignite, and coal	Uranium-bearing organic compounds; autunite; tyuyamunite
Glauconitic sandstones	Radium and uranium-bearing iron-oxides; heavy minerals
Fluvial and lacustrine sandstones	Roll-front deposits, which include uraninite, coffinite, pitchblende, secondary uranium minerals (tyuyamunite, carnotite, uranophane, and other uranyl vanadates); uranium and radium adsorbed onto organic material; iron and titanium oxides; placer deposits, which include heavy minerals
Phosphorite and phosphate	Phosphate complexes; apatite
Chalk and Marl	Phosphate complexes; apatite
Carbonates	Uranium and radium adsorbed onto iron-oxide coatings; radium with organic material in soils; tyuyamunite, carnotite, and uranophane in karst and caves
Glacial deposits	Bedrock-derived clasts that compose the glacial deposits are usually the principal source of radioactivity; uranium and radium bearing iron-oxide and carbonate coatings on clasts are common
Granites	Heavy minerals; uraninite; brannerite; apatite
Granitic metamorphic rocks	Heavy minerals; ultrametamorphic minerals, which include uraninite and uranothorite
Volcanic rocks	Heavy minerals; uranosilicates
Faulted rocks	Heavy minerals; uraninite; uranium precipitated with hematite and titanium oxide; minerals found in uranium vein deposits
Vein and vein-like deposits	Many kinds of uranium minerals; heavy minerals; apatite
Syenites, carbonatites, and pegmatites	Uraninite; other uranium minerals; heavy minerals
Bauxite	Heavy minerals

Radiometric Data

Aerial gamma-ray data can be used to quantify and describe the radioactivity of rocks and soils. Although radiometric data comprise spectral as well as total-count gamma-ray data, spectral gamma, particularly equivalent uranium (eU) data, are typically used because they provide an estimate of the near-surface concentrations of radon parent materials (uranium, radium) in rocks and soils. The majority of the gamma-ray signal is derived from the upper 20 to 25 cm of the surficial materials [*35,36*]. A gamma-ray detector is mounted in an aircraft that is flown over an area at a certain altitude, usually 120 to 150 m (400 to 500 ft). Equivalent uranium is calculated from the counts received by the gamma-ray detector in the wavelength corresponding to ^{214}Bi. This technique assumes that uranium and its decay products are in secular equilibrium. A contour map of eU is then produced for the area. Ground-based measurements of eU can also be made using a portable gamma spectrometer.

The primary source for aerial radiometric data in the United States is reports of the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s. These data have been integrated into a contour map of equivalent uranium for the conterminous United States [*37*]. NURE aerial radiometric data are best used for characterizing large areas such as a state or geologic province because of the relatively wide spacing between adjacent flight lines. The primary NURE flight lines are oriented east-west and are generally spaced 4.8 km (3 miles) apart in the western United States and 9.7 km (6 miles) apart in the eastern United States. With this flight-line spacing, a

large unmeasured area exists between flight lines. This is less important when data from several flight lines, covering a large area with relatively uniform geology, are integrated; however, localized anomalies may be overlooked. For example, the uranium anomaly underlying homes that have some of the highest indoor radon levels in the United States, located in the Reading Prong near Boyertown, Pennsylvania, is located between flight lines and therefore did not appear in the NURE reports. The entire Reading Prong, however, does display an elevated ^{214}Bi signature in the NURE reports.

Although radon is highly mobile in soil and its concentration is affected by meteorologic conditions, relatively good correlations have been noted between average soil-gas radon concentrations, average eU measured at the surface, and indoor radon values for some soils. Figure 5 is a plot of data from 278 measurements of equivalent uranium and radon in soil gas in Montgomery County, Maryland. A useful correlation is not discernible because of the high degree of scatter. However, when the data are grouped according to geology, as in Fig. 6, which shows data from only the sheared rocks, a correlation can be seen. A regional relationship can be determined by plotting the median values of eU against median soil radon values for each rock type (Fig. 7). The point that does not neatly fit the line is the one representing data from the sheared rocks, which have higher emanation coefficients and permeability and yield a much higher soil radon concentration than would be predicted by eU. When the undeformed rock types, excluding the sheared rocks, are plotted, a high degree of correlation is achieved (Fig. 8). This example illustrates that, when analyzed in the context of geology, radiometric data can be extremely useful for estimating radon potential.

RADON POTENTIAL IN THE UNITED STATES

Areas of the United States that are geologically similar can be grouped and delineated on a map (Fig. 9). Each area, referred to as a "geologic province," is characterized by a basic geology and climate that determine its radon potential.

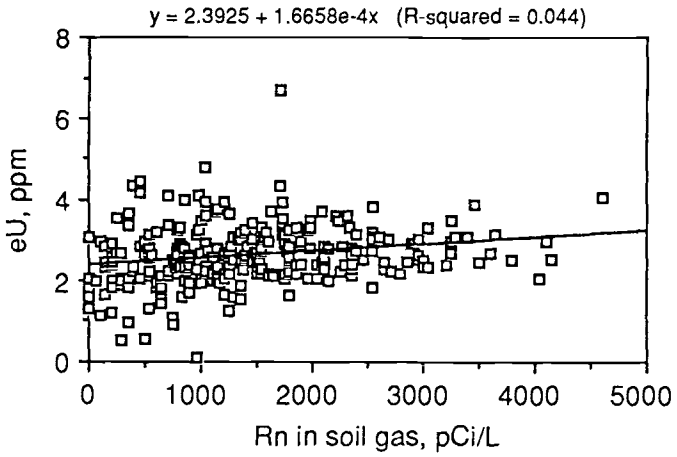

FIG. 5–Plot of radon in soil gas versus equivalent uranium for 278 samples collected in Montgomery County, Maryland [*38*].

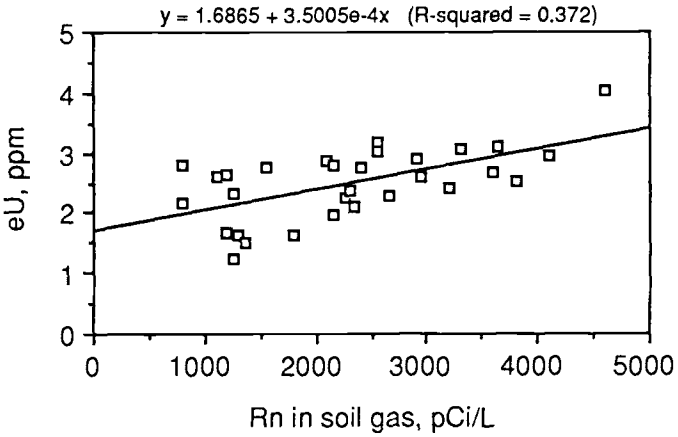

FIG. 6–Plot of radon in soil gas versus equivalent uranium for samples from sheared rocks in Montgomery County, Maryland [*38*].

By examining and correlating available geologic, aerial radiometric, soil radon, and indoor radon data, generalized estimates of the radon potential of each province can be made. The aerial radiometric data referred to in this section are from the compilation of NURE data into an equivalent uranium map of the United States [*37*]. Geologic information was obtained from the geologic map of the United States [*40,41,42*] and indoor radon data summarized from the State/EPA national indoor radon survey [*43,44*]. The following is a discussion of major geologic features and rock types and their known or expected radon potential for each geologic/physiographic province. In each case, large-scale, well-known, or highly anomalous features are discussed. This list is by no means exhaustive; rather, it is intended to give the reader a general feeling for the geologic features in each area that are likely to produce elevated indoor radon values, to point out important rock units or other geologic features where they are known, and to act as a general guide for using geology to predict radon potential on a regional scale.

Coastal Plain

The Coastal Plain of the southern and eastern United States has the lowest radon potential in the continental United States. Some of the lowest average values for aerial radiaoctivity and radon in soil gas have been recorded in this province. Soil radon, surface radioactivity, uranium and radium concentrations, permeability, and soil grain-size distributions have been measured along more than 1600 km of transects in five states underlain by Coastal Plain sediments [*45,46*]. In general, the data suggest that the Inner Coastal Plain (primarily Cretaceous and lower Tertiary rocks) has higher radon potential than the Outer Coastal Plain (middle to upper Tertiary and Quaternary rocks and sediments). Grab samples of radon in soil gas collected at a depth of 1 m averaged 26 000 to 37 000 Bq/m^3 (700 to 1000 pCi/L). The two highest soil radon measurements were taken in Inner Coastal Plain sediments: 600 000 Bq/m^3 (16 200 pCi/L) was measured in the glauconitic sands of the Nevasink Formation in New Jersey and 233 100 Bq/m^3 (6300 pCi/L) was measured in the carbonaceous shales of the Eagle Ford Group in Texas. In general, total uranium concentrations range from 0.5 ppm to

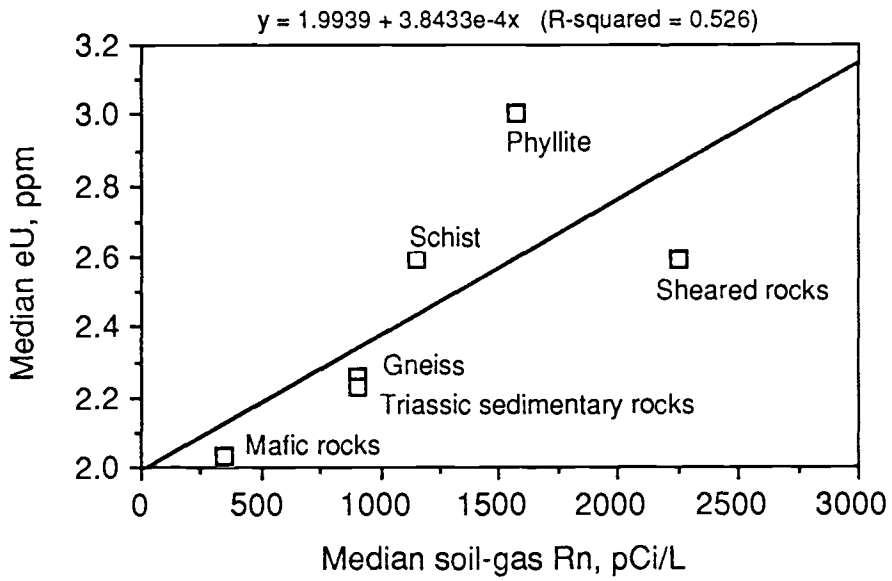

FIG. 7–Plot of median values for radon in soil gas and equivalent uranium in Montgomery County, Maryland, grouped by rock type [*38*].

as much as 4 ppm, with an average of 1.3 ppm. Radium-226 concentrations average 26 Bq/kg (0.7 pCi/g), and radium appears to be in secular equilibrium with uranium.

Comparisons with indoor radon data from the State/EPA Indoor Radon Survey (winter screening measurements from 1986 to 1989) and other data sources show good correlations among soil radon, radionuclide data, and indoor radon data. On the whole, they indicate a low radon potential; the geometric mean for indoor radon concentrations is 44 Bq/m^3 (1.2 pCi/L) or less in different parts of the outer Coastal Plain. Areas underlain by Cretaceous chalks, carbonaceous shales, phosphatic sediments, and glauconitic sandstones of the Inner Coastal Plain have an indoor radon average of 85 Bq/m^3 (2.3 pCi/L) and have the highest radon potential.

Localized concentrations of uranium in marine sands and phosphorites in Florida have produced some moderate to high indoor radon occurrences. The geologic units thought to be responsible for these problems include the Miocene Hawthorn, Alachua, and Bone Valley Formations. Uranium in some Tertiary sedimentary rocks in Texas may also be a source for elevated indoor radon levels. Heavy mineral deposits found throughout the Coastal Plain also have the potential for creating scattered local radon anomalies and are a potential source of thoron as well.

Appalachian Mountains

Much of the Appalachian Mountains province of the eastern United States is underlain by Proterozoic and Paleozoic metamorphic and igneous rocks. These rocks have low to moderate radon potential with localized areas of high potential. More than a thousand indoor and soil-gas radon mea-

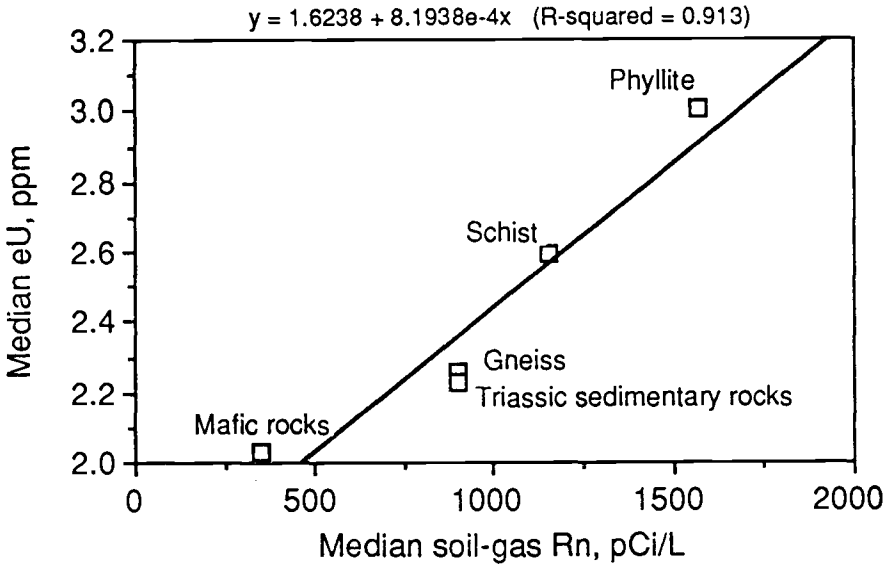

FIG. 8–Same plot as Fig. 7, excluding data point representing sheared rocks. Note high value of correlation coefficient.

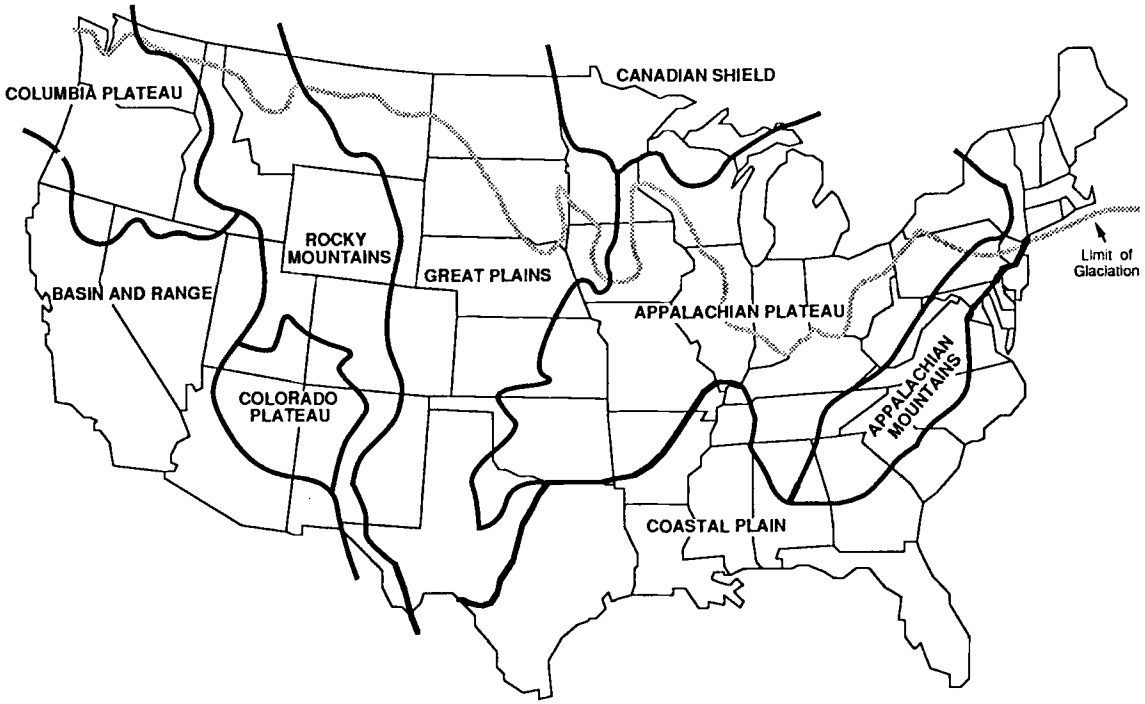

FIG. 9–Geologic/physiographic/radon potential provinces of the conterminous United States (based in part on Refs *39–42*).

surements have been averaged for metamorphic and igneous rocks in the Appalachian region of Pennsylvania, New Jersey, Maryland, and Virginia, and are plotted in Fig. 10 [*38,47,48*]. Studies thus far have yielded an average soil-gas radon concentration of 37 000 Bq/m^3 (1000 pCi/L) for rocks of granitic composition and an average of 22 000 Bq/m^3 (600 pCi/L) for rocks of mafic composition. Data from rocks of the Reading Prong and the Piedmont are included in the plot (Fig. 10). The plot shows that, on the average, the indoor radon concentration is approximately 1% of the soil radon concentration. Permeability and emanating power are the main factors affecting this relationship. Low permeability and emanation, such as in the mafic rocks, will cause this ratio to be less than 1%. In the sheared rocks, which have high emanation coefficients, the ratio is as high as 10%.

Paleozoic rocks cover an extensive area of the Appalachians and consist of sandstones, siltstones, shales, and carbonate rocks. The carbonate soils, black-shale soils, and black-shale bedrock can generate moderate levels of radon. Carbonate soils derived from Cambrian and Ordovician rock units of the Valley and Ridge Province cause known indoor radon problems in eastern Tennessee, eastern West Virginia, western New Jersey, and eastern Pennsylvania. The carbonate rocks themselves are low in uranium and radium. However, the soils developed on these rocks are derived from the residue that remains after dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including uranium. Groundwater derived from these areas, however, commonly contains radon concentrations of 37 000 Bq/m^3 (1000 pCi/L) or less [*49,50*]. Carbonate rocks also form karst topography, characterized by solution cavities, sinkholes, and caves, which increase the overall permeability of the rocks in these areas. Rinds containing high concentrations of uranium and uranium minerals can be formed on the surfaces of rocks affected by $CaCO_3$ dissolution.

In the Appalachians, the highest indoor, soil, and water radon values occur in association with faults and fractures in the rock [*30,48,51,52*]. Fault zones may be responsible for the majority of very high radon occurrences in the United States. The two highest known indoor occurrences are associated with sheared fault zones in Boyertown, Pennsylvania [*47*],

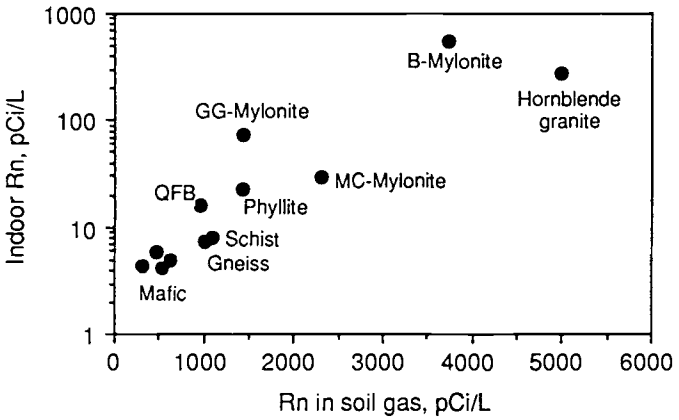

FIG. 10–Plot of average soil radon against average indoor radon concentrations for rock types in the northeastern United States. The data represented by these points are from the following areas: Mafic rocks—Montgomery County, MD [*38*], Boyertown, PA [*47*], and Glen Gardner, NJ [*48*]; Schist, Gneiss, and Phyllite—Montgomery County, MD [*38*]; Hornblende granite—Glen Gardner, NJ [*47*]; QFB (quartz-feldspar-biotite gneiss)—Boyertown, PA [*47*]; Mylonites: MC—Montgomery County, MD [*38*], GG—Glen Gardner, NJ [*48*], B—Boyertown, PA [*47*].

and Clinton, New Jersey [*53,54*]. The highest radon concentrations in groundwater appear to be associated most commonly with concentrations of uranium and radium in shear zones, coating fractures and faults, and coating grain surfaces in two-mica granites and high-grade metamorphic rocks [*55,56*]. Uraniferous granites from Maine to Georgia produce many of the severe indoor radon problems and the most severe waterborne radon problems in the Appalachians.

Appalachian Plateau

The Appalachian Plateau province contains areas of low, moderate, and high radon potential. The carbonate soils and shales associated with domes or basins in this part of the United States have moderate to high radon potential. Of specific interest are the uranium-bearing Upper Devonian and Lower Mississippian Chattanooga and New Albany Shales in Kentucky and Tennessee [*57*], the Devonian and Mississippian black shales in Ohio, Pennsylvania, New York, and Indiana, and the Ordovician, Mississippian, and Pennsylvanian carbonate rocks and black shales in Alabama, Indiana, Tennessee, Kentucky, Michigan, Illinois, Missouri, Iowa, and Arkansas [*58*]. Although exposed in a limited area, Precambrian granites in southeastern Missouri are among the most highly uraniferous igneous rocks in the United States [*59*]. A large area of low radon potential is underlain by the Lower and Middle Pennsylvanian Pottsville Sandstone and equivalent units, which extend from eastern Ohio through West Virginia, eastern Kentucky, east-central Tennessee, and northern Alabama.

Great Plains

The Great Plains are also characterized by extensive basins, although these are much younger than those in the Appalachian Plateau province. Marly clays and black shales of the Upper Cretaceous Niobrara and Pierre Formations are uranium bearing and are suspected of causing many of the indoor radon problems in South Dakota, Kansas, and eastern Colorado [*60*]. Roll-front uranium deposits in Tertiary sedimentary rocks in the Powder River, Shirley, Wind River, and Red Desert basins, and the Gas Hills, Wyoming, have high radiometric signatures on the national eU map [*37*], but the extent of indoor radon problems they may cause is not known. Members of the White River Group are significant radon producers in the northern and central Great Plains, whereas the Ogallala and Arikaree Formations are principal sources for indoor radon in the central and southern part of the province from Colorado to west Texas. Carbonaceous shales and uranium-bearing coals in the Tongue River member of the Fort Union Formation [*61*] and the White River Group in unglaciated southwestern North Dakota generate locally very high radon levels. Other Tertiary sedimentary units, including the Green River, Wasatch, and Fort Union Formations and their equivalents, are also exposed in the area from Colorado to eastern Montana, but are of less importance in terms of radon potential. Also included in this area are the Black Hills of southwestern South Dakota, which are underlain by Precambrian granitic and metamorphic rocks and Paleozoic sedimentary rocks with moderate radon potential.

Rocky Mountains

The Rocky Mountains have a radon potential similar to that of the Appalachian Mountains for many of the same reasons. The metamorphic and igneous rocks in the Rocky Mountains are generally similar in composition, degree of deformation, and granitic intrusion to those of the Appalachians. However, the Rocky Mountains have undergone several periods of intense and widespread hydrothermal activity creating vein deposits of uranium that cause localized high concentrations of indoor radon and radon in water in Colorado and Idaho [*62,63,64*]. Colluvium and alluvium derived from crystalline rocks of the Rocky Mountains cover much of the plains east of the Front Range from New Mexico to Canada and cause known moderate indoor radon problems in Colorado and Idaho [*64,65*]. In the Wyoming Basin, the Permian Phosphoria Formation has moderate to high radon potential. It covers an area of 350 000 km^2 in southeastern Idaho, northeastern Utah, western Wyoming, and southwestern Montana and has a uranium content that varies from 0.001 to 0.65% (10 to 6500 ppm). Other rocks with high radon potential in the Wyoming Basin are the Cretaceous Mancos Shale, which is uraniferous in places, and Tertiary sandstones, siltstones, and shales, which contain uranium deposits and uranium-bearing coals.

Basin and Range and Colorado Plateau

The Basin and Range and Colorado Plateau provinces, located between the Rocky Mountains and the Sierra Nevada, include most of the sedimentary-rock hosted uranium reserves of the United States. Significant uranium deposits occur in Mesozoic sedimentary rocks of the Colorado Plateau. Localized sandstone-type uranium deposits are hosted by the Upper Triassic Chinle and Upper Jurassic Morrison Formations in this area. Mine tailings from such sedimentary deposits caused some of the earliest detected indoor radon problems [*66*]. Tertiary volcanic rocks in Nevada and Arizona are also high in radioactivity. Because this area is sparsely populated, there is a paucity of indoor radon information and relatively little is known about its actual radon potential.

Sierra Nevada, Pacific Coast Ranges, and Great Valley

The Pacific Coastal Range and Sierra Nevada, included in the Basin and Range province on Fig. 9, are areas of high radioactivity on the eU map of the United States. The Sierra Nevada is underlain by Paleozoic and Mesozoic metamorphic rocks, with the metamorphic rocks dominant in the northern part of the range and the granites dominant in the southern part. Tertiary volcanic rocks are also found in the northern part of the range. The granites of the Sierra Nevada Mountains are very high in uranium content and have high radon potential, as does the colluvium formed from the granites on the eastern and western flanks of the mountains. The granite and colluvium are associated with high indoor radon in Nevada as well as California.

The Southern Coast Ranges include the Franciscan Formation, a complex assemblage of metamorphosed marine sedimentary rocks and ultramafic rocks, Cretaceous and Tertiary

sedimentary rocks, and Mesozoic metamorphic and igneous rocks. The Tertiary marine sediments and Mesozoic igneous and metamorphic rocks are uraniferous and have moderate indoor radon associated with them. The Miocene Rincon Shale may be the source for indoor radon levels exceeding 150 Bq/m^3 (4 pCi/L) in 75% of the homes in Santa Barbara County [67].

The Great Valley of California is underlain by alluvium and colluvium derived from both the Coastal Ranges and the Sierra Nevada. Its radon potential is moderate overall but is controlled by source rock and permeability, causing locally high indoor radon levels.

Columbia Plateau

The Columbia Plateau is underlain predominantly by Tertiary volcanic rocks extruded over an older basement complex of igneous and metamorphic rocks. Tertiary marine deposits occur along the western coasts of Washington and Oregon. A comprehensive radon potential assessment of the area has been made by Duval et al. [68]. They found that on a township scale, radiometric data and indoor radon data corresponded very well and indicated an overall low to moderate radon potential. Tertiary marine deposits, local areas of highly permeable, dry soils and permeable soils formed on steep slopes, yielded high indoor radon values in areas that were not indicated as such by the aerial radiometric data. The Willamette River Valley also has moderate radon potential overall. Much of the area has moderately elevated uranium concentrations in soils, and many areas have excessively drained soils and soils with high emanating power. Many townships in the valley have indoor radon averages between 75 and 150 Bq/m^3 (2 to 4 pCi/L). Precambrian granites and metamorphic rocks exposed in the northern part of Washington are uranium bearing (as much as 17 ppm) and host mineable uranium deposits [8]. The generally elevated uranium content and radioactivity signature of these rocks suggest that this area may have a moderate to high potential for elevated indoor radon values.

Canadian Shield, Glaciated Areas

The northern part of the United States is underlain by Pleistocene glacial deposits. The southernmost extent of continental glaciation is delineated by a dotted line on Fig. 9. Glaciated areas present special problems for assessment because bedrock material is often transported hundreds of kilometers from its source. Glaciers are quite effective in redistributing uranium-rich rocks; for example, in Ohio, uranium-bearing black shales have been spread over much of the western part of the State, now covering a much larger area than their original outcrop pattern, and they create a prominent radiometric high on the radioactivity map of the United States. The physical, chemical, and drainage characteristics of soils formed from glacial deposits vary according to source bedrock type and the glacial features on which they are formed. For example, soils formed from outwash or ground moraine deposits tend to be more poorly drained and contain more fine-grained material than soils formed on moraines or eskers, which are generally coarser and well drained. In general, soils developed from glacial deposits are poorly structured, poorly sorted, and poorly developed, but are generally moderately to highly permeable and are rapidly weathered because the action of physical crushing and grinding of the rocks to form tills may enhance and speed up soil weathering processes [69]. Clayey tills, such as those underlying most of North Dakota and a large part of Minnesota, have high emanation coefficients [70] and usually have low to moderate permeability because they are mixed with coarser sediments. Soils formed on tills consisting of mostly coarse material tend to emanate less radon because the larger grains have lower surface area-to-volume ratios, but because these soils have generally high permeabilities, radon transport distances are generally longer, so buildings constructed in these soils are able to draw soil air from a larger source volume. Thus, moderately elevated indoor radon concentrations may be achieved from comparatively lower radioactivity soils [71,72].

Glacial drift derived largely from the Pierre Shale in North Dakota and from crystalline rocks of the Canadian Shield in Minnesota generate elevated indoor radon levels in a large number of homes. Glaciolacustrine silty clays deposited by glacial Lake Agassiz, in the present-day Red River Valley along the Minnesota-North Dakota State line, display a prominent, moderate aerial radioactivity anomaly and have produced a significant number of elevated indoor radon levels. Precambrian granites and metamorphic rocks of the Canadian Shield, which underlie much of northern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan, may produce elevated radon levels where these rocks are exposed at the surface or are covered by a thin veneer of glacial drift in the area delineated on Fig. 9. However, these rocks also provide a bedrock source for glacial drift that has been transported to the south and east of this area as well, and may cause problems in areas where they are a major source component in the tills [73,74]. Other rock types with moderate radon potential are poorly sorted glacial tills and moraine deposits derived from uranium-bearing granites and metamorphic rocks in New England, southern New York, Connecticut, and New Jersey.

South of the glacial limit, loess deposits also cover extensive areas of the Great Plains and Appalachian Plateau. Soil-gas radon and uranium concentrations of loess in Tennessee indicate the possibility for moderate radon potential over these deposits [46].

CONCLUSIONS

Indoor radon has several possible sources: outdoor air, natural gas, building materials, domestic water derived from wells or springs, and rock and soil. Of these sources, the air contained in the pores of soil and rock is the most common source of indoor radon at levels high enough to be of concern. The geology of a locality determines the concentrations of the uranium-series radionuclides in the rock and soil and the ease with which radon and radon-bearing fluids can move through them. Rock types that are most likely to cause indoor radon problems include black shales, glauconite-bearing sandstones, some fluvial sandstones, phosphorites, chalk, some carbonate rocks, some glacial deposits, bauxite, lignite, some coals, uranium-bearing granites and pegmatites, meta-

morphic rocks of granitic composition, felsic and alkalic volcanoclastic and pyroclastic volcanic rocks, syenites and carbonatites, and many sheared or faulted rocks.

Climate has a strong influence on the redistribution of the long-lived radionuclides of the uranium series and on the short-term mobility of radon in the ground. The indoor radon potential of an area may be assessed by considering the geology, soil type, and climate, and, if possible, by making supplementary measurements of radioactivity and critical soil characteristics such as permeability and moisture content.

Areas of the United States with high radon potential include: *NL-test 4.

1. *The Proterozoic rocks of the Appalachian and Rocky Mountains.* These uraniferous metamorphosed sediments, volcanics, and granite intrusives are highly deformed and often sheared. Shear zones in these rocks cause the highest indoor radon problems in the United States.
2. *Glacial deposits of the northern Midwest, particularly those derived from uranium-bearing shales and glacial lake deposits.* The clay-rich tills and lake clays have high radon emanation coefficients, in part because of their high specific surface areas, and exhibit higher-than-expected permeabilities due to desiccation cracking when dry.
3. *Devonian and Cretaceous black shales.* The Chatanooga and New Albany Shales and their equivalents in Ohio, Tennessee, and Kentucky and some members of the Pierre Shale in the Great Plains are often moderately uraniferous and have high emanation coefficients and high fracture permeability.
4. *Phosphorites.* Natural and manmade accumulations of phosphorites in Florida, phosphatic clays in Georgia and Alabama, and the Permian Phosphoria Formation in Wyoming, Idaho, Utah, and Montana are typically associated with uniformly high concentrations of uranium or anomalously high concentrations of uranium caused by subsequent physical and/or chemical alteration of the rocks.

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7

Concentration Patterns

by Michael D. Koontz[1]

DURING THE 1970S AND EARLY 1980S, radon measurements collected in U.S. residences resulted mainly from isolated research efforts involving a variety of measurement techniques and relatively small numbers of homes. As described by Nero et al. [*1*], most of these data sets were collected either (1) as a basis for estimating the potential effects of reduced air infiltration due to energy conservation measures or (2) to better characterize certain geographic areas thought to have a high likelihood of elevated indoor radon concentrations. After carefully assimilating and analyzing these collective data sets, the authors projected that approximately 7% of U.S. residences had average indoor radon concentrations at or above 148 Bq/m^3 (4 pCi/L), the level at which the U.S. Environmental Protection Agency (EPA) has recommended that citizens take action to reduce their exposures [*2*]. More recently, a nationwide survey of annual average radon concentrations by the EPA [*3*] has indicated that about 6% of U.S. residences would be expected to have average indoor concentrations at or above 148 Bq/m^3.

Attention increasingly focused on indoor radon during the mid-1980s, particularly with the discovery in late 1984 of a house on the Reading Prong geological formation in southeastern Pennsylvania with an indoor concentration exceeding 37 kBq/m^3 (1000 pCi/L). Soon thereafter, states such as Florida [*4*], New Jersey [*5*], and New York [*6*] initiated statewide radon measurement surveys. At about the same time, the EPA began to offer assistance to states in the design and conduct of statewide surveys [*7*]. Through this effort, ten states were surveyed during the 1986–1987 winter season, seven states during 1987–1988, eight states during 1988–1989, nine states during 1989–1990, and six states during 1990–1991 [*8*].

The focus of this chapter is on the radon concentration patterns and related factors that can be deduced from the systematic statewide studies conducted as of 1991. Following an initial summary of measurement results from national and regional perspectives, results at state and sub-state levels are presented. The chapter concludes with a presentation and discussion of illustrative efforts to correlate radon concentration patterns with other factors such as structural features of residences, radiometric results from aerial surveys, geologic profiles, and soil measurements or characteristics. The data reported in this chapter are useful for examining radon concentration patterns from various geographic perspectives, but are inappropriate for assessing health risks. As discussed below, the data are based on results of short-term screening measurements, which tend to overstate long-term exposures and associated risks that would occur under normal living conditions.

To provide a common basis for comparison, the measurement results presented in this chapter are restricted to those resulting from statewide surveys which used activated-carbon monitors (charcoal canisters) for short-term screening measurements lasting several days. Because such measurements typically have been taken during the winter in the lowest level of a residence under closed-house conditions, the results will overstate the fraction of homes with an annual radon concentration above a given level of concern (e.g., 148 Bq/m^3). Statewide surveys that have been conducted in New York [*6*] and California [*9*] with longer-term integrating samplers are not included because the results would appear artificially low relative to the screening results from other states.

The results included in this chapter also are restricted to those surveys based on randomly selected sets of residences. Most such samples have been drawn from published or computerized lists of residential telephone numbers. As illustrated by Ronca-Battista et al. [*7*], surveys involving volunteers or test kits purchased by individual homeowners tend to have positively biased results, most likely because the participants disproportionately represent areas known or thought to be at higher risk. For this reason, relatively comprehensive data bases that have not resulted from random samples, such as those reported by Alter and Oswald [*10*] and by Cohen and Nason [*11*], are excluded from this analysis, as are data sets from regions such as the Pacific Northwest [*12*].

NATIONAL AND REGIONAL PERSPECTIVES

Figure 1 indicates the states from which measurement results have been assembled to provide the summary statistics given in this chapter, together with the number of measurements taken in each. Of the 40 states assisted by the EPA in conducting measurement surveys as of 1991, results are included for all but two, Colorado and Connecticut, in which the surveyed housing units were not randomly selected. Results from three additional states—Florida [*4*], New Jersey [*5*], and New Hampshire [*13*]—that initiated their own radon sampling programs without EPA assistance are also included. The 41 states represented by the results presented herein collectively account for about 85% of the owner-occu-

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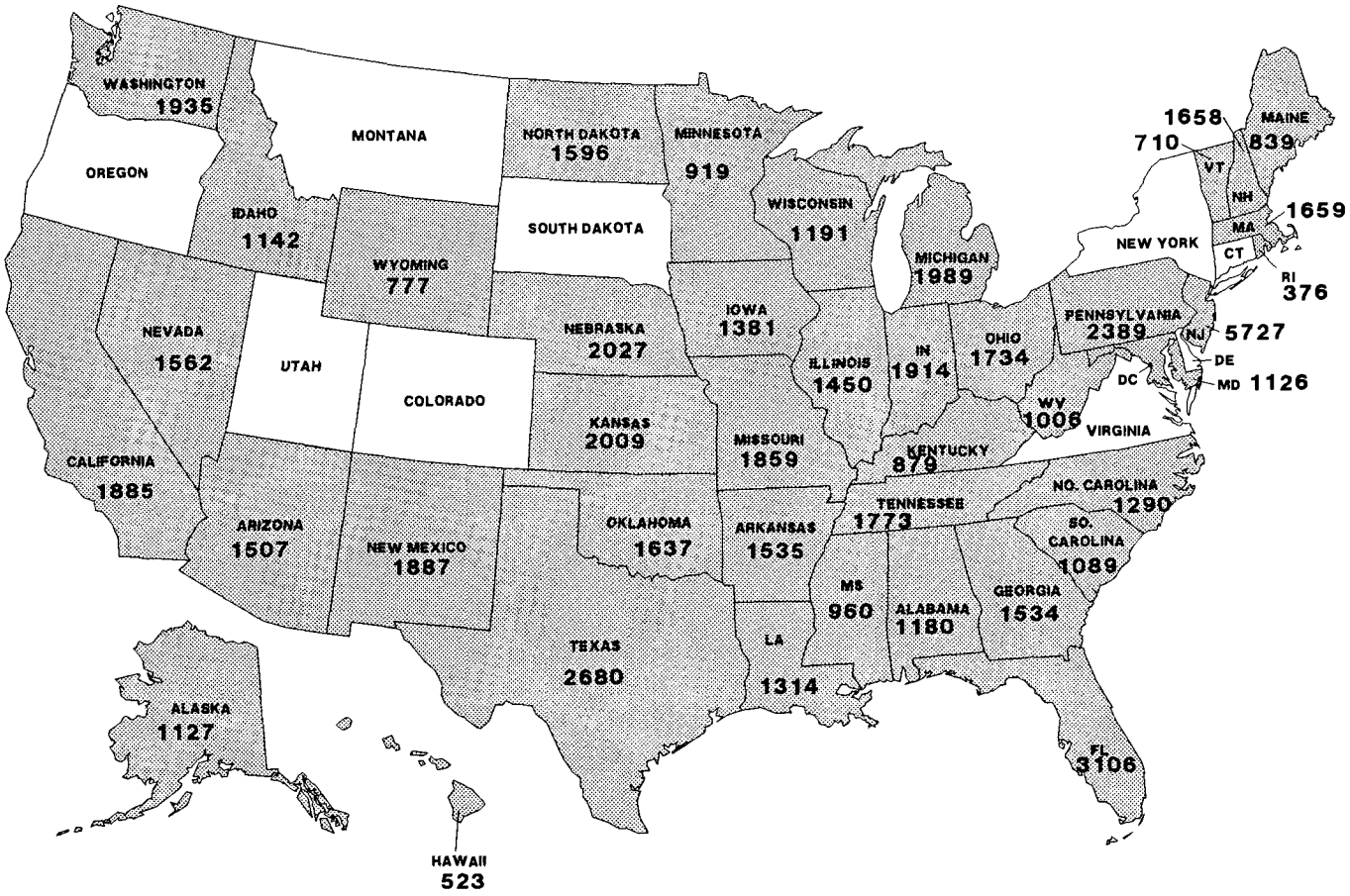
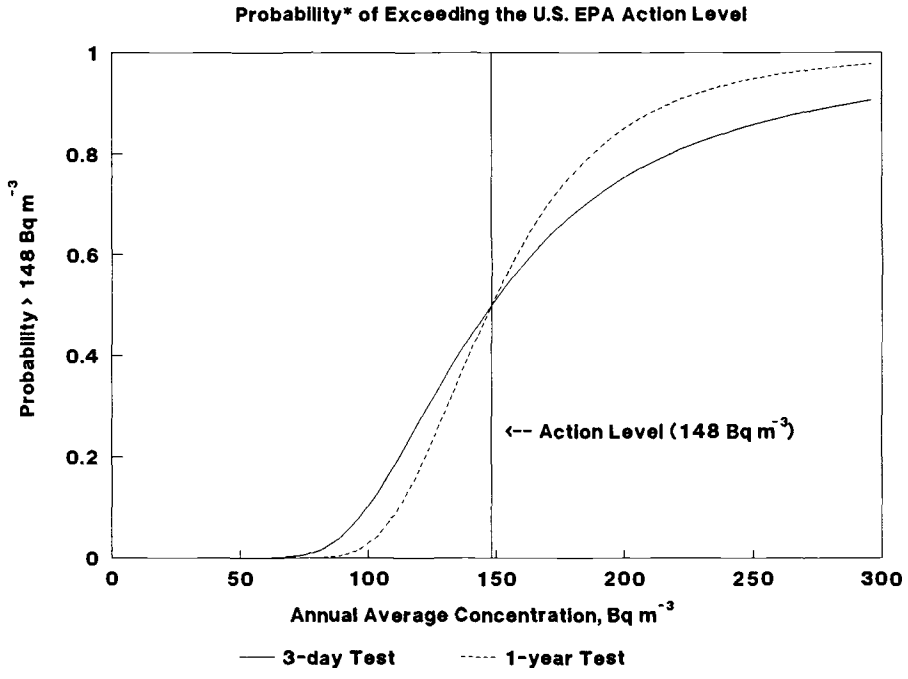


FIG. 1–States conducting radon surveys with activated-carbon monitors in randomly selected residences and number of residences surveyed in each.



* Assuming a normal distribution and a coefficient of variation (i.e., ratio of the standard deviation to the annual average) of 38% for 3-day tests and 25% for 1-year tests.

FIG. 2–Likelihood that short-term or long-term radon test results will exceed the U.S. EPA action level in relation to the annual average concentration.

TABLE 1—Summary statistics for radon concentrations measured throughout the United States using activated-carbon monitors.

Number of states surveyed	41
Number of residences sampled	64 881
Number of owner-occupied housing units represented[a]	44 549 300
Average radon concentration, Bq/m^3 (pCi/L)	107.3 (2.9)
Percent of residences with concentrations between 148 and 739.9 Bq/m^3 (4 and 19.9 pCi/L)	17.8
Percent of residences with concentrations of 740 Bq/m^3 (20 pCi/L) or higher	1.4

[a]Source: U.S. Department of Commerce [*14*].

pied housing units in this country, based on data from the 1980 Census of Population and Housing [*14*].

Table 1 provides summary statistics for the United States projected from the 41 statewide surveys. These summary statistics were developed by weighing each state's results in proportion to the number of owner-occupied housing units as of 1980. To date, measurements have been conducted in more than 60 000 residences, representing about 0.1% of all owner-occupied housing units in the 41 states. The average concentration, 107 Bq/m^3 (2.9 pCi/L), is fairly close to the action level recommended by the EPA, and nearly 20% of U.S. residences are projected to have indoor concentrations at or above 148 Bq/m^3.

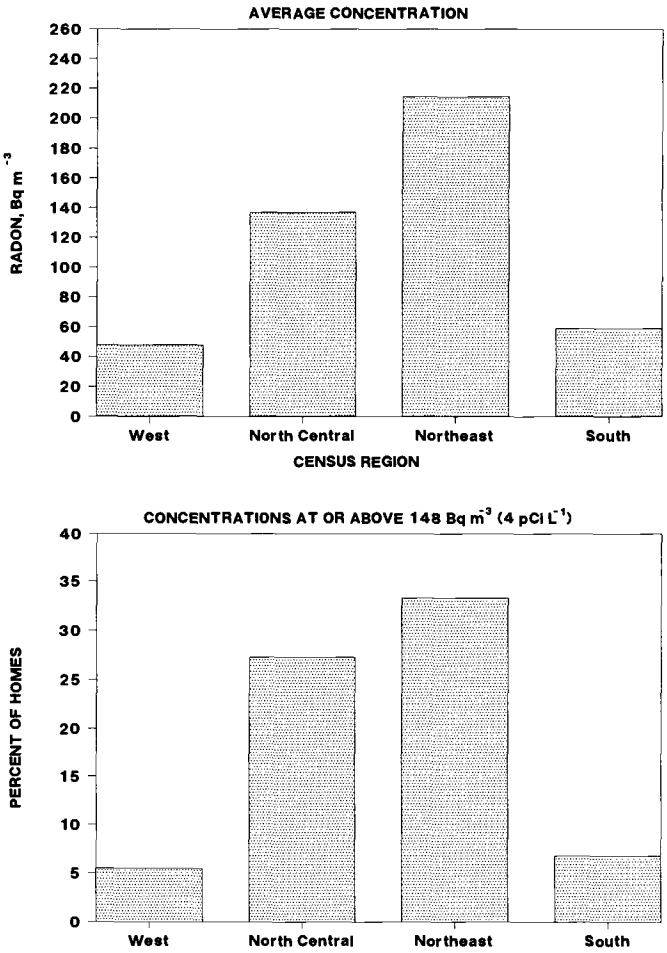


FIG. 3–Summary radon statistics by geographic region based on measurements with activated-carbon monitors.

The projection of 20% of housing units at or above the EPA action level, based on statewide survey results, is substantially greater than the 7% projected earlier by Nero et al. [*1*] or the 6% estimated by the EPA [*3*]. Most of the difference is likely due to exclusive reliance on short-term screening measurements for the statewide surveys; as noted earlier, such measurements (typically collected in winter weather under closed-house conditions) will tend to produce higher results than year-long measurements collected under normal living conditions. Even if the screening measurements were evenly distributed throughout the year, they would still tend to yield a higher fraction of results above the action level than would year-long measurements because (1) screening measurements have greater variability than long-term measurements [*15*] and (2) the true annual average for the majority of U.S. residences is below the action level. As shown in Fig. 2, for residences with a true annual-average concentration below the action level, the likelihood of a measurement result exceeding the action level is greater for short-term (e.g., three-day) measurements.

Given a national average approaching 148 Bq/m^3, it might have been expected that considerably more than 20% of U.S. residences would have radon levels above this level. However, as demonstrated by Nero et al. [*1*] and by Ronca-Battista et al. [*7*], the distribution of measured radon concentrations typically can be approximated fairly well by a lognormal curve. In such cases, the geometric mean, which will be lower than the arithmetic mean for a lognormal distribution, is a better indicator of the central tendency of the distribution because the arithmetic mean can be excessively influenced by results toward the upper tail. The arithmetic mean has been used here, however, because it was commonly reported for all statewide surveys completed to date.

Measurement results are summarized by U.S. Census Bureau-defined regions of the country in Fig. 3 in terms of the average radon concentration and the percentage of results at or above 148 Bq/m^3 (the states associated with each census region are indicated in Fig. 4). Most notable are the considerably lower values for the southern and western regions of the country. As noted in the previous chapter, the Coastal Plain comprising southern and eastern states has the lowest radon potential in the continental United States, and the measurement results reflect this lower potential. The north-central and northeast regions have values above the national average. According to data collected in the Residential Energy Consumption Survey [*16*] by the U.S. Department of Energy, the percentage of homes with basements is much lower in the south (12.7%) and west (12.2%) regions than in the northeast (44.2%) and midwest (42.4%) regions.

STATE AND SUB-STATE PERSPECTIVES

Summary radon statistics for each state, grouped by region, are given in Table 2. Two of the three states with the highest averages—Iowa with 326 Bq/m^3 (8.8 pCi/L) and North Dakota with 259 Bq/m^3 (7.0 pCi/L)—are in the north-

FIG. 4–States associated with four census regions of the United States.

central region; the other—Pennsylvania with 285 Bq/m^3 (7.7 pCi/L)—is in the northeast region. For both Iowa and North Dakota, more than 50% of the homes measured to date have results of 148 Bq/m^3 (4 pCi/L) or higher, and 40% of the Pennsylvania homes have levels of this magnitude. Four additional states—Minnesota, Nebraska, New Hampshire, and New Jersey—have average concentrations close to 185 Bq/m^3 (5 pCi/L). The statewide averages vary by a factor of three to six within each region—from 33 to 133 Bq/m^3 in the west (discounting the very low value for Hawaii), from 78 to 326 Bq/m^3 in the north-central, from 93 to 285 Bq/m^3 in the northeast, and from 19 to 115 Bq/m^3 in the south. Even though the south and west regions have the lowest overall averages, average values for several states in each of these regions exceed the lowest statewide average found in each of the other two regions.

The spatial pattern of average results across states is shown more directly in Fig. 5, based on a classification of average concentrations into four intervals: under 74 Bq/m^3, 74 to 147.9 Bq/m^3, 148 to 221.9 Bq/m^3, and 222 Bq/m^3 or higher. "Pockets" of one or more states with a relatively high average (i.e., ≥148 Bq/m^3) can be seen in three areas: (1) northern states in the north-central region (North Dakota, Minnesota, Nebraska, and Iowa), (2) the southern part of the northeast region and eastern part of the north-central region, centering on Pennsylvania and including two adjacent states (Ohio and New Jersey), and (3) the northernmost part of the northeast region (Maine and New Hampshire). Categorization of the percentage of residences with results ≥148 Bq/m^3 in each state (Fig. 6) indicates a similar trend, but with greater spatial extent for the two highest categories. The states with the lowest fractions of residences having elevated concentrations tend to lie along the western, southern, and southeastern coasts.

Within-state variations in radon concentrations can be more striking than those across states. An indicator of relative variability is the coefficient of variation (CV), or ratio of the standard deviation to the mean. Based on statewide means, the CV across the 41 states with results given in this chapter was calculated to be near 0.6. For comparative purposes, CVs were calculated within three states (Pennsylvania, New Jersey, and Florida) based on county means provided in reports from their respective measurement programs [*17,18,19*]. The calculated CVs were near 0.8 for Pennsylvania and New Jersey and close to 1.0 for Florida.

Spatial patterns within states typically reveal a relatively smooth transition from areas with high radon potential to those with medium and low potential, as illustrated for New Jersey in Fig. 7 and for Florida in Fig. 8 (criteria for defining radon potential were different for the two states). It also should be noted that a relatively low statewide average does not guarantee that the state will have no radon problems. For example, among states with relatively low average concentrations, Florida had several counties with more than 20% of

TABLE 2—Summary radon statistics by state within each U.S. region based on measurements with activated-carbon monitors.

Region and State	Number of Owner-occupied Housing Units (1000s)	Average Radon Concentration, Bq/m³ (pCi/L)	Percentage of Measurement Results	
			148 to 739.9 Bq/m³ (4 to 19.9 pCi/L)	≥740 Bq/m³ (20 pCi/L)
West Region				
Alaska	76.7	62.9 (1.7)	7.1	0.6
Arizona	653.8	59.2 (1.6)	6.4	0.1
California	4825.4	33.3 (0.9)	2.3	0.1
Hawaii	151.9	3.7 (0.1)	0.4	0.0
Idaho	233.4	129.5 (3.5)	17.5	1.8
Nevada	181.3	74.0 (2.0)	9.4	0.8
New Mexico	300.6	118.4 (3.2)	21.0	0.8
Washington	1011.3	62.9 (1.7)	7.5	1.3
Wyoming	114.7	133.2 (3.6)	24.4	1.8
North-Central Region				
Illinois	2534.8	107.3 (2.9)	18.4	0.8
Indiana	1381.9	136.9 (3.7)	27.0	1.5
Iowa	756.5	325.6 (8.8)	63.5	7.5
Kansas	612.4	114.7 (3.1)	21.8	0.7
Michigan	2322.0	77.7 (2.1)	11.3	0.4
Minnesota	1035.7	177.6 (4.8)	44.0	1.4
Missouri	1248.8	96.2 (2.6)	16.3	0.7
Nebraska	390.0	203.5 (5.5)	51.6	1.9
North Dakota	156.5	259.0 (7.0)	56.4	4.3
Ohio	2623.0	159.1 (4.3)	26.2	2.8
Wisconsin	1127.4	125.8 (3.4)	25.8	0.8
Northeast Region				
Maine	280.4	151.7 (4.1)	28.0	1.9
Massachusetts	1169.8	125.8 (3.4)	21.4	1.3
New Hampshire	218.8	177.6 (4.8)	23.7	0.7
New Jersey	1580.1	192.4 (5.2)	27.9	4.6
Pennsylvania	2950.7	284.9 (7.7)	32.6	7.9
Rhode Island	199.1	118.4 (3.2)	18.7	1.9
Vermont	122.6	92.5 (2.5)	15.0	0.9
South Region				
Alabama	941.2	66.6 (1.8)	6.1	0.3
Arkansas	575.5	44.4 (1.2)	4.7	0.3
Florida	2557.2	25.9 (0.7)	2.6	0.1
Georgia	1216.4	66.6 (1.8)	7.5	0.0
Kentucky	884.7	99.9 (2.7)	15.6	1.5
Louisiana	925.2	18.5 (0.5)	0.8	0.0
Maryland	905.7	114.7 (3.1)	17.5	1.4
Mississippi	587.7	33.3 (0.9)	2.1	0.1
North Carolina	1397.4	51.8 (1.4)	6.4	0.3
Oklahoma	790.6	40.7 (1.1)	3.3	0.0
South Carolina	722.6	40.7 (1.1)	3.4	0.3
Tennessee	1110.1	99.9 (2.7)	14.5	1.3
Texas	3169.6	62.9 (1.7)	3.4	0.3
West Virginia	504.9	96.2 (2.6)	14.9	0.8

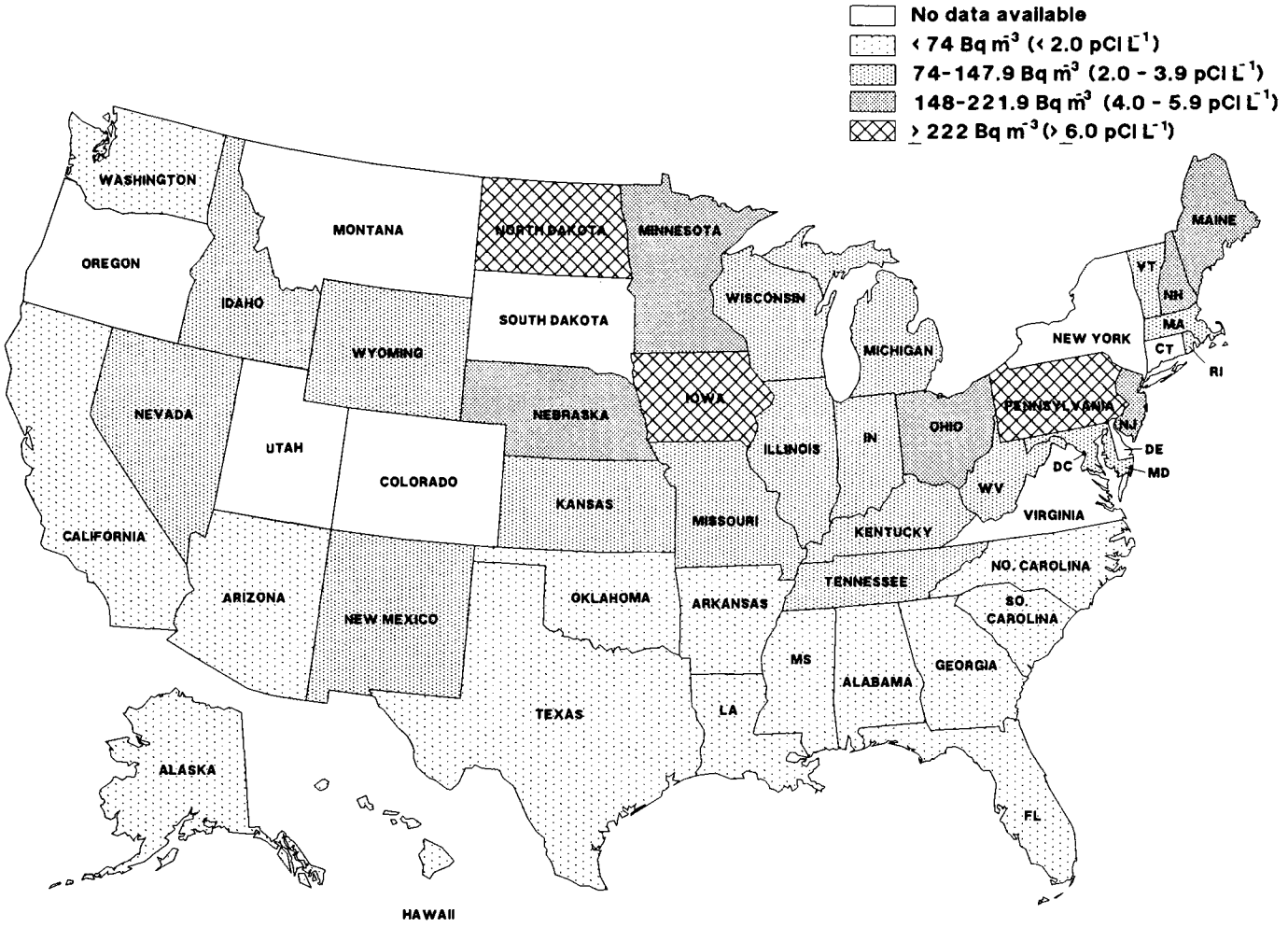


FIG. 5–Spatial pattern of radon survey results with states categorized according to average concentration, based on measurements with activated-carbon monitors.

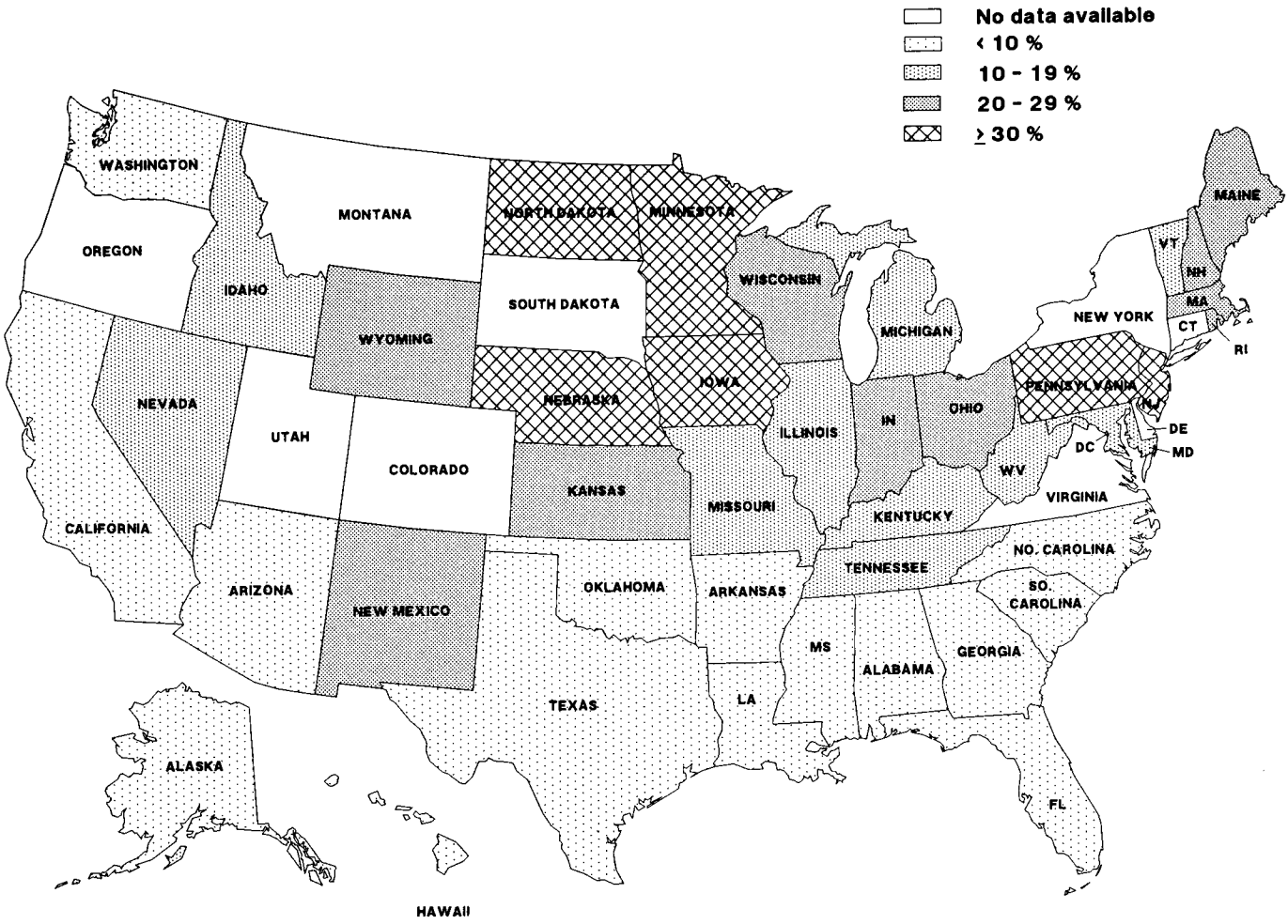


FIG. 6–Spatial pattern of radon survey results with states categorized according to percent of residences ≥148 Bq/m^3 (4 pCi/L), based on measurements with activated-carbon monitors.

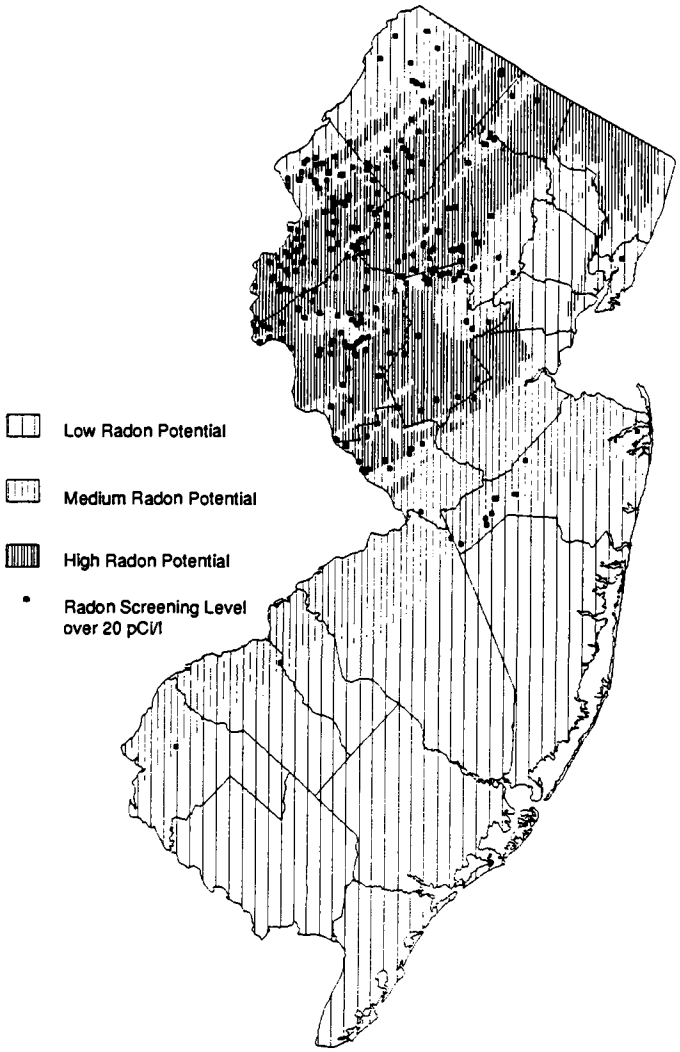


FIG. 7–Spatial pattern of radon potential in New Jersey (after Ref *18*).

surveyed residences measured at 148 Bq/m^3 or higher [*19*], and Alaska had a residence with a measurement result close to 7400 Bq/m^3 (200 pCi/L).

FACTORS RELATED TO INDOOR RADON CONCENTRATIONS

Various factors have been investigated as potential predictors of indoor radon, including type of foundation, geologic and soil characteristics, aerial radiometric surveys, and radon levels in nearby soil. Table 3 provides a breakdown of radon concentrations within two states according to type of foundation. In both cases, concentrations are highest in homes with basements, which provide greater contact with surrounding soil and, therefore, greater opportunities for radon entry than homes with slab-on-grade foundations. Homes with crawlspaces require careful definition and interpretation. If the crawlspace is below ground (often combined with a basement), there again will be greater opportunity for radon entry; however, if the crawlspace is above ground, as in the case of most mobile homes, this type of substructure can allow significant dilution of radon prior to entry into the house. The more detailed breakdown of results for New Jersey in Table 3 indicates that homes with combined crawlspaces and basements have concentrations similar to those in homes with full basements, whereas the levels in homes with crawlspaces only are lower than for slab-on-grade residences.

When the New Jersey study was designed, it was assumed [*18*] that the distribution of radon concentrations across the state would tend to have a spatial pattern dependent on underlying geology (Fig. 7). Consequently, the state was divided into six geologic provinces to help organize the sampling and analysis efforts. As illustrated in Fig. 9, the results were consistent with expectations; the highest levels were found in valley/ridge and highlands provinces, where geology was expected to favor radon production, and the lowest levels generally were found in the coastal plain areas. There were, however, homes above 148 Bq/m^3 in all provinces, but more than 50% of sampled residences were above 148 Bq/m^3 in the valley/ridge and highlands provinces. Results of prior aerial radiometric surveys that were flown under the National Uranium Resource Evaluation (NURE) survey also provided indications of geographic locations at higher risk. As shown in Fig. 10, the spatial patterns of gamma anomalies greater than three standard deviations above the mean (2.4 ppm-equivalent uranium) bore a striking resemblance to the relative density of indoor concentrations $\geq$740 Bq/m^3 (20 pCi/L).

In Florida, there were also expectations of elevated radon risk for certain areas based on geological profiles. Geological occurrences known as the Bone Valley and Hawthorn formations have greater uranium content and phosphatic soils expected to favor radon production. As illustrated in Fig. 11, counties with definite evidence of elevated radon potential (as determined from several types of measurements) tend to cluster near these geological occurrences.

A more quantitative approach also was taken for Florida [*19*] in analyzing the relationship between indoor radon concentrations and indications of radon potential based on factors such as soil radon levels, terrestrial uranium levels determined from the NURE survey, and other information such as geological profiles that existed at the outset of the study. Indices of radon potential ranging from one (lowest) to five (highest) were developed for each county for indoor radon, soil radon, terrestrial uranium, and other information. A nonparametric statistical test appropriate for data scaled in this fashion was used to assess the extent of association among these indices. Indoor radon measurements were significantly associated with all other indicators; the strongest association was with soil radon (Kendall's tau [*20*] of 0.66), followed by terrestrial uranium (0.50) and other existing information (0.36).

The relationship between indoor radon concentrations and other indicators also was explored at Florida sub-county levels, using quadrangles of a 1:24 000 scale defined by the U.S. Geological Survey. An example of one of the higher-risk counties (Alachua) with striking similarities in spatial patterns for all indicators is given in Fig. 12 (shading indicates quadrangles at higher risk and an asterisk indicates a fraction that is significantly different from zero). The indoor radon, soil radon, and terrestrial uranium results all show a pattern of elevated risk that runs diagonally through the county,

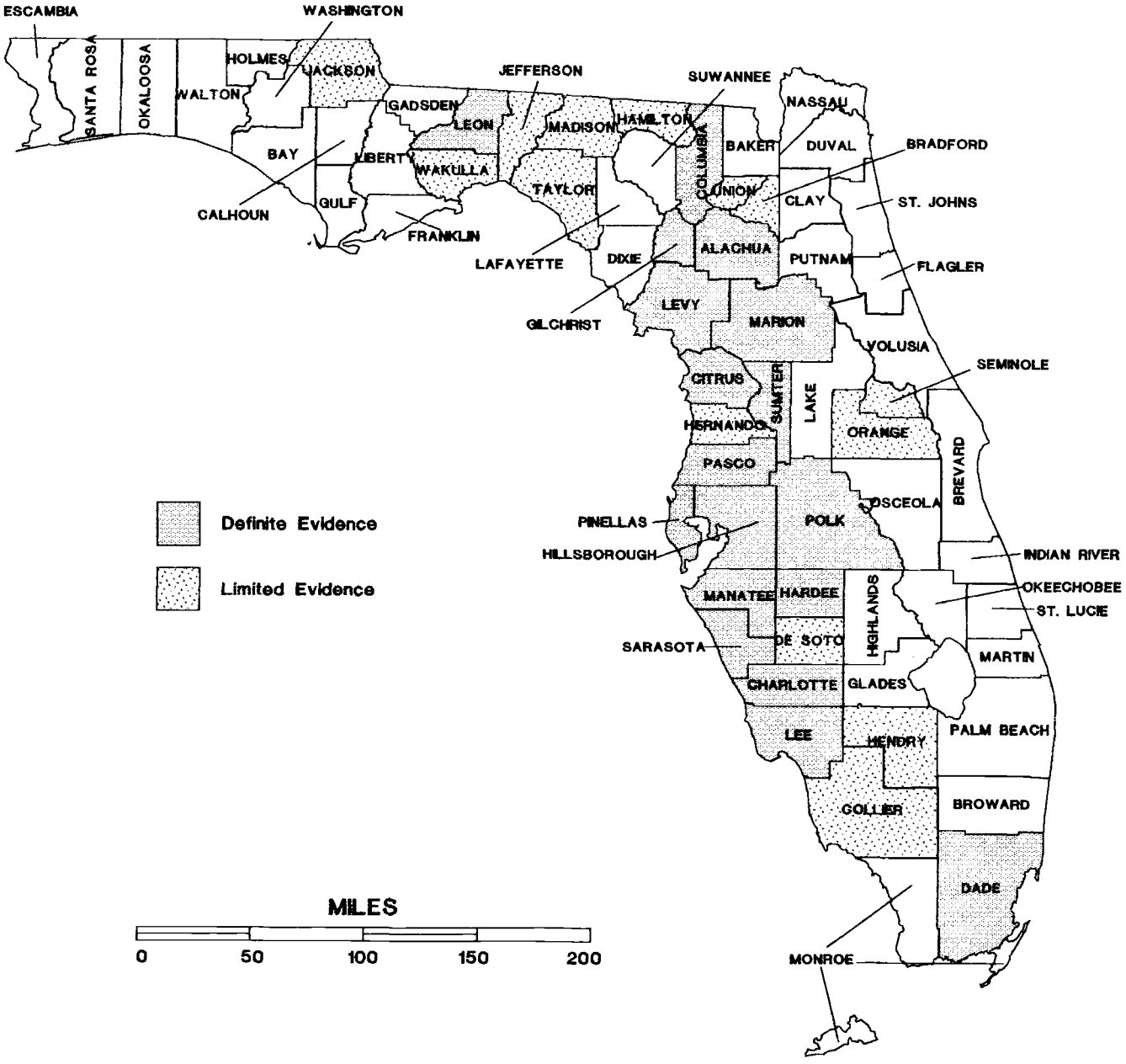


FIG. 8–Spatial pattern of radon potential in Florida (after Ref *19*).

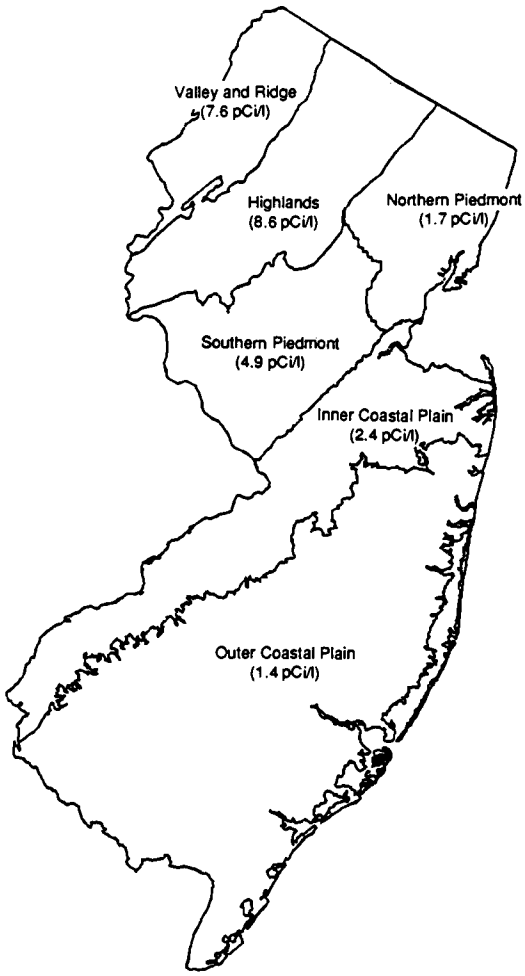


FIG. 9–Radon sampling results by geologic province for New Jersey (after Ref *18*).

consistent with occurrences of the Hawthorn (Tmh) formation.

The Florida study also examined the association between indoor radon and soil radon based on more than 2700 homes with both types of measurements. The association was examined at the quadrangle level, based on quadrangles having at least four homes with paired indoor-soil measurements, and for individual homes as well. The Pearson correlation coefficient [*21*] was 0.8 based on quadrangle averages, but dropped to 0.5 for individual homes. This finding illustrates the point that geographic areas at higher risk can be delineated with a reasonable degree of certainty, but individual homes at risk cannot be predicted as easily. Pugh [*22*] evaluated the Florida data further by focusing on homes with the highest measured indoor radon levels. As shown in Table 4, soil radon measurements that varied over an order of magnitude produced less than a twofold range in indoor concentrations.

CONCLUSIONS

This chapter has illustrated that there are fairly well-defined patterns of radon concentrations across the United States and that variations within states can be even greater than those across states. Information such as soil radon measurements, aerial radiometric surveys, and geologic profiles can provide indications of relatively small geographic areas with elevated radon potential, but there is no method short of indoor measurements for determining whether an individual structure has a radon problem. During the period from 1986 to 1991, 41 of the 50 states in the United States conducted radon surveys involving owner-occupied housing units that were selected at random from largely unbiased sampling frames. These statewide surveys have utilized short-term screening measurements that typically were taken during the winter in the lowest level of a residence under closed-house conditions. These conditions tend to overestimate radon concentrations relative to longer-term samplers used to measure radon concentrations under normal living conditions.

Based on the short-term screening of nearly 65 000 residences, the projected national average radon concentration in residences is 107 Bq/m^3 (2.9 pCi/L), and approximately 20% of U.S. residences are projected to have averages above 148 Bq/m^3 (4 pCi/L), the action level established by the EPA. These figures are considerably higher than those estimated from long-term measurement surveys (e.g., year-long samplers); for example, a previous assimilation of data sets involving long-term measurements projected that 7% of U.S. residences would exceed the action level. The short-term results have been used to assess concentration patterns because of their common use in most states.

Indoor radon concentrations are considerably lower in the southern and western regions of the country than in the northcentral and northeast regions, consistent with lower radon potential based on factors such as geology and soil type (see Chapter 6). The percentage of homes with basements also is much lower in the southern and western regions. Two of the three states with the highest averages—Iowa with 326 Bq/m^3 (8.8 pCi/L) and North Dakota with 259 Bq/m^3 (7.0 pCi/

TABLE 3—Radon concentrations by type of foundation for two states (after Refs *5* and *13*).

Type of Foundation	Average Concentration for State Bq/m^3 (pCi/L)	
	New Jersey	New Hampshire
Full basement	210.9 (5.7)	188.7 (5.1)
Crawlspace and basement	203.5 (5.5)	136.9 (3.7)
Crawlspace only	59.2 (1.6)	
Slab-on-grade	103.6 (2.8)	170.2 (4.6)
Other	74.0 (2.0)	144.3 (3.9)

TABLE 4—Highest indoor radon concentrations measured in the Florida study and corresponding soil radon concentrations near each house (after Refs *19* and *22*).

Ranking by Indoor Concentration	(Radon Concentration, Bq/m^3 (pCi/L)	
	Indoors	Nearby Soil
1	1198.8 (32.4)	58 871 (1591)
2	1091.5 (29.5)	68 335 (1847)
3	1036.0 (28.0)	29 115 (787)
4	936.1 (25.3)	20 568 (556)
5	936.1 (25.3)	7 404 (200)
6	925.0 (25.0)	13 094 (354)
7	891.7 (24.1)	16 269 (440)
8	847.3 (22.9)	131 768 (3561)
9	847.3 (22.9)	79 347 (2145)

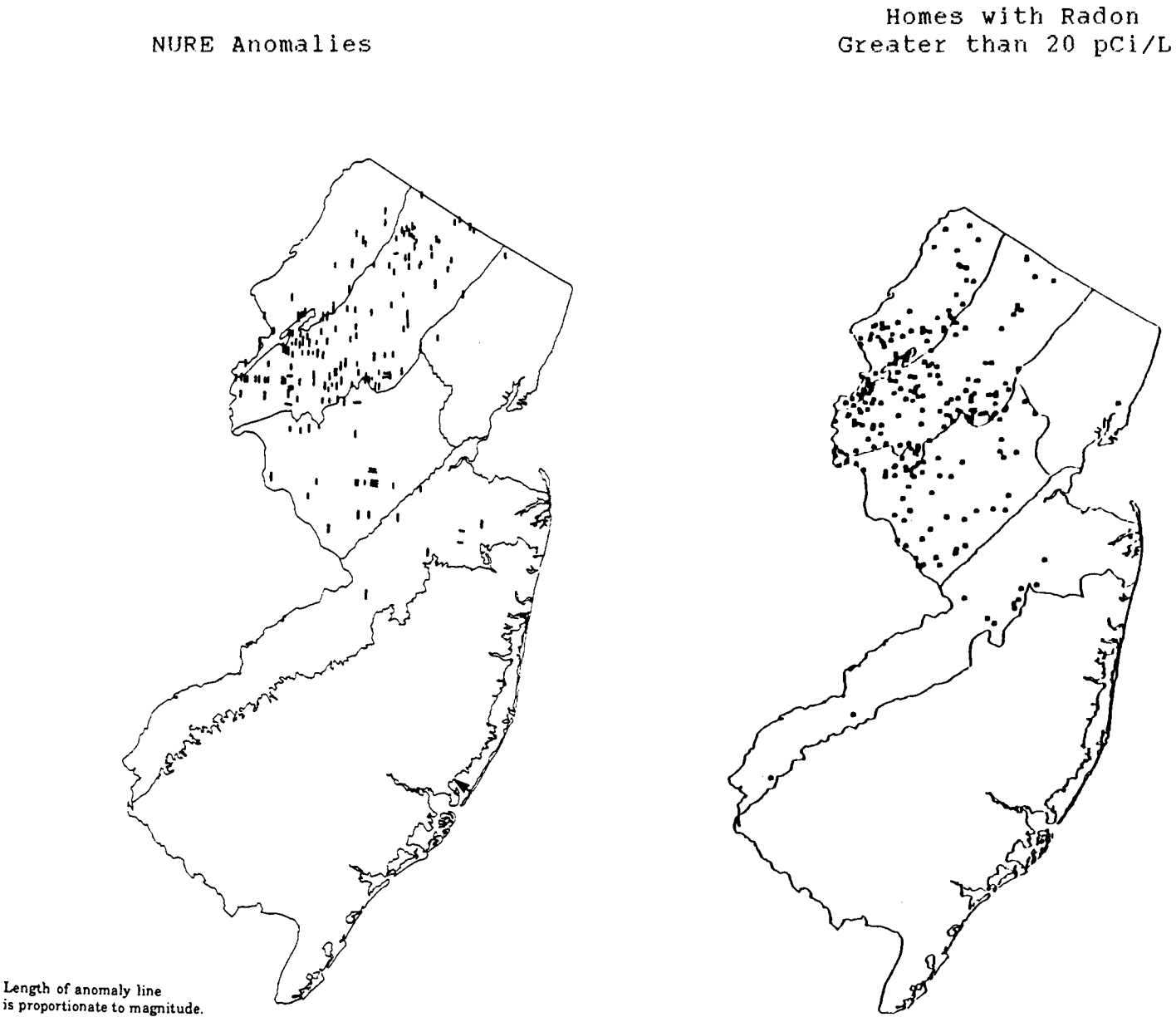


FIG. 10–Spatial pattern of NURE gamma anomalies and elevated indoor radon concentrations in New Jersey (after Ref *5*).

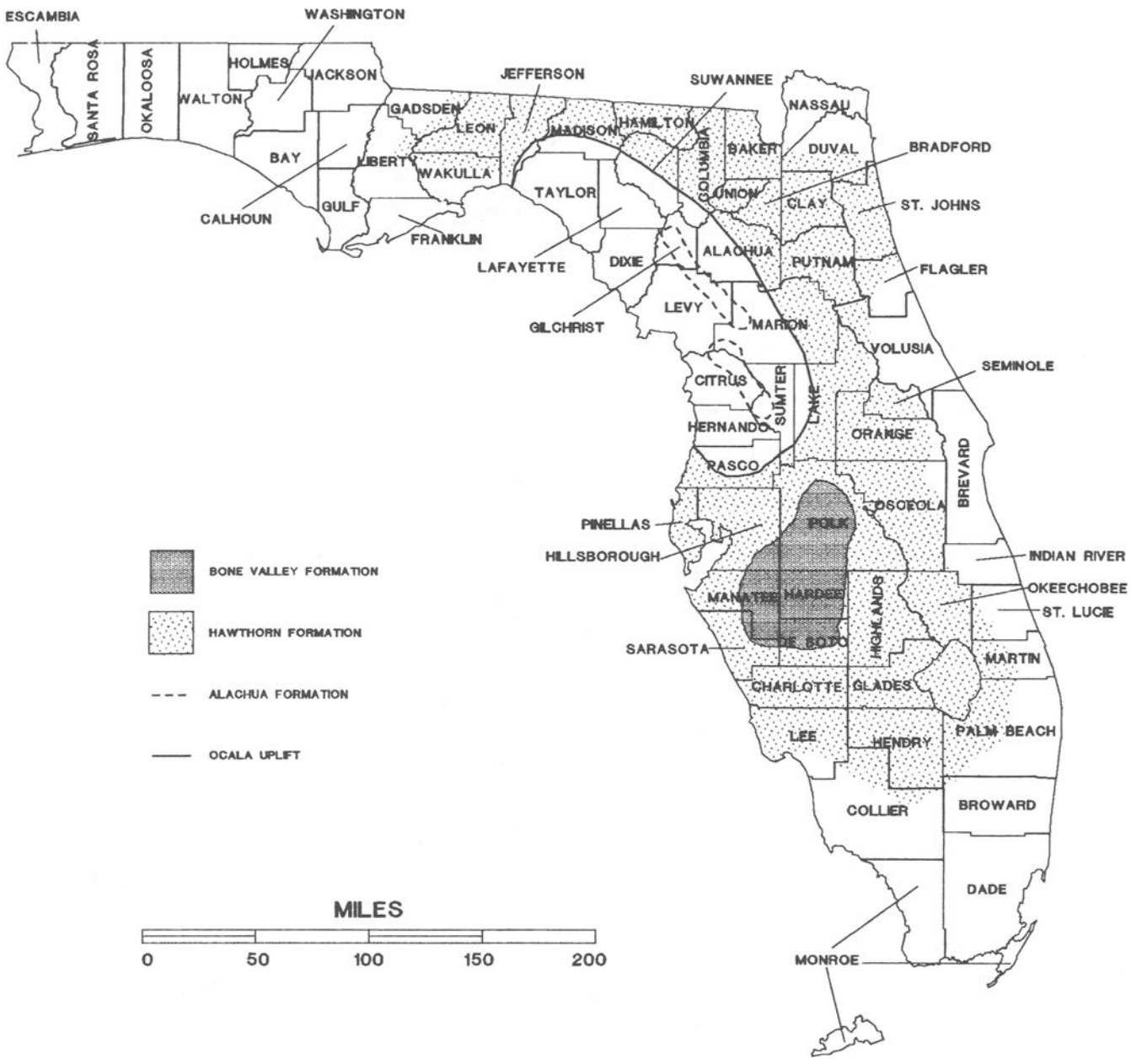


FIG. 11–Comparison of geologic profiles and elevated radon potential (based primarily on radon measurements) in Florida (after Refs *19* and *23*).

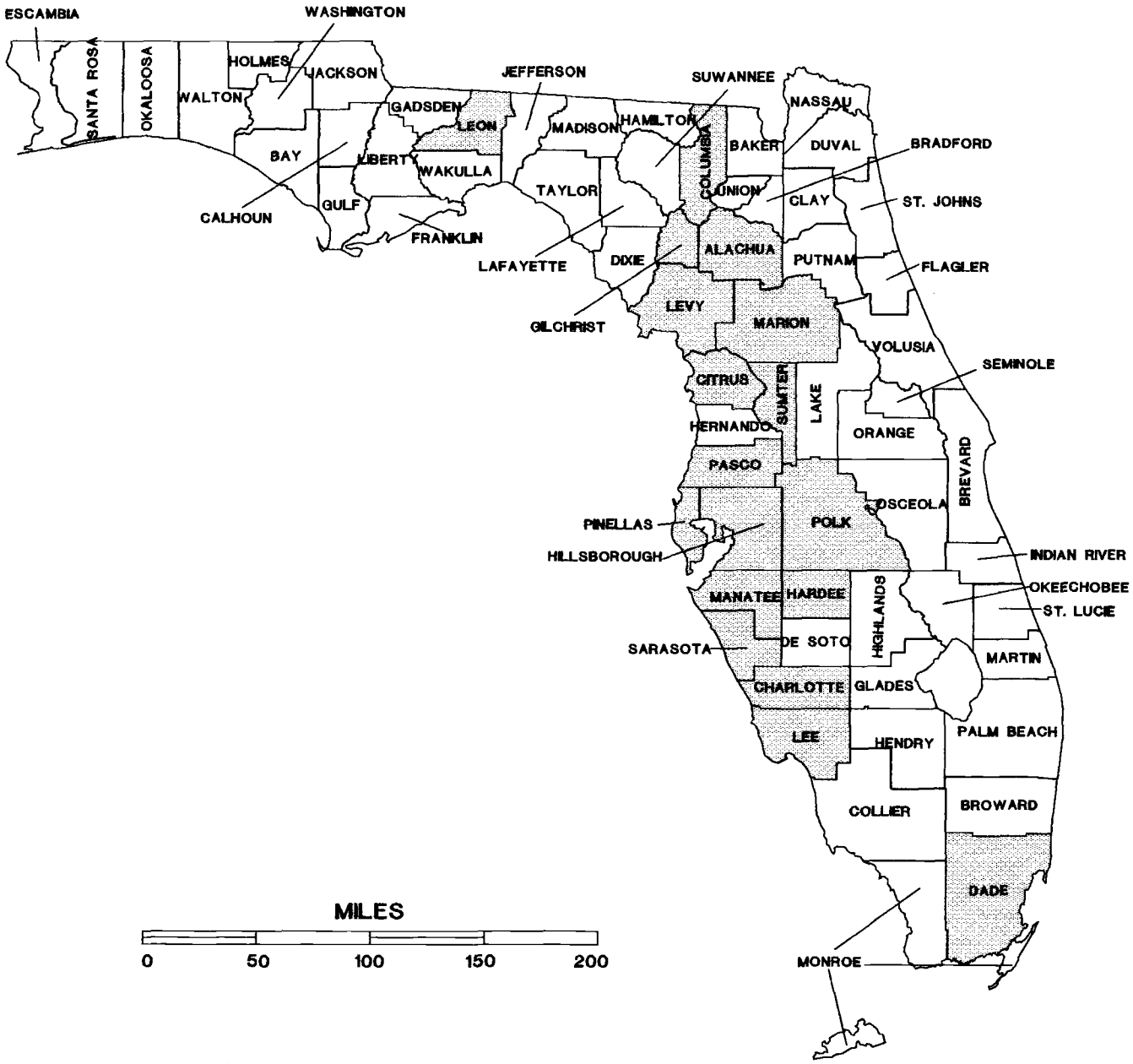


FIG. 11–(Continued). Shaded areas indicate elevated radon potential.

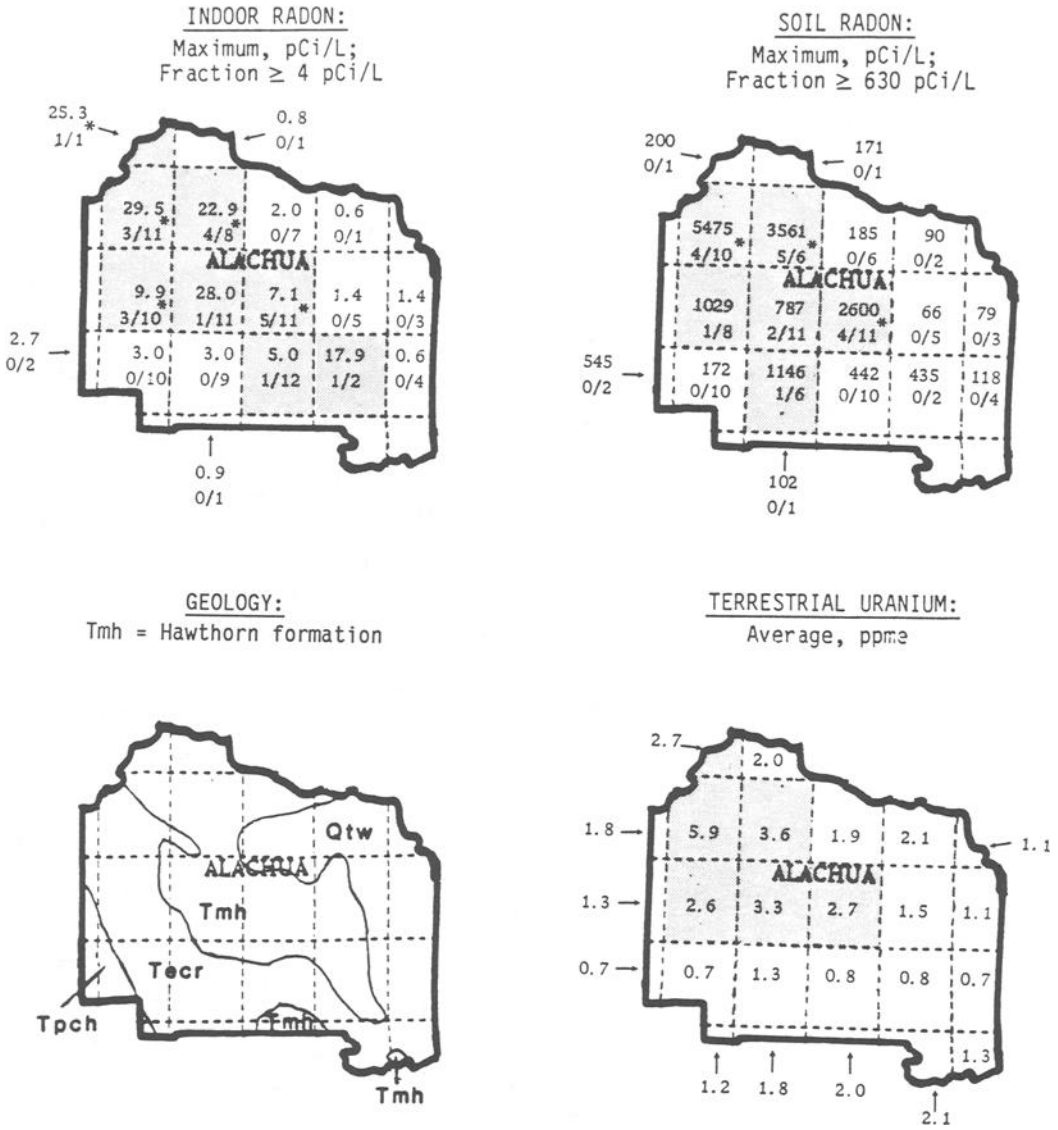


FIG. 12–Patterns of indoor radon, soil radon, geological occurrences, and terrestrial uranium in Alachua County, Florida (after Ref *19*).

L)—are in the northcentral region; the other, Pennsylvania, with 285 Bq/m^3 (7.7 pCi/L), is in the northeast region. Four additional states in these two regions—Minnesota, Nebraska, New Hampshire, and New Jersey—have average concentrations close to 185 Bq/m^3 (5 pCi/L). The states with the lowest fractions of residences having elevated concentrations tend to lie along the western, southern, and southeastern coasts.

Within each of the four regions, the statewide averages vary by a factor of three to six. Even though the southern and western regions have the lowest overall averages, average values for several states in each of these regions exceed the lowest statewide average found in each of the other two regions. Spatial patterns within states typically reveal a relatively smooth transition from areas with high radon potential to those with medium and low potential. Even among states with relatively low average concentrations, it is possible to find individual counties with 20% or more of residences exceeding the EPA action level and individual residences with measurement results close to 7400 Bq/m^3 (200 pCi/L).

Various factors have been investigated as potential predictors of indoor radon. Measured concentrations generally have been highest in homes with basements, which provide greater contact with the surrounding soil and, therefore, greater opportunities for radon entry. Spatial patterns of indoor radon concentrations within states generally have been consistent with expectations from geologic and soil characteristics. Results of prior aerial radiometric surveys that were flown under the National Uranium Resource Evaluation (NURE) survey also have provided indications of geographic areas at higher risk and measurements of radon in the soil also have demonstrated predictive capabilities. However, although information such as soil radon measurements, aerial radiometric surveys, and geologic profiles can provide useful indication of relatively small geographic areas with elevated radon potential, there is no method short of indoor measure-

ments for determining whether an individual structure has a radon problem.

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8

Radon Control Strategies

by Kelly W. Leovic[1] and Richard Roth[2]

BECAUSE EXPOSURE TO ELEVATED LEVELS of radon is estimated to cause 7 000 to 30 000 lung cancer deaths each year, the U.S. Environmental Protection Agency (EPA) and the Surgeon General have recommended that indoor radon levels be reduced to less than 148 Bq m^{-3} [*1*]. This chapter covers strategies that can be used to effectively reduce elevated radon levels in buildings.

The introductory section discusses common radon entry routes and provides an overview of radon control strategies. The remainder of the chapter covers methods for diagnosing radon problems and detailed descriptions of the following radon control strategies—soil depressurization, sealing of radon entry routes, building pressurization, removing the sources of radon, ventilation, air cleaning, and removing radon from water. Preventing elevated radon levels in new construction is also covered. The chapter concludes with a summary table of radon control strategies with typical ranges of radon reduction, contractor installation costs, and operating costs; information on post-installation testing; long-term maintenance of radon control systems; and a chapter summary.

The chapter is intended to provide an overview for the reader in diagnosing radon problems and in selecting radon control strategies both in existing structures and in new construction. The reader should not expect specific, detailed information in this chapter. For detailed EPA technical guidance, see Refs *2* through *10*. EPA periodically updates these technical guidance manuals. Detailed information on radon control strategies can also be found in Refs *11* through *17*. In addition, technical information on radon diagnostics and the design and installation of radon control strategies is available in many of the mitigation courses offered by the EPA and other local and regional institutions and professional organizations.

Causes of Radon Entry into Buildings

The most common way for radon to enter a building is from the soil gas through pressure-driven transport. Radon can also enter a building through diffusion, well water, and construction materials. These modes of radon entry are explained below.

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Pressure-Driven Transport

Pressure-driven transport occurs when the indoor air pressure is lower than the air pressure in the soil gas. Radon in soil gas can enter a building through pressure-driven transport if the following exist:

1. A source of radium to produce radon.
2. A pathway from the source to the building.
3. An opening in the building substructure in contact with the soil to permit radon to enter the building.
4. A driving force to move radon from the source into the building through the opening.

A discussion of sources of radon and pathways from the source to a building are covered in Chapters 2 and 6. Openings in the building substructure that allow radon to enter—generally exists in most buildings regardless of foundation type. Typical radon entry routes include: cracks in floors, slabs, and walls, the floor/wall crack, areas of exposed soil, open sump pits, untrapped drains, openings around below-grade utility penetrations, open block tops in foundation walls, and pores in below-grade block walls. Figures 1, 2, 3, and 4 show common radon entry routes for buildings constructed on slab-on-grade, basement (masonry block walls and poured concrete walls), and crawl space foundations, respectively.

A driving force or a negative pressure inside the building relative to the subslab soil gas, is due in part to building shell effects and in part to occupant activities. Building shell effects include indoor/outdoor temperature differences, wind, air leaks in the shell of the building, and open windows on upper floors.

When the temperature inside a building is warmer than outside, the warm air in the building rises, causing a "stack effect." The stack effect is similar to a chimney stack and creates negative pressures in lower levels of the building relative to the soil gas, increasing the driving force for radon entry [*18,19*]. At some level in the building is a point referred to as the "neutral pressure plane," where the pressure inside the building is equal to the outside pressure. The space above the neutral plane is slightly pressurized, and air is pushed out of the building; the space below the neutral plane is depressurized and pulls air in from the outdoors and from the soil gas.

Occupant activities, including operation of mechanical ventilation systems, vented combustion appliances, bathroom exhaust fans, kitchen exhaust fans, whole house attic or window exhaust fans, dryer exhaust fans, and use of fire-

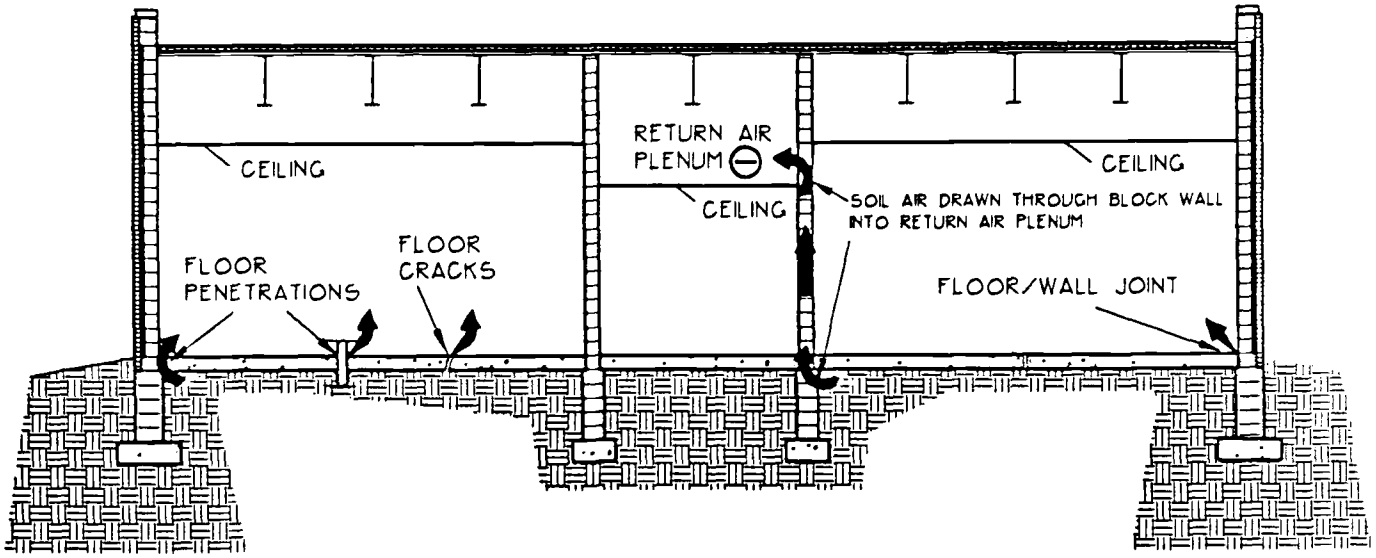

FIG. 1–Typical radon entry routes in slab-on-grade construction.

places can also contribute to negative pressures. Opening windows on upper floors without also opening windows in the basement or on the main floor can also contribute to the stack effect.

Othe Radon Transport Mechanisms

Radon also can enter buildings without a pressure difference. This type of radon movement is called diffusion-driven transport and occurs when radon moves from areas of high concentration to areas of lower concentration. Diffusion-driven transport is rarely the cause of elevated radon levels in existing buildings.

Another way radon can enter a building is through well water. If well water is in contact with radium-bearing formations and is supplied directly to a building, it can be a source of radon in a building. Currently, the only widely accepted health risk associated with exposure to radon in water is the airborne radon that is released from the water when it is used. A general rule for *houses* is that 10 000 Bq m^{-3} of radon in water contributes approximately 1 Bq m^{-3} to airborne radon levels [*20*]. It is unlikely that municipal water supplied from a surface reservoir would contain elevated levels of radon.

Radon can also emanate from building materials. The extent of the use of radium-containing building materials is unknown but is generally believed to be very small. Examples

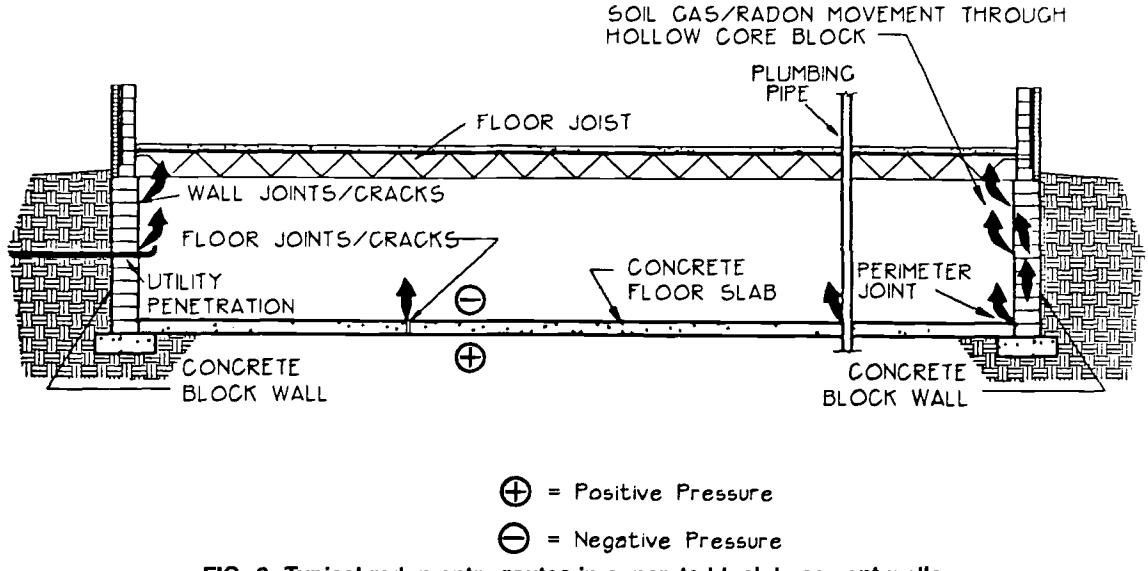

FIG. 2–Typical radon entry routes in concrete block basement walls.

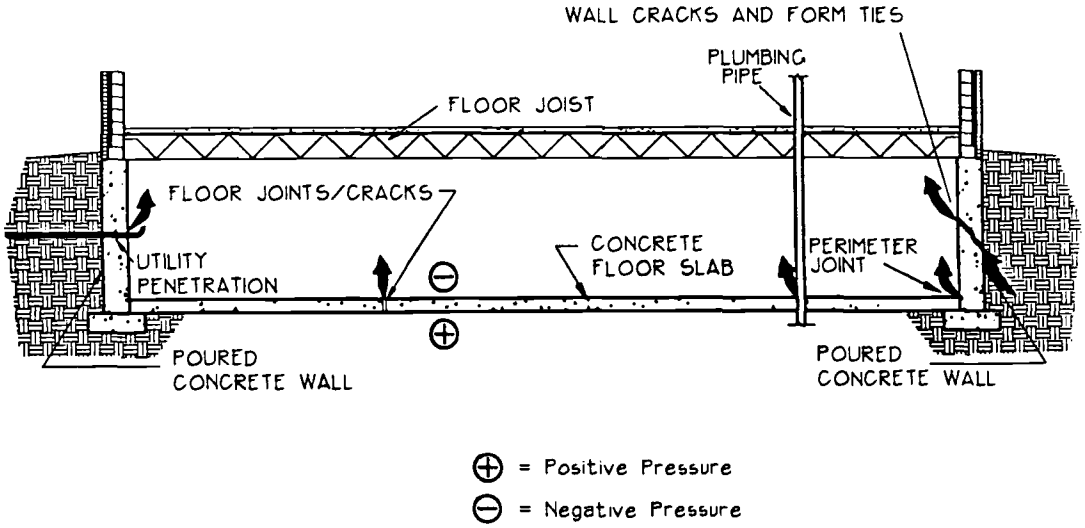

FIG. 3–Typical radon entry routes in poured concrete basement walls.

in the United States include homes constructed using uranium mill tailings for fill dirt, concrete from phosphate slag, and wallboard and other materials from phosphogypsum.

An Overview of Radon Reduction Methods

Radon reduction methods described in this chapter fall into two categories: methods that prevent radon from entering the building and methods that reduce the radon levels after radon enters the building.

The cost, complexity, and effectiveness vary a great deal among radon control methods. When evaluating the most appropriate technique, a number of factors need to be considered; for example, the percent radon reduction needed, building type, installation and operation costs of the radon control system, system maintenance, and local climate and geology.

Methods That Prevent Radon Entry: Soil Depressurization, Sealing, Building Pressurization, and Source Removal

Active soil depressurization (ASD) is the most widely used radon reduction method. For ASD, a fan is used to create a negative pressure field in the soil under the building relative to the lower levels of the building. As shown in Fig. 5, this negative pressure field reverses the flow of radon. Instead of entering the building, the radon is exhausted by the fan to the outdoors, where it is quickly diluted. Types of ASD techniques include subslab depressurization, sump hole depressurization, drain tile depressurization, block wall depressurization, submembrane depressurization, and crawl space depressurization.

A second control method that prevents radon entry is sealing of radon entry routes. Sealing, closure, or isolation of entry routes limits (or eliminates) the flow of radon gas into

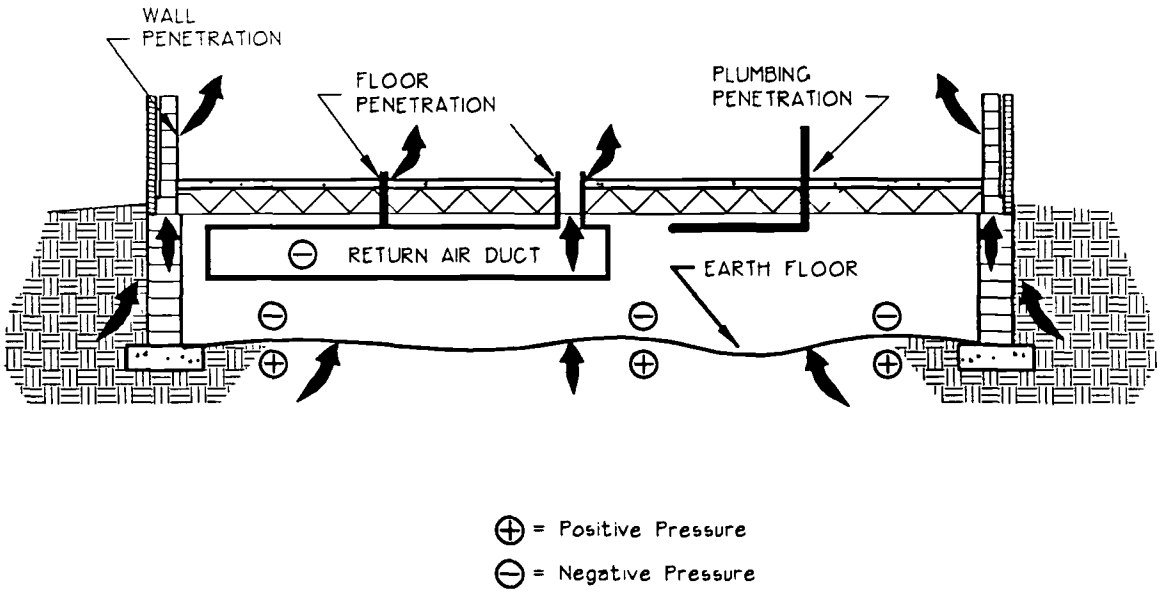

FIG. 4–Typical crawl space foundation entry routes.

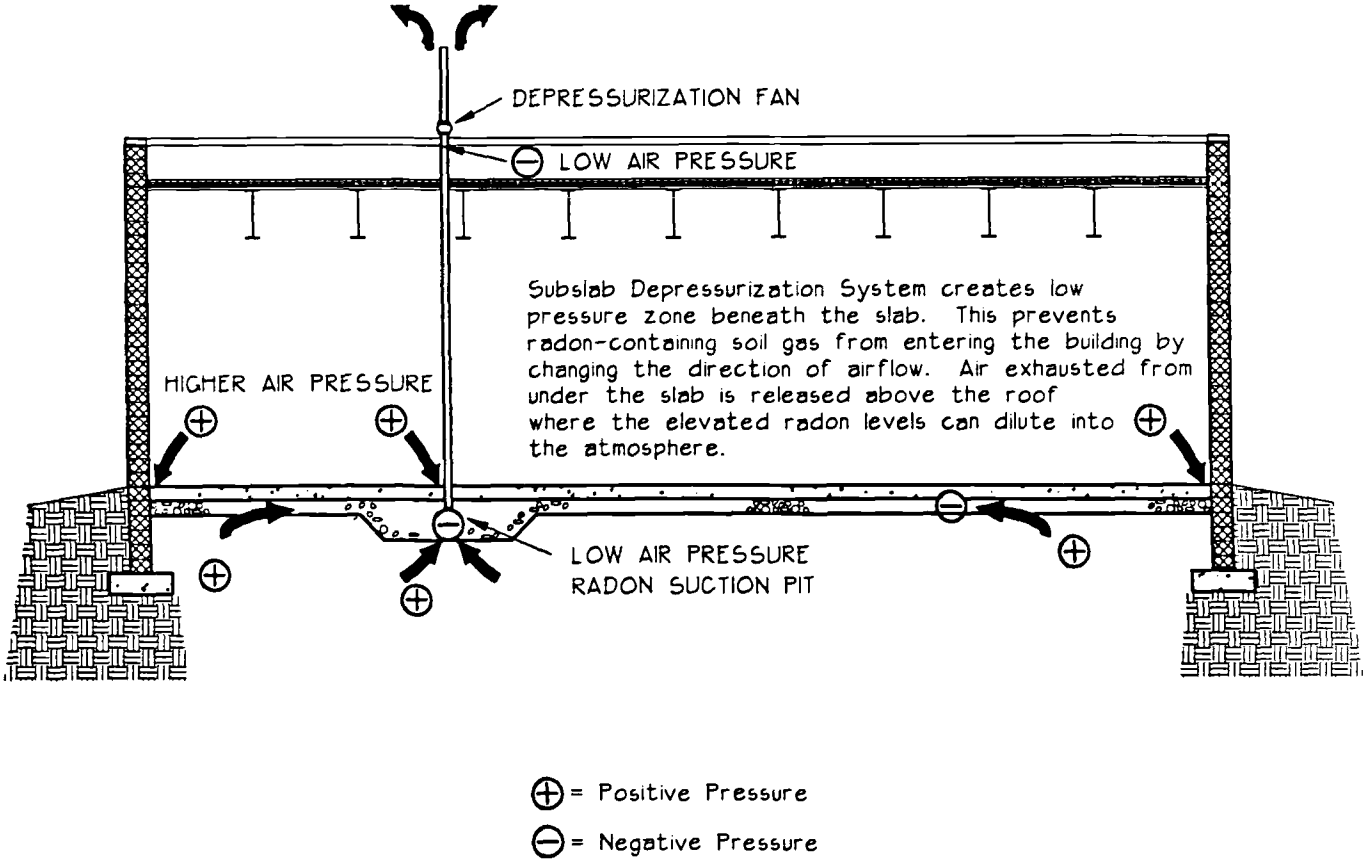

FIG. 5–Subslab depressurization theory.

the building. Sealing of major radon entry routes is considered an essential part of most approaches to radon reduction. However, the effectiveness of sealing is limited by the ability to identify, access, and seal all the places where radon is entering. Radon reductions from sealing vary widely depending on whether the important entry points were sealed and the quality of the sealing job. Only rarely has sealing alone been sufficient to significantly reduce radon levels.

Building pressure control is a third approach that can be used to prevent radon entry. Since building depressurization draws radon in, avoiding activities that depressurize the building, such as using exhaust fans, or actually pressurizing the building can minimize or eliminate radon entry. Building pressurization involves bringing more air into the building than is exhausted, causing a slightly positive pressure inside the building relative to the subslab area. The positive pressure in the building causes air to flow from inside the building to the outdoors through openings in the substructure and building shell; this effectively seals radon entry routes. Building pressurization is similar to ASD in that both methods block radon entry routes using air pressure barriers, but are different in that, with building pressurization, air is pushed out of the building from inside rather than being drawn out from under the slab, as with ASD. Building pressurization also helps to reduce radon levels through dilution with outdoor air. These first three methods—ASD, sealing, and building pressurization—are also very effective in preventing radon entry in new buildings constructed in radon prone areas.

In rare cases, the building materials may contain elevated levels of radon. This fourth approach to prevent radon entry, source removal, generally refers to removing the materials that are sources of elevated radon levels. If this is impossible or impractical and the contamination is severe, the building may need to be abandoned. Removal of uranium-containing soil surrounding a building can be a very costly radon control strategy and is not covered in this chapter.

Methods That Remove Radon After Entry: Ventilation, Air Cleaning, and Removal of Radon From Water

Ventilation reduces radon levels by increasing the air exchange rate. In addition to reducing radon levels, ventilation can also help to reduce levels of other indoor air contaminants through dilution. The types of ventilation discussed in this chapter are natural ventilation, forced-air ventilation using the building's heating, ventilating, and air-conditioning (HVAC) system, and heat recovery ventilation. Generally, ventilation is not an effective stand-alone radon reduction technique if radon levels are highly elevated. In addition, it is often less reliable and more costly to operate than methods that prevent radon entry.

Two air cleaning approaches have been used to control radon decay products and radon, respectively. The first approach involves removal of the radon decay products ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po by filtration or plateout. The purpose is

to reduce the lung dose of the decay products by removing or reducing the concentration of particles in indoor air without reducing the radon concentration. The second approach involves removal of the radon directly through adsorption onto a sorbent bed—usually activated carbon—after it enters the building.

Radon levels in water can be reduced either by a granulated activated carbon (GAC) unit or by aeration of the water before it enters the building. Although GAC units are often effective in removing radon from the water, radioactive lead may build up in the units which may be a later disposal problem.

EPA Recommendations for Reducing Radon Levels

If radon concentrations are above 148 Bq m^{-3}, EPA recommends reducing the levels to below 148 Bq m^{-3} [*1*]. If radon concentrations in a building are highly elevated (e.g., 3000 Bq m^{-3}), the occupants should consider taking interim steps to reduce the concentration if a permanent radon reduction system cannot be installed immediately. Interim steps could include: minimizing the use of exhaust fans; opening a window near exhaust fans to provide makeup air; sealing suspected radon entry routes such as open sump pits and cracks in the floor or below-grade walls; ventilating by opening windows or other vents in the lower levels, basement or crawl space (open windows should be located on the windward side of the building rather than the leeward/downwind side); or using fans to blow air into the building.

Obviously, the effectiveness of these interim steps is limited by weather considerations. Increasing ventilation can greatly increase heating costs during the winter and cooling costs during the summer. The freezing of pipes in basements and crawl spaces must also be considered. These are generally considered temporary and/or preliminary approaches to radon reduction, and a permanent system should be installed as soon as possible.

DIAGNOSING RADON PROBLEMS

Selecting the most appropriate radon reduction method for a specific building can be complicated. It is important to understand the source of the radon and how the building influences radon entry into and within the building. Properly selected diagnostic tests can lower the overall cost of the radon control system, making it more likely to work on the first try and yielding better radon reductions.

Diagnostic measurements for radon mitigation include any test, quantitative or qualitative, and inspection procedure which evaluates the building to determine the most appropriate radon control strategy. Inspections and measurements are typically performed by experienced radon reduction contractors. EPA tests radon reduction contractors and maintains a radon contractor proficiency (RCP) list of those who have passed the test [*5*]. EPA also issues photo identification cards to those on the RCP list. Many states also run their own certification programs and require RCP listing as a component of the certification.

The sections below describe the most common radon diagnostic procedures: measuring radon levels, reviewing building construction plans, conducting a building investigation, measuring subslab pressure field extension, evaluating the HVAC system, measuring building tightness, and determining if building materials are a radon source.

The number and type of diagnostic tests required in a given building depend on a number of factors such as the building structure, the HVAC system, and the initial radon levels. It is unlikely that each of the diagnostic tests described below will be necessary in every building. In general, the most critical diagnostic steps are to measure radon levels and to conduct a building walkthrough. In addition, if a subslab depressurization radon control strategy is under consideration, measuring subslab pressure field extension is also very important. Flowcharts for conducting these diagnostic measurements and the subsequent selection of control strategies are found in Ref *8*.

Measure Radon Levels

Radon measurements can be made in a number of locations: in occupied ground-contact rooms, near suspected radon entry routes, and in well water. All measurements should be conducted and analyzed by a reputable contractor listed with the EPA's Radon Measurement Proficiency (RMP) Program [*21*].

Radon Measurements in the Building

In addition to the initial radon screening measurements described in Chapter 5, additional radon measurements are often made a part of the diagnostic process. These measurements serve a number of purposes: confirmation of elevated radon levels, mapping of radon levels and entry points within the building, and identification of any seasonal and/or diurnal variations in radon levels.

Radon measurements can be taken with either passive or continuous monitors. Passive or integrating monitors, such as carbon canisters, alpha-track detectors (ATDs), or electretion chambers, provide radon results integrated over the entire exposure period of the monitor. Many continuous monitors are also equipped for collecting "grab samples" and "sniffing" for radon entry routes. Measurements of radon daughter products (RDPs) are also sometimes taken with continuous working level monitors [*22*].

When analyzing the radon measurement results, consider the following questions: Are rooms with elevated radon levels clustered? Does the entire building have elevated radon levels? Are there only a few widely separated rooms with elevated radon levels? Do radon levels vary diurnally or seasonally? The answers to these questions should help target areas of primary interest for the building investigation.

Radon Measurements to Determine Entry Routes

Grab sampling and sniffs with continuous monitors are commonly used to determine radon concentrations at a location and at an instant in time. Grab samples or sniffs taken in potential radon entry routes (such as cracks in floors and walls, sump pits, crawl spaces, or from the top sections of

unsealed block walls) may prove useful in identifying their relative contribution to indoor radon levels.

Radon Measurements in Water

If well water is used, it may be contributing to elevated radon levels in the building. A rule of thumb for houses is that 10 000 Bq m^{-3} of radon in water contributes approximately 1 Bq m^{-3} to airborne radon levels [*20*]. Radon in water tests can normally be obtained through local testing firms.

Review Building Construction Plans

All available building construction plans and specification documents should be reviewed. Plans are usually available for most larger buildings; however, they may not be available for older buildings or for single-family residences. Pertinent drawings include architectural, structural, mechanical, and electrical plans. The following summarizes the pertinent information typically provided by these plans.

- The *architectural* drawings will give general information on building design and also provide details on typical wall sections.
- The *structural drawings* will contain information on the foundation, footing and thickened slab locations, and subslab fill. These may be helpful to assess the potential effectiveness of an ASD system by indicating the presence and thickness of subslab aggregate and any barriers to subslab communication such as below-grade walls. The structural drawings may also provide clues to possible radon entry routes such as expansion joints.
- The *mechanical drawings and specifications* will provide information on the HVAC system design (such as duct system design, duct run length, supply/return airflow design capacity, outdoor air intakes, and exhaust systems). For buildings with intra-slab radiant heat systems, the plans are particularly important in locating subslab piping. Where applicable, the balancing report should also be consulted and compared with the most current ventilation standard for the American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE [*23*].
- The *plumbing and electrical drawings* will provide information on potential radon entry routes. If pressure field extension (discussed later in this section) is to be measured to determine the potential for an ASD system, these plans should be studied to determine the locations of subslab utility lines prior to drilling test holes through the slab.

Conduct Building Investigation

A thorough building investigation should be conducted to assess potential radon entry routes and confirm information cited in the building plans. Entry routes include floor/wall cracks, unsealed or deteriorated expansion joints, utility penetrations, and open pores of block walls or unsealed tops of block walls that penetrate the slab [*7,8,9*]. As the types and magnitudes of radon entry routes are identified, the feasibility of sealing may be considered.

A chemical smoke stick can be used to determine the direction of air movement along potential entry routes, and a micromanometer can be used to determine the magnitudes of pressure differentials. It is useful to have a continuous radon monitor capable of sampling potential radon entry routes during the building investigation. The following subsections provide more specific information on what to look for when inspecting floors, walls, and crawl spaces for potential radon entry routes.

Floor Inspection

Radon entry routes in the floor include openings around pipes and other utility lines, cracks in the slab, exposed soil, sump holes, untrapped drains open to the soil, and wall/floor interfaces (e.g., an expansion joint or a French drain). Some buildings have utility lines in subslab utility tunnels. The tunnels normally have many openings to the soil gas and, as a result, radon can pass into the tunnel and enter the building interior through utility line penetrations (e.g., risers to unit ventilators).

A thorough inspection should include examination of potential entry routes concealed behind or under appliances, furnaces, work benches, or elevator shafts. Any line or pipe which is penetrating or appears to be penetrating the slab should be inspected. Separations between sections of the slab, gaps between slab and walls, and slab cracks can provide major routes for radon entry. Shrinkage of the concrete after pouring may cause gaps at the edge of slabs and cracks throughout the floor areas. The size of cracks and gaps may change seasonally depending on moisture and temperature. For example, expansive soils may cause slab movement.

Wall Inspection

Inspect walls for cracks, openings around utility penetrations, separations between blocks, and missing mortar. Also examine block wall permeability. Since most blocks used in walls have hollow cores, radon can enter the blocks from the soil gas and be readily transported into the building via open pores in the blocks, cracks or separations, and open tops of the blocks. Block texture and density provide some information on block wall permeability: generally, the more coarse block has the greater permeability [*24*]. Radon in the block walls is of particular concern in buildings that have unducted return air plenums in the dropped ceiling because the radon that enters the plenum can then be distributed throughout the building by the HVAC system [*12*]. Poured concrete walls should be inspected similarly to floor slabs for cracks, separations at seams and corners, and gaps around utility penetrations.

Crawl Space Inspection

Crawl spaces with poured concrete slabs should be inspected as basements or slab-on-grade structures. In crawl spaces where there is a dirt floor, inspections of the floor should be conducted in the crawl space, if feasible, and within the structure. Radon entry routes from the crawl space to occupied areas include: the area around electrical and pipe openings, air returns, separations or cracks in floor boards, and utility penetrations, including plumbing, electrical, and sanitary connections. If the floor above the dirt floor is constructed of wood, rather than concrete, there are typically many radon entry routes.

Measure Subslab Pressure Field Extension

To determine the feasibility of installing an ASD system in a building and to help determine system design parameters, it is important to conduct measurements that provide information on the materials under the slab. These measurements determine the subslab pressure field, commonly referred to as pressure field extension (PFE) or subslab communication. This section describes the basic principles and steps for conducting subslab PFE measurements [*2,7–9,12*]. The methods are specific to measuring PFE under the slab. This procedure should be modified for other types of ASD systems such as block wall depressurization [*8*].

To measure PFE, drill one large hole (approximately 5 cm diameter) and, depending on the size of the building, about five to ten small holes (approximately 0.5 to 1.25 cm diameter) through the slab at various distances and directions from the larger hole. It is important to carefully determine the locations of all subslab utility lines before drilling through the slab.

At this point, subslab grab samples or sniffs through these holes are sometimes collected in order to determine the subslab radon levels. It may also be possible to look into the holes using a flashlight and/or fiber optic probe. The next step is to measure the subslab pressure in each of the holes relative to the building interior in order to obtain "baseline" subslab pressures. This can be done using a sensitive device such as a micromanometer; however, something as simple as a chemical smoke stick could be used to qualitatively determine if air flows into or out of the slab. If air flows into the slab, the building is under a positive pressure relative to the subslab. If air flows from the subslab into the building, then the building is under a negative pressure relative to the subslab. Some radon mitigators also take measurements of airflow with a device such as an anemometer.

After the baseline subslab differential pressure measurements are made, the measurements are repeated with the subslab area depressurized. To depressurize the subslab area and simulate an ASD system, the end of a vacuum cleaner hose is inserted into the large hole. A variable-speed vacuum cleaner or a radon mitigation fan will help to better determine the depressurization effects anticipated with an ASD system. As with the baseline measurements, depressurization can be determined either qualitatively (e.g., with a smoke stick) or quantitatively (e.g., with a sensitive pressure sensing device). These test results will indicate the extension and magnitude of the pressure field created under the slab, providing a realistic mapping of subslab pressure differentials expected with an ASD system. This is used to determine the number and location of subslab depressurization points, pipe diameter, and depressurization fan specifications.

When conducting PFE measurements, it is important to exhaust the vacuum cleaner directly to the outdoors due to the high radon levels often found under the slab. Once the PFE tests are complete, all holes should be carefully sealed with concrete patching material.

When conducting PFE measurements in a school or other large building, it is important to consider structural characteristics that may affect PFE. Larger buildings often have interior footings and/or thickened slabs. These structural features may create subslab barriers to airflow and, consequently, affect the number and placement of subslab suction points. For example, if all block walls surrounding the rooms extend to footings creating individual subslab compartments, it may be necessary to install a suction point for every room [*7*]. If the walls between rooms are set on thickened slabs rather than on below-grade walls resting on footings, subslab depressurization from one suction point will usually extend under these thickened slab areas.

Evaluate HVAC System

Pressure differentials that contribute to radon entry can result from operation of a HVAC system under conditions that cause negative pressures in the building relative to the subslab area. Alternatively, the HVAC system can be used to control radon levels if it pressurizes and/or ventilates the building. This section covers some of the steps that can be used to better understand the HVAC system's effect on radon levels in the building. The reader should refer to ASHRAE Standard 62-1989 [*23*] for current ventilation standards.

Types of HVAC Systems

First it is important to identify the type of HVAC system in the building. HVAC systems in residences and in many older large buildings are not designed to provide conditioned outdoor air to the occupants. In these cases, the HVAC system should affect radon levels or radon distribution in the building only if forced-air systems are used.

Types of HVAC systems common in large buildings include: central air-handling systems, unit ventilators, fan-coil units, and radiant heat. The central air-handling systems and unit ventilators are typically designed to provide outdoor air to the occupied areas and would pressurize the building if operated in this mode. However, many HVAC system outdoor-air intakes are deactivated or closed during temperature extremes [*7*]. In addition, HVAC systems in buildings occupied only during business hours are normally set back or turned off when unoccupied; so, even if the HVAC system pressurizes the building during operation, radon levels may increase during setback periods.

Some buildings use exhaust fans to increase outdoor air infiltration into the building or to remove internally generated contaminants. If more air is exhausted from the building than supplied, the building (or zones of the building) will be under negative pressure, potentially increasing radon entry.

HVAC System Measurements

The HVAC system can be evaluated during the building investigation or separately. In a school or other large building, the engineer or other knowledgeable person(s) responsible for operation and maintenance of the HVAC system should be present during the evaluation.

The first step is to confirm information found in the mechanical plans and specifications. For example, is the HVAC system actually installed and/or operated as designed or, for example, have outdoor air intakes been restricted, causing the building to be under negative pressure? The HVAC system should be reviewed in regard to the overall balance of building tightness, duct leakage, makeup air, and exhaust air. Fans, vents, and intakes should be observed for proper settings and openings. Idle fans or closed vents and louvers are

immediate indications that the system is probably not operating properly [*11,13*].

A chemical smoke stick can be used to qualitatively determine whether the building envelope is pressurized or depressurized relative to the outdoors, hallway, and subslab, and a micromanometer can be used to quantify the pressure differentials. When analyzing the pressure differentials induced by the HVAC system, it is important that measurements be made under "typical" operating conditions. To measure airflow through HVAC registers requires a flow hood. Airflow in ducts and pipes can be measured using an anemometer or a Pitot tube in conjunction with a sensitive pressure gauge.

In occupied areas, particularly larger buildings, a portable carbon dioxide (CO_2) monitor is useful in determining if there is sufficient outdoor air for occupants [*11*]. ASHRAE recommends CO_2 levels below 1000 ppm [*23*].

A question to consider when collecting data on the HVAC system is: If the HVAC system is causing the building to be under negative pressure, is it a result of the HVAC system design or is it due to operation and maintenance practices? If the system has the design capacity to maintain all building zones under positive pressure, it may be possible to control radon levels by adjustment of the HVAC system. If modification of the HVAC system is under consideration as a permanent approach for radon control, consideration should be given to the operation and maintenance costs that may be incurred, and building maintenance personnel must thoroughly understand proper system operation.

If it is suspected that radon is being distributed throughout the building by the air-handling system, radon "sniffs" in the supply air should be compared with radon levels in the room(s). Depending on the system design, radon can enter into the return-air system and subsequently be distributed to rooms using recirculated air. This may happen in HVAC systems that have, for example, subslab return air ductwork, unducted return air plenums in the drop ceiling that are open to the subslab via open tops of block walls, and air intakes for unit ventilators that are open to the soil at the floor/wall joint.

Measure Building Tightness

Blower door tests can be used to determine building, basement, or crawl space leakage area [*14,15*]. The leakage area (or airtightness) can then be used to calculate the air exchange rate. These data can provide information regarding the applicability of basement or crawl space pressurization, crawl space depressurization, or an air-to-air heat exchanger.

Additionally, blower doors can be used to exhaust air from the building to simulate building depressurization during cold weather by depressurizing the substructure (typically by 1.5 to 10 Pa). While the building is depressurized, airflow through cracks and holes can then be located to find major entry routes.

A blower door can also be used to depressurize parts of the building to simulate the potential for backdrafting of combustion appliances when considering radon control strategies such as ASD and basement or crawl space depressurization. Backdrafting is the reverse of the normal movement of combustion products up a flue, so that the combustion products can enter the building. Backdrafting of combustion appliances (such as fireplaces, woodstoves, and/or some types of fossil-fueled space heaters or furnaces) can occur when depressurization in the building overwhelms the buoyant force on the hot gases. Backdrafting can also be caused by high air pressures at the chimney or flue termination. Combustion appliances can backdraft into the building if a significant negative pressure is applied to the local area where they are operating. Ideally, no combustion appliances, fireplaces, or wood stoves/furnaces should be located in an area to be depressurized.

Tracer gas measurements using sulfur hexafluoride or other non-reactive gases can also be used to determine building air change rates [*25,26*]. Correlations between indoor radon concentration and air infiltration rate are generally poor; however, better correlation is found between indoor radon and the radon levels in the soil under the building [*25,27*].

Determining if Building Materials Are a Source of Radon

If it is suspected that building materials may be a source of elevated radon levels, gamma radiation measurements should be made. Building materials that may be a source of elevated radon levels include gypsum board, contaminated cinder block, concrete, exposed basement rock, and stone (fireplaces and foundations). Reference *28* provides information on radon entry pathways into buildings, through building materials, and from building materials.

CONTROL METHODS THAT PREVENT RADON ENTRY

This section covers the four techniques that prevent radon from entering a building: active soil depressurization (ASD), sealing, building pressurization, and source removal. The emphasis is on ASD, the most successful and widely used radon control technique for existing buildings [*2,7*].

Active Soil Depressurization (ASD)

Radon-containing soil gas is drawn into buildings by a lower air pressure in the building relative to the surrounding soil. An ASD system reverses this pressure difference causing the pressure in the surrounding soil to be lower than the indoor pressure (Fig. 5). This air pressure differential keeps radon-containing soil gas from entering the building. ASD systems use a suction fan to produce the negative-pressure zone beneath the slab, hence the system is referred to as "active."

ASD systems are most effective for slabs that are built over a layer of clean, coarse gravel or coarse soil that allows air to flow through it. Even if the air movement underneath the slab is poor, ASD may still work, depending on the number and location of suction points and the type of fan used [*29*].

For radon levels above about 700 Bq m^{-3}, ASD is usually the most effective and reliable radon reduction method. In fact, ASD systems are also often installed in buildings with radon levels less than 700 Bq m^{-3} because of their performance in reducing radon levels.

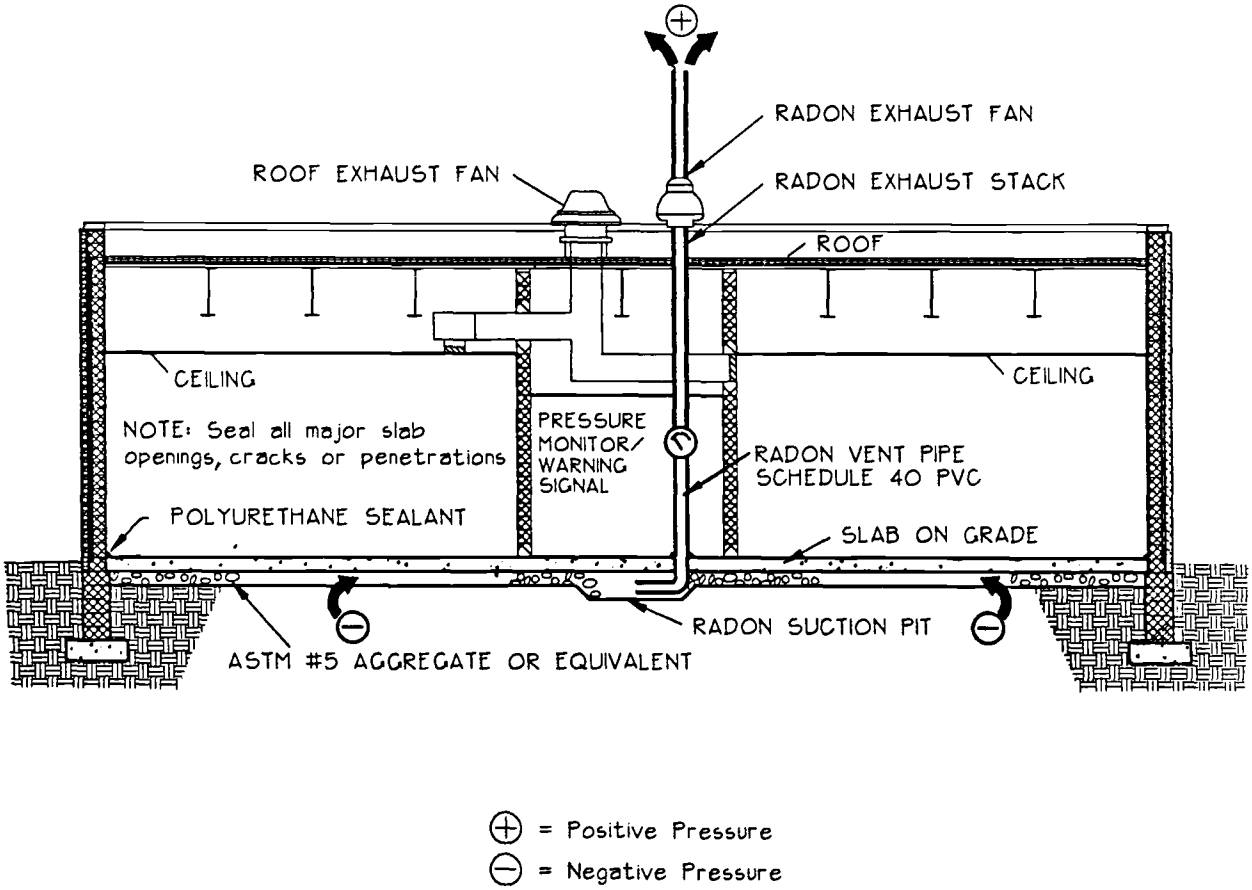

FIG. 6–Typical subslab depressurization system.

The widest application of ASD is subslab depressurization. For subslab depressurization, pipes are inserted through the slab directly into the crushed rock or soil beneath as shown in Fig. 6. Other applications of ASD discussed in this chapter are: sump hole depressurization, drain tile depressurization (with remote discharge rather than sump hole discharge), block wall depressurization, and submembrane depressurization (typically used in a dirt floor crawl space). Depressurization of the entire crawl space can also be considered a variation on ASD. The general design features for ASD systems are discussed below, followed by a more detailed description of the six types of ASD.

General Design Features for ASD Systems

Polyvinyl chloride (PVC) pipes are typically used for ASD systems because of their ease of handling and relative cost; however, building codes in some areas of the country might prevent the use of PVC piping in some sections of buildings. Special restrictions may apply to pipe used in firewall penetrations and plenums above dropped ceilings. In most areas, codes require suitable fire stop details at any location where the piping penetrates a fire-rated wall, a ceiling deck, or a floor deck. Building codes in some areas require steel pipe. All relevant building codes must be followed when installing an ASD system. In addition, ASD systems must avoid backdrafting of combustion appliances as discussed above in the section on building tightness.

Clearly label the exposed radon vent pipes and other system components indicating that they may contain high levels of radon. Place labels at regular intervals (at least every 2 m) along the entire pipe run. At the roof exit, attach a weatherproof label to the vent stack with a warning such as "Soil gas vent stack—may contain high levels of radon." Refer to local codes to determine the specific minimum distance for air intakes placed near the radon exhaust. Since the soil gas concentration is normally considerably higher than radon levels in the building interior, reentrainment of even small volumes of the soil gas could significantly increase indoor radon concentrations. Examples of suitable discharge configurations are presented in Refs *18* and *30*.

ASD system fans must be operated continuously. All ASD systems should have pressure gauges or pressure-activated alarms to indicate if the system stops operating properly. One type of warning system has an electronic pressure-sensing device that activates a warning light or an audible alarm if the system pressure drops below a specified level. Install the warning device in an area frequently visited by residents or building occupants. For example, in some large buildings, warning devices have been connected to the energy management system computer.

To increase the effectiveness of a subslab depressurization system, all major openings in the slab and walls should be sealed. Refer to the section below on sealing for guidelines.

An operating manual describing the system and its purpose should be provided to the occupants. For example, the man-

ual should contain information on (1) checking the pressure gauge(s) and/or alarms in the radon vent pipes to ensure that the fan is maintaining adequate negative pressure to depressurize the subslab area, (2) inspecting the fan for failure (e.g., bearings), (3) inspecting the discharge location of the vent pipe to ensure that no air intake or operable windows have been located nearby, and (4) checking the HVAC system to determine if it is being maintained and operated as designed (e.g, an HVAC system exhaust with inadequate makeup air might overcome an ASD system).

One may ask "Is it possible to install a soil depressurization system that works passively, that is, without a fan?" The passive depressurization system relies on the building to maintain a "stack effect" based on the ability of the building to provide sufficient airflow to permit air in the stack to rise. For the passive stack to operate best, the building stack effect should be minimized by sealing all leaks in the upper levels [*19*]. Wind effects must also be considered. Although research has shown that passive systems are sometimes effective in carefully designed and constructed new homes [*19*], their effectiveness has not been demonstrated in large buildings [*3*]. Many competing negative pressures in large buildings can easily overcome a passive system.

It may be possible to operate some types of ASD systems by applying pressure rather than suction to the soil gas in the space under slabs or within block walls. Experience has shown that pressurization is better than suction only when the underlying soil is a deep layer of highly permeable material. There is also some evidence to indicate that pressurization might cause radon, soil moisture, termaticides or pesticides, and odors to enter the occupied area. As a result, pressurization of the soil is not discussed further in this chapter.

Six different applications of ASD—subslab, sump hole, drain tile, block wall, submembrane, and crawl space—are described in the following subsections.

Subslab Depressurization

For subslab depressurization, pipes are inserted through the slab directly into the crushed rock or soil underneath. Designing and installing an ASD system in basement, slab-on-grade, or crawl space buildings that have a concrete slab in contact with the soil are similar. The primary difference is that basement walls provide additional radon entry routes that must be sealed. In slab-on-grade buildings, the suction pipes can also sometimes be inserted below the slab from outside the building, horizontally through the foundation wall.

As mentioned above, subslab depressurization is most effective for slabs built over a layer of clean, coarse gravel or coarse soil that allows air to flow through it. Figure 6 illustrates how the creation and extension of a negative pressure field beneath the slab will cause air to flow from the building into the subslab area. This direction of airflow will prevent entry of soil gas into the building.

If the subslab material has low permeability (such as tightly packed sand or clay) or is interrupted by interior subslab walls, the pressure field might not extend to all areas of the soil under the slab. Research has shown that the use of high-suction, low-flow fans improves the effectiveness of subslab depressurization systems if the subslab material has a low permeability. Detailed instructions are provided in Ref *29*.

The subslab depressurization created by the system must be sufficient to overcome the worst case scenario of building depressurization. The subslab depressurization in a given building will vary depending on the measurement conditions (e.g., weather) but, as a minimum, should at least be measurable [*2*].

Design of ASD systems generally proceeds as outlined below. Technical guidelines on design and installation of ASD systems are detailed in several EPA publications [*2,3,5–10,29*].

1. *System Design:* Determine the optimal design (e.g., number and location of suction points, type of fan, and pipe diameter and length) based on PFE measurements or experience in similar types of buildings. The number of suction pipes needed depends on the permeability of the material underneath the slab and on the strength and location of the radon source. If the subslab material has good permeability, one suction pipe may be enough. If the material does not allow easy air movement, more pipes probably will be needed. Every subslab area isolated by subslab walls will normally need a radon suction point.
2. *Building Codes:* Follow all relevant building codes that need to be addressed in the design and installation of the system (e.g., penetrating fire walls, placing pipes in plenums).
3. *Suction Pits:* Excavate suction pits below the slab to extend the negative pressure field. The size of the suction pit depends on the area to be depressurized and the anticipated subslab pressure field. In houses, for example, subslab suction pits are normally about 0.3 m in diameter and depth. In larger buildings such as schools, larger suction pits are generally needed (e.g., 1 m in diameter and 0.3 m in depth).
4. *Radon Vent Pipe:* Install radon vent pipes from the radon suction pit to the outdoors and follow manufacturers' instructions for sealing all piping joints. In houses, 7 to 10-cm-diameter PVC pipe is normally used. For schools and other large buildings, 15-cm-diameter PVC pipe is recommended because of the greater airflow. It is important to pitch all horizontal pipe runs about 1 cm per m so that accumulating condensation drains back to the radon suction pit. It is also important to avoid any low areas in the horizontal pipe that could block airflow if condensation were to accumulate in the pipe. Seal any openings between the pipe and the floor slab using a high adhesive sealant such as polyurethane. Also, insulation of the piping in areas such as dropped ceilings, finished areas, or attics helps to avoid problems such as condensation, noise, and freezing pipes.
5. *Suction Fan:* ASD systems generally use in-line duct fans for a number of reasons: the performance curve is in the range needed; their in-line configuration facilitates their installation; the price is reasonable (about $85 for a smaller fan and up to $500 for the largest fan); and they are relatively quiet [*2*]. Install a suction fan designed for outdoor use in radon control systems. Fans used in homes with good subslab communication are normally rated at about 130 L/s at zero static pressure. In homes with poor

subslab communication, fans with lower flow and higher suction, such as 10 L/s at 13 to 100 cm static pressure, are generally used. Fans used for schools and other large buildings with good subslab communication are normally rated at from 235 to 282 L/s at zero static pressure. Detailed information on fan selection, including fan curves, is available in Ref 2. Because piping on the exhaust side of the fan is under positive pressure and might be subject to leaks, always mount the fan outdoors.

6. *Sealing Radon Entry Routes:* For an ASD system to be most effective, it is important to seal large openings (slab and foundation joints and cracks and utility and pipe penetrations) that can defeat extension of a low-pressure field. Large openings in the slab not only reduce system effectiveness, but also increase operating costs by drawing too much air from inside the building. The section below on sealing provides comprehensive guidelines.

Sump Hole Depressurization

In basements with a sump, the sump pit can often be used as a ready-made hole through the slab. The sump pump will need to be replaced with a submersible unit. The sump hole is then capped with an airtight, removable cover. Suction is applied to the sump hole through a suction pipe connected through the sump cover, following Steps 4 through 6, above. In many cases, sump pits are connected to the drain tiles around the foundation of the house. If so, they provide an excellent opportunity to draw radon away from the foundation.

Drain Tile Depressurization

In some buildings, water is directed away from the foundation by perforated drain tile pipes. The pipes usually drain the water to an above-ground discharge located away from the building or to an internal sump. When these drain tiles form a complete loop around the exterior or interior of the footings, they may be used to draw radon away from the surrounding soil. If the soil allows easy air movement, suction from the tiles sometimes extends underneath the entire slab.

Where drain tiles are present, drain tile depressurization is often a relatively low-cost way to reduce radon. The system usually can be installed without disturbing the finished space, which is an advantage in a building with limited internal access. These systems work best when the drain tiles form a complete loop around the building. Often, drain tile loops either are not complete or have been blocked or damaged. If this happens, part of the building may not be effectively treated.

If the tiles drain to a sump inside the building, the sump should be capped with an airtight cover and suction drawn from the sump cavity as discussed in the previous section. If the tiles drain to an above-grade discharge area, install a PVC pipe and an exhaust fan in the drain tile system away from the building. To maintain an effective airtight system, a water-filled trap or reverse-flow valve must be installed in the collection pipe beyond where the fan is attached. The water trap must be placed below the frost line and must be kept filled.

Block Wall Depressurization

The concrete blocks used to construct many basement walls contain hollow spaces that are normally connected both vertically and horizontally. Radon from the soil, entering the wall through joints, pores, and cracks, can move through these hollow spaces and enter the basement through similar openings on the interior side, or through uncapped openings in the top row of blocks. Block wall depressurization removes the radon from these void spaces before it can enter the building by creating a zone of lower pressure that reverses the direction of soil gas flow. This can work only if the openings at the top of the wall are closed and other major cracks and openings in the wall are sealed.

Block wall depressurization has been researched by EPA in a number of houses [9]. It has not, however, been widely applied in larger buildings. Because the effectiveness of block wall depressurization can be difficult to predict, subslab depressurization should be considered first. In buildings where subslab depressurization does not adequately reduce radon, subslab and wall depressurization might be applied together.

There are two ways to install block wall suction. The simplest is to insert one or two PVC pipes into each wall and to draw radon out with fans vented to the outdoors. Another approach involves installing a plastic or sheet-metal baseboard duct around the perimeter of the basement floor. Holes are drilled into the hollow spaces in the block wall behind the duct.

The baseboard approach generally results in better suction and is less obtrusive, but it is more expensive. It works best where the hollow portions of the block wall are not continuous, where drainage problems exist, or where there is a perimeter drain around the floor.

Block wall suction can be costly. Another disadvantage of block wall suction is that all major wall openings must be carefully sealed in order for the technique to work. Air moving through the basement walls can cause a greater increase in heating and cooling costs than either subslab or drain tile suction. Painting or otherwise coating the interior block walls will help to reduce the loss of conditioned air.

Submembrane Depressurization

There are two soil depressurization techniques for radon reduction in crawl space buildings: submembrane depressurization (SMD) and crawl space depressurization. SMD is a variation of the successful ASD method and is shown in Fig. 7. It is typically a much more effective approach than crawl space depressurization for maintaining low radon levels in both the crawl space and occupied area [*31*].

To install a SMD system, place wide polyethylene sheets (with at least 0.3 m overlaps between the sheets) directly on the crawl space floor. Be sure to remove any large rocks, broken concrete blocks, or other obstructions before placement. Where the soil surface is exceptionally hard and smooth or the crawl space is very large, use a radon suction pit or perforated piping manifolded under the sheeting to improve the pressure field extension. To increase system effectiveness, seal the seams in the vicinity of the suction point using a sealant recommended by the sheeting manufacturer. In large crawl spaces with many support piers, it might be more difficult to install SMD. If many support piers are present, or if the radon suction point has to be located close to support piers, seal the polyethylene sheeting to the piers. The polyethylene sheeting can also be sealed to the foundation walls to reduce air leaks; however, this additional sealing has

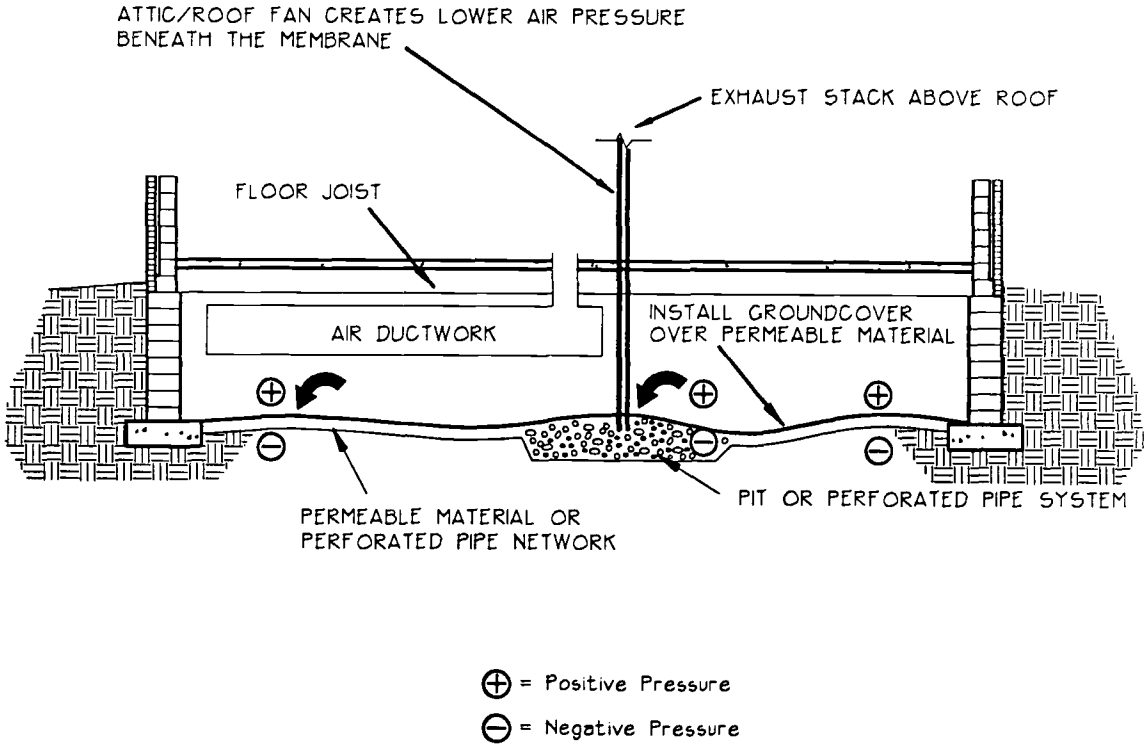

FIG. 7–Submembrane depressurization in crawl space.

proved to be unnecessary in some existing homes. In small crawl spaces with few support pillars, active SMD systems have worked effectively without sealing the plastic sheet to the foundation walls.

Once the membrane is installed, a suction fan and vent stack are used to depressurize the area under the membrane, as discussed in Steps 4 and 5, above.

Crawl Space Depressurization

For crawl space depressurization, a fan is used to depressurize the entire crawl space area. The negative pressure in the crawl space relative to the building interior keeps the radon from entering the building. However, the negative pressure in the crawl space will increase radon levels in the crawl space, so this technique should not be used if people need to enter the crawl space frequently.

Because of the potential for high radon levels in the crawl space, it is very important to seal the area between the crawl space and building interior (refer to the section below on sealing). Sealing is also important to reduce energy loss from air flowing from the building interior into the crawl space. The crawl space vents and other major openings in the crawl space should also be sealed in order to achieve a sufficient negative pressure in the crawl space. Research has shown that closing the crawl space vents will not create a moisture problem if a vapor retarder is placed over the ground [*32*].

Sealing Radon Entry Routes

Radon can enter a building through cracks in floor slabs and walls, areas of exposed soil, sump holes, drains, below-grade utility penetrations, pores in block walls, and open block tops in foundation walls. Sealing, closure, or isolation of radon entry routes can limit or eliminate the flow of radon gas into the building.

Sealing of major accessible entry routes should be considered an essential part of most approaches to radon reduction. However, the effectiveness of sealing is limited by one's ability to identify, access, and seal the places where radon is entering. Complete sealing is often impractical, labor intensive, and expensive. In some buildings, certain areas will be difficult or impossible to seal for a reasonable cost. Hard-to-reach areas include tops of block walls, spaces between block walls and exterior brick veneer, openings concealed by masonry fireplaces and chimneys, the floor above a crawl space, and below-ground areas that have been converted into living space. Normal settling of the building can also open new entry routes and reopen old ones. Another limitation of sealing is that bonding between the sealant and the surface is often difficult to make and maintain.

Radon reductions from sealing vary widely depending on whether the important entry points were sealed and the quality of sealing. Radon reductions from thorough sealing efforts are typically about 50%. Results from EPA research have ranged from no radon reduction to 90% [*9*]. Research indicates that a near perfect sealing job is necessary to achieve a high radon reduction. In a building with slightly elevated radon levels (about 400 Bq m^{-3}), sealing may be a relatively economical first attempt at radon reduction. In buildings with high radon levels, sealing alone usually will not reduce radon levels to below 400 Bq m^{-3}.

The following subsections cover recommended sealants and application techniques, sealing concrete slabs, sealing below-grade walls, and sealing crawl spaces.

Recommended Sealants and Application Techniques

Sealants must have good adhesion to concrete and be durable and elastic. The popularity of polyurethane as a suitable elastomeric joint compound is based on a combination of strong adhesion to concrete under difficult conditions, long service life, and good elasticity [*6*]. Silicone caulks do not always adhere well to concrete. The ability of the caulks to provide sealant performance under stress must be considered. If increased movement in the crack, slab, or block is anticipated, a caulk which is able to take up the strain is preferable [*33,34*].

When sealants are applied, be sure that surfaces are clean, dry, and free of grit and that the surface temperature is above freezing. Apply sealants in accordance with the manufacturers' recommendations. Typical dimensions for caulk beads are 1.25 cm deep by 0.75 to 1.25 cm wide. It may be necessary to use backer rod when applying sealant in wide gaps.

The application of caulks in cracks and holes around pipes or slab separations should generally be heavy and thick. A thicker caulk bead will provide a greater barrier to radon than a thinner bead. A continuous caulk bead is important since even small openings can permit radon entry.

Sealing Concrete Slabs

This section addresses sealing of slabs on grade, basement slabs, and crawl space slabs. Concrete is normally a good radon barrier. The major problems with concrete slabs are joints, slab penetrations, and cracks.

Slab joints of concern include the floor/wall joint, pour joints, and control saw joints. The floor/wall joint (also called perimeter crack) of a slab is located between the edge of the floor slab and the interior or exterior load-bearing walls. In addition to typical radon entry routes at the floor/wall joint, buildings constructed with a combination of different substructures may have additional entry routes at the interface between the two substructures (i.e., at the basement and slab-on-grade interface).

Gaps around utility penetrations in the slab should be sealed. These include: water and sewer lines, lines to unit ventilators and radiators, electrical service entries, subslab conduits, air conditioner condensate drains, and roof drains.

In most buildings, floor drains empty into a sewer pipe rather than the soil. In these cases, the drain itself is not of concern as a radon entry route. The only concern is the opening around the pipe penetration as discussed above. Where the floor drain does drain into the soil, the drain should include a filled-water or mechanical trap to prevent soil gas from entering the building.

Open sump holes can also serve as major radon entry routes. Seal the sump hole with a gasket and lid and install a submersible sump pump. Silicone rather than polyurethane caulk is sometimes used to seal sump lids and access ports because it makes a tight-fitting gasket that can be removed. The sump hole can also be used as a ready-made radon collection system by venting the sump to the outdoors as discussed above in the ASD section.

Sealing Below-Grade Walls

Below-grade walls and stem walls are normally constructed of either poured concrete or masonry blocks. Because these walls are in direct contact with the soil, they can be major radon entry routes. Penetrations and openings through below-grade walls into the soil can also be major radon entry routes. These penetrations and openings should always be sealed as discussed above for penetrations through slabs.

A poured concrete wall can be an excellent barrier to radon; however, as with concrete slabs, the major problems are cracks, joints, and penetrations. Concrete blocks are more porous than poured concrete, although the parge or waterproofing coats can moderate the difference. Recent EPA laboratory tests have confirmed that concrete masonry walls can allow substantial airflow, although there is a great deal of variation in the porosity of blocks [*24*].

Interior paints can be used as radon barriers for masonry block walls. A variety of interior-applied masonry paints are available. Some of these have been tested by EPA, and results show that a number of interior paints can be effective radon barriers if properly applied [*24*].

Sealing Crawl Spaces

Elevated levels of radon can build up inside a crawl space, especially if the crawl space has a dirt floor rather than a poured concrete slab. Radon in the crawl space can then enter the occupied area above the crawl space through cracks and openings in the floor (see Fig. 4). Thorough sealing of these cracks and openings will help to reduce radon entry into the occupied area.

In schools and other large buildings, the floor above the crawl space is typically a suspended concrete slab rather than a wooden floor used in houses. A poured concrete floor slab is a good barrier to radon; however, joints and cracks in the slab are potential radon entry routes and must be sealed as recommended in the section above on sealing concrete slabs.

Other openings and penetrations between the crawl space and the occupied area above include: water and sewer lines, utility lines to unit ventilators and radiators, electrical service entries, and gaps in wood floors. Radon in the crawl space can also enter the occupied area above if ductwork for the HVAC system is located in the crawl space. Therefore, in radon-prone areas, neither air supply nor return ductwork should be located in the crawl space [*23*].

If the building has high radon levels or if people frequently enter the crawl space, it may also be necessary to install a SMD system in the crawl space. This will reduce radon levels in the crawl space. SMD is covered above in the section on ASD.

Building Pressure Control

Since depressurization is a primary factor contributing to the flow of radon into a building, minimizing or eliminating depressurization will reduce radon entry. If the lower levels of the building can be maintained at an air pressure higher than that of the underlying soil gas (i.e, pressurized), then the flow of radon into the building may be stopped. Reducing building depressurization and building pressurization are discussed separately below.

Reducing Building Depressurization

Simple, low-cost steps can sometimes be implemented by occupants to reduce building depressurization. Exhaust fans, such as window fans, kitchen fans, bathroom fans, attic fans, clothes dryers, and whole-house fans, can contribute to building depressurization. If these exhaust fans are used, consider opening windows near the fan. Fireplaces, coal or wood stoves, central furnaces, water heaters, and other vented combustion devices can also depressurize the building if combustion air is not provided.

To reduce depressurization caused by central, forced-air heating and cooling systems, seal off cold-air return registers in the basement. Where accessible, cold-air return ducting in the basement or crawl space should be carefully taped or caulked to reduce any leakage of radon-containing air into the ducts.

Opening windows in the basement might help to reduce depressurization caused by the stack effect. Closing airflow by-passes between floors, such as stair wells, utility penetrations, and laundry chutes, may also reduce the stack effect.

Building Pressurization With the HVAC System

This approach is applicable only in buildings where the HVAC system has been designed to provide conditioned outdoor air (i.e, typically in schools and other large buildings but not in residences). A building is pressurized by bringing in more outdoor air than is removed by mechanical exhaust systems. Excess air then exfiltrates out of the building through cracks and unsealed openings in the building shell. Because building pressurization brings in outdoor air, it also helps to reduce radon (and other indoor air pollutants) through dilution.

The concepts of building pressurization and depressurization are illustrated in Figs. 8 and 9, respectively. In both examples the building HVAC system has a supply of 47 000 L/s (100 000 cfm) and an exhaust fan that withdraws 7050 L/s (15 000 cfm). However, in Fig. 8 there is an outdoor air supply of 9400 L/s (20 000 cfm), or 20% of the total supply. As a result, the building illustrated in Fig. 8 is under a positive pressure and 2350 L/s (5 000 cfm) of air will exfiltrate from the building. This positive pressure will keep radon from entering the building while the HVAC system is operating. On the other hand, the scenario in Fig. 9 shows an outdoor air supply of only 2350 L/s (5 000 cfm), or 5% of the total air supply. In this case, the building is depressurized because the exhaust fan withdraws 7050 L/s (15 000 cfm) of indoor air and only 2350 L/s (5 000 cfm) of outdoor air is supplied. This depressurization, together with the natural stack effect, will cause about 4700 L/s (10 000 cfm) of air to infiltrate into the building. This can pull radon into the building from the soil gas.

If building pressurization is being considered as a radon control strategy, the following facts must be considered:

- Open windows and doors make it very difficult to achieve a consistent positive pressure in the building.
- Start/stop operation of the HVAC system for various occupancy modes does not allow for continuous building pressurization.
- The design and operation limitations of different types of HVAC systems must be considered when adjusting a system to pressurize the building. For example, the design of variable air volume (VAV) systems must take into consideration the effects of minimum flow conditions on ventilation and pressurization throughout the building.

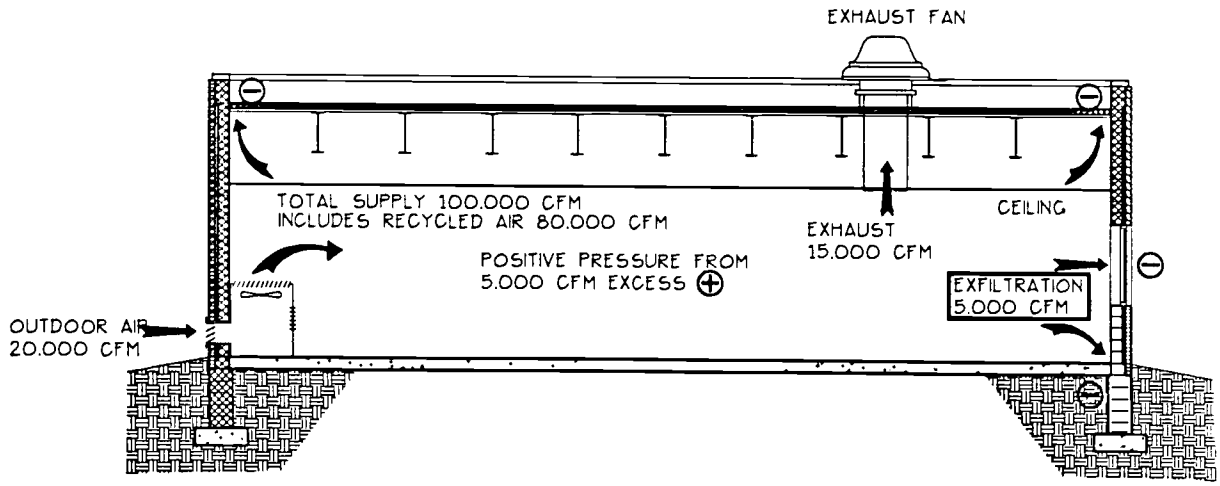

FIG. 8–Building *pressurization* with HVAC system.

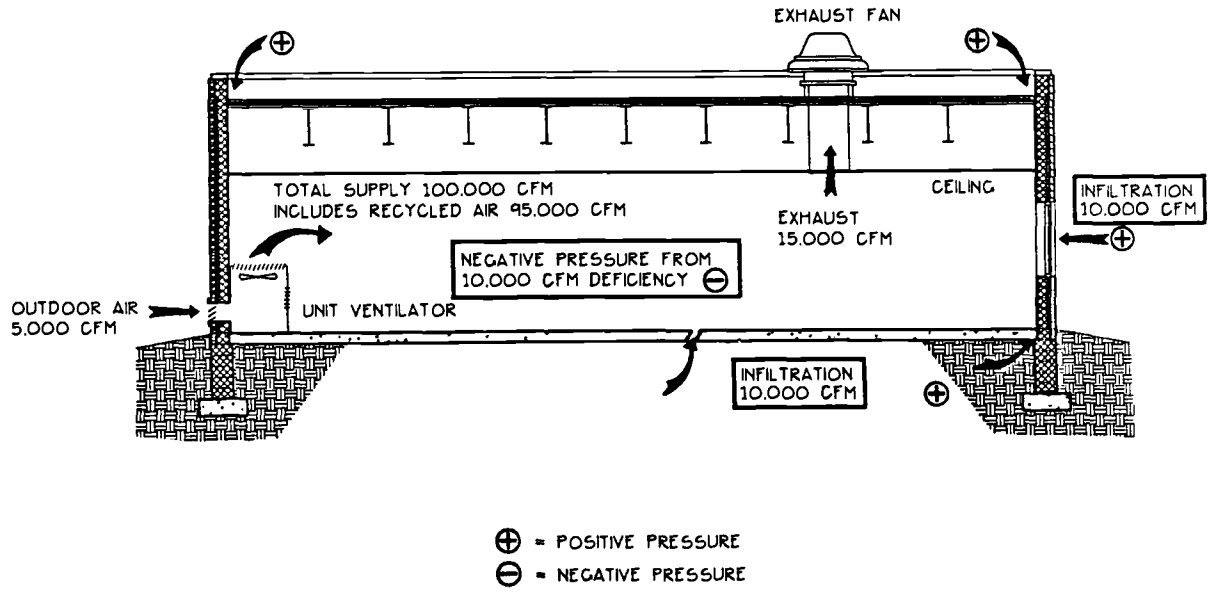

FIG. 9–Building *depressurization* with HVAC system.

The following basic guidelines for building pressurization should be followed:

- Adjust the HVAC systems so that the building interior in all ground contact rooms is at least slightly pressurized (for example, 5 Pa). A qualified engineer should be involved when adjusting the HVAC system for radon control.
- Avoid subslab supply and/or return ductwork, and do not locate air supply or return ductwork in a crawl space [*23*].
- Seal all supply and return ductwork at all seams and joints.
- Seal all floor and wall penetrations (especially under through-wall units and in mechanical rooms).
- Minimize air leakage through the building shell. In addition to facilitating building pressurization, a tight building shell will reduce energy costs and allow for improved environmental control. For details on measuring air leakage rates, see Ref *35*.
- Control operation of the HVAC relief dampers so that they modulate to maintain a positive building pressure.
- Be sure all applicable building and safety codes, standards, and guidelines are followed.
- Be sure to preserve the intended indoor air quality purposes of mechanical ventilation devices. Exhaust fans should remove the moisture, fumes, and other contaminants generated within the building. Supply air systems should provide conditioned air, free of objectionable quantities of contaminants.
- Proper HVAC system maintenance is *essential* to ensure continued reduction of radon levels and adequate indoor air quality.

Building Pressurization Without the HVAC System

Most residences and some large buildings are not designed to deliver conditioned outdoor air to occupied spaces. In these cases, a fan system can be installed to pressurize lower levels of a building, such as a basement or crawl space, to prevent radon entry. Air can be blown in from either the upstairs or the outdoors. Basement pressurization has been shown to be very effective in some houses and not applicable in others. The ability to seal the basement off from the first floor and the outdoors and the general structural integrity appear to be the limiting factors.

Basement pressurization can be used only in very tight basements. The pressurization fan must provide a sufficient amount of pressure to overcome the building stack effect and any other activities that depressurize the building. In addition, openings between the basement and the main floors should be sealed. Opening a basement window or door will reduce the basement pressure, as well as increase the airflow and heating/cooling costs by allowing conditioned air to flow outdoors.

Pressurization of the crawl space prevents soil gas from entering the crawl space by reversing the soil gas flow. It requires sealing of the vents and floor, just as for crawl space depressurization, and installation of a pressurizing fan. Unless the floor is sealed extremely well, this technique has the possibility of forcing any radon in the crawl space back through cracks and gaps into the living area. Crawl space pressurization could be easily defeated if a vent or access door were left open [*31*]. Also, pressurizing with warm air from the building could pose a humidity problem for the wooden floor joists.

Source Removal

In rare cases, the source of the radon may be materials in the building. The most appropriate action in these cases is to remove the radium- or uranium-bearing material. Cases in the United States include homes constructed with uranium mill tailings, concrete from phosphate slag, and wallboard or other materials from phosphogypsum [*36*]. European homes constructed with alum shales and phosphogypsum are also

listed in literature [37]. In some cases the materials were removed; in others, the homes have been abandoned.

METHODS TO REMOVE RADON AFTER ENTRY

Although it is always preferable to prevent radon from entering the building, there are a few strategies available to remove the radon or radon daughter products after they have entered. This section covers three of these methods: ventilation, air cleaning, and removing radon from water.

Ventilation

Once radon has entered a building, levels can be reduced by ventilation or dilution with outdoor air. Ventilation with outdoor air may also help to improve the general indoor air quality. However, if radon levels are highly elevated, it is unlikely that dilution will be an effective stand-alone radon reduction technique. For a given constant rate of entry, radon concentrations in a building are inversely proportional to ventilation rates. Thus, for example, to reduce radon levels by a factor of 10, one would have to increase the air exchange rate by that same factor [38]. In most cases, such a large air exchange rate may be neither practical nor desirable. The types of ventilation discussed in this section are: natural, forced-air, and heat recovery ventilation.

Natural Ventilation

Some natural ventilation occurs in all buildings as outdoor air is drawn in through cracks and openings. Air exchange rates typically range from about 0.5 to 2.5 air changes per hour, although the rate could be lower or higher if the building were very tight or very leaky, respectively [9,39]. An increase in air exchange rates through ventilation—by opening windows, doors, and vents on the lower floors—can reduce radon levels. It does this both by replacing indoor air with outdoor air and by reducing building depressurization.

Basements and crawl spaces can be easily ventilated and can often be isolated from the rest of the building. However, natural ventilation techniques must consider freezing of the pipes and drains and the effect on the temperature in the occupied areas of the building. Results from natural ventilation are highly variable and depend on the specific building (e.g., typical air exchange rate, effect on radon entry rate).

Forced-Air Ventilation

Forced-air ventilation can help to maintain a specific air exchange rate independent of weather conditions. Forced-air ventilation could range from blowing air into the building with a window fan to supplying conditioned outdoor air through the HVAC system (if system design allows). As discussed above, in the section on building pressurization, outdoor air should be supplied in accordance with ASHRAE Standard 62-1989 [23]. To reduce highly elevated radon levels, it may be necessary to supply higher quantities of outdoor air than those recommended by ASHRAE.

The major disadvantages of natural and forced-air ventilation are increased energy costs during extreme weather conditions, security concerns (from open windows), and the increased entry of hot or cold outdoor air into the building. Natural and forced-air ventilation are practical, permanent, year-round solutions only if the area to be ventilated is completely isolated, i.e, a crawl space or an unoccupied basement. For buildings with very high indoor radon levels, ventilation might be an effective short-term radon reduction approach until a permanent radon reduction system is installed.

Heat Recovery Ventilators (HRVs)

To reduce energy costs from increased ventilation, a HRV, also called an air-to-air heat exchanger, can be used. A HRV will increase ventilation while recovering some heat during winter and cooling during summer. HRVs are most useful in tight buildings in climates with cold winters or hot summers. They may be installed in any substructure type and can be designed to ventilate all or part of a building.

The primary advantages of the HRV over natural or forced-air ventilation are smaller increases in heating or cooling costs, and improved comfort during weather extremes. HRVs also can improve indoor air quality in buildings with low air exchange rates.

HRVs are either placed in existing air-handling ducts or window/wall mounted. For an HRV to be a reasonable mitigation option, the anticipated savings from the reduced energy penalty should be more than the initial cost of the HRV. (See the section on radon decay product behavior indoors in Chapter 2).

Air Cleaning

Two air cleaning approaches are available to remove radon decay products (RDPs) and radon, respectively. The first approach, air cleaning, involves removal, not of the radon gas, but of the RDPs. This approach attempts to reduce the lung dose by removing or reducing the concentration of RDPs in the indoor air without reducing the concentration of radon. The second approach, radon gas adsorption, involves removal of the radon directly through adsorption onto a sorbent bed, usually activated carbon. Additional information on air cleaners can be found in Refs *40* through *47*.

RDP Removal

RDPs can be removed from the air by continuously circulating the air through a device which removes particles. These devices include mechanical filters, fabric filters, and electrostatic devices which can be incorporated into the air-handling system associated with a central forced-air heating and cooling system, or they can be stand-alone units [8].

RDPs will rapidly attach to other, larger particles in the air [8]. If no air cleaner is in use, the concentration of aerosol particles will be sufficient so that only a small fraction of the RDPs will not be attached. Air cleaners remove the aerosol particles so that newly created RDPs, which are continuously being generated by the radon gas, find many fewer aerosol particles to which to adhere. Therefore, while air cleaners can reduce the total concentration of RDPs, they can actually increase the concentration of unattached RDPs.

Air cleaners, if designed for high efficiency, can be highly effective in removing the radon decay products (both attached and unattached) which pass through them. However,

a difficulty arises in circulating air through the devices fast enough to provide high, building-wide reductions as radon decay products are constantly generated. The challenge is to remove these products in the air cleaner before they can be inhaled.

At present, particle-removal air cleaners cannot be recommended for the purpose of reducing the health risk due to radon and RDPs. Unattached RDPs may result in a greater health risk than those attached to dust particles because the unattached progeny could deposit selectively in a fairly small portion of the lung, giving that portion a high dosage of alpha particle bombardment. Current measurement techniques do not allow direct determination of radiation dose to the breathing airways. The dose must be computed from deposition models. These models indicate that air cleaners may reduce the radiation dose to the breathing airways by as much as 50 or 60%. While such reductions may be significant, they are usually not enough to serve as a stand-alone control strategy. Although the dose reduction has been small in some cases, there were no cases where the computed dose was increased by the use of air cleaners. Therefore, the use of air cleaners to control other pollutants (e.g., allergens) is not likely to increase the risk from radon.

Radon Gas Adsorption

Sorbents have been shown to remove many air contaminants such as formaldehyde and hydrogen sulfide. This technique has also been applied to remove radon from indoor air. A commercially available activated charcoal device operates by flowing air alternately through two sorbent beds [*48,49*]. One bed of activated carbon adsorbs the radon, while the other is "flushed" with fresh air. At prearranged intervals the beds are switched: the bed "full" of radon is ventilated to outdoor air with fresh air, while the second bed is utilized for adsorption of radon indoors. The switching of beds continues, periodically exposing "renewed" activated carbon after each ventilation sequence. The radon adsorbed is desorbed before significant decay occurs. Research and field experience with radon gas adsorption is quite limited.

Removing Radon From Water

Radon gas from the surrounding soil can dissolve in groundwater. Because radon is relatively insoluble in water, it can then readily add to airborne radon levels in the building when water is used for cooking, drinking, dish washing, showers, baths, clothes drying, and toilets [*50*]. If the groundwater is drawn directly into a building from an individual well (or perhaps from a small community well), the dissolved radon can escape into the air, contributing to airborne radon levels [*51*]. Buildings using water from a municipal water treatment plant will not have this potential problem because any radon in the water supply will have been released during storage treatment and handling before the water reaches the building [*8*]. If water concentrations are sufficiently high (above perhaps 1 000 000 Bq m^{-3}, some effort to address the water source of radon would be advisable in addition to efforts addressing the soil gas source. One option for reducing the radon in water is to ventilate the building near the point of usage whenever water is used. A second option—more practical as a long-term solution—is to treat the well water before it is used.

One approach for treating the water is to install a granular activated carbon (GAC) treatment unit on the waterline entering the building from the well, following the pressure tank [*8*]. These GAC units have been used in residential applications for removing water contaminants other than radon (for example, organics), and a number of GAC units have been installed recently for radon removal. If the unit is properly sized and contains a brand of carbon specifically selected for radon removal, radon removals of over 99% have sometimes been obtained. The reported performance of these carbon units, which have been in operation for several years, suggests that the units can operate with no degradation in radon reduction performance for at least several years with minimal maintenance.

One consideration with GAC units is that they may need to be shielded (or else located remote from the house) in order to protect the occupants from gamma radiation resulting from radon and radon decay products accumulated on the carbon bed. Another consideration is that, depending upon state regulations, the spent carbon might in some cases have to be disposed of as a low-level radioactive waste.

Aeration of the well water is another treatment option to release and vent the dissolved radon before the water is used. Several aerator designs have been tested for residential use, and reductions above 90% have been reported with some of them. Aerators will avoid the need for gamma shielding that carbon units have and will avoid concerns regarding the disposal of waste carbon. However, aeration units are more expensive to install and operate than are GAC units, and the radon removal capabilities of the aerators currently being marketed are generally lower than the 99+% that has sometimes been reported for GACs. Although home aeration units are commercially available, experience with aerators for residential use is limited to date. In addition, aerators will be more complex than GAC units, generally requiring at least one additional water pump (to boost the low-radon water from the aerator back up to the pressure needed to move it through the plumbing) and a fan or air compressor (to provide the stripping air).

PREVENTING RADON IN NEW CONSTRUCTION

It is typically easier and much less expensive to design and construct a new building with radon-resistant and easy-to-mitigate features than to add these features after the building is completed and occupied [*3,6*]. Therefore, when building in an area with the potential for elevated radon levels, architects and engineers should use a combination of radon prevention construction techniques. To determine if your building site is located in a radon-prone area, refer to Chapters 6 and 7 as well as contact EPA for more recent information.

A combination of the following three radon prevention techniques is recommended for construction in radon-prone areas: (1) install an ASD system, (2) seal major radon entry routes, and (3) in schools and other large buildings, pressurize the building using the HVAC system. This section summarizes each of these techniques. Guidelines on how to incorporate these radon prevention features in the design and

construction of new buildings are detailed in Refs *3*, *6*, and *52*.

Installing a Soil Depressurization System During Construction

The following instructions are important for the design and construction of a soil depressurization system:

- Place a clean layer of coarse aggregate beneath the slab.
- Eliminate all major barriers to extension of the subslab low-pressure zone, such as interior subslab walls.
- Install radon suction pit(s) beneath the slab in the aggregate (one radon suction pit for each area divided by subslab walls).
- For crawl space buildings with exposed soil, install a submembrane depressurization system. The crawl space can also be constructed with a concrete slab floor with subslab aggregate and treated with a subslab depressurization system.
- Install a vent stack from the radon suction pit(s) under the slab to the roof.
- For an ASD system, install a suction fan on the vent stack and equip the system with an alarm.
- Seal all major slab and foundation penetrations.

Rough-in for an ASD System

A rough-in for an ASD system is the same as an ASD system except that the fan is not installed initially. For new construction where radon levels are elevated even marginally, the installation of a rough-in system, along with an electrical supply near a potential fan location, is a prudent investment and is recommended. If a building is found to have a radon problem after completion, then a rough-in can easily be converted into an ASD system by installing a fan.

Passive Soil Depressurization

Research has shown that passive systems are sometimes effective in home construction; however, they are not recommended for use in schools and other large buildings [*3*].

Sealing Major Radon Entry Routes During Construction

Many of these sealing techniques are standard good construction practices. As a minimum, radon entry routes that should be sealed are:

- Floor/wall cracks and other expansion joints. Where codes permit, replace expansion joints with pour joints and/or control saw joints because they are more easily and effectively sealed.
- Areas around all piping systems that penetrate the slab or foundation walls below grade (utility trenches, electrical conduits, plumbing penetrations, etc).
- Masonry basement walls and penetrations through poured concrete basement walls.

Designing HVAC Systems to Prevent Radon Entry

The HVAC system design and operation guidelines listed below should be followed for radon prevention. (Note that HVAC systems supplying outdoor air are generally installed in large buildings and that residential heating and cooling units are currently not designed to supply outdoor air.)

- In radon-prone areas, eliminate air supply and return ductwork located beneath a slab, in a basement, or in a crawl space in accordance with ASHRAE Standard 62-1989 [*23*].
- Supply outdoor air in accordance with guidelines in ASHRAE Standard 62-1989 [*23*].
- Construct a "tight" building shell to facilitate achieving a slightly positive pressure in the building.
- Seal slab, wall, and foundation entry points, especially in areas of the building designed to be under negative pressure (such as restrooms, janitor's closets, laboratories, storage closets, gymnasiums, shops, kitchen areas).
- Provide proper training and retraining of the HVAC system operators, together with an adequate budget, so that the system is properly operated and maintained.
- In areas with large exhaust fans, supply more outdoor air than air exhausted.

New Construction Standards and Codes

The ASTM Subcommittee E6.41 on Infiltration Performances is developing a consensus document on standardized approaches for controlling radon in buildings. For example, a standard guide for radon control options in the design and construction of low-rise residential buildings was approved by ASTM in 1992 (E 1465-92) [*52*]. ASTM is also developing a standard for prevention of radon entry in large buildings. In addition, EPA is developing proposed model standards and techniques for control of radon in new buildings.

A number of states (e.g., Florida, New Jersey, Washington) have also developed model codes for preventing radon in new construction. New design criteria for radon resistance are also being incorporated into the construction design policy for some companies with such standard features as ASD systems, passive subslab depressurization systems, and controls for building pressurization with the HVAC system.

A Florida standard covers five types of control strategies: sealing, soil depressurization, indoor air pressure control to prevent depressurization at ground contact, ventilation, and crawl space ventilation [*53*]. Rather than giving guidance for installation, the document provides brief minimum standards for work performed and materials employed and references appropriate Florida building codes.

A document similar to the Florida standard has been developed by the National Institute of Building Sciences with assistance from EPA [*54*]. The document recommends constructing buildings with all applicable radon-resistant construction techniques or, as a minimum, enabling the building to be easily mitigated if elevated radon concentrations are measured after construction. Although, for the most part, specific installation or materials guidance is not provided, suggested approaches or preventive measures are outlined and other construction guidance documents referenced.

In addition, a summary of current radon resistant practices from a number of organizations is included as an appendix to the EPA radon resistant residential new construction guide [*6*].

OTHER CONSIDERATIONS FOR RADON CONTROL STRATEGIES

This section covers the costs of radon control strategies, post-installation testing and inspection of radon control systems, and long-term maintenance concerns.

Costs of Radon Control Strategies

The radon control strategies discussed in this chapter are summarized in Table 1 together with typical ranges of radon reduction, contractor installation costs for houses, and operating costs for houses [*4*]. Additional cost information for houses can be found in Refs *2* and *55*.

Cost data for schools and other large buildings are more limited. One survey of radon mitigators indicated diagnostics and mitigation costs for ASD of about $6 per m^2 for a "typical" school [*56*]. These costs would be higher in schools with extensive subslab walls, very poor PFE, and extensive building code and/or asbestos complications. Costs would be lower in schools with simple construction, very good PFE, and no subslab barriers to a negative pressure field extension.

Post-installation Testing and Inspection

Short-term tests are needed after the installation of a radon reduction system to determine if radon levels have been adequately reduced [*4*]. A two- to seven-day measurement taken at least one day after system installation is usually the best way to initially test the system's effectiveness. This is because a longer-term measurement may not provide information quickly enough if radon levels have not been satisfactorily

TABLE 1—Installation and operating costs [*2,4,55*].

Technique	Typical Radon Reduction	Typical Range of Installation Costs in Houses (Contractor)[a]	Typical Annual Operating Cost Range for Fan Electricity and Heated/Cooled Air Loss (Houses)	Comments
Active subslab depressurization	80–99%	$800–2500	$40–300	Works best if air can move easily in material under slab
Drain tile depressurization	90–99%	$800–1700	$40–300	Works best if drain tiles form complete loop around house
Blockwall depressurization	50–99%	$1500–3000	$70–500	Only in houses with hollow blockwalls; requires sealing of major openings
Sump hole depressurization	90–99%	$800–2500	$100–225	Works best if air moves easily to sump under slab or if drain tiles form complete loop
Submembrane depressurization	80–98%	$1000–2500	$30–225	Less heat loss than natural ventilation in cold climates
Crawl space depressurization	70–96%	$400–1000	$50–350	Most common in inaccessible crawl spaces; less effective than SMD
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	$100–500	Works best with tight basement isolated from outdoors and upper floors
Natural ventilation	Variable	$0–600	$50–700	Significant heated/cooled air loss; operating costs depend on utility rates and amount of ventilation
Heat recovery ventilation	25–50% if used for full house; 25–75% if used for basement	$1200–2500	$50–400 for continuous operation	Limited use; best in tight houses; for full house, use with levels no higher than 300 Bq m^{-3}; no higher than 600 Bq m^{-3} for use in basement; less conditioned air loss than natural ventilation
Air cleaners	25–90% RDP[b]	$400–1200	Variable	Rarely used by contractors or installed by homeowners for radon reduction
Radon gas sorption units	25–75%	Insufficient experience	Insufficient experience	Limited experience to date
Water systems: aeration	95–99%	$3000–4500	$40–90	More efficient than GAC; requires annual cleaning to maintain effectiveness & to prevent contamination; carefully vent system
Granular activated carbon (GAC)	85–99%	$1000–2000	None	Less efficient for higher levels than aeration; use for moderate levels (around 200 000 Bq m^{-3} or less); radon by-products can build on carbon, may need radiation shield around tank and care in disposal

[a]The fan electricity and heating/cooling loss cost ranges are based on assumptions for climate, house size, and fuel costs.
[b]RDP = radon decay products.

lowered. However, once a short-term test indicates that a system is working properly, a long-term device should be used.

Radon levels in all occupied or potentially occupiable areas should be lower than the EPA action level of 148 Bq m^{-3} [*1,4*]. If levels are above this level, confirm that the radon control system is operating properly, then consider additional control techniques.

In addition to monitoring radon levels, post-installation measurements should be made to ensure that active (fan-assisted) systems are operating properly. Potential modifications for better system operation and increased radon reduction may also be identified by these tests. If additional radon reduction is needed, it may be possible to modify the existing system. If not, it may be necessary to install an entirely new system.

Radon grab samples of exhaust air and the air near exhaust vents can also provide useful information on system operation.

Long-term Maintenance of Radon Reduction Systems

The fans for radon control systems should be operated continuously, and warning devices should be checked regularly to make sure that the system is working properly. In addition, radon levels in a building with a radon control system should be measured at least every two years [*4*].

Literature suggests that many mitigation systems have failed due to occupant intervention; thus, occupants should be reminded of the important aspects of system operation, the need for maintaining the system, and how to use the monitors or alarms [*57,58*]. In addition, any alteration of the building structure for repair or renovation should consider the operation of the radon control systems installed.

Occupants have, for reasons of comfort, noise, cost efficiency, or carelessness, turned off an active system or prevented operation of a passive system, such as blocking crawl space vents or reducing the air intakes to subslab or wall ventilation installations [*56*]. In one study, all homeowners reported they did not always operate the systems. One of the major reasons for turning off the systems was fan noise and vibration [*57*].

A study concluded that any mitigation system needs to be checked periodically and that occupants should understand the use and operation of the system [*57*]. Requesting occupants to re-explain the system to the installer may help to confirm that they understand proper system operation and maintenance.

In general, ASD systems have performed well in the long-term [*2*]. Fans may last five years or more (although manufacturers' warranties tend not to exceed three years). Fan failures generally involve bearings or capacitors; bearings failures are more noticeable due to noise [*57*]. Also, fan mountings have been found to either loosen or vibrate. Piping should be inspected on a regular basis for any breaks, cracks, or openings in joints, particularly in the areas surrounding fans and blowers.

Sealants can dry and fail over time, or new cracks/holes can occur following remodeling or damage. Sealed areas should be inspected regularly, and occupants should check for any new cracks or openings.

Research has shown that, when adequately maintained and serviced, air-to-air heat exchangers operate well over time with few mechanical problems [*57,58*]. The only maintenance required was replacement of some surrounding insulation to the units. However, some systems were reduced in speed by the occupants, decreasing the air exchange rates.

Basement pressurization has been shown to keep radon levels generally below the initial baseline radon concentration [*57,58*]. However, each system tested showed periods of equal or elevated concentrations from the baseline. These periods were correlated to occupants' altering the sealing of the tightness of the basement or turning off the system fans. Each of the systems exhibited a 20 to 25% decrease in airflow which prevented complete pressurization of the basement. Findings of incomplete sealing of the basement led the researchers to suggest that the system be oversized in order to accommodate future decreases in fan operating performance and increased leakage area in the basement [*57*].

SUMMARY

The most common way for radon to enter a building is through pressure-driven transport of soil gas. Other, but less prevalent, reasons for elevated indoor radon concentrations include emanation of radon from well water containing radium and use of uranium-contaminated building materials. Thus, much of the emphasis of radon reduction or control is on prevention of radon entry from the soil gas into the building.

For radon control to be effective, proper diagnosis of radon entry routes and an understanding of the building's construction are important. The most common steps used in diagnosing a radon problem and determining the most appropriate radon control strategy include: measuring radon levels (in room air, near suspected radon entry routes, and, if well water is used, in the water), reviewing building construction plans, conducting a building investigation to determine radon entry routes, measuring subslab pressure field extension, evaluating the HVAC system, measuring building tightness, and determining if building materials are a radon source.

Active soil depressurization (ASD) is the most widely used radon control method. For ASD, a fan is used to create a negative pressure field in the soil under the building relative to the pressure in the building. This negative pressure field reverses the flow of radon—instead of entering the building, the radon is exhausted by the fan to the outdoors. Depending on the prevalent entry routes and building construction features, ASD techniques include: subslab depressurization, sump hole depressurization, drain tile depressurization, block wall depressurization, submembrane depressurization, and crawl space depressurization.

A second control method that can prevent radon entry is sealing of radon entry routes. Sealing of major radon entry routes is considered an essential part of most approaches to radon reduction. However, the effectiveness of sealing alone is limited by the ability to identify, access, and seal all the places where radon is entering. Building pressure control is a third approach that can be used to prevent radon entry. Building pressurization involves bringing in more air to the

building than is exhausted, causing a slightly positive pressure inside the building relative to the subslab area.

Another approach for reducing risk from radon exposure is by dilution with outdoor air or by treatment to remove radon or radon decay products. These techniques remove radon only after it enters the building, but do not prevent radon entry. Ventilation reduces the radon concentration through dilution, but its application is limited because of the impracticality of increasing the ventilation rate by severalfold in order to achieve a sufficient reduction in radon concentration. Further, energy penalties associated with even moderate increases in ventilation often make this approach unattractive. Removal of radon decay products by air cleaning and removal of radon through carbon adsorption are other alternatives to reduce the risk due to radon, but the actual benefit in reducing health risks from these approaches is uncertain. To remove radon from water, an activated carbon unit or an aeration unit can be used.

New construction offers an opportunity to reduce the potential risk of elevated radon, typically at a much lower cost than a retrofit. These techniques focus on prevention of radon entry into the building and include: specifications for designing and constructing buildings to include an ASD system or, as a minimum, a rough-in of an ASD system for future use if needed; sealing of major radon entry routes; and designing the HVAC system (if the building has one) to pressurize the lower levels.

The ASTM Subcommittee E6.41 on Infiltration Performances is developing a consensus document on standardized approaches for controlling radon in buildings. For example, a standard guide for radon control options in design and construction of low-rise residential buildings was approved by ASTM in 1992 (E 1465-92) [*52*].

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9

EPA's Strategy to Reduce Risk of Radon

by Steve Page[1]

SINCE THE DISCOVERY OF EXTREMELY HIGH RADON LEVELS in the Reading Prong region in 1985, there has been extensive progress in the nation's program to reduce the risks of indoor radon. EPA's Radon Program has grown from a handful of researchers in isolated problem areas to an organized partnership of government agencies and private organizations working together on numerous fronts. To accommodate this rapid growth and to keep national radon efforts on track, EPA has continually evaluated and refined its strategy by adapting to new knowledge, increased experience, Congressional direction, and changing needs.

The Indoor Radon Abatement Act of 1988 (IRAA) directed EPA to undertake a variety of activities to address the growing concern over dangers posed by exposure to indoor radon. Among other requirements, the law directed the Agency to study radon levels, evaluate mitigation methods, establish proficiency programs, assist states with program development, develop training centers, and provide public information. EPA has developed and implemented programs to address each of the key provisions of this statute.

This chapter presents EPA's broad national strategy to reduce radon risks. It combines and reinforces EPA's basic foundation, including its guiding policies and cooperative partnerships, with an overall management approach and focus for the future. The chapter starts with an overview that introduces the strategy's four key elements: underlying policies and scientific principles, a decentralized system of states and other partners for targeting the public, multiple strategies for achieving radon risk reduction, and a strong focus on five key program priorities. The chapter then discusses each of these elements in more detail and describes how they interact to guide future efforts and directions of the Agency.

STRATEGY OVERVIEW

As illustrated in Fig. 1, EPA's radon strategy consists of four key elements:

1. *Science and policy* that provide the program foundation.
2. *A decentralized system* for informing the public that consists of multiple, highly respected organizations that can deliver radon messages through established channels to targeted audiences.
3. *A continuum of strategies* for reducing radon risks, ranging from public information efforts that let people make their own decisions about the need to test and fix their homes to regulatory approaches that may ultimately require people to take action.
4. *A strong focus* on those strategies that hold the greatest promise for achieving long-term institutional change.

These four key elements of EPA's strategy evolved over time. The initial emphasis of early efforts was scientific research on the magnitude and extent of the radon problem, mitigation research, health risk research synthesis, and development of sound policy guidelines. EPA then began development of a unique system for delivering this information and recommendations to the public, and began to explore a variety of strategies for getting the public to take action. Most recently, EPA has consulted with scientists, government officials, health organizations, and others to sharpen its focus on those strategies which have the greatest potential for reducing radon risks.

Today, EPA is continuing work in each of these four key areas. EPA is advancing and refining radon science and policy, expanding and improving the system for delivering programs, incentives, and focusing all elements of this system on those strategies which have a high potential for risk reduction.

Although some scientists were aware of the U.S. indoor radon problem, it was not until the Reading Prong discovery in 1985 that the U.S. Government developed a program to address this issue. The government was unequipped to begin to advise the public on what, if anything, should be done in response to the problem and how to do it. The overriding need at the early stages of the Radon Program, therefore, was to develop guiding policies and scientific principles on which to base national risk reduction efforts. In response to this need, federal agencies, the states, and the scientific community initiated and have continued an extensive research program to establish and refine several underlying principles that serve to guide the entire radon effort and as a basis for all radon messages. These guiding scientific and policy principles are outlined in the section of this paper entitled, "Guiding Scientific and Policy Principles."

Early on, EPA recognized the importance of working with leading national organizations. EPA thus began to develop a decentralized system in the late 1980s. In this system, EPA has worked to empower states and key national organizations that serve as additional sources of radon messages. These partners have the special expertise, credibility, and commu-

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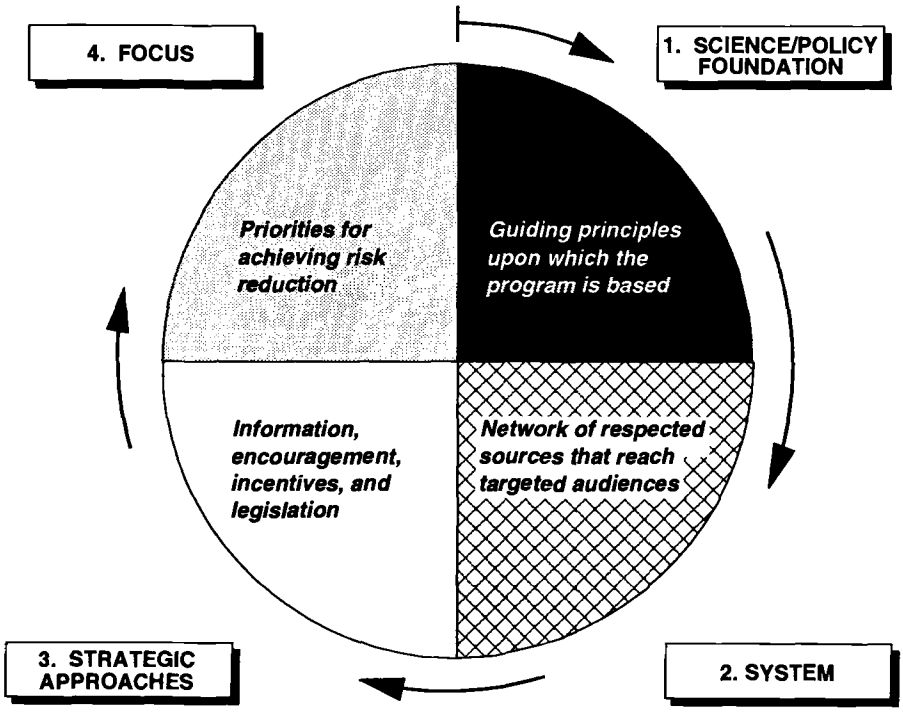


FIG. 1–Overview of key elements of the Radon Program strategy.

nications channels needed to reach target audiences. Such a decentralized system is more flexible, innovative, and effective than the centralized system traditionally used in government. The Agency's outreach system is explained in further detail in the section of this paper entitled "Decentralized System for Reaching a Diverse Public."

Through this network, the Agency's principal approach has been a nonregulatory public information campaign designed to accurately and effectively inform and enable people to reduce their health risk through voluntary action. However, after years of public information efforts with limited public response, states and national organizations have begun to pursue a variety of other, more direct strategies. Similar trends in approach have been observed during the evolution of other national health and safety campaigns [*1*]. Many initiatives are now underway to actively encourage homeowners to test and fix their homes, as are activities to provide incentives for radon action. Regulations that require people to take action are being pilot tested in some areas. Congress, state governments, and local authorities are also considering or implementing legislation that would mandate actions to reduce radon risk [*2*]. The continuum of strategies being used by EPA partners is described in the section of this paper entitled "A Continuum of Strategies for Solving the Radon Problem."

Finally, the Agency is focusing its efforts in five major areas recommended in a 1992 Radon Program review that was conducted by leaders inside and outside of EPA [*3*]. These five areas are: targeting efforts on the greatest risks first, promoting radon-resistant new construction, supporting testing and mitigation in connection with real estate transactions, using public information and motivation programs to promote institutional change, and developing a coordinated research plan. Program plans to focus efforts in these five key areas are summarized in the section of this paper entitled "Focus on Key Priorities." Further detail on these plans is also provided in "Implementation of OPPE Panel Recommendations," which is the Radon Program's formal response to the Radon Program's review panel [*4*].

GUIDING SCIENTIFIC AND POLICY PRINCIPLES

EPA has used the best available scientific data in developing risk assessments. Over the last several years, considerable effort also has been spent to build a national consensus on the foremost scientific issues related to radon and on the translation of this scientific understanding into national policy. The most significant scientific and policy principles that have been developed through this process are summarized below.

There is No Known "Safe" Level of Radon Exposure

Although uncertainty exists, we know more about radon than most other cancer-causing environmental risks. In assessing residential radon risk, EPA assumes that the exposure-response relationship is linear at low exposures [*5,6*]. This assumption is consistent with the evidence for linearity at a wide range of cumulative exposures in the radon epidemiological studies of underground miners. There is no evidence of a threshold for lung cancer from radon exposure, that is, a level of radon exposure below which no increased risk of lung cancer would exist. It is generally recognized that even at low doses of alpha radiation, most DNA damage is not effectively repaired [*5,6*]. Research further indicates that at low doses of alpha radiation the dose-response relationship

for cell transformation and tumorigenesis is linear and independent of dose rate [5,6].

Continuing scientific research has helped to improve EPA's projection of lung cancer risk to the general population due to radon exposures in the home. EPA now estimates that 7000 to 30 000 lung cancer deaths per year in the United States are caused by residential radon exposure. Figure 2 places the estimated cancer deaths from radon in context by showing the number of annual fatalities due to common occurrences that the public tries to reduce through safety and health programs. Further scientific evaluation of radon hazards will serve to refine EPA's estimate of the annual number of radon-induced lung cancer deaths. The Agency is committed to seeking the best science to guide its program.

Homes With Indoor Radon Levels Above 4 pCi/L (148 Bq/m^3) Should be Mitigated

EPA recommends that homeowners mitigate their homes if radon levels above 4 pCi/L (148 Bq/m^3) are found and confirmed. This action level is based on a combined analysis of risk (no known "safe" level) *and* technological feasibility.

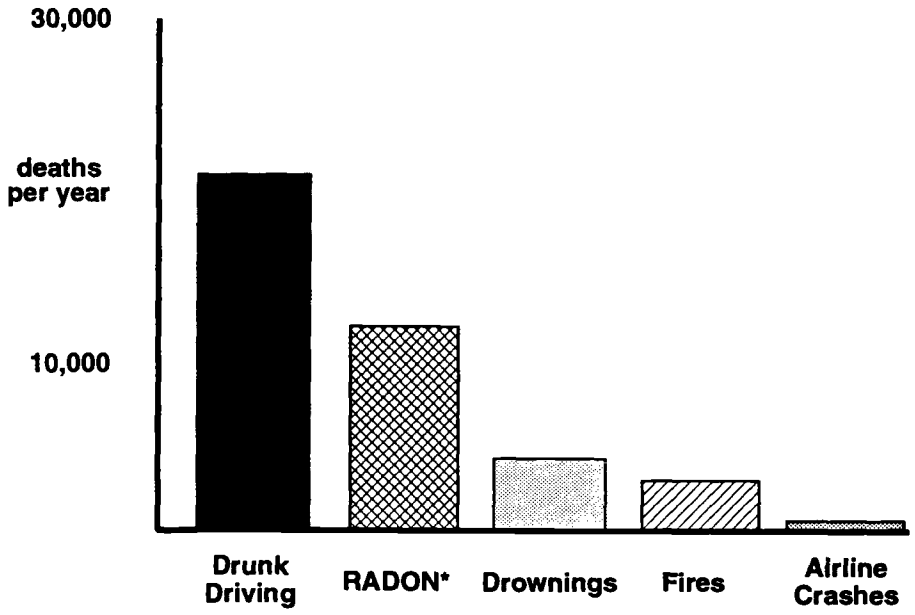
Because we have assumed that there is no "safe" level of radon exposure, EPA has investigated a range of action levels and found that mitigation technology available today can reduce elevated radon levels to 4 pCi/L (148 Bq/m^3) more than 98% of the time [7]. Available technology is consistently less able to reduce radon levels down to lower levels, although an estimated 70 to 80% of homes with elevated radon levels would be able to achieve an action level of 2 pCi/L (74 Bq/m^3) at reasonable cost [7]. The 4 pCi/L (148 Bq/m^3) guideline is also supported by research showing that it is more difficult to accurately measure radon at lower levels (e.g., measurement device error is significantly greater at 2 pCi/L (74 Bq/m^3) than at 4 pCi/L (148 Bq/m^3) [7]). Based on these considerations, EPA recommends 4 pCi/L (148 Bq/m^3) as the action level but advises homeowners that they should consider mitigating homes that have confirmed radon levels between 2 pCi/L (74 Bq/m^3) and 4 pCi/L (148 Bq/m^3).

People Should Use Proficient Radon Measurement and Mitigation Companies

A basic function of the Agency has been to equip the public with the information necessary to make knowledgeable radon decisions, including information on competent measurement and mitigation firms. Accordingly, the Agency has operated two voluntary proficiency programs for several years—the Radon Measurement Proficiency (RMP) Program and the Radon Contractor Proficiency (RCP) Program—to evaluate the proficiency of radon measurement and mitigation companies, respectively. Last year, EPA added a new component to the RMP designed to evaluate the proficiency of those persons offering on-site residential measurement services. Both the RMP and RCP programs provide a mechanism for informing the public on proficient companies by publishing updated lists of firms that pass all relevant criteria. If a person plans to hire a trained contractor to test or fix their home, the Agency recommends that he or she hire a qualified radon firm as determined by the RMP or RCP programs. If a person plans to take his or her own measurement, EPA recommends the use of an EPA-listed radon measurement device.

All Homes and Schools Should Test for Radon

Elevated levels of radon have been found in all states and in all types of homes. State/EPA radon screening surveys show



* Radon is estimated to cause about 14,000 deaths per year-however, this number could range from 7,000 to 30,000 deaths per year. The numbers of deaths from other causes are actuarial data taken from 1990 National Safety Council reports.

FIG. 2–Annual deaths from selected causes.

that individual homes in relatively low-risk areas may have high radon levels depending on the complex interaction of soil, atmospheric, and ventilation factors [*8*]. Based on results from EPA's National Residential Radon Survey, nearly 1 out of every 15 homes in the United States is estimated to have annual average indoor radon levels exceeding 4 pCi/L (148 Bq/m^3) [*8*]. The only way to know the radon level in a given home is to test it. Therefore, EPA and the Surgeon General recommend testing all homes below the third floor. EPA estimates that about nine million homes have been tested to date [*8*].

Similarly, based on data collected in its National School Radon Survey, the Agency estimates that 2.7% of ground-contact schoolrooms, or about 75 000 rooms, have short-term measurements greater than the recommended action level of 4 pCi/L (148 Bq/m^3) [*8*]. Nearly 20% of the public schools nationwide, approximately 15 000 institutions, have at least one ground-contact room with a short-term measurement greater at 4 pCi/L (148 Bq/m^3) [*9*]. Based on this research, the Agency recommends testing for radon in schools. EPA estimates that about 20% of schools nationwide have been tested to date [*9*].

Ongoing efforts to identify areas where radon problems are more common, including the project to develop a Map of Radon Zones and the High-Risk Areas Project, will be instrumental in targeting resources to high-risk areas. Such targeting can provide the maximum amount of risk reduction for each dollar spent and is a major program priority.

The Health Risks Posed by Radon are Especially High if a Person is a Smoker

Tobacco smoke acts synergistically with radon to cause many of the radon-related lung cancers. That is, while exposure to elevated radon levels may pose a serious health risk by itself, exposure to radon in combination with smoking poses an even more serious risk. EPA estimates that radon risk for current smokers is 15 to 20 times the risk for never-smokers, and the risk to former smokers may be over 8 times greater than the risk to never-smokers [*10*]. Still, never-smokers can be at substantial risk from radon. The individual risk to a person who has never smoked and is exposed to an average of 4 pCi/L (148 Bq/m^3) in their residence over their lifetime is estimated to be 2×10^{-3}. Table 1 shows how these radon risks compare.

This scientific information about the synergistic relationship between radon and tobacco smoke has important implications for radon outreach programs. Beginning with the 1986 *Citizen's Guide*, EPA has consistently incorporated "stop smoking" messages into radon messages and materials. An important initiative in this area was the development and distribution of a 1992 public service announcement featuring the U.S. surgeon general, Antonia Novello, on the hazards of radon and smoking. Messages and programs for smokers and former smokers will increase as the program further expands its focus on the highest risk areas and populations.

Short-Term Tests Can Be Used to Decide if a Home Needs Mitigation

Short-term radon tests are conducted over a period ranging from 2 to 90 days. Long-term tests are conducted for more than 90 days. Because radon levels tend to vary from day to day and season to season, long-term tests are more indicative of annual radon exposures. This is why EPA has always recommended use of long-term radon tests to determine whether homes should be remediated. However, due to time constraints like those encountered in real estate transactions, many consumers will not use long-term tests. Six years of program experience and extensive communications research show that people are unwilling to take long-term tests [*11,12*].

Given limited consumer response to long-term radon testing, EPA conducted an extensive study on the mitigation decision-making accuracy of different testing protocols involving different combinations of short-term and long-term radon tests. Combining device accuracy data with information from numerous studies on seasonal variability, floor-to-floor radon variation within homes, and the radon distribution in homes across geographic areas, EPA developed a model for estimating the accuracy of different national testing scenarios [*13*].

In the 1992 *A Citizen's Guide to Radon*, EPA recommends a testing protocol that allows homeowners the flexibility of reaching a mitigation decision based on either (1) two se-

TABLE 1—Radon risk comparison for smokers and non-smokers.

Radon Level	If 1000 people who smoked were exposed to this level over a lifetime . . .	If 1000 people who never smoked were exposed to this level over a lifetime . . .
20 pCi/L (740 Bq/m^3)	About 135 people could get lung cancer	About 8 people could get lung cancer
10 pCi/L (370 Bq/m^3)	About 71 people could get lung cancer	About 4 people could get lung cancer
8 pCi/L (296 Bq/m^3)	About 57 people could get lung cancer	About 3 people could get lung cancer
4 pCi/L (148 Bq/m^3)	About 29 people could get lung cancer	About 2 people could get lung cancer
2 pCi/L (74 Bq/m^3)	About 15 people could get lung cancer	About 1 person could get lung cancer
1.3 pCi/L (48.1 Bq/m^3)	About 9 people could get lung cancer	Less than 1 person could get lung cancer
0.4 pCi/L (14.8 Bq/m^3)	About 3 people could get lung cancer	Less than 1 person could get lung cancer

quential short-term tests or (2) a short-term test followed by a long-term confirmatory test [*14*]. The *Citizen's Guide* discusses the trade-offs between short- and long-term testing, explaining that long-term tests are more representative of actual exposures, but enabling citizens to choose a short-term measurement process, especially for confirming initial measurements above 10 pCi/l (370 Bq/m^3). Similarly, the new *Home Buyer's and Seller's Guide to Radon* recommends three short-term testing options when long-term testing is not possible. Like the *Citizen's Guide,* the *Home Buyer's and Seller's Guide* recommends long-term tests, but gives people the option to choose an accurate short-term test when time is limited in the context of real estate transactions.

Continuing Scientific Research on Radon

EPA is currently conducting, contributing, or coordinating research to address a number of key scientific issues. For example, EPA is supporting a National Academy of Sciences BEIR VI study to update the radon risk information. Additional ongoing research on radon includes: further refining estimates of the magnitude of the health risk posed by *residential* radon exposure, assessing the interactive effect of smoking and radon, evaluating the distribution of indoor radon levels in counties across the country, identifying geographic areas with the highest potential for radon problems, research into the variation of radon levels in new homes, and studies to determine the cost and reliability of approaches for measuring, mitigating, and preventing elevated radon levels in a variety of building types. Only with a better understanding of these and other scientific issues can the Agency continue to articulate and implement effective national policies for radon action.

Translating Principles and Policies into Radon Action

The scientific principles and policies guiding the Radon Program have been distilled into succinct, "user-friendly" information for dissemination through radon public outreach programs. For example, the 1992 version of the *Citizen's Guide* contains each of these key scientific and policy messages. Consistent and accurate information about radon is critical to the sources of a nonregulatory health protection program like the Radon Program. However, the message is only one component of the overall communication process. Accordingly, EPA has developed and employs a decentralized communications system for reaching the diverse audiences potentially at risk from indoor radon.

DECENTRALIZED SYSTEM FOR REACHING A DIVERSE PUBLIC

As shown in Fig. 3, a basic communications model has five major components. The model starts with a *source* (e.g., government agency) developing a *message* (e.g., "test for radon"). The message is then delivered through selected *channels* (e.g., brochures, technical background documents, TV programs, and press releases) to reach the intended *audience* (e.g., homeowners). Feedback and evaluation from the audience is used to refine the process until the desired effect is achieved.

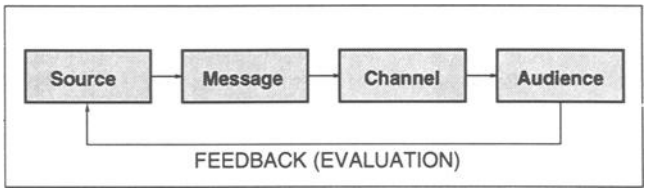


FIG. 3–Basic communications model.

EPA recognizes that it should not be the sole "source" for communicating about radon risks for a variety of reasons. First, EPA messages would have a limited effect on many of the diverse audiences that must be reached with radon information. Second, informational materials produced by bureaucracies are often not timely, and because they are written for a "generic" and general audience, they will not reach many of the diverse groups that make up the U.S. public. For example, national-level messages prepared for an "average audience," consisting of people at middle income and education levels, may not spark the interest of low-income and low-education populations. These "generic" messages may not be appealing and effective in prompting action among minority audiences. Third, compared to numerous other sources, EPA has only a few effective channels available for sending out radon information to the public. Finally, other sources besides the federal government are closely associated with target audiences and thus are in the best possible position to quickly and easily evaluate the success of their communications efforts. For all of these reasons, EPA has established an expanded communications network in which multiple, key organizations serve as sources of radon information. Multiplying sources increases the likelihood that radon information will effectively reach different segments of the public and encourage public action.

As shown in Table 2, EPA works with prominent leaders in each of the key areas of state government, local government, public health protection, media contact, and consumer protection. For example, EPA works with Radon Program contacts in all 50 States, the District of Columbia, and Guam. These contacts use their special affinity and geographic proximity to encourage radon action by their state constituents and other organizations.

Similarly, the American Medical Association, the National Medical Association, the American Lung Association, the National Association of Counties, the Consumer Federation of America, the National Association of Homebuilders, the Regional Radon Training Centers, National Safety Council and others have joined with EPA in cooperative programs to reduce radon health risks. These cooperative partners use their expertise to reach target audiences such as doctors, county health officials, public service directors, homebuilders, and others.

Each state and respected national organization sends radon information to many target audiences through a variety of innovative and diverse communications channels. For example, the American Medical Association has its own communications channels like the *Journal of American Medicine,*

TABLE 2—Reaching audiences through radon partners.

Source	Message(s)	Channel(s)	Audience(s)
American Medical Association	Physicians should encourage radon action.	AM news, conferences, TV shows, physicians guide	Physicians
American Lung Association	People in this area should test/ fix.	Local media campaigns, health fairs, direct marketing, promotions	Local public
Advertising Council	Radon is bad in your area. Use the radon PSAs.	TV, radio, print media, public service announcements	Public service directors
National Association of Homebuilders	Build radon-resistant homes in highest risk radon areas. Use the following techniques.	National resolution, EPA/NAHB radon in new construction brochure, research program	Homebuilders
National Association of Counties	County governments need to reduce radon health risks.	Conferences, "county news" radon articles, National Advisory Committee, model radon counties, county grants in high-risk areas	County commissioners, county health directors, code officials
American Public Health Association	Radon is bad in this area. Health leaders should lead on radon.	State radon campaigns, low income and minority radon programs	State and local public health officials
American College of Preventive Medicine	Employers, HMOs and preventive medicine physicians need to encourage radon action.	Radon leader kits, radon training programs, newsletter; articles	Preventive medicine physicians, corporate medical executives
Consumer Federation of America	People in this area should test/ fix.	Door-to-door campaigns, local media campaigns	Local public
National Conference of State Legislators	Need more legislation regarding radon. Need education for State legislators concerning radon issues. State governments need to reduce radon risks.	Director membership, newsletters, conferences, radon seminars, model radon legislation	State legislatures
International City Managers Association	City governments need to reduce radon health risks.	Radon testing of administrators homes, training conferences, model city radon programs	City administrators
Surgeon General	Use this PSA. Radon is bad. Test your home. Fix high levels. Call 800-SOS-Radon	Radon public service announcement, letter to public service directors	Media public service directors, general public health professionals
ARELLO	States should address radon in real estate transactions.	Conferences	State real estate officials
National Safety Council	Radon is worse than most people think. News media should cover the issue more often.	Reporter's guide to radon, NSC newsletters, regular "radon tips" mailings to reporters	Environmental journalists
Conference of Radiation Control Program Directors	Promote information exchange between states concerning radon legislation. Keep states in communication with current EPA legislation regarding radon.	Radon bulletin, newsletters	State radon contacts
National Medical Association	Member physicians should be informed regarding radon issues.	Fact sheets, newsletters	African American physicians
National Coalition of Hispanic Health and Human Services Organizations	Radon is a health hazard and home testing is necessary.	Newsletter, community-based computer link up	Hispanic, Spanish-speaking population of the United States
Environmental Law Institute	Radon is a health risk. Radon should be addressed during real estate transactions.	Press releases from Public Affairs Office	Public, homebuyers and sellers, the radon industry

AM News, American Medical Television, and frequent continuing education conferences. These organizations have developed a wide range of channels for delivering information to their target audiences—their members and affiliates.

In turn, each of these target audiences uses its own channels to deliver radon information to individual members of the public. This means that the ultimate consumer, the homeowner, ends up receiving a consistent message on radon from a number of key sources. The radon communications program is thus highly leveraged, as illustrated in Fig. 4. Each target audience, like physicians and local government officials, becomes a source of information for new target audiences like their patients and local constituents. Consistent and accurate information delivered by multiple sources through multiple channels will repeat and reinforce the need for public action.

Management of the Radon Program's decentralized system is predicated on four basic operating principles. First, the Program has developed a *clear mission*—to reduce the public health risk of indoor radon. The Radon Program seeks to accomplish this overall mission by setting *measurable goals* that keep efforts focused and allow the Program and its cooperative partners to both quantify success and eliminate waste (Table 3). The Program, however, maintains *flexibility* so that the states and cooperative partners can achieve program goals in ways that make the most sense considering their individual capabilities and constraints, and that enable rapid program adjustments and improvements.

Finally, the Radon Program stresses *evaluation* to ensure that results are monitored routinely and program activities are redirected and refined as needed. For example, EPA works with the states and other partners to evaluate the effectiveness of each radon initiative according to a number of key evaluation criteria. These criteria include: the number of people contacted, number of radon tests conducted, and the number of homes mitigated or built with radon-resistant construction. In addition, bottom-line environmental results are also evaluated through extensive state and national surveys by CRCPD, CDC, and others. These surveys assess public awareness, testing rates, and number of homes mitigated.

Through this decentralized system, EPA has made significant progress in raising public awareness and understanding of the health risks associated with indoor radon. Surveys show that about 70% of the U.S. public is aware of the radon health problems [*15*]. In addition, the Program has fostered the development of a well-trained and competent industry for radon testing and mitigation, as well as a large and diverse group of program partners that stand ready to provide the public with necessary advice and assistance.

A CONTINUUM OF STRATEGIES FOR SOLVING THE RADON PROBLEM

In developing strategies for reducing radon risks, the Radon Program is learning from the experience of other successful national public health campaigns. As summarized in the examples below, the experience gained through these programs provides valuable lessons that have been integrated into the Agency's strategy to reduce risk from radon.

- *U.S. Anti-Smoking Campaign.* Beginning in 1966, the Department of Health, Education, and Welfare (later reorga-

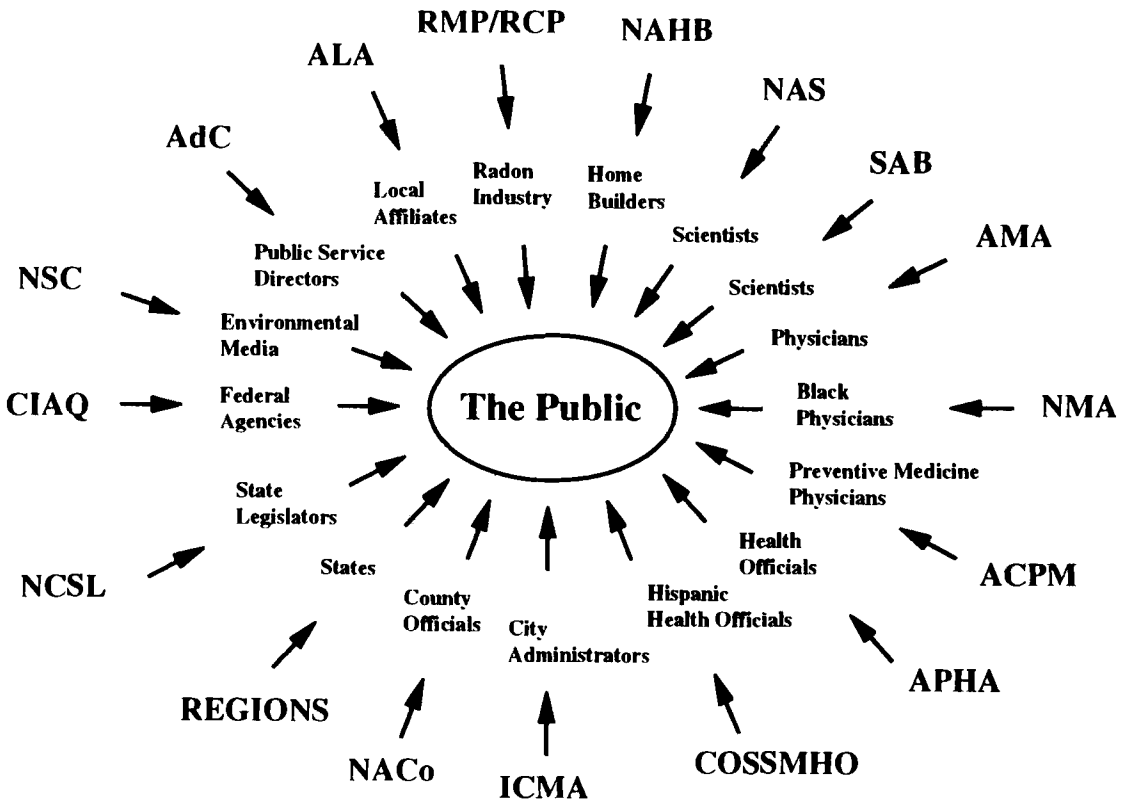


FIG. 4–Repetition and reinforcement of radon messages.

TABLE 3—Measurable goals for the radon program.

Key Area	Current Estimates		1993 Targets		2000 Targets	
	National	High-Risk	National	High-Risk	National	High-Risk
Awareness	63%	NA*	65%	+5%	75%	90%
Testing	9%	NA*	2.3M (2.9%)[2,3]	1.0M (5.0%)[2,3]	26.1M (31%)[3]	11.3M (57%)[3]
Mitigation	NA*	NA*	50K (0.8%)[2,4]	31K (1.3%)[2,4]	810K (13.5%)[4]	480K (20%)[4]
School testing[1]	22%	NA*	29%	62%	75%	90%
New construction: radon-resistant homes built	4%	NA*	5%	+10K homes[2]	33%[2]	50%[2]
New construction: laws or policies	NA*	NA*	2 states	1 state; 5 localities	20 states; 25% of localities w/code authority	20 states; 33% of localities w/code authority
State real estate laws or policies	5 states with laws; 2 states with policies	NA*	6 states with proposed laws; 5–10 states with policies	3 states with proposed laws; 3–7 states with policies	45% of zones 2 and 3 with disclosure laws or policies	45% of zone 1 testing or disclosure laws (5 states)

NOTE: M = million; K = thousand.
*NA: Data not available at this time.
[1]Figures are cumulative by years 1993 and 2000.
[2]Figures show incremental gain in years 1993 and 2000.
[3]Percentages are of all homes covered by EPA's testing policy (83 million national; 20 million in high-risk areas). Target for 2000 assumes base of 9 million homes (10.8%) tested to date.
[4]Percentages are of homes testing greater than 4 pCi/L [148 Bq/m^3] (6 million nationally; 2.4 million in high-risk areas).

nized into HHS) began a public awareness campaign to inform the public and reduce cigarette consumption. While the campaign has achieved dramatic success over the past 26 years, this success has come only after concerted efforts through a variety of strategies. Namely, HHS combined forces with a number of cooperative partners (e.g., the American Lung Association, states, the private sector, and others) to disseminate public information and actively encourage people to quit smoking. The campaign also has put in place incentives to stop smoking, such as insurance premium discounts, and has sought and helped to establish anti-smoking regulations [*16*].

- *U.S. Seat Belt Program.* Since its beginning in the mid-1970s, this program has increased front seat belt use from about 11 to 49%. Most of this increase followed the passage of state mandatory use laws, which were enacted through the combined efforts of states, medical and public health organizations, the automobile industry, and grassroots organizations like Mothers Against Drunk Driving. While the passage of these laws in most states has resulted in an initial, significant increase in seat belt usage, the rate of belt use has subsequently stabilized or declined moderately. This "post-law stabilization" is partly due to the fact that most states are not actively enforcing mandatory use laws, nor are they providing public information that calls attention to the laws and the penalties for not wearing seat belts [*17*].
- *Saskatchewan Seat Belt Program.* To combat the same "post-law stabilization" in seat belt use rates in Canada as has been observed in the United States, the Province of Saskatchewan initiated a combined public relations and advertising campaign. This campaign, which showed drivers being ticketed for not wearing their seat belts, increased belt usage in Saskatchewan to more than 90% in just a few years. Both British Columbia and Quebec have implemented similar programs and now have usage rates greater than 90% as well [*18*].

A review of these and other national programs reveals a number of important lessons for EPA. For example, success in changing human behavior takes time and comes only through strong national and local networks delivering consistent information. The experience of these programs, as well as the Radon Program experience, also shows that success requires a mixture of diverse strategies. The continuum of strategies used by these programs is shown in Fig. 5.

Several of the strategies shown in Fig. 5 are now being used by states and cooperating national organizations. Federal and state programs have developed and disseminated public information materials and public education materials that inform people about the risk of indoor radon and what they can do to reduce that risk. Over time, these materials have grown more specialized as large, technical documents are being replaced with more targeted materials designed to encourage specific actions among certain groups. For example, the *Home Buyer's and Seller's Guide to Radon* is specifically designed to encourage informed decisions during real estate transactions. Radon brochures and public service announcements also encourage the public to act by linking radon to family health risks. And the *Consumer's Guide to Radon Reduction* provides guidance to consumers who have already tested for radon and are considering their mitigation options. At the same time, EPA is researching incentive programs to promote radon testing and mitigation, such as discounted or free test kits, especially for high-risk populations.

Finally, states and other organizations are pursuing a variety of regulatory radon initiatives. Some states have already enacted laws that require school testing and disclosure of

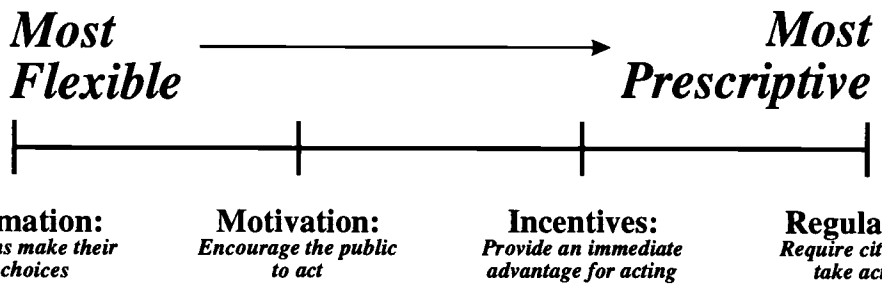


FIG. 5–Continuum of radon risk reduction strategies.

potential radon problems in real estate transactions. Several states and local jurisdictions are either implementing or considering radon-resistant new construction requirements. Many new homebuilders are voluntarily using radon-resistant new construction techniques. Some real estate associations are voluntarily incorporating the use of radon disclosure forms into their regular business practices. Congress is considering new regulatory options such as mandatory testing of schools and federal buildings, as well as minimum radon reduction measures for new construction. In the future, all of these strategies will continue to be pursued in combination by states, national organizations, EPA, and others to combat the radon problem.

FOCUS ON KEY PRIORITIES

Given the breadth of radon scientific issues and policies, as well as the decentralized outreach system and range of strategies outlined above, the number and diversity of ongoing Radon Program activities is significant. While flexibility is in itself an important element of the Program, it is also crucial, especially in light of substantial budget constraints, that the Program set priorities to help concentrate efforts on those activities that will be most effective in achieving the overall mission of radon risk reduction.

The Radon Program is establishing these priority activities based on recent recommendations from a broad internal and external Radon Program Review which was coordinated by EPA's Office of Policy, Planning and Evaluation (OPPE). In the fall of 1990, the Radon Division requested that OPPE organize a process to evaluate the Radon Program and make recommendations on future directions to increase risk reduction. OPPE organized a panel of senior headquarters and regional managers from across the Agency who held a series of meetings with experts outside the Agency to include their perspectives. As part of its review, the panel discussed the relative merits of a range of radon strategies, including geographic targeting, testing, and mitigation during real estate transactions, and public information strategies. Radon Program plans for focusing efforts in each of the five key areas are further detailed in the strategy entitled "Implementation of OPPE Panel Recommendations."[1] The Radon Program Review panel issued the following recommendations in their final report:

- *Target the greatest risks first.* The Radon Program Review panel recommended that the Radon Program focus its efforts and resources in the near-term on high radon potential areas and smoking-related risks.
- *Promote radon-resistant new construction.* The Program should encourage and support pilot projects at the state and local levels to promote radon-resistant new construction, which has the potential to reduce risks in a very cost-effective manner.
- *Support testing and mitigation in connection with real estate transactions.* The panel recommended that the Radon Program encourage and support pilot projects at the state and local levels to further promote testing and mitigation as part of real estate transactions.
- *Develop a new strategy for public information.* The Radon Program should continue its nationwide public information efforts such as the *Citizen's Guide* and the advertising campaign, focusing on high radon potential areas and high-risk populations in the short-term. In the longer-term, the panel recommended that the Program use public information, motivation, and incentives programs to build institutional support for construction of radon-resistant new homes and for regulations or policies to require testing and mitigating when existing homes are sold.
- *Develop a coordinated research plan.* Finally, the panel recommended that the Radon Program develop a long-term research plan to prioritize and coordinate potential future research.

The Radon Program, states, and cooperating national organizations have, for several years, focused on many activities that are consistent with the recommendations and directions developed by the Radon Program Review panel. The Program is now aggressively reviewing and expanding these ongoing efforts.

Target Greatest Risks First

The Radon Program is focusing resources and initiatives aimed at targeting the greatest risk areas and populations. Examples of new and ongoing activities include: developing and releasing the National Radon Potential Map, targeting State Indoor Radon Grant (SIRG) funds to highest risk geographic areas and populations, cooperating with the U.S. Geological Survey and the Department of Energy on a special project to develop a model which could further refine the identification of high radon areas, cooperating with the American Lung Association and others to target smokers, a new initiative in cooperation with the Consumer Federation

[1]Copies can be obtained from the EPA Radon Division; the address is provided at the end of the reference section.

of America to encourage mitigation among people who have tested and found high radon levels, a new cooperative program with the National Association of Counties to establish 25 "Model County Radon Programs" in high-risk areas, and others.

Promote Radon-Resistant New Construction

The Radon Program is expanding initiatives aimed at promoting radon-resistant new construction especially in high-risk areas. Examples of ongoing and new activities in this area include: completing review of and issuing the EPA Model Radon Building Standards and Techniques, working with the national building code organizations to encourage incorporation of these radon-resistant techniques into the national and regional building codes in high-risk areas, working with builders to encourage voluntary use of radon-resistant construction techniques, cooperative research to refine and improve existing techniques for reducing radon in new construction, a cooperative program with the National Association of Counties to promote adoption of radon-resistant techniques into local building codes and builder practices in high-risk areas, a cooperative project with the National Conference of States on Building Codes and Standards Initiatives to identify the state and local building code authorities, and others.

Promote Radon Action During Real Estate Transactions

The Radon Program is expanding initiatives aimed at promoting radon action in the context of real estate transactions. Examples of ongoing and new activities include: releasing the new *Home Buyer's and Seller's Guide to Radon*, working with national organizations and state governments to promote radon disclosure, testing and mitigation policies and mandates in connection with real estate transactions especially in high-risk areas, conducting a series of forums in partnership with the Environmental Law Institute to educate realtors on radon action, research with the Massachusetts Institute of Technology to assess the efficacy of existing state radon disclosure requirements, and others.

Sustain Public Information Campaign

The Radon Program is sustaining major national public information programs and expanding initiatives to target key populations. Examples of ongoing and new activities in this area include: continuing to update and provide basic radon public information materials such as the *Citizen's Guide to Radon*, the *Physician's Guide* and others, continuing the national radon TV, radio, and print advertising campaign, continuing National Radon Action Week, and expanding advertising and cooperative minority and low-income outreach programs aimed at achieving action on radon in minority and low-income populations. The Radon Program is expanding initiatives aimed at targeting high-risk areas and populations through initiatives such as a cooperative public service announcement with the U.S. Surgeon General aimed at smoking-related radon risks, increasing the proportion of grants to the American Lung Association, the Consumer Federation of America, and the American Public Health Association affiliates in high-risk areas, and working with the National Association of Counties and the International City Managers Association to develop dozens of model city and county radon programs in high-risk areas.

Develop Coordinated Research Plan

EPA and other federal agencies have conducted extensive research and collected large amounts of data on radon-related issues. However, there are still many areas that require further research. In order to ensure that the Agency's additional radon-related research efforts are coordinated, taken advantage of by key organizations developing programs, prioritized, and do not duplicate efforts by other offices within EPA or other agencies, the Radon Division is working to develop a long-term coordinated research plan. The Radon Division plan has three objectives: (1) identify key research needs; (2) identify research gaps; and (3) encourage responsible agencies to fill research gaps. The Radon Division is initiating a plan to work with other EPA offices, the Department of Energy (DOE), the EPA Science Advisory Board, and others to develop the overall coordinated research plan.

CONCLUSION

As discussed in the preceding sections, EPA's strategy to reduce radon risk consists of four key elements: guiding scientific and policy principles, a decentralized management system, a continuum of strategies, and a strong program focus. These elements are summarized in Fig. 6.

The states, the scientific community, the radon industry, local governments, national health and consumer organizations, EPA, and others that contribute to the national Radon Program have accomplished a great deal since 1985. In the years since the Reading Prong discovery, EPA has significantly increased radon awareness and understanding. There are numerous radon publications in wide circulation that provide information to targeted audiences (see Table 4). A competent and well-trained industry for radon testing and mitigation has emerged. About nine million homes have been tested for radon, and three hundred thousand homes have been mitigated [*14*]. Many builders now incorporate radon-resistant features in new homes—about 300 000 have been built with such features—and the first state and local radon building codes have been adopted [*19*]. Grass roots awareness and support have produced real estate radon disclosure laws in five states, and the real estate industry has voluntarily adopted disclosure policies in many other areas of the country. The relocation industry regularly requires a radon test and remediation, if necessary, as a condition of property transfer [*19*]. About one fifth of U.S. schools also have been tested for radon [*9*].

EPA is committed to focusing on environmental results to assess programmatic progress, "The Radon Risk Communication and Results Study," a survey effort conducted by the Conference of Radiation Control Program Directors (CRCPD) in 1993, is the first comprehensive study of all 50 states and the District of Columbia which addresses key Radon Program indicators of progress. The extensive survey

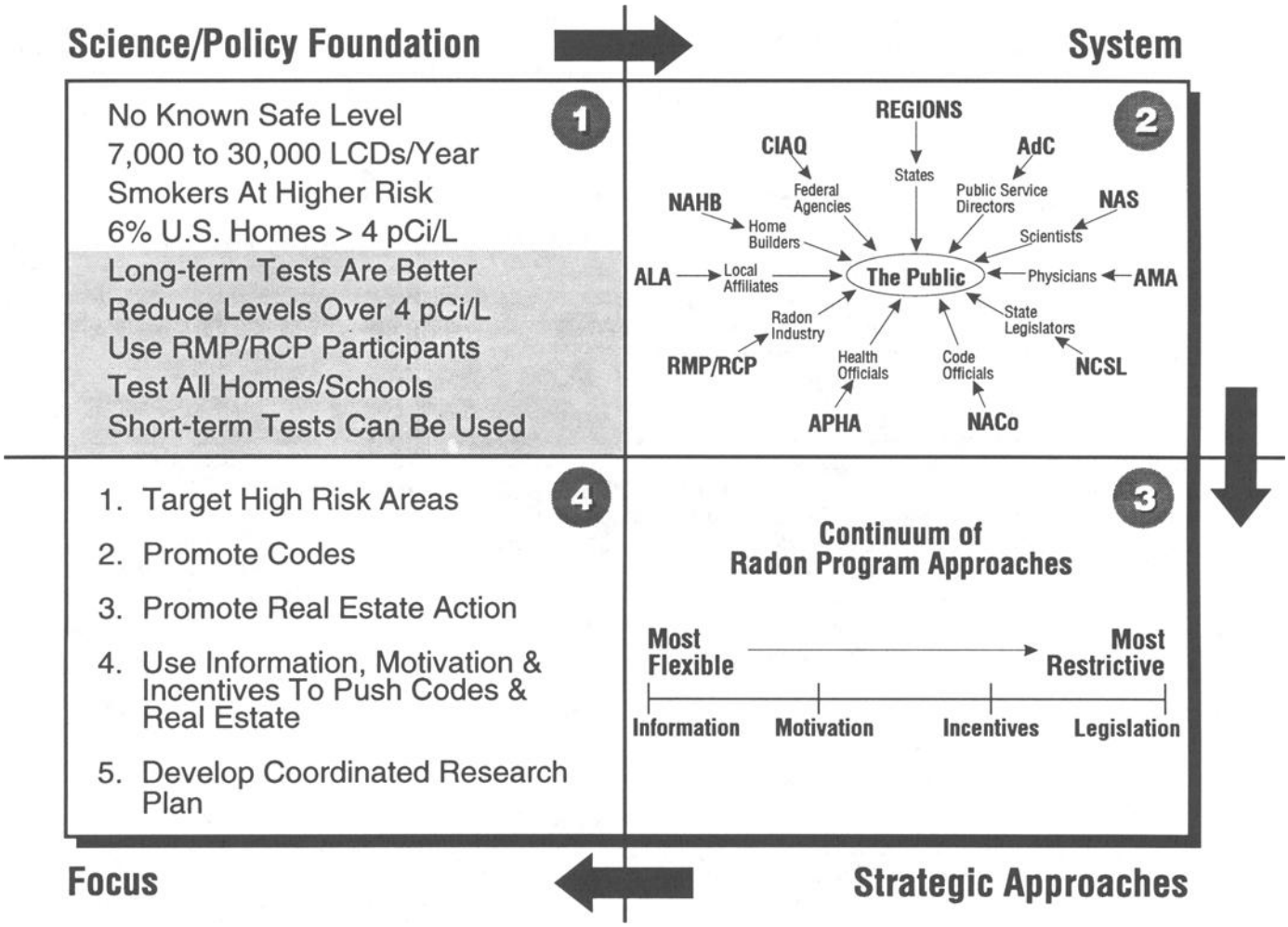


FIG. 6–Summary of key elements of EPA's strategy to reduce radon risk.

provides statistically valid baseline information about a wide array of indicators of program progress and indicates that national and state efforts have been successful at achieving respectable levels of radon awareness and testing throughout the country, particularly in upper-income caucasian families. Less success has been achieved with both ethnic minorities and low to moderate income groups. A summary of some of the results are included in Figs. 7, 8, and 9. The results of the study will allow EPA and states to set program goals and targets for increased risk reduction, to share successful ap-

TABLE 4—List of currently available radon publications.

- *Radon in Schools* brochure
- *Reducing Radon Risks,* general public radon brochure
- *Physicians Guide to Radon*
- *Consumer's Guide to Radon Reduction*
- *Citizen's Guide to Radon*
- *Technical Support Document to the Citizen's Guide*
- *Removal of Radon in Water,* Factsheet
- *Homebuyer's and Sellers Guide*
- *Radon Reduction Techniques in Schools*
- *Radon-Resistant Construction Techniques for New Residential Construction*
- *Radon Reduction Techniques for Detached Houses*
- *Application of Radon Reduction Techniques*
- *Interim Protocols for Screening and Follow-up Radon and Radon Decay Product Requirements*
- *State Indoor Radon Grants Policy Priorities for FY 1993*
- *Radon Measurements in Schools*
- *Indoor Radon Survey Results*
- Community action kits (including all the brochures and a 10-min videotape).

NOTE: The publications listed above are available from the EPA's Public Information Center at (202) 260-7751 or from EPA's Radon Division at (202) 233-9370.

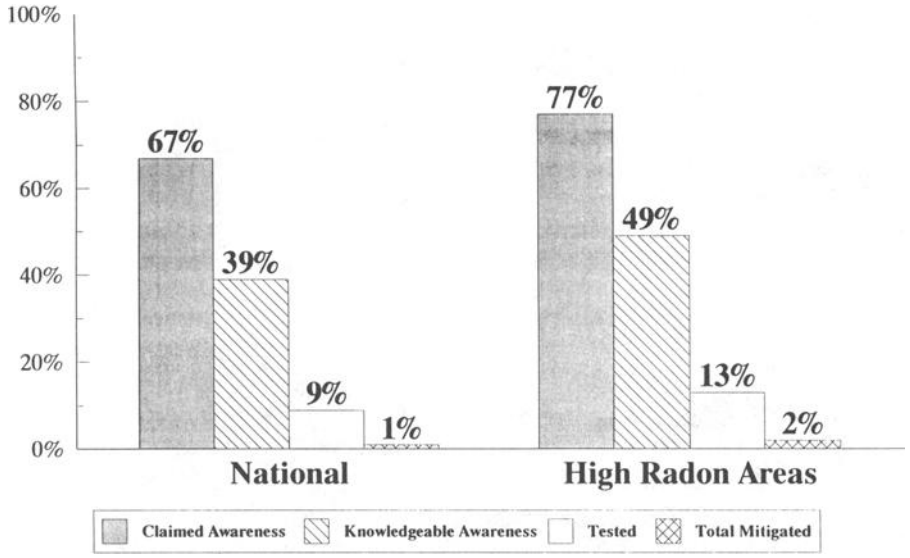


FIG. 7–National summary of CRCPD results.

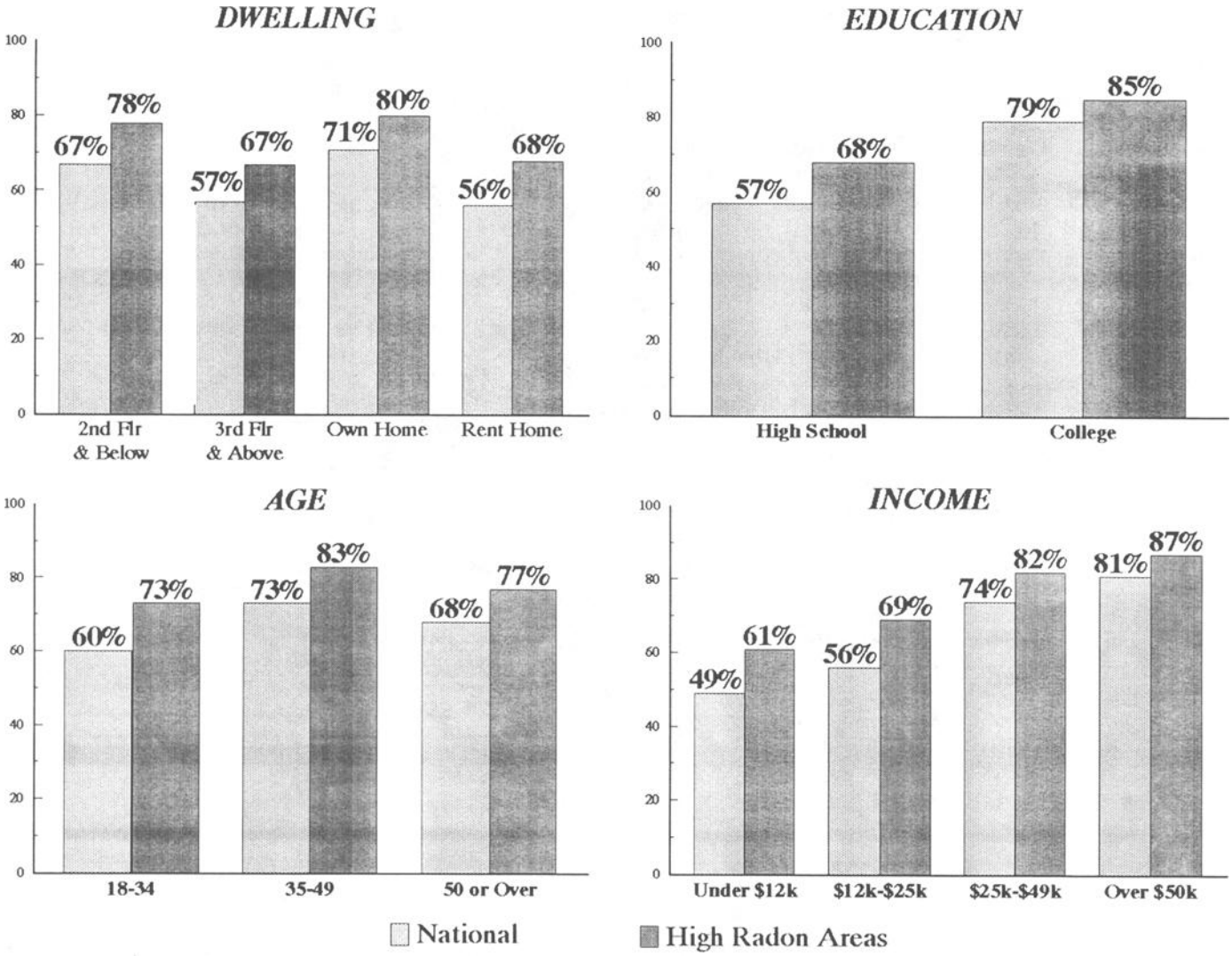


FIG. 8–National demographics on radon awareness from CRCPD results.

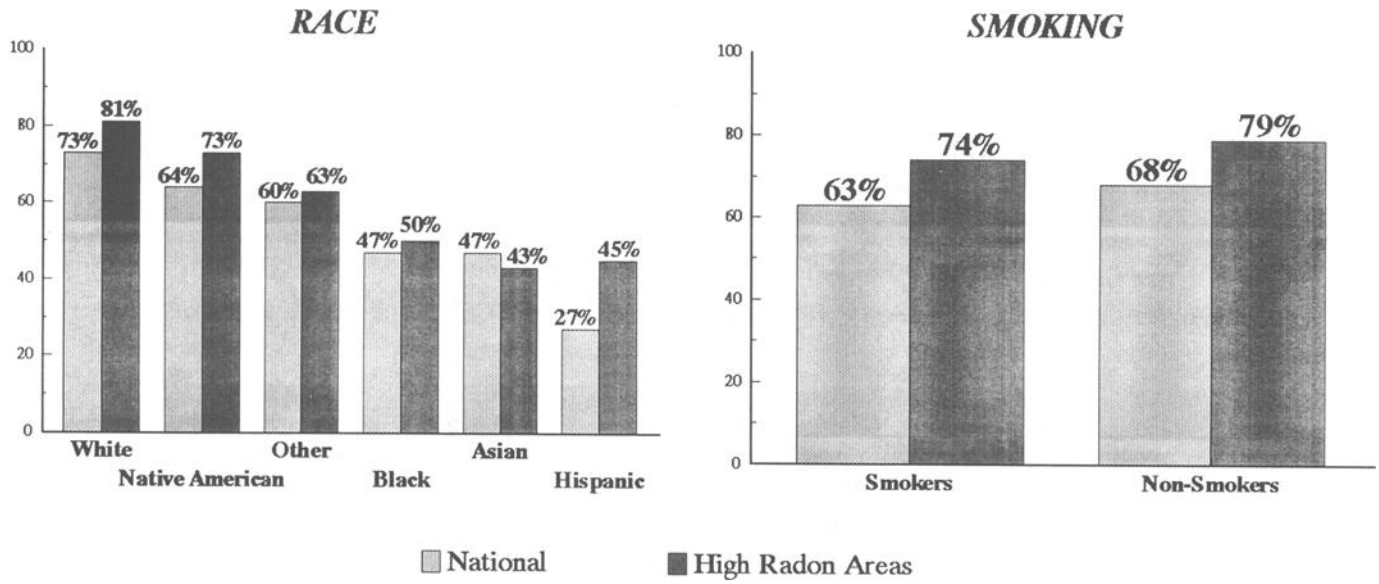


FIG. 9–National demographics on radon awareness from CRCPD results (cont'd).

proaches, to assess and refine current efforts, and to ensure that the radon message is directed effectively to all populations at risk. CRCPD plans to continue to conduct the study periodically to assess the ongoing efforts of each state radon program.

The Agency is also committed to continuing scientific research on health risks. EPA will continue to work closely with the National Academy of Sciences (NAS), EPA's Science Advisory Board (SAB), and other members of the scientific community to use the latest scientific research to estimate risks to the general population from indoor radon exposure.

To build on initial success, EPA will also continue to deliver consistent radon information to the public, continually reinforcing basic scientific principles and policies that guide the Program. To increase the likelihood that radon messages will result in public action, the Program also will continue to rely on its network of states and other organizations. Effective cooperating national organizations serve as multiple sources of radon messages, have special expertise and communications channels needed to reach target audiences, and leverage EPA, state, and local efforts by enlisting their members and affiliates as catalysts for local radon action. The Program will continue to develop and implement activities along a continuum of strategies. Efforts to inform the public and encourage action are important and will be continued, but they will be combined with incentive programs and initiatives to build institutional support for building codes and policies to require radon testing and mitigation when existing homes are sold, especially in high-risk areas. Finally, the Radon Program will increase its focus on the priority activities recommended in the Radon Program Review to ensure that the overall mission of radon risk reduction is accomplished as rapidly and efficiently as possible.

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Written requests for copies of the referenced materials may be sent to:

EPA's Radon Division 6604-J
401 M St. SW
Washington, DC 20460

10

Current and Future Perspectives*

by Susan L. Rose[1]

THE PREVIOUS CHAPTERS HAVE FOCUSED on our current understanding of the prevalence of radon in indoor environments, the potential health risks associated with indoor exposure, the available techniques to measure and mitigate indoor radon levels, federal radon legislation, and the U.S. Environmental Protection Agency's (EPA) Radon Action Program. This final chapter builds upon this understanding and the existing uncertainties in the knowledge base to identify future policy perspectives and the research needed to adequately support these policies.

The chapter is divided into five sections. The first section addresses current federal radon policies and activities. The second section examines reactions to current radon policies from the perspective of the various interest groups, e.g., the public, business, and government agencies at several levels. The third section identifies the unresolved issues surrounding current radon policies and develops potential options for future policies. The fourth section identifies the research needed to support different policy options and provides basic scientific information on radon. The fifth and concluding section provides additional perspectives on indoor radon to provoke further discussion on the subject.

CURRENT RADON POLICIES

By 1984, federal and state policies on radon had been in place for some time, including regulations of mine ventilation and guidelines for use of uranium mill tailings in Colorado and reclaimed phosphate lands in Florida. Research on indoor radon was already under way and small surveys had been done. Yet, in late 1984 when the Stanley Watras house in Eastern Pennsylvania became news with a level of 10 000 Bq m^{-3} (2700 pCi L^{-1}) of radon, even radon-aware scientists and policymakers were stunned. This event proved catalytic for major federal and state actions, surveys, and research, as well as causing public alarm and a media blitz.

Since 1984, the EPA has been the leading federal agency in radon outreach and mitigation activities. Early EPA efforts to work with the state of Pennsylvania, citizen's groups, and others were followed by the initiation of a radon program whose cornerstones were laid in 1984–85 and which has grown exponentially in size and scope.

This program, to many, is a model federal program, emphasizing outreach and public information. It has been viewed within and outside EPA, despite some excesses, as one of the better programs that EPA has produced. The EPA program is unique in that it addresses a pollutant which occurs naturally (no one caused it), is found indoors (in homes where EPA does not regulate the air quality), and is a well-documented (at least for smoking uranium miners) health risk. In fact, this risk is better documented than almost any other risk about which EPA is concerned. Radon is found virtually everywhere. The EPA radon action program addressing these issues is located in the Office of Radiation and Indoor Air. The original aspects of the radon program are still in place today. These are: problem assessment, mitigation development, capability development, and public information.

The program objectives are:

1. To reduce and prevent risks from exposure to naturally occurring radon through nonregulatory activities.
2. To build a state–private sector partnership to respond to the issue.
3. To develop an effective national program to consider existing and new structures.
4. To conduct a modest federal program that maximizes involvement by the homeowner, the private sector, and the states [*1*].

All U.S. indoor radon actions, policies, industries, and research needs derive from the EPA program. Obviously, this has had a major impact, and EPA is working toward meeting the original goals. In retrospect, neither EPA nor any other radon-involved entity could have perceived the impact and repercussions of the Watras house and the resultant federal actions, some of which will be explored in the following pages.

The core of present U.S. policy for controlling exposure to indoor radon includes the following: the EPA and the Centers for Disease Control (CDC) have made recommendations to all homeowners for taking radon measurements and following federal guidelines for remedial action; in October 1988, Congress passed an amendment to the Toxic Substances Control Act Title III, Indoor Radon Abatement, that, among other provisions, established a long-term national goal for reducing radon exposure; and the EPA Office of Drinking Water has proposed a standard to limit radon in public water supplies [*2*].

[1]Radon Research Program Manager, U.S. Department of Energy, Health Effects & Life Sciences Research Division, GTN, ER72, Washington, DC 20585.

*The opinions expressed in this chapter do not necessarily reflect the opinions of the U.S. Department of Energy.

In September 1988, EPA and CDC issued a joint health advisory recommending to homeowners that a screening measurement be made for indoor radon concentrations in every U.S. household below the third story level. The measurement protocol, now modified, called for a two-day sample to be taken on the lowest livable level of the home. Depending on the results, one of four responses was recommended with increasing urgency in responding. The lowest criterion, 4 pCi/L^{-1} (150 Bqm^{-3}), corresponded to EPA's current recommended action level for radon reduction. The rationale for this particular level combines historical precedent, the objective of reducing exposures to the lowest extent possible, and EPA's assessment of the level of reduction that could practically be achieved [*3*]. At the direction of Congress, this recommendation has been reevaluated and reissued and will be again in the future, possibly to a lower "health-based" standard.

It is important to note that this recommendation does not constitute a standard. At present, the EPA does not have legislative authority to regulate indoor air quality. According to current policy, individual homeowners must weigh the risk of radon exposure against the cost of control. In this regard, the strategy for controlling indoor radon departs radically from that for controlling outdoor air pollutants. In the latter case, federal standards have been established, and the imposition of sanctions has been threatened for regions that do not achieve compliance. The differences in approach arise naturally because outdoor air is a community resource, whereas indoor environments are largely private. The outdoor pollutants that are regulated are not naturally occurring, a very different situation from indoor radon. However, this position does not accommodate the large number of public buildings whose radon levels have yet to be determined [*2*].

Using available scientific knowledge on radon, radon policymakers worldwide have developed a full spectrum of radon policy responses ranging from no action to guidelines to standards. Although all policies were developed to reduce indoor radon exposure, international policies differ in their approach, choice of recommended levels, and impact on affected populations. European policymakers, in contrast to those in the United States, have selected different policy approaches to reduce indoor radon levels. For example, in the United Kingdom and Sweden a two-tiered system was created which treated new dwellings differently from existing structures. In addition, in Canada, policymakers have chosen an action level of 0.1 WL, corresponding to 7400 Bq m^{-3} (20 pCi L^{-1}) for all residences. Figure 1 [*3,4*] superimposes different international policies onto the frequency distribution of radon concentrations in U.S. homes. It is important to emphasize that the percentage of homes affected, and hence populations affected and costs incurred, are dramatically affected by the choice of action level.

PUBLIC, INDUSTRY, AND STATE REACTIONS

The differing perspectives of the public, radon measurement firms, radon mitigation contractors, real estate agents, home builders, and state and local governments are reflected in their reactions to current radon policies and activities. The radon issue, therefore, has provided a unique opportunity to examine public reactions to what appeared to be a "new risk"—a colorless, odorless, radioactive gas entering private homes that was not a concern for homeowners just a few years ago. Suddenly there is a radon industry, major radon legislation, vast radon programs in local, state, and federal agencies, radon media, radon risk communicators, and a great increase in local, state, and federally sponsored radon surveys, radon research, and proposed regulations. The focus of all this attention is on homeowners or renters and eventually school districts and workplaces. The apparent goal is to make them respond to this issue. Will homeowners/renters read information? Do they measure? Will they mitigate? What are their exposures? Can they buy, sell, or build homes without being involved, even inadvertently, in this issue? Are they being "informed" or "persuaded," and by whom? Are they victims of fraud and deceit? Who will protect the public? Who will provide scientific answers? Can mortgages be affected?

The Public

In many parts of the country where radon surveys have been undertaken by the government or the media, the public often responds to promotional materials by a surge in purchases of radon measuring devices, a lesser number of measurements actually being made, and fewer yet repeat measurements and mitigations installed. This response appears to be predictable from many studies on risk communication and risk perception for a variety of hazards including radon. Radon is not a regulated pollutant in residences, has no sensory clues, has a delayed health effect, occurs naturally, and is competing with myriad other government pollutant alarms. Yet this is a radiation issue, a term which appears to frighten most people, and it presents a greater and better documented health risk than most other risks regulated by the EPA [*5*]. What can or should be done to change the public response pattern?

While individual choice is the optimum goal in terms of citizen action, the better educated, more affluent, and more risk-averse segments of the population seem to respond in greatest numbers to this issue. For example, as reported by Fisher and Sjoberg [*5*], a sample of homeowners studied in Maine showed that over half reported mitigation in their homes, but less than half of these had radon levels over 4 pCi/L^{-1}. Given current EPA guidelines and documented health effects, this may appear as a waste of resources, with analysis showing no relation between mitigation performed and elevated radon levels. The issue here remains—how to present the scientifically sound information that citizens require, encourage actions designed to reduce actual health risk, and allow citizens freedom of choice to do nothing if they so choose. Indeed, states where high radon areas have been identified, accurate information has been made available, and appropriate responses have resulted should be models for other areas of the country. Government and health departments clearly must avoid actions to manipulate the public response, a great temptation once goals are set. Two views of risk communication are stated by Sandman et al., [*6*]; one is grounded in information, while the other is grounded in audience attitudes, emotions, and behavior.

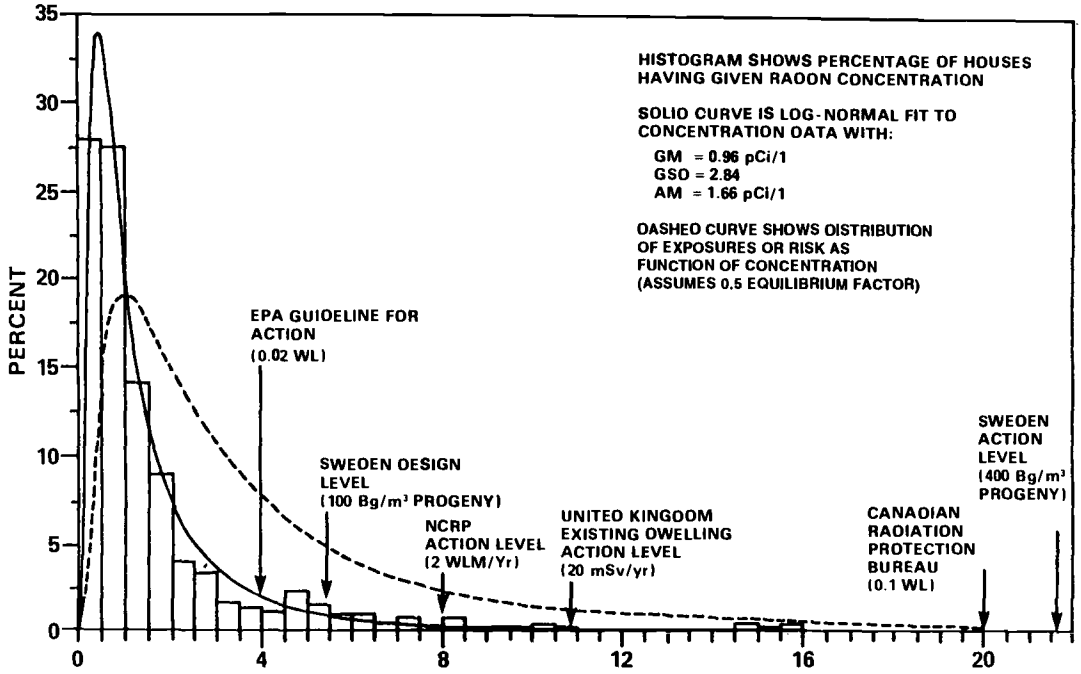

FIG. 1–Distribution of Radon Concentrations and Lung Cancer Risk in 552 Homes (3,4)

Each risk communicator must design differing communication strategies to accomplish his or her goals. When communication of risks is intended as an educational process, "risk communicators (especially government agencies) should avoid the arrogance of prejudging what citizens ought to think, feel, or do. Instead, they should confine themselves to explaining the relevant information as clearly as they can and should measure their success by what facts the audience has learned. . . . The boundary between persuasion and information is far from well defined" [*6*].

State Responses—Minnesota, California, and Florida

At present, the majority of states either have performed their own residential radon surveys or have participated in EPA-assisted surveys. Studies of radon in the workplace and in schools are underway, or will be, in many states.

As case studies for this chapter, the "radon experience" in three states is briefly examined: (1) Minnesota, where a 1988 EPA press release characterized Minnesota as the "second Reading Prong," a charge that Minnesota officials reacted to strongly; (2) California, where state surveys have found very limited areas of elevated radon [7]; and (3) Florida, where elevated levels of radon generally correlate with elevated levels of soil phosphate.

Minnesota

As part of uranium exploratory drilling, radon testing of many wells and municipal drinking water supplies was conducted in the late 1970s. When the Watras home was discovered in 1984 and the national indoor radon issue hit Minnesota, the state was already alert to this topic. It took an independent stance and rejected the first *EPA Citizens Guide,* instead creating its own information brochure. While originally intending to recommend twelve-month alpha-track measurements to its citizens, Minnesota eventually participated in the EPA state survey using short-term charcoal canister measurements in the state. Several small radon surveys, however, had been made with longer term measurements. A significant number of homes in Minnesota appear to have radon levels in excess of 4 pCi/L^{-1}, although not many are greatly elevated. Wherever possible, long-term measurements are the preferred option as state policy. Minnesota also participated in the EPA nonrandom school survey and carefully informed schools and parents when elevated levels were found. Attention to public reaction has been a major part of the effort expended on this issue.

The state acquired funding for an EPA Radon Training Center and is establishing radon as part of a total Indoor Air Quality Plan. It encourages testing whenever possible with twelve-month detectors to better understand average annual exposures. The state is also working with health care providers, the American Lung Association, Honeywell, Inc., and several health insurance companies to approach this issue in as comprehensive a way as possible. The plan design and the frankness and willingness of the state health department to undertake research and create its own educational materials provide an excellent model.

California

The radon issue in California also began prior to the discovery of the Watras house, with a failed attempt to obtain federal funding for a statewide indoor radon survey. The state has since performed its own twelve-month alpha-track survey, and there have been others statewide, including a survey with twelve-month alpha-track measurements by the *Los Angeles Times* [*8*]. The state also performed a random survey of

two-day measurements in schools. The approach in California has been centralized, and state research funding has often been provided. Except for a very localized geographic area, *no* significantly elevated radon problems have been seen in California. In 1988, the state's Health Director, Ken Kizer, went on record to say "that it is *not* necessary for *all* homeowners in California to test for radon," [*8*], a policy directly at odds with EPA's national policy. California policy continued to differ from EPA policy, the issue of radon in schools being another example. California officials found virtually no elevated levels of radon in schools and thus publicly questioned the usefulness and cost of the national policies on school measurements.

For years, California continued to do its own research, to perform random surveys, and to set policy goals as deemed appropriate for its geological/geographical setting. The state has 11% of the U.S. population, so its radon actions deserve attention. California is an example of the need to tailor environmental policies to local and unique conditions. National policies often take a more generic approach.

At the state level, it does appear that public reaction to the radon issue is mixed: the more publicity, the more interest. This has ranged from near hysteria to extreme skepticism. The numbers of measurements and mitigations undertaken, resulting from state surveys or media coverage, seem to ebb and flow with media events. Both California and Minnesota, with different geologic settings, have taken very proactive roles on this issue. Both states have acted with great concern in terms of public health, public information, and potential expense. Both continue to attempt to carry out radon activities within state funding constraints, and both differ from federal policies and actions when conditions appear to merit their own responses.

Florida

The state of Florida became involved in the issue of indoor radon for a unique reason—phosphate mining and reclaimed phosphate lands in the state. These areas provided a source for elevated radon exposure to citizens. In the 1970s, concerns led to a survey of over 1000 homes, primarily in two counties, where a number of elevated radon levels were found. Seasonal and annual measurements were made in 100 of these homes, and no significant seasonal difference was found.

In 1984, the state of Florida developed, with EPA guidance, an administrative rule on radon for new construction in certain areas of the state, a guideline of 4 pCi/L^{-1} indoor radon. In 1986–1987 the state undertook a radon survey to categorize counties with definite evidence of elevated radon, counties with limited evidence of elevated levels, and counties with no potential for excessive radon levels [*9*].

A radon statute passed in 1988 [*10*] provided Florida with a radon program to identify and eliminate radon problems and to change and verify building codes. The statute established a radon trust fund which levied a surcharge of 1 cent per square foot on new construction and renovation of buildings. The trust fund, in turn, supported a wide-ranging radon research program in Florida.

The statute also provided the Florida program with required testing, certifying, and training of measurers and mitigators. The statutes included a public information component for the creation and distribution of materials. The program requires mandatory testing for all state owned, operated, regulated, or licensed properties, as well as kindergarten through high schools and 24-h care facilities. State money is not provided for testing or mitigation. Measurers must notify the state with the numbers being compiled. The state developed and used its own public service announcement.

Although the state is moving ahead vigorously with radon activities, building code revisions, and legislative activities, it is apparent that costs, both public or private, are a constraining factor. The Florida phosphate problem is unique and the radon approach has been scientific and balanced, yet cost considerations here, as elsewhere, affect the goals of the state radon program. The state calls its original radon program a "discovery phase." Once finished, no one is certain what will follow. Florida has worked long and hard with EPA on the radon issue, as well as with the phosphate industry. Both EPA and DOE had research programs in the state and have learned much from a unique but generalizable radon problem.

Radon Measurement Companies

Some insights may be gained from looking at the experiences of both a small and a large radon measurement company. One small Maryland company sees measurement requests peak, as would be predicted, in fall and early winter. It observed an initial large response to the early media radon pronouncements in the Washington, DC area, followed by a lesser, more brief, flurry of interest each time radon has appeared in the news. Many "risk averse" customers appear to be testing, indifferent to whether the media highlights the issue or not. This company does not follow up on which customers mitigate or not. It does see some "panic" reactions at *all* levels of measurement results. This panic seems to relate more to families with children, especially where suburban lifestyles have children playing in lower level family rooms much of the time. The most steady radon-measuring business for this firm continues to come from schools and parent-teacher organizations, where reduced rates are offered to families when their schools are measured under county contracts. Another avenue for steady business appears to be homeowners associations when group rates are provided because equity concerns motivate interest in radon.

Larger firms appears to be less vulnerable to radon media attention because they have established major contracts with large corporations and school districts and are suppliers to government surveys. One large firm sells alpha-track, electret, and charcoal canister measuring devices, while the smaller firm interviewed sells only charcoal canister devices and measurements. For situations where EPA protocols are unavailable, the large firm designs sampling protocols for corporate needs. Even though their business is corporate and real estate driven, EPA radon publicity is still eagerly awaited.

For measuring companies, some earlier problems with moisture and inaccurate charcoal canister readings were resolved. Significantly though, many companies often serve real estate transactions based solely on short-term charcoal measurements. This occurs despite the widespread knowledge that tampering with canisters can occur, that user in-

structions are often *not* followed, and that short-term measurements do *not* reflect average annual exposure.

The small measuring firm does not recommend specific mitigators to its clients but nonetheless does get customer feedback on good and bad mitigators (some large firms do both measuring and mitigating). Health information from the "EPA Citizens' Guide" is provided to its customers. In many large and small measuring companies the staff participate actively in scientific and technical societies for radon-measuring professionals, which gives them an advanced look at what problems and solutions may be heading their way. Information provided to customers in most cases is limited to government-provided scientific data sheets, while advice on risk and mitigation action is often not given.

The companies providing information for this chapter are responsive to a climate of changing EPA protocols and new products. They are also subject to the EPA Radon Measurement Proficiency Program, a voluntary program in which successful measurers are listed. A variety of problems have arisen with EPA Radon Measurement Proficiency Program delays, business lost, increasingly poor results industry-wide, and no appeal process. Many of these issues have been resolved by EPA and the industry.

Radon Mitigation Companies

Radon remediation companies and construction firms have now sprung up over the country; they constitute a new industry, with both new and retrofitted businesses participating. In some cases, pesticide or home-improvement companies or construction firms have added radon mitigation to their list of services, while, in others, entrepreneurs have learned the techniques required and set up business de novo. Radon mitigation is not difficult engineering technology, but does present some diagnostic challenges and some interesting ethical issues. The most significant ethical issue is that those who measure and those who mitigate a home should not be the same due to the potential conflict of interest. The person mitigating should be properly trained to identify and correct a problem at minimal expense.

Several mitigation companies have provided typical customer patterns for use in this chapter and insights into the radon mitigation business. For one small company, the service area includes the affluent Washington, DC suburbs, where residents have been subjected to many radon media events, including a campaign by a local TV station and a major food chain. The typical profile of calls is a handful of homeowners with radon levels between 2 and 4 pCi/L^{-1}, most between 4 and 40 pCi/L^{-1}, some between 40 and 200 pCi/L^{-1}, and a handful over 200 pCi/L^{-1}. Phone call intensity does not seem to be directly related to media events. About half the calls received are generated by real estate transactions, possibly 20 to 30% are based on fear of radon, and most of the rest are based on a belief that radon mitigation is a cost-effective means of risk avoidance.

In many companies, the staff are radon professionals who have been trained in EPA courses; these businesses have established model business ethics. There appears to be concern voiced by these mitigators, perhaps generic to the mitigation industry, about the accuracy and reliability of various radon testing methods which they use for post-mitigation confirmation testing. Mitigators fear that current quality control procedures are not reliable. Some mitigators return annually to mitigated homes for follow-up radon measurements to assure themselves that the mitigation techniques they installed are still operating correctly. This is not a required service, but the way some companies have developed their operation. Others may not return for post-mitigation testing, but do guarantee a certain maximal level of radon in homes they have "fixed."

One Reading Prong mitigator expressed observations about the engineering quality and the escalating cost of mitigation, as well as a lack of reality as to published mitigation costs. Even for new construction, costs are probably closer to $500 per home than the $200 figure often cited. The following of EPA guidelines, continual training, and expensive government fees imposed on mitigators to regulate the industry all contribute to rapidly increasing costs. Other major concerns voiced include getting and paying for insurance and worker liability issues. Another significant consequence of much mitigation practice was the resultant violation of fire codes, an issue that has been addressed. Backdrafting from combustion appliances in mitigated homes has been of concern as well.

The radon industry has experienced the vagaries of a new industry, one that perhaps grew too rapidly. In addition, because EPA policies have recommended winter radon measurements, the industry suffered a summertime slump. To compensate, the industry has marshalled its resources to legislatively encourage national or state requirements for radon measuring and mitigating. At present, radon industry goals include programs to keep the radon issue strong in the public mind, requiring certain types of certification and training for radon specialists and attempting to make radon testing and mitigation by EPA-listed professionals a legal requirement in Congress and in the states. They also want mandatory school and workplace measurements and regulations requiring radon measurements when real estate transactions occur. The outcome of these efforts is uncertain, as other competing forces, including mortgage lenders, home builders, real estate firms, and banking interests, all have an interest in these issues.

As seen by the radon industry [*11*], the primary "drivers" of the radon business are law, mortgage lenders and guarantors, real estate companies, the media, public awareness, and the radon industry. As any other industry would do, the radon industry uses, and will continue to use, whatever drivers will increase business and profits.

Real Estate Industry/Homebuilders

The real estate, homebuilding, and mortgage banking industries are directly affected by radon policies and media activities. Potential liability, real estate equity, radon measurements for real estate transfers, availability of insurance, radon "proofing" of homes, employee relocation policies, etc. are among the many facets of the radon issue of concern to these industries. That radon measurements are most often short-term charcoal canister, are not tamper proof, and do not relate to inhabitants' average annual exposure all play havoc with radon measurements for real estate transactions. The real estate industry's initial position was that real estate

transactions should not drive the radon issue, which is a public health matter. Yet the situation has evolved that real estate transactions are a major driving force for radon measurements and mitigation [*12*] and may very well be imposed by future regulation, either state, local, or federal.

These affected industries work closely with the EPA, federal and regional trade association offices, the Employee Relocation Council, and others concerned with the radon issue to see that the public gets the information necessary to make an educated choice about radon measuring and mitigation and that federal and local policies are modified if possible to suit consumer or industry needs. These industries also lobby federal and state legislatures when legislation is proposed that will directly affect the homebuilding or real estate industries and add costs and uncertainties with questionable benefit.

These affected industries have witnessed a surge of local interest in radon when a local TV station or newspaper does a radon series or when a local governmental agency releases a radon survey or finds elevated radon levels locally. Because these industries work closely with federal and local agencies and Congress, their individual members are usually well informed on radon through their national organizations. Their trade associations have provided policy guidelines, "radon-proof" home building techniques, radon fact sheets, and workshops and symposia for members. They have, for the most part, stayed well ahead of local concerns regarding the need for information. Nonalarmist, sound, nonregulatory radon policies based on adequate scientific information remain the working goals of all these organizations. National organizations seek to address radon as part of a comprehensive federal approach to all indoor and environmental pollutants, while at the same time advocating research to obtain better risk estimates and selectively targeting areas of elevated radon [*13*].

POLICIES AND SCIENCE

Radon policies have been established fairly rapidly in the United States, both nationally and locally following the discovery of Stanley Watras' house. Yet there remains much uncertainty in every aspect of the radon issue—location of the geologic areas with elevated radon potential, radon concentrations and distributions nationally and within individual residences, actual radon risk to nonsmokers, measurement technology, durability of mitigation systems, and much more. While many federal agencies are involved in performing research to reduce these uncertainties, policy choices may not always reflect available scientific knowledge. It remains to be seen what will be learned from current radon research. The economic costs of radon policies (in excess of 40 billion dollars) require that there be a strong link between the science and policy.

This book has taken a broad look at what is known about the radon issue: how a new radon industry has grown up and its problems, how state governments have reacted to protect citizens and allay their concerns, and how scientific and policy uncertainties have impacted the realtors and homebuilder industries. Clearly, much remains to be done from a research perspective to resolve important scientific questions remaining in this issue and to aid policymakers in making wise and economically sensible choices.

Radon policy changes are likely in the near future. The government has chosen to try to actively influence citizens to take radon actions rather than to just provide them with scientific information, for example, the radon ad campaigns [*14*] distributed nationwide. Short, pithy, advertising spots have been designed to strongly motivate people to take action. No indication of the vast uncertainties of risk at low levels of radon has been provided in order not to confuse the advertising goal of making the public measure the radon in their homes. Information related to the uncertainties is especially important for nonsmokers so that they may realistically look at their lung cancer risks.

The two-measurement strategy recommended initially by EPA as a way to quickly identify elevated homes proved confusing to consumers. Current policy has altered this strategy. The great variability of radon levels from day to day or the uncertainties of current measurement technology may not be reflected in short-termed testing. Risk numbers, once up to 43 000 radon deaths per year [*15*] and now lowered to an upper bound of 30 000 (with a central value of 13 600), are again being evaluated by the National Academy of Science Beir IV panel. The lowering of the range to 30 000 in 1991 reflected a significant report by an National Academy of Science (NAS) panel on Comparative Dosimetry of Radon in Mines and Homes [*16*]. This panel determined that risk in homes per unit of exposure is 30% less than in the mining atmosphere. No change in guidelines is contemplated as a result. The EPA Science Advisory Board has recommended that the central value be the figure used consistently and that uncertainty bounds be applied.

EPA measurement protocols for residences, workplaces, and schools are changing as problems become apparent or new information is made available. It is still recommended that every home in the U.S. be measured for radon. Should scientific input modify federal policies for local applicability? Should homeowners be told that their risk, while likely small, is never zero?

Population-risk versus individual-risk policies represent very different strategies and remedies. Highly elevated homes represent fairly certain individual risk, yet how do we identify these homes without measuring everywhere? Will targeting the entire population for radon reduction actually accomplish anything in terms of lung cancer reduction? Should our immediate goal be to find and fix truly elevated homes and address the overall reduction in population exposure over many years? The costs will be dramatically lower.

New radon programs and surveys are looking at schools, workplaces, and commercial buildings. Are workplaces a source of radon risk? What does it add to one's cumulative exposure to work in a workspace that is over 4 pCi/L^{-1} for several hours per day, or sit in a classroom over 4 pCi/L^{-1} daily for nine months? Are children at greater risk? Available evidence seems to indicate they are not [*17*], and the well-publicized BEIR IV study [*18*] describes the effect of exposure earlier in life as diminishing over time.

Federally recommended radon levels are currently in the form of guidelines, not standards. Will the objectives set for the country be possible on a voluntary basis or will regulations ultimately be necessary? What about smokers and

radon? Isn't realistic hope for lowering lung cancer rates really based on changes in smoking incidence and smoking policies?

Short-term tests are the currently recommended federal approach. What do these tests tell us about average annual exposure? What do they tell us about real exposure at all? Are measurements currently reliable enough to set hard numerical goals instead of ranges? If equity in a home is at issue, can one feel comfortable making a two-day measurement with a technique that can be off routinely by 25 to 50% (either through sampling error or analytical accuracy)? Blind testing is providing a bleaker picture of measurer reliability. Several years ago, a study and campaign by the Buyers Up organization with the attendant publicity resulted in EPA revising the radon measurement program to make quality assurance stronger. There has also been interest in having the National Institute of Standards and Technology (NIST) become involved in radon standard setting as a national reference laboratory for indoor radon measurements. Similarly, consensus protocols and standards being developed by such bodies as the American Society for Testing and Materials (ASTM) will be of considerable benefit. What would be the effect of either a tougher certification program at EPA or the availability of an NIST standard? Both presumably would contribute to making the measurements received by homeowners a more reliable and accurate representation of the actual value at time of sampling.

There is great variability in radon levels in homes over time, and great uncertainty in short-term radon measurement accuracy and precision. Are the spikes, blanks, and duplicate samples being measured enough to assure the consumer that a radon concentration obtained is really the value for their home? Are the uncertainties greater at lower levels of radon? And what of mitigation? Are licensing and training programs sufficient or are they too restrictive?

Some residential radon epidemiology studies are showing an effect, others are not. What do limited residential radon epidemiology results mean? Some studies have not adequate statistical power to show an effect individually. They will need to be part of a major data pooling effort [*19*]. What do environmental epidemiology studies (those that make correlations without individual measurements) mean? Pooling of case control studies needs to be done but is not yet available.

From the perspective of public policy, it is also important to consider the future rates of radon-associated lung cancer incidence. Such projections are highly uncertain because, among other factors, smoking habits have changed substantially with time. A *Journal of the National Cancer Institute* article, reported in the *Washington Post*, acknowledged that for the first time U.S. lung cancer rates appear to be declining [*21*]. The documented decreases in lung cancer incidence, however, are actually occurring. They are a reflection of success with anti-smoking campaigns. What does this decline mean in terms of radon policies and radon and lung cancer? Smoking remains the overwhelming cause of lung cancer.

What of mitigation? Can we use different techniques for different initial radon levels or different geographic areas? There are requirements to measure workplaces and schools. Do we know how to measure, or when or where? What do "elevated levels" mean and how does one mitigate in a large commercial building? Does the level of contractor proficiency alter the outcome? Do radon mitigation systems survive years of use? How do we know if levels have crept back up, or if the ground or foundation underneath a house cracks from years of radon mitigation? The United States differs from other countries by recommending that new and existing housing have the same action level for radon. It is easier and cheaper to put radon mitigation systems into new construction. What will be the cost and effect if a two-tier policy is adopted in the United States? Should only certain geologic areas be required to build these systems into new construction? Gradually lowering population exposure represents an alternative. What about groundwater as an indoor radon source? Radon in groundwater regulations are pending that would put many water supplies out of use. What is the risk? In some granular-activated charcoal systems that remove radon from water, the mitigation itself creates a hazardous waste disposal problem as well as a potential source of gamma-ray exposure.

Lastly, risk communication has not produced an adequate national citizens response, according to the radon industry and EPA. What should one do to convey to citizens the need to measure while not unduly alarming people? An adequate description of the issue, its risks, and uncertainties must also be communicated.

Having established that indoor radon presents a risk, especially for smokers, that is admittedly more serious at higher exposures, what do we do about it? We have seen that we often must go ahead with policy choices before all the scientific answers are in. Let us now explore the radon research that is or should be on-going to address the major uncertainties in the radon problem.

FEDERAL RESEARCH: CURRENT AND FUTURE

Radon research undertaken since the late 1970s has provided much of our current information on radon concentrations in U.S. homes, factors that influence indoor concentrations, and the risk of lung cancer associated with indoor exposures. The results strongly indicate the need for further investigations because many scientific uncertainties continue to exist. During the same time period, discoveries of exceptionally high indoor radon concentrations in the eastern United States raised the level of public concern. The increased scientific and public interest resulted in the initiation of a more comprehensive research program in order to respond better to the public health concerns and provide a stronger basis for formulating national policy decisions [*22*].

At present the U.S. Department of Energy and the NIH support large federal programs of basic radon research and epidemiology, while EPA funds applied (mitigation oriented) research and outreach programs. The National Cancer Institute, the National Institute of Environmental Health Sciences, the Centers for Disease Control, the United States Geological Survey, and the National Institute of Standards and Technology are each doing radon research in the area of their expertise and mission. Additionally, state, local, and private research and a multitude of indoor radon surveys will all contribute vitally needed information on this issue.

Basic Science [22]

Availability and Transport of Radon

People living in areas of the United States that have high concentrations of uranium and radium in the soil and soil that allows for rapid gas transport are likely to receive the highest radiation exposures from indoor radon progeny. Thus, it is important to identify these areas for more detailed evaluation. As part of this effort, studies are being conducted to determine the applicability of using existing geological and radiometric data such as airborne surveys of gamma-emitting radioactivity in the ground, regional radon measurements, uranium geology, and soil maps to predict radon availability at different geographical locations.

The rate at which radon is transported in soil depends upon many factors. These include soil properties such as porosity, moisture content, and nonhomogeneous layering of different soil types, as well as atmospheric parameters such as temperature and pressure gradients caused by wind and changes in weather. Because the interactions of these parameters are complex, both model calculations and detailed field measurements are necessary to predict the rates at which radon may be transported at different locations. The resulting information along with indoor radon surveys has been utilized to accomplish two policy significant outputs, one, the *EPA Radon Potential Maps of the U.S.*, and, two, the "Hot Homes Feasibility Study" funded by EPA and DOE to identify those areas of the United States expected to have the majority of homes greater than 20 pCi/L. The EPA National Residential Radon Survey, based on long-term measurements, estimates less than 6% of U.S. homes have more than 4 pCi/L. This study, underway for several years, is being validated in Minnesota, New York, and Washington State.

Transport of Radon Into and Within Buildings

Current understanding of radon entry into houses suggests that it is a function of differential pressures between the soil gas bearing the radon and the houses. The pressures inside the houses can change from operation of heating, ventilating, and air conditioning systems. Also, internal combustion sources and external weather patterns can have major effects on radon entry and transport inside buildings. Studies on these issues provide valuable information on mitigation practices and contribute to the "Hot Homes" study base.

Only a small number of homes have been surveyed to characterize the aerosols in indoor air to which radon progeny attach. Better knowledge of the types of aerosols in homes is required before predictive models of radon progeny behavior can be formulated. It is likely that the aerosols are influenced by seasonal variations, geographic location, presence of cigarette smokers, and home ventilation patterns. It is also important to improve the techniques and instrumentation by which radon and radon progeny may be measured, as well as the measurements of particles and other indoor co-contaminants. These aerosols contribute to dosimetric calculations and evaluating mine versus home differences.

Physical-Chemical Interactions of Radon Progeny in Ambient Air

To predict the behavior of radon progeny in indoor air, a fundamental knowledge of basic aerosol physics is required. Current understanding of the mechanisms that govern radon progeny kinetics is not sufficient for accurate predictions. Physical-chemical properties of radon progeny aerosols obtained for use in exposure assessment and dosimetric studies may lead to more reliable and cheaper measurement and mitigation techniques.

Relationship Between Exposure to Radon Progeny and Dose to Cells at Risk

A major obstacle to quantifying radiation doses to people exposed to radon progeny indoors is the lack of information on several key factors of exposure that impact on the dosimetry calculations. Research has recently shed light on the types of activities and locations of people within homes, the amount of time spent indoors, breathing modes, and the amounts of indoor air that people inhale. This information is critical to estimating the total amount of radon progeny inhaled, as is the influence of age and gender on the population dose distribution. The National Academy panel that examined this research established a 30% decrease between indoor and mine doses at the same exposure levels [*16*].

Studies have been done to determine the influence of aerosol parameters, body size, and breathing pattern on adults and children for the purpose of extrapolating exposure-dose-risk relationships obtained for underground miners to exposures to the general population. The huge estimated economic costs of radon measurement and possible mitigation for large portions of U.S. building stock make it essential that radon risk numbers be narrowed and uncertainties reduced so that costs relate to actual risk reduction.

Lung Cancer Risk to the Public from Exposure to Radon Indoors

While respiratory tract cancer risk from exposure to radon progeny in homes may be estimated from the epidemiologic studies of underground miners, these estimates are uncertain for several reasons. Important differences between miners and the general public are: (1) the uranium miners' exposure estimates and smoking histories were very poor, (2) the miners were exposed to an occupational setting that included a variety of toxic airborne pollutants, (3) nonmalignant respiratory disease is more prevalent among miners, and (4) miners perform heavier manual labor. Lastly, in dusty mine environments a larger fraction of the radon progeny is attached to particles, which differs greatly from residential settings.

Mathematical models are now being developed to estimate risk from radon. These models accommodate new information about differences between exposures in mines and homes as well as new information about radon doses to cells at risk [*16*].

Mechanisms of Lung Cancer Induction

Cellular and molecular studies are being used to investigate the mechanisms of radiation injury and repair from high linear energy transfer (LET) radiation and the interactions between radiation and carcinogenic chemicals (e.g., cigarette smoke) in producing respiratory tract cancer.

Measurements of chromosome and DNA damage and repair and of cell transformation can be used with exposures to

radon progeny to assess the effect of combined radon and co-pollutant exposures. The effectiveness of DNA repair mechanisms and the validity of extrapolating from effects observed at high doses to doses near background level is also being determined. Genetic susceptibility, which may play a key role in lung cancer development, is being explored in a study using uranium miners, some of whom have not yet developed frank tumors.

Besides contributing to an understanding of radiation-induced lung cancer, these fundamental studies may ultimately provide a general understanding of the process of carcinogenesis and lead to early detection and possible therapeutic outcomes. These studies—new in technique and approach—provide the only hope for identifying any effects at the low levels of radon exposure common to the majority of homes, schools, and workplaces.

Applied Research

Mitigation

Because the radon issue is amenable to solution and because it is largely the federal government that has raised the issue as a major public concern, efforts are underway to provide radon mitigation for homes, schools, and commercial buildings. Government research provides the basic techniques, which are then used by private sector mitigators. The goal of the research is cheap, durable, and reliable mitigation techniques for different levels of radon problems, different types of housing or other buildings, and different geographic areas. Research is also underway to develop diagnostic tests that provide adequate information on how long mitigation systems can operate reliably and how long-term mitigation will affect the house foundation or subsurface soil.

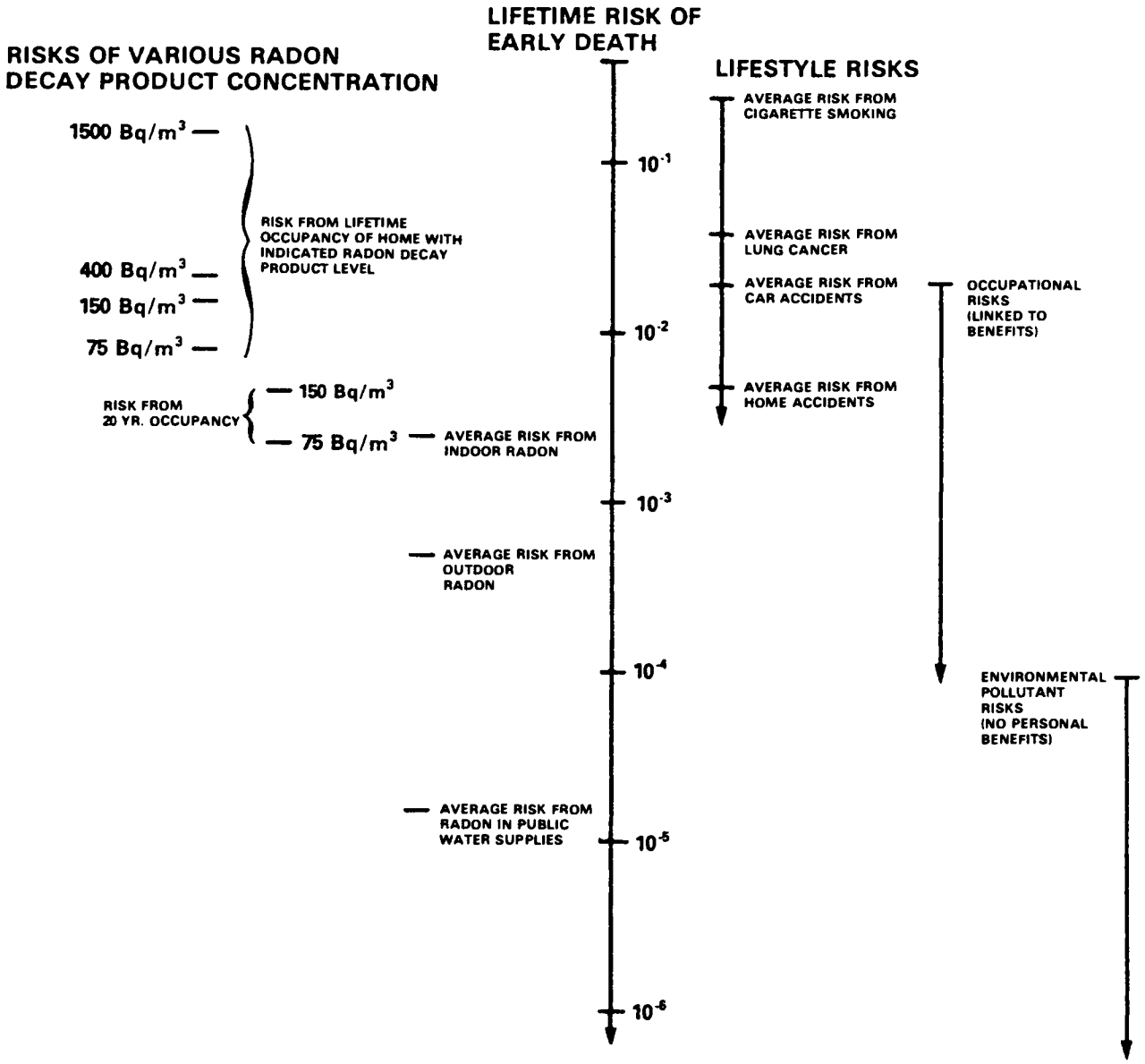

FIG. 2–Comparison of risk (reprinted with permission of A. V. Nero, Lawrence Berkeley Laboratory).

Mitigation in new construction differs greatly from mitigation as a retrofit procedure. It is usually easier, cheaper, and more reliable. Research is being done to develop inexpensive passive and active systems for various types of new construction. This is especially important for regions with elevated radon potential where builders can install this "radon proofing" in all new homes and only activate the active system when the indoor measurements of the finished home indicate a need. Results of mitigation research are quickly adapted into building codes and EPA protocols. Systems built into new construction need not be used if actual indoor radon measurements are low. Mitigation studies continue to address problems such as optimal gravel size and backdrafting that has been observed in systems that are being used widely.

Risk Communication

Risk communication is an important applied area of radon research. It may be motivational or educational in intent. Research and field testing is underway to develop a myriad of written and visual informational radon materials that address different groups, needs, and levels of education, and yet provide a balance of easily understood scientific information with appropriate motivational impact. These materials must recommend sensible actions, provide solutions, and answer questions that the public will raise. These are not easy goals, and effective risk communication must be an on-going testing and refining process. These materials must also be updated as more scientific information becomes available and as the most effective methods of risk communication are determined.

CONCLUSIONS

An often-raised argument is that radon exposure at lower levels represents a hazard known to be much greater than many other environmental hazards regulated with far less scientific knowledge. Dr. Anthony Nero of the Lawrence Berkeley Laboratory says that, "Radon risk is in the same range as the risks from dying of a fire in one's home or dying from falling down the stairs, risks we accept everyday" [*23*] (Fig. 2). The level of radon-related risk will never be zero, and national policies must reflect the different situations encountered in an indoor life style. Although radon-related risks can be reduced through mitigation, just as fire-related risks can be reduced through the use of smoke detectors, a risk as low as one death per million population may not be achievable for radon.

Another view of this same issue comes from Dr. Judith Klotz of the State of New Jersey Department of Health: "When we talk about added environmental risks that have been caused by either negligence or ignorant actions by humans, . . . we have to separate those we can avoid from those which happen to be there because this is the planet we are living on. We can't do anything about cosmic rays and nobody talks about not flying in planes because that may increase radiation doses. There are certain risks that are inherent in being a human being . . . on this planet. Unavoidable risks that are natural may have to at times be on a slightly different scale from avoidable risks which are put there by human beings by negligent or ignorant activity and which can be regulated against in a prospective sense" [*24*].

The message from these two perspectives is that we cannot use traditional assessments and policies for these differing situations. A reasoned and comprehensive approach should be sought just as other issues such as asbestos, electromagnetic fields, and indoor lead must also be addressed. As the debates on the radon issue get noisier, the science hardens, and policies become institutionalized, other nontraditional perspectives are worth thinking about.

As in all such areas of government involvement, much more needs to be done in terms of research and transfer of information. Policies that were developed quickly will need to be refined as more information becomes available. The push and pull of the industry and the costs borne by the real estate and home-building sectors add an element of check and balance to this unfolding story. Research progresses slowly when compared to policy needs. Compromise between the two must be undertaken.

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Subject Index

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