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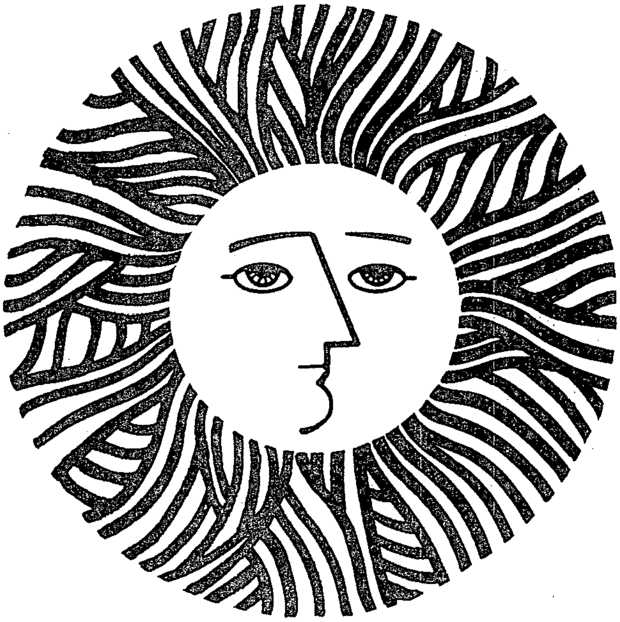
Anthony V. Nero, Jr.

August 1981



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A VIEW OF THE ISSUE

Anthony V. Nero, Jr.

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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INDOOR RADIATION EXPOSURES FROM RADON AND ITS DAUGHTERS: A VIEW OF THE ISSUE

Anthony V. Nero, Jr.

ABSTRACT

Exposure to radon daughters indoors can result in significant risk to the general public, particularly those living in homes with much higher than average concentrations. This paper reviews what is known about indoor concentrations, associated risks, and the effect of measures to save energy by reducing ventilation rates. It concludes that, by employing appropriate control measures in homes having unacceptably high concentrations, the average exposure (and therefore risk) of the general public can remain at its present level, or even decrease, despite programs to save energy by tightening homes.

KEYWORDS: health risk, indoor air qualiy, monitoring programs, indoor radon, radon daughter exposures, indoor air quality standards

INTRODUCTION

Radon and the radioactive elements to which it decays are universally present in outdoor air, and typically reach higher levels in indoor air. Very high airborne concentrations of these elements in uranium and other mines have been shown to increase the incidence of lung cancer among mine workers. If the increase in cancer incidence is proportional to exposure (roughly speaking, the airborne concentration times the duration of exposure), then the concentrations in the present U.S. housing stock -- although much lower than in mines -- could be causing thousands, perhaps more than ten thousand, cases of lung cancer annually among the U.S. population. A substantial number of cancer cases could be concentrated in a relatively small segment of the population, i.e., those exposed to levels much higher than average. Unless care is taken, the estimated radon-related cancer incidence could be increased by measures that reduce the ventilation rate, measures which are planned for national energy conservation programs for buildings. Through a careful program of screening and the use of specially-designed control programs concentrating on houses with high radon levels, such increases could be avoided; in fact current exposures and associated health risks could even be reduced. Associated with such a program would be a new kind of standard, one for indoor air quality. Such a standard could have a considerably different philosophical basis, structure, and implementation strategy than other air quality standards.

This paper summarizes available information on indoor radon concentrations and associated health implications, examines the effect of programs to reduce ventilation rates in buildings, and suggests how monitoring strategies and standards might be formulated to control, and even reduce, indoor concentrations of radon and its daughters.

CHARACTERISTICS OF RADON AND ITS DAUGHTERS

Radon is a gas that arises from the radioactive decay of radium, a naturally-occuring trace constituent of the earth's crust. Radium is found in small concentrations in rock and soil, as well as in building materials derived from crustal components. Because radon is a noble gas and therefore does not react chemically with the solid material in which it is formed, it can move through this material more readily than most elements and thereby reach water or air to which humans have access. The radon isotope of most concern, radon-222, arises from radium-226 and has a half-life of 3.8 days. (The "half-life" of a radionuclide is a period during which any given atom has a 50% probability of decaying to the next member of the decay sequence.) The first decay product, or "daughter", of radon-222 is polonium-218, which also decays radioactively. This sequence of decays continues until lead-206, a stable isotope, is reached (Figure 1).

Polonium-218 and the members of the decay sequence, immediately following (lead-214, bismuth-214, and polonium-214) have greater radiological significance than radon-222, because -- unlike the latter -- they are chemically active and may attach themselves to dust particles in the air. Should either these particles or the unattached daughters be inhaled, they can lodge in the lung. Because the daughters from polonium-218 through polonium-214 have short half-lives (no greater than 30 minutes), once they are collected in the lung, they are likely to decay to lead-210 and irradiate the surrounding tissue before the body's lung-clearance mechanisms remove them. In biological terms, the most significant radiation dose arises from the alpha particles emitted by polonium-214 and -218.

CONCENTRATIONS AND EXPOSURES IN U.S. HOMES

The radon in houses arises primarily from radon that migrates, by various mechanisms, from materials underlying the house or, in some cases, those making up the house. The house acts as a container for this radon, which leaks out as indoor air is exchanged for outdoor air. The rate at which air is exchanged is usually expressed in "air changes per hour" i.e., the number of house volumes exchanged per hour. Typical air-exchange rates for U.S. homes, averaged during seasons when windows and doors are ordinarily closed, are in the range of 0.5 to 1.5 air changes per hour, with a fairly small percentage of houses above and below this range.

For a specific radon source magnitude, expressed as the rate at which radon enters a building, the indoor concentration is roughly inversely proportional to the air-exchange rate; that is, for a given house and indoor radon emanation rate, halving the air-exchange rate will approximately double the indoor radon concentration (assuming, as is usually the case, that the outdoor radon concentration is considerably lower than the indoor concentration).

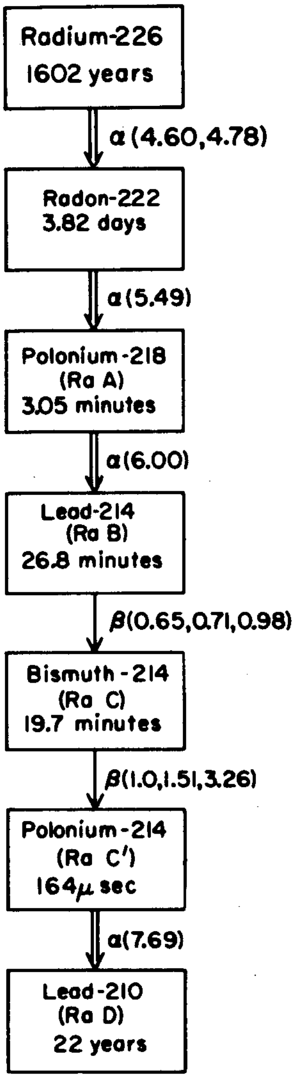

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Figure 1. Decay Chain, Radium-226 to Lead-210, indicating half lives and α or β decay energies (in MeV).

Typical radon concentrations in U.S. houses, averaged over the year,[1]* are in the range of 0.2 to 4 picocuries per liter of air (pCi/l). (A picocurie is an amount of radioactive material that yields 0.037 decays per second.) In a portion of U.S. homes, radon concentrations are higher, sometimes considerably higher, than this range. In some cases, these higher radon levels have been traced to building materials, either in the house or in its foundation, that incorporate industrial by-product material containing unusually high concentrations of radium. In other cases, however, the radon appears to arise from natural concentrations of radium in soil or rock under or near the house.

Because it is the radon daughters that pose the greatest radiological risk, a special unit has been devised to express the amount of exposure to the daughters: the "working level month" (WLM), so called because it was devised for measuring the monthly exposure of mine workers.[2] Ventilation and other mechanisms, such as filtration and plateout, tend to remove a portion of the radon daughters, so that in any given house or group of houses, there is some variability in the ratio of daughters to radon. Living continuously in daughter concentrations typically associated with a radon-222 concentration of 1 pCi/l would result in an annual exposure of about 0.3 WLM.[2] Assuming that individuals spend two-thirds of their time indoors, the indoor exposure would be approximately 0.2 WLM per year; and for the range of radon concentrations cited above for the national housing stock (0.2 to 4 pCi/l) exposures would be approximately 0.04 to 0.8 WLM per year. Those whose homes have higher radon concentrations would be subject to larger exposures, and a significant number of homes appear to have concentrations of 4 pCi/l or more.[1]

THE RISK FROM EXPOSURE TO RADON DAUGHTERS

The incidence of lung cancer among uranium (and certain other) miners is considerably higher than that among the general population, a difference that has been attributed to large exposures to radon daughters accumulated by these miners from working for prolonged periods in high daughter concentrations. Before adequate control measures were introduced, concentrations in mines were high enough that exposures of miners often considerably exceeded the current occupational limit of 4 WLM per year. The elevated incidence of lung cancer among such miners is the principal basis for determining a numerical relationship between radon daughter exposure and lung cancer. The results of studies of uranium and other miners may be summarized by stating that each WLM of exposure experienced by a miner apparently induced an added chance of lung cancer of 200 to 450 in a million.[3] Thus a miner who received about 10 WLM per year for 30 years (experiencing a total of 300 WLM) stood about one chance in ten of getting lung cancer from radon daughter exposures.

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*The numbers 1-7 in the text refer to technical notes at the end of the paper.

Extending this information to the the general population, whose exposure is much lower than miners', is difficult and uncertain: the typical mine worker of the epidemiological studies of radon and lung cancer was a male smoker who worked under conditions of high concentrations of airborne particles and who experienced very high radon daughter exposures. Exposures in homes are typically much lower. Ignoring the possible synergism of radon-daughter exposures with smoking or dust inhalation, and assuming the added chance of lung cancer to be proportional to exposure and equal to 200 to 450 per million per WLM, then an exposure of 0.2 WLM from living for one year in a U.S. home would induce 40 to 90 chances in a million of getting lung cancer. Hence subjecting a large male population to this exposure annually would eventually cause an incidence of 40 to 90 cases per million population per year. If the lung cancer incidence among miners were due primarily to a synergism between smoking and daughter exposure, the increased incidence might apply only to smokers. In this case, assuming 40% of the male population to be smokers, 15 to 35 males per million per year would be expected to contract the disease from the assumed exposure. Given these various uncertainties, the lung cancer incidence projected for the male population as a consequence of radon exposures of 0.2 WLM per year would range from 15 to 90 per million per year.

The experience of miners provides little direct information on the effect of radon daughters on the female half of the population. The existing lung cancer rate among women is a fraction of that among men, less than 50 per million per year as recently as 1960, giving an upper limit for radon-induced lung cancers among women that lies in the middle of the range cited above for men. (Recent increases in the lung cancer rate among women appear to be caused by smoking.) Based on this consideration alone, the estimated lung cancer incidence among women from radon exposures could be anywhere from 0 to 50 per million per year. This range must be viewed with some caution, however, since the historical exposure rate may have been less than 0.2 WLM per year and, in any case, there is no fundamental reason to expect a substantially different rate for men and women experiencing the same exposures.

Nevertheless, averaging these rates for men and women yields a nominal range for lung cancer incidence among the general population, assuming annual exposures of 0.2 WLM per year, of 7 to 70 per million per year. Corrections for age-distribution differences between miners and the general population may alter this risk estimate somewhat, probably to the higher side. It appears reasonable to adopt about 10 to 100 lung cancers per million per year as a rough estimate, corresponding to approximately 2000 to 20,000 cases annually among the U.S. population.

It is possible, on the other hand, that the cancer rate resulting from radon daughter exposures has little dependence on smoking, sex, or factors such as particle size distribution. Recent evidence, for example, indicates that the synergism thought to exist between radon exposure and tobacco smoking may have been based merely on earlier appearance of radon-daughter induced lung cancer among smokers than among nonsmokers. If such synergism does not exist, then the anticipated incidence of radon-related lung cancer at an exposure of 0.2 WLM per year, assuming linearity with no threshold, would be approximately 50 to

100 per million cases per year. This projection does exceed the observed lung cancer rate among the non-smoking population, however, particularly that portion of the population living outside cities. This discrepancy suggests that either the average radon daughter exposure is less than 0.2 WLM per year or that some of the factors noted do, in fact, affect the incidence. Because such factors may be important and because of uncertainties inherent in the data itself, it appears prudent to retain an estimate of 10 to 100 per million per year for the radon-related risk for the general population, if the average exposure is 0.2 WLM per year. This estimate is consistent with the present range of expert opinion on the risks from radon-daughter exposures.[3]

As indicated, such estimates are highly uncertain because we cannot yet accurately account for the possible synergisms involved and because uranium miners as a group do not represent a cross section of the general population. It is, furthermore, difficult to assess the reliability of radon risk estimates because of the fundamental uncertainty associated with the assumption that risk is proportional to exposure, even for low exposures. Nevertheless, indoor radon-daughter exposures in the typical range of 0.04 to 0.8 WLM per year may cause thousands, perhaps more than 10,000, lung cancers per year among the U.S. population--an incidence sufficiently high to require careful examination of any measure that could increase these exposures significantly. Of more immediate concern is the fact that some members of the general public may already be receiving radon daughter exposures high enough to add several percent to their probability of contracting lung cancer, an unusually large environmental risk. This portion of the population deserves our serious attention.

IMPACT ON HEALTH OF REDUCING VENTILATION

About a third of the energy used to heat (or cool) buildings is required because of losses due to the exchange of air between building interiors and outdoors. This energy requirement may be lowered by reducing infiltration (typically by weatherstripping or caulking) or, in commercial buildings, by reducing mechanical ventilation rates. While such measures save energy, they can also be expected to increase average indoor radon concentrations, average radon-daughter exposures, and the estimated radon-related incidence of lung cancer, unless steps are taken to avoid these increases. Residential buildings are of most concern in this respect, since current radon levels are typically higher in homes than in other types of buildings.

Comprehensive data on ventilation rates, whether from infiltration, open windows, or mechanical ventilation, do not exist for the present U.S. housing stock. Based on limited data, however, it appears that the infiltration rate in most U.S. houses lies in the range of 0.5 to 1.0 air changes per hour,[4] averaged over the heating and cooling seasons. During these seasons windows and doors are normally kept closed, so that natural ventilation contributes only a small portion (say 20 percent) of the total air exchange rate.

Nor do we have a precise view of the effect of energy-conserving retrofit programs (or of performance standards for new buildings) on the air exchange rate. If the average infiltration rate were as high as 1.0 air change per hour, as is often supposed, it would appear possible that an extremely vigorous energy-conservation program -- one that reached virtually every housing unit and was very effective for the vast majority -- could reduce the average infiltration rate by a factor of 2, i.e., to about 0.5 air changes per hour. (As indicated in note 4, the average infiltration rate actually appears to be lower than 1.0 air change per hour, so that a halving of the rate is not likely.) This fifty percent reduction could be expected to roughly double the radon level during periods when the building windows are closed (which is when most of the annual exposure would be expected to occur). Daughter levels would also roughly double (although in some cases the ratio of daughters to radon could increase, because a smaller portion of them may be removed by ventilation).[5] Unless attention is given to control measures, such a vigorous energy-conservation program could therefore approximately double the indoor radon-related lung cancer incidence of 10 to 100 cases per million per year that we have estimated for indoor radon levels of 1 pCi/l.

Less vigorous programs, such as the U.S. Department of Energy's Residential Conservation Service (RCS), can be expected to have a proportionately smaller effect on the estimated risk. This program, which is soon to provide energy audits recommending retrofit measures for reducing residential energy use, is expected to reach 10 to 30% of the nation's housing stock over the next five years and is expected to reduce their average infiltration rates by up to 25%. Thus the RCS program would reduce the infiltration rate for the entire housing stock by 10% or less, causing a corresponding increase in radon daughter exposures. The radon-related incidence of lung cancer would presumably be increased by a similar amount. On the assumption that current exposures are 0.2 WLM per year and no attention is given to avoiding increases, we could expect from 200 to 2000 additional lung cancer cases across the nation annually as a result of the 5-year program. This estimated increase could be avoided if, in the course of the program, areas where unusually high concentrations occur were to be identified and remedial action taken.

At the other extreme, very strong conservation measures could incorporate special features, particularly in new houses, to reduce infiltration rates to the vicinity of 0.2 air changes per hour, a fraction of the infiltration rate typical of a conventional house. This reduction would result in substantially higher radon concentrations, as well as radon daughter exposures, unless the house has features that prevent radon from entering or that remove radon or its daughters from indoor air. Energy performance standards presently proposed by Federal agencies for new buildings do not encourage such reductions in infiltration. Should they be modified to reduce infiltration substantially, as is being considered, such performance standards could also recommend measures to control radon daughter concentrations, as well as to avoid other indoor air quality difficulties.

One possible radon control strategy is to reduce the radon entry rate by sealing cracks, holes, or building materials from which radon emanates. In new building, construction techniques could be chosen to reduce transport of radon into the house. An active control technique is to clean the air with systems that use filtration, electrostatic precipitation, or absorption to remove airborne particles or gases. An alternative possibility, and one that would also control the levels of other indoor pollutants than radon, is to install a mechanical ventilation system that incorporates a heat exchanger, which recuperates most of the heat that would normally be transferred with the ventilating air stream.[5]

Some combination of these measures seems clearly warranted in two classes of energy-efficient houses: newly built super-tight houses where infiltration rates are a fraction of one air change rate per hour, and existing houses that are subjected to "super" retrofits that reduce infiltration rates to well below 0.5 air changes per hour. Another class of houses in which control measures should be introduced consists of those now having unusually high radon concentrations. It appears, for example, that a substantial fraction of the general public's total exposure to radon daughters may be occurring in the small portion of houses that have very high concentrations. Many such houses appear to cluster geographically, making it possible to rely on regional surveys to identify areas where remedial measures may be needed. Use of controls in unusually tight houses and proper attention to areas needing remedial measures would avoid, and even reverse, the trend to higher radon daughter exposures that could be associated with decreasing infiltration rates (see Figure 2).

Even before all such areas with higher-than-average radon concentrations are identified, efforts such as the Residential Conservation Service program can include ordinary infiltration-reduction measures, bringing infiltration rates to the vicinity of 0.5 air changes per hour. In the vast majority of houses, with relatively low radon levels, radon-related risks will remain very low, not warranting control measures. Those found to have such high concentrations as to constitute a significant risk for the occupants can be improved by incorporation of measures to reduce concentrations, thereby decreasing radon-related risks.

HEALTH COSTS AND BENEFITS OF REDUCED INFILTRATION

Reducing residential ventilation rates offers the clear benefit of reducing energy use. In order to make a purely economic decision on whether or not to incorporate infiltration-reducing measures in new or existing residences, the cost of reducing ventilation, say by weatherstripping or caulking, would have to be compared with the monetary value of the energy saved. However, altering the infiltration rate can have health effects, including those discussed above, which must be considered in weighing costs and benefits. Moreover, in addition to effects directly associated with energy use or production, reducing energy use also entails broader societal effects, including changes in the employment structure, reduced dependence on foreign oil, and even changes in the probability of war. Such societal effects must be

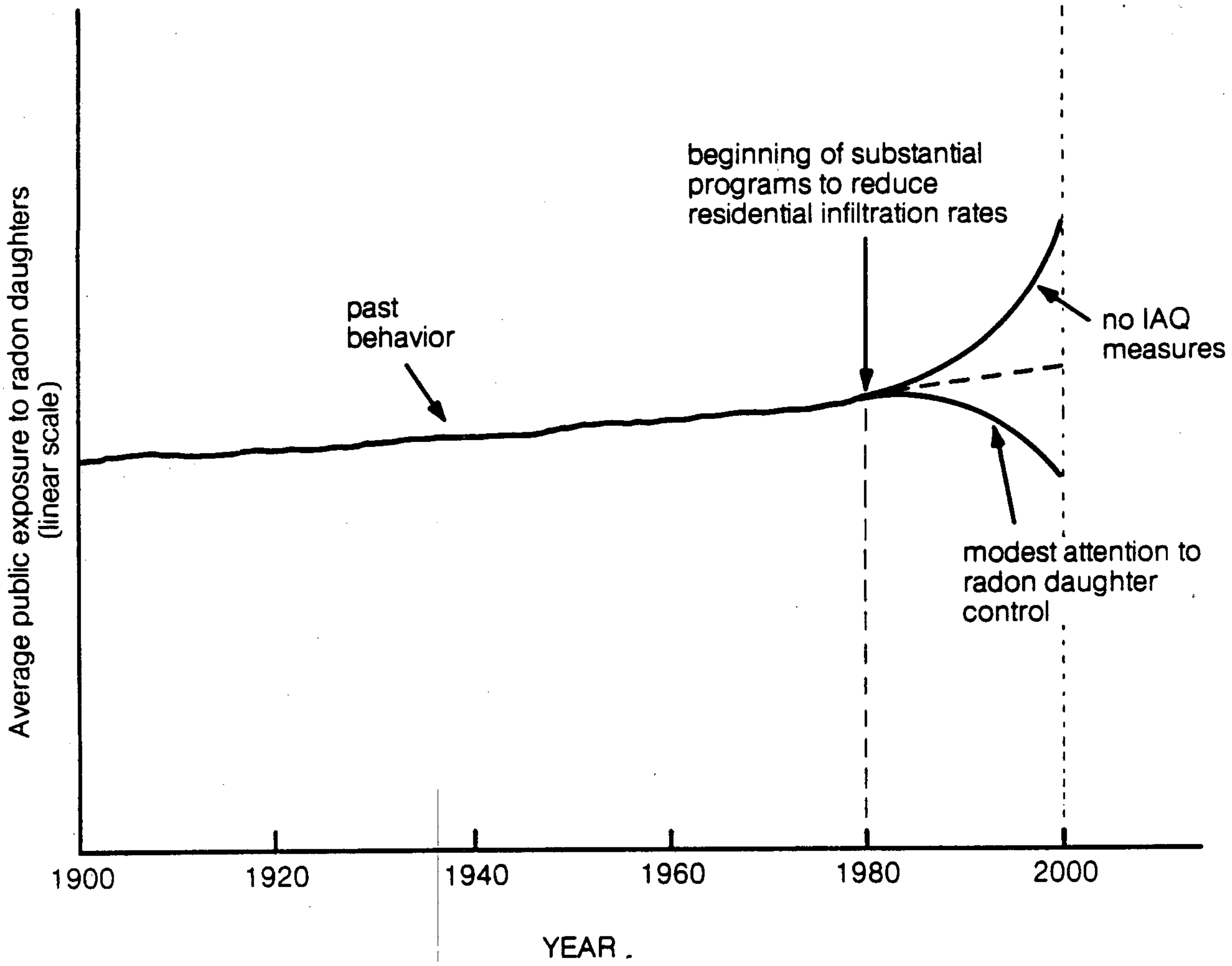

Figure 2. Illustration of Possible Trends in Public Exposure to Radon Daughters.

considered in themselves and also have a different range of health effects than those arising directly from changes in the energy system itself.

The health effects that may be specifically associated with reduced infiltration include those occurring as a result of direct effects on indoor air quality and effects owing to changes in the quality of outdoor air. Increased radon concentrations are only one potential effect on indoor air quality. Indoor concentrations of other pollutants that arise from indoor sources may increase. Indoor pollutants whose significance may be as great as radon daughters are combustion products (including carbon monoxide, nitrogen oxides, and particulates) and organics (including formaldehyde). In contrast to these, indoor concentrations of pollutants generated outdoors can be decreased by infiltration reductions. However, reduction of indoor pollutants from external sources is probably not as important as the increased levels of indoor-generated pollutants.

On the other hand, reduced energy use of itself would avoid health effects associated with the development and use of energy resources. For example, a national reduction in energy use due to reductions in infiltration due to the RCS program could be reflected in a reduced demand for electrical generation. Based on the level of infiltration reduction the RCS program could achieve, United States need for electricity generation could be reduced by several gigawatts. The health impact associated with several gigawatts and avoided by the RCS program is in the range of several to hundreds of deaths per year; for fossil-fueled generators, many thousands of cases of respiratory disease would also be associated every year. The annual death rate avoided is at the very bottom of the range of lung cancer incidence (200 to 2000 per year) estimated above for the RCS program, assuming current exposures of 0.2 WLM per year and no attention at all to controlling radon concentrations. A more important consideration may be the prospect of avoiding the much larger incidence of non-fatal diseases.[6]

A more realistic possibility, in any case, is that infiltration reduction, rather than avoiding electricity generation, would result in reduced combustion of gas or oil for heating individual houses. Although little is known about the health impact of locally-generated combustion products in outdoor air, dispersed combustion is likely to result in a greater health impact per unit energy than central station electric generation. The difference is likely to be widened by the existence in the housing stock of a significant number of faulty and inefficient systems. On the other hand, cracks in furnaces and flues could cause some fraction of combustion products to be injected directly into the home, in which case infiltration reduction could exacerbate associated indoor concentrations, perhaps to a degree that is more significant than the estimated health effects of increased radon daughter exposures. It is therefore not known whether reducing infiltration, of itself, increases or reduces net health risk.

There are, of course, other considerations, including other benefits of infiltration reduction and of reduced oil use in itself. The non-monetary, non-"health" benefit of reduced dependence on extranational sources of oil supply has been a principal incentive for reduced oil use. Increased personal independence from supply (or price) fluctuations due to supplier (or government) action is not insignificant. An ordinarily perceived benefit of infiltration reduction is the higher degree of comfort due to reduction in drafts and temperature variations. These reductions, in turn, make it more feasible to operate a house at a lower temperature. They may also improve health and well-being to a degree that is not now quantifiable.

Such consideration of various health effects, including those due to indoor air pollutants other than radon, indicate that it is simply not now known whether, on the average, infiltration reduction and associated changes in the energy system will have deleterious or beneficial effects on health. Regardless of the average effect, it appears that, for houses or communities found to have radon levels significantly greater than the typical range of 0.2 to 4 pCi/l, measures that could control radon daughter levels should be considered. In houses with very high levels of radon, remedial action should be taken whether or not infiltration-reducing measures have been taken, thereby providing a clear health benefit for the affected portion of the population.

An intriguing possibility is to associate with energy retrofit programs a screening element whose purpose would be to identify areas where indoor radon levels are unusually high.[7] This may be accomplished by sampling radon in a percentage of houses planned for retrofit. Alternatively, it may be sufficient simply to identify areas whose soil and related building materials have significantly higher than average radium content. Screening of this kind would be practical if houses with high indoor radon concentrations indeed tend to cluster by geographic area. The objective of such a screening element would be to find a large proportion of homes with high indoor radon concentrations, thereby permitting control and remedial efforts to be directed to the population at significant net risk.

Including a screening element would permit the program of saving energy to proceed apace, a program that has clearly perceived and substantial non-"health" benefits. Conversely, the retrofit program would serve as a vehicle for more fully characterizing the indoor radon problem. And the effort devoted to identifying houses or communities with high radon levels could result in a net decrease in average daughter exposures (and associated lung cancer incidence) and could identify for remedial action those houses that pose unacceptably high individual risks for occupants.

STANDARDS FOR INDOOR RADON DAUGHTER EXPOSURES?

The quality of indoor air can be assured using two distinct approaches, which are complementary in principle. The first is to regulate actual concentrations of indoor pollutants, an approach that requires formulation of indoor air quality standards. A more indirect approach is to control the major factors that affect indoor concentrations, primarily pollutant source magnitudes and ventilation rates.

In the absence of actual indoor air quality standards, attention commonly turns to the possibility of selecting a minimum ventilation rate. This approach suffers from two difficulties, in addition to the lack of information on current ventilation rates.[4] The first is that variations in source magnitudes, e.g., for radon, formaldehyde, or nitrogen dioxide, appear to be more responsible for variation in airborne concentrations than is the ventilation rate. Regulatory efforts to assure indoor air quality by prescribing housing characteristics ought therefore to devote adequate attention to controlling pollutant sources, perhaps even more than to the ventilation rate, at least for conventional residences.

The second consideration, often overlooked, is that any ventilation standard should be utilized as a <u>design goal</u> and not as a <u>minimum</u>. The ventilation rate selected as a design goal would be chosen considering many of the factors discussed above and would be achieved by careful formulation of building standards, taking air quality, energy efficiency, and other factors into consideration. Choosing a goal rather than a minimum would avoid the danger of overdesign, leading to excessive ventilation rates that unnecessarily waste energy, and would correspond well with indoor air quality standards that, as one component, seek to achieve acceptable <u>average</u> indoor concentrations. Taking this approach appears particularly important for controlling exposures to radon daughters, where both average concentrations and their frequency distribution are of interest.

Although a daughter exposure limit of 4 WLM per year applies to individuals who are occupationally exposed, no standard has been established for members of the general public. For exposure to man-made radioactivity (as well as a number of non-radioactive airborne contaminants), limits for the general public are generally one-tenth of the values established for workers. For radon daughters, which are, of course, not man-made, such a limit would be difficult to implement since surveys have shown that a significant number of houses have concentrations yielding more than 0.4 WLM per year, and variability also exists from area to area, house to house, and time to time.

In fact, it is because of this variability that we need to determine a philosophical basis for indoor air quality standards prior to designing a standard for indoor exposures to radon daughters. Present "ambient" air quality standards applying to the general public are designed for outdoor air pollutants. These standards are implemented on the basis of a few measurements that characterize the exposure of a population in an air basin. Assuming that measured concentrations of pollutants characterize air quality throughout the air basin, such standards also protect each individual in the basin. Such compatibility of limits applicable to populations and to individuals does not exist for indoor air quality, not only because internal pollutant sources vary from one building to another, but also because pollutant levels depend on how the building is operated. While indoor limits could be formulated for application to "worst-case" situations, e.g., with windows closed, little wind, or high source strength, such an approach would not provide a basis for realistic evaluation of actual risks and control possibilities.

A practical solution to the problem of developing a standard for indoor radon daughter exposures may be to construct a two-part standard--one part limiting the exposure for individuals and the other part setting an acceptable average value for population exposures. A precedent for such an approach can be found in standards related to individual and population exposure to radiation from nuclear power plants and other facilities during routine operation. In the case of radon daughters, a comparable approach could be designed to protect virtually every individual from excessively high exposures and also to maintain the average exposure of the population at a much lower level. The lower exposure, corresponding to an acceptable average risk for the population, would be chosen considering the average behavior of buildings (perhaps with some variability by geographical area), and would be implemented through ordinary building standards, possibly even including quality control on materials that emit radon or other pollutants. The individual would be protected against excessive risk by enforcement of the higher individual limit, which would be met by virtually every building. For buildings suspected of exceeding the individual limit, indoor air quality could be monitored to determine whether remedial action is needed. (As a practical matter, a "trigger" level for such action could be set somewhat lower than the individual limit, therefore taking some account of measurement uncertainties, variability in the way each building is operated, and so on.)

In devising standards for radon daughter exposures, one way of applying this approach is apparent: an individual limit could be established in the range of 0.4 to 4 WLM per year, i.e., 10 to 100 percent of the occupational limit, and the general-population average value could be based on an acceptable level of risk, considering the costs and benefits of various options. Individuals would be protected by a limit that is at least as strict as that applied to workers. Assuring a smaller risk to the average member of the population could be accomplished by carefully formulated building standards that--among other things--take into account both the building type and local radon source strengths.

Such a two-part indoor radon standard would accommodate the existing situation. On the one hand, it would require remedial action to reduce the risk to that portion of the population now exposed to high levels of radon and, on the other hand, it would not require that individual houses meet standards devised to protect populations. For the present, the population risk from radon daughter exposure would be held essentially constant or even reduced, in spite of programs to reduce infiltration rates in buildings, because remedial measures to meet the individual standard would reduce the risk of those who are highly exposed and presently at greatest risk.

CONCLUSIONS

The present exposure of the general public to radon daughters may account for a substantial number of lung cancers in the United States. Moreover, a significant number of individuals may suffer exposures large enough to increase the risk of lung cancer during their lifetime by a few percent or greater. Enough is therefore known about exposure of the public to radon daughters to warrant a vigorous program to understand more fully the size and variability of exposures and to identify that portion of the population exposed to excessive concentrations of radon daughters. In addition, programs that would reduce building ventilation rates significantly below the range now typical of U.S. housing should incorporate measures to safeguard, if not improve, indoor air quality. Less vigorous conservation programs--those that would have only modest effects on ventilation rates (and thus indoor air quality) and very significant effects on individual and national energy requirements-- could be used as vehicles for monitoring radon concentrations in the housing stock and, especially, for identifying houses with high levels. Ultimately, indoor air quality standards should be developed to protect every individual from excessive exposures and, through building standards, to control average exposures to an even lower level.

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TECHNICAL NOTES

1. Measured Indoor Concentrations of Radon and Its Daughters

The table (adapted from Ne81) summarizes indoor measurements of radon and daughter concentrations in U.S. residences. (See note 2 for discussion of PAEC.) As indicated in the table, a variety of sampling approaches were used in these measurements, including single grab samples and integrated year-round sampling. Although it is clear that levels greater than 4 pCi/l occur, it is not known how frequently they occur or in how many cases annual average concentrations exceed this level. Because health effects are thought to be associated with cumulative exposure (rather than with peak concentrations), average concentrations (e.g., averaged over a year) are of greatest interest for health risk assessment purposes (see note 3).

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Table. Selected radon and radon daughter measurements in U.S. residences (residences are single family except where noted)

Location	Reference	^{222}Rn (pCi/l)[a]	Daughter PAEC (WL)[a]	Number of Residences	Type of Measurement	Comments
ORDINARY AREAS:						
Tennessee	Lo80		0.008(0.0008-0.03)	15	Grab	Shale area; mostly concrete construction
Boston	Ye72	0.07(0.005-0.2)	(up to 0.002)	7	Grab and ventilation	Single family; air exchange rate: 1-6 h^{-1}
		0.09(0.01-0.2)	(up to 0.002)	3	Grab and Ventilation	Multiple family; air exchange rate; 5-9 h^{-1}
NY/NJ	Geo78	0.8[b](0.3-3.1)	0.004[b](0.002-0.013)	21	Several integrated measurements over year	17 single family; 3 multiple family; 1 apartment bldg.
New York	F181	1.0(0.4-2.1)		11	Integrated winter[c]	Conventional houses
		6.4(2.0-26)		7	Integrated winter[c]	"Energy-Efficient" houses; ventilation rate not measured
Illinois	Ru79	(0.3-33)		22	Grab	Wood-frame construction, unpaved crawl spaces (windows closed)
San Francisco area	Be79	(0.04-0.8)		26	Grab and ventilation	Air change rate: 0.02-1.2 h^{-1} (windows closed)
U.S./Canada	Ho80	(0.6-22)		17	Grab and ventilation	Energy-efficient houses; air change rate: 0.04-1.0 h^{-1}(windows closed)
Maryland	Mo81	(0.1-27)	(0.001-0.12)	53	Grab and ventilation	Air change rate: 0.06-1.6 h^{-1}
SPECIAL AREAS:						
Grand Junction Colorado	Ba75		0.006[b]	29	Integrated year round	Controls for remedial action program (which has included houses in range 0.02-1 WL)
Florida	Gu78		0.004(0.0007-0.014)	26	Integrated year round	Controls on unmineralized soils
	Gu78		0.014 (up to 0.10)	133	Integrated year round	Houses on reclaimed phosphate lands
Montana: Butte	En80		0.02	56	Integrated year round	Intensive mining area
Anaconda	En80		0.013	16	Integrated year round	Intensive mining area

[a] Individual values are averages; values given in parentheses are ranges. All measurements are in living space; values in basements are typically higher.

[b] Geometric mean.

[c] Limited sampling indicates summer concentrations are approximately 20% of winter.

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Ne81 Nero, A.V., 1981, "Airborne Radionuclides and Radiation in Buildings: A Review," Lawrence Berkeley Laboratory Report LBL-12948, submitted to *Health Physics*.

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2. Units for Measuring Radon Daughter Concentrations and Exposures

Airborne concentrations of radon daughters, like radon itself, can be specified in picocuries per liter (pCi/l) or equivalent units. For radiation protection purposes, it has been useful to characterize radon daughter concentrations in terms of the total alpha energy emitted as a result of decay of the short-lived daughters (polonium 218 to polonium 214) to lead 210, a long-lived radionuclide. This "potential alpha energy concentration" (PAEC) is an indicator of potential dose to the lung which, in turn, may be associated with increased lung cancer incidence on the basis of epidemiological studies and other evidence (see note 3).

The conventional unit for PAEC is the working level (WL), which has a value of 1.3×10^5 MeV/l, the potential alpha energy per unit volume that would be associated with air containing approximately 100 pCi/l of each of the short-lived daughters. For an arbitrary mixture with polonium 218 concentration I_A, lead 214 concentration I_B, and bismuth 214 concentration I_C, the PAEC is approximately equal to $(0.10\ I_A + 0.51\ I_B + 0.37\ I_C)$ WL/(100 pCi/l). The associated exposure unit, working level month (WLM), is the exposure that an individual would experience remaining in 1 WL of daughters for 173 hours (an average working month).

Were a volume to have a constant source of radon and no mechanisms (other than radioactive decay) for removal of radon or its daughters from the enclosed air, the activity concentrations of each radionuclide (given in pCi/l) would eventually reach a state where all were numerically equal. Such a condition (referred to as "equilibrium") is never achieved in practice because of removal mechanisms such as ventilation and daughter "plateout". Ventilation both reduces the radon concentration and decreases the ratio of daughters to their parents below one. Plateout, the attachment of daughters to walls and other surfaces, also decreases this ratio.

The equilibrium condition of radon and its daughters is conventionally indicated by an "equilibrium factor" (F) that is the ratio of actual daughter PAEC to the PAEC were each daughter to have the same activity concentration as that of the radon actually present. Thus F = PAEC/(radon concentration/100), where the PAEC is given in WL and the radon concentration in pCi/l. In spaces with low daughter-removal rates, F is close to one. In houses, equilibrium factors have usually been found to lie in the range 0.2 to 0.8, although factors above and below this range have sometimes been found. (See references for note 1.)

Taking 0.5 as a typical equilibrium factor, the annual exposure associated with a constant radon concentration of 1 pCi/l may be calculated as follows:

exposure rate for 1 pCi/l =

$$\left[0.5 \times 1 \text{ pCi/l} \times \frac{1 \text{ WL}}{100\text{pCi/l}}\right] \times \left[\frac{1 \text{ WLM}}{1 \text{ WL} \times 173 \text{ hrs}}\right] \times \left[\frac{8760 \text{ hrs}}{\text{year}}\right]$$

$$= 0.25 \text{ WLM/year.}$$

The WLM is not a direct indication of dose for a variety of reasons, such as: the degree to which daughters are collected depends on particle size; lung mass and lining area depend on age; breathing rates differ between workers and the general population. In some cases, it is suitable to define a "working level month equivalent" (WLME). For example, the average breathing rate of the general population is thought to be 50% less than that for uranium miners. If uranium miners are taken to be the standard for defining the WLME, then the public would have to be exposed to 1 WL for about 350 hours to accumulate an exposure of 1 WLME.

This discussion has not expressed radiation doses in the more ordinary units of rad, rem, or Sievert. It is possible to convert WLM to these units using detailed models of breathing rate, particle sizes, and lung deposition patterns, but in any case, it would be necessary to convert these results back to WLM to utilize the epidemiological data from miners. Little is gained, therefore, for purposes of risk assessment or radon daughter control, by utilizing the more ordinary units, since dependence of risk on doses to specific tissue is not adequately understood.

3. Models for Health Effects from Exposure to Airborne Radon Daughters

The dose-response factor used in this paper is taken from the 1977 report of the United Nations Scientific Committee on the Effects of Atomic Radiation (Un77), which reviewed a variety of epidemiological data from uranium and other miners. This dose-response factor is given as an "absolute" risk factor, i.e., a risk (from radon daughter exposure) that occurs independently of and in addition to risks from other causes. The data can also be interpreted in terms of "relative" models, which assign an added risk that is proportional to the risk that would otherwise occur. Either approach permits age-related factors (age at exposure or age at onset of disease) to be accounted for explicitly.

The difference in the lung cancer risk from radon daughter exposure as estimated from an absolute and a relative risk model can be significant, although it is not necessarily a large factor. To some extent, the differences depend on how the possible synergism with smoking is treated. For example, estimates by the U.S. Environmental Protection Agency (Gu79) use a relative risk model that treats smokers and nonsmokers together and, because it assigns the same multiplicative risk per WLM to either group, it effectively assumes synergism between smoking and exposure to radon daughters. Nonetheless, the EPA risk estimates are at the high end of the range indicated in the text of this paper (probably because the percentage of smokers among the public is assumed to be the same as among miners). This contrasts with the estimate in a recent comment of the National Council on Radiation Protection and Measurements, which suggested that only "about 20% of the spontaneous (nonsmoking) lung cancer incidence of the U.S. population could be attributed to natural radon daughter exposure" (Ra80). The Council used a recently formulated model (Ha81) and obtained an estimate of about 15 lung cancers per million per year among the general population from 0.2 WLM per year exposures. Thus, their estimate, although based on a substantially different approach from that of the EPA and regarded by the authors to be "conservative" (i.e., more likely to be an overestimated than underestimated), is toward the bottom of the 10 to 100 per million per year estimate employed in this paper. Hence, expert reviews of the available data result in a wide range of estimates, though all assume the increased probability of lung cancer to be proportional to the exposure, and even this assumption is a hypothesis. (A recent review (Na81) notes that the maximum effect per WLM appears to occur for cumulative exposures of hundreds of WLM, less than the occupational exposures sometimes encountered in the past, but much larger than typical exposures of the general population.)

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Ha81 Harley, N.H., and Pasternak, B.D., 1981, "A Model for Predicting Lung Cancer Risks Induced by Environmental Levels of Radon Daughters," Health Physics 40, 307-316.

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Un77 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1977, Sources and Effects of Ionizing Radiation, United Nations, New York.

4. Ventilation and Infiltration Rates in U.S. Homes

There are few data available on ventilation or infiltration rates in residential buildings. The few measurements that have been performed, however, suggest that most existing residences have infiltration rates (averaged during the heating season) in the range of 0.5 to 1.0 air changes per hour (ach). But the distribution extends above and below this range: a long tail extends substantially higher, with a few percent of houses greater than 2.0 ach, and a significant number of residences are in the 0.3 to 0.5 ach range. Because of occupant behavior--opening doors, windows, and fireplace dampers-- total ventilation rates average somewhat more than the infiltration rates (e.g., 20 percent greater in a typical case).

Infiltration rates depend strongly on the type of house, the climate, and, indeed, the microclimate. One might expect, for example, newer housing to be "tighter" than older, and this appears to be the case. Grimsrud et al (Gr81) present estimates of heating-season infiltration rates based on measurements in over 200 houses distributed throughout the United States and Canada. For the entire sample, the average estimated infiltration rate was 0.67 ach but for the half of the houses built within the two years prior to measurement, the average estimate was 0.48 ach. Even among 200 low-income, often older, residences in U.S. cities, measured heating season infiltration rates--before weatherization--averaged 1.1 ach, with most below 1.0 ach: 18% less than 0.5 ach, 39% between 0.5 ach and 1.0 ach, 19% 1.0 - 1.5 ach, 10% 1.5 - 2.0 ach, and 10% > 2.0 ach (Gr79).

It thus appears that average infiltration rates in U.S. housing are less than 1.0 ach, probably in the vicinity of 0.7 - 0.8 ach, and that--considering occupant behavior--net ventilation rates may average in the vicinity of 1.0 ach in heating/cooling seasons. Houses with significantly higher-than-average infiltration rates can be tightened substantially by fixing broken window panes, caulking, weatherstripping, and plugging holes. To postulate that even an extremely vigorous program could reduce average infiltration rates in the entire housing stock by half, as has been suggested, appears optimistic and must be considered a rather far-fetched upper limit for the effectiveness of infiltration-reduction programs; to achieve this goal, virtually every house in the U.S. would have to better the energy performance of well-constructed new housing that uses weatherstripping and caulking, but not unusual construction features.

References:

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5. Control Techniques for Radon and Its Daughters

The ultimate purpose of any radon control technique is to reduce human exposure to radon daughters. This goal may be accomplished by controlling the radon source strength. It may also be accomplished by cleaning or refreshing the air to remove the daughters directly or to reduce the concentration of radon, from which the daughters arise.

Radon can enter a house from various sources and by various transport mechanisms, so that control of source strength can take several forms. The two basic possibilities are to remove the source material or to obstruct transport mechanisms. As remedial actions for existing housing, the first possibility is very costly, but it does have limited potential for application in new housing. Transport mechanisms include diffusion through solid material and convective movement of air through the building shell or through source material that is within the shell. Sealants and barriers can reduce diffusion and close convective routes. Assuming no change in the effectiveness of radon daughter removal, the daughter concentration is reduced by the same proportion as the radon source strength.

Active control techniques have a more complex effect on daughter concentrations. Increasing ventilation of the building reduces the radon concentration in a relatively simple way. This of itself causes a corresponding decrease in daughters. In addition, increased ventilation can reduce the ratio of daughters to radon, thereby causing an additional decrease in daughter concentrations. The effectiveness of reduced ventilation in reducing this ratio, however, depends on the importance of other mechanisms for removing daughters, which attach to particles, as well as walls, fan blades, and other surfaces. As a result there is no simple way to characterize the daughter concentration associated with a given radon concentration and ventilation rate (see also note 2). For example, removal of airborne particles by filtration removes daughters, but also may affect the fraction of daughters that are unattached, which may affect the radiation dose from a given daughter concentration. To complicate matters even more, the unattached daughters may deposit more readily on walls, thus decreasing their airborne concentrations. Circulating air within the house (without ventilation) also can increase daughter deposition significantly, thereby decreasing airborne concentrations. Depending on the circumstances, such deposition may be a more effective removal mechanism than ventilation; thus ventilation rate alone is not a good indicator of the ratio of daughters to radon. Some of the lowest equilibrium factors (note 2) have been found in relatively tight houses. For these reasons, the evaluation of active control techniques is a complex undertaking.

Only modest efforts have, to this date, been devoted to testing the effectiveness of the two basic approaches to controlling radon daughter exposures. Experience with radon source control techniques has been primarily the result of efforts to reduce indoor exposures to radon daughters in U.S. and Canadian communities associated with uranium mining operations. In some cases, structures have been built on or with uranium tailings, which have high radium concentrations and, when used in building materials or as landfill under structures, can contribute unusually large amounts of radon indoors. In some of the communities, high indoor concentrations appear to arise merely because the structures are built in areas with naturally high uranium concentrations. Several communities have faced this problem, and intensive remedial programs have been initiated during the last decade or so. The principal measures used have been to remove the tailings, often a difficult and expensive process, and to seal cracks and openings by which radon enters the house, an approach that has met with success in some cases. Many of the results achieved in such programs undertaken in Canada are reported in recent annual workshops on this subject (At78-80). The effectiveness of sealants as a radon barrier have also been measured in laboratory studies (Au74, Cu78).

Active measures to clean the air, or refresh it, have begun to be investigated. Windham et al. (Wi78), Holub et al (Ho79), Cliff (Cl80), Nazaroff et al (Na80), and Jonassen (Jo80) have begun to study the effect of air mixing, furnace fan operation, ventilation, and filtration on radon daughter concentrations. More intensive studies are required because of the complex effect these measures can have on daughter removal processes. The effectiveness of mechanical ventilators with air-to-air heat exchangers in controlling radon concentrations has been demonstrated in one energy research house (Na81). During the winter of 1980-81, a series of studies of the effectiveness of air-to-air heat exchangers as an air quality control measure in conventional houses with relatively low infiltration rates was conducted in the eastern United States; results are now becoming available (Of81).

<u>References</u>:

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Wi78 Windham, S.T., Savage, E.D., and Phillips, C.R., 1978, *The Effects of Home Ventilation Systems on Indoor Radon-Radon Daughter Levels*, U.S. Environmental Protection Agency Report EPA-520/5-77-011, Washington; October.

6. *Health Risk Assessment for Energy Technologies*.

It is not possible to make precise estimates of health risks from fossil-fuel use, energy conservation, or any other energy technology. Large uncertainties arise from variability in the mode of use, and in the type and level of emissions or concentrations, as well as from complexities in the nature of the exposures, and lack of knowledge of the health effects of specified exposures. Perhaps even more important, the effects of different technologies often are not directly comparable. For example, one cannot compare the added risk from increased indoor exposures with the risk from continued dependence on foreign oil, or the risk of lung cancer from radon exposures with the diverse respiratory illnesses associated with breathing emissions from homes that burn oil (or from electricity generating plants that burn coal). At the same time, there is an unfortunate, and often misleading, tendency to compare what can be compared and ignore the rest, a practice that often ignores the most important risks.

Note 3 discusses the quantifiable risks from exposure to radon daughters. The risk estimate indicated in the text for fossil fuels arises from studies in the U.S. population correlating "premature death" and respiratory illness with airborne concentrations of particles, sulfates, and other substances that arise from combustion of fossil fuels, especially coal. The effects depend, inevitably, on the measures taken to control emissions at the plant, the manner in which emissions are transported and undergo conversion, and the populations exposed. Actual estimates of the effects are highly uncertain, even controversial, and sometimes staggering. For example, it has been estimated that U.S. mortality from coal burning may be up to 50,000 deaths per year (Of79). On the other hand, estimates based on reasonably well-controlled coal-fired plants yield annual fatalities on the order of ten per gigawatt of electricity (which includes deaths due to accidents or breathing coal dust) and a much larger number of associated illnesses (Sc79).

References:

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Sc79 Schurr, S.H., Darmstadter, J., Perry, H., Ramsay, W., and Russell, M., Energy in America's Future: The Choices Before Us, John Hopkins University Press, Baltimore.

7. Monitoring Radon and Its Daughters

A large variety of techniques is available for monitoring radon and its daughters. All of the techniques that are practical for measuring airborne concentrations that occur in the general environment, including indoors, use devices that detect the radiation emitted when radon or its daughters decay. Many such devices are sensitive to the alpha particles emitted (the same ones responsible for most of the dose to the lungs), but a few detect beta or gamma radiation.

No single monitoring instrument satisfies the requirements associated with all applications. Instruments vary widely in cost and type of measurement. Possible applications of monitoring instruments range from detailed research studies of the behavior of radon daughters, requiring complex instruments costing tens of thousands of dollars, to large-scale surveys, which may deploy fifteen-dollar devices that are used for only one measurement. Complex instruments can often measure the variations of radon or daughter concentrations with time, whereas simpler, less-expensive devices often yield average concentrations over a long period of time or the concentration at a single time. The least expensive devices also tend to be relatively inaccurate at low concentrations, but this may be acceptable in a large-scale survey whose purpose is to determine the average concentration in the houses selected. In contrast to this, greater accuracy may be required of an instrument used in surveys to determine compliance of individual houses with some standard. A particular difficulty is that often the device that is most satisfactory in terms of cost or accuracy is unsatisfactory in that it measures the wrong parameter, e.g., the concentration of radon, rather than its daughters.

For any survey, whether to determine concentration averages (or frequency distribution) or to check that concentrations in individual houses do not exceed some limit, formulation of the program and selection of instrumentation strongly affect one another. Instruments, measurement procedures, support laboratories, and data analysis techniques all influence the degree to which specified monitoring objectives can be achieved, and program objectives must be chosen with a realistic view of the costs, capabilities, and limitations of various measurements techniques.

A 1974 paper by Budnitz (Bu74) reviewed instrumentation for monitoring radon and its daughters. This review has recently been revised and updated (Ne81b). George (Ge80) surveyed monitoring instruments, giving particular attention to calibration techniques.

References:

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Ne81b Nero, A.V., 1981, "Radon-222 and Its Daughters: A Review of Monitoring Instrumentation," Lawrence Berkeley Laboratory Report LBL-11565, submitted to Health Physics.

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